Modelling future flood risks for inland and coastal adaptation planning

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Abstract

Floods have historically threatened human and natural systems and the risk they represent is likely to be affected by climate variability and change over the next century. With rising sea levels putting further pressure on low-lying regions, there is a need for a catchment-to-coast understanding of flooding hazard to inform on potential anticipatory measures. Computational flood modelling advances offer opportunities to better support decision-making on flood risk management. While adaptation is increasingly recognised as needed in the face of climatic changes, the implementation of adequate solutions has faced fundamental barriers. This has led to a call for integrated assessments of flood risk that adopt a holistic approach in the depiction of physical flooding processes and engage with local stakeholder knowledge.

Britain's largest protected wetland – the Broads – and its neighbouring coast, were chosen as a study site to assess future flood risk and stakeholder-defined adaptation measures. A 1D-2D hydraulic model was developed in HEC-RAS to simulate flooding impacts under 21st-century scenarios of extreme sea level, extreme river discharge and for combined events, based on UK Climate Projections (UKCP18). The model was designed iteratively, engaging with local perspectives of flood risk and adaptation, notably during a scientist-stakeholder workshop. The results highlighted the area's sensitivity to different rates of sea level rise, with inundation extent increasing by 15-135% and river saline incursions up to 30 km inland by 2080. While highly unlikely, combined events were found to exacerbate flooded area by 5-40% and average depth by 1-32%. Stakeholders showed a willingness to act on these threats and deviate from current practices, favouring a protective strategy based on a tidal barrier or storage areas. This research shows the potential for integrated modelling approaches to create an interface for science and practice, producing usable information for decision-makers and thereby promoting action on adaptation.

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Chapter 1 – Introduction

1.1. Research problem and motivation

Floods represent significant and regular threats to a great number of people worldwide. In Europe, flooding is the costliest natural hazard (Whitfield, 2012) with damages on the rise as populations grow in flood-prone areas (Hallegatte *et al*., 2013) and human activities lead to land-cover changes (He *et al*., 2013). Recent severe disruptions in the UK during the 2013/2014 and 2015/2016 winters were reminders of the devastating potential of extreme flooding. While there is still much uncertainty in attributing a climate signal to a possible trend in extreme events (Wilby *et al*., 2008), climate models suggest that more frequent and intense precipitation could be expected (Wang *et al*., 2017), therefore increasing flood risks. On the other hand – as the Intergovernmental Panel on Climate Change (IPCC) reported (Church *et al*., 2013) – there is a high level of confidence that sea levels will continue to rise throughout and beyond the next century (Rohling *et al*., 2013). Changes in mean sea level are fundamental drivers for extreme sea level events (Menéndez and Woodworth, 2010), thereby putting further pressure on coastal regions. These trends highlight the need for better preparedness and an improved understanding of future hazards.

Coasts and low-lying regions are among the most sensitive areas to climatic changes and related hazards (Wong *et al*., 2014). These complex zones hold significant value for both human and natural environments, which are generally tightly coupled into what is referred to as a socio-ecological system (Hopkins *et al*., 2012). Their vulnerabilities can vary in nature and scope. Storm surges can for example cause significant flooding and erosion damages to coastal towns or agricultural land (Neumann *et al*., 2015). Extreme sea levels can moreover threaten plant and animal communities in estuaries through the intrusion of saltwater (Mulamba *et al*., 2019). As the interface between land and sea, coastal regions are at the intersection of a wide range of hazards. Flooding alone can occur as a result of coastal, fluvial or other sources. There has been growing concern in the way these different processes may interact and combine to exacerbate flooding (Ganguli and Merz, 2019). With Sea Level Rise (SLR) projected to continue to accelerate over the next century (Church *et al.*, 2013), particular attention towards managing flood risks in coastal areas is therefore necessary.

While the decrease of anthropogenic greenhouse gas emissions can have important impacts of the rate of SLR, global mean sea levels are expected to continue to increase for the foreseeable future, even if significant mitigation measures are adopted (Nauels *et al*., 2019). There has therefore been a recognition of the need for coastal regions to adapt to be able to better cope with the potential impacts of climate change and SLR (Wilby and Keenan, 2012). Adaptation to environmental changes is not exclusive to, but closely linked to Flood Risk Management (FRM) in coastal regions and has been a historical feature of human societies. Although a wide range of options and strategies have received increased attention in the context of climate change (Nicholls *et al.*, 2007), adaptation has faced challenges in its implementation.

Barriers to adaptation are diverse (Moser and Ekstrom, 2010), and can be attributed not only to the underlying uncertainties of future climate projections, but also – in the case of coastal areas – to the presence of competing interests and management priorities from varied stakeholders (Wong *et al.*, 2014, Thorne *et al.*, 2017). Mastrandrea *et al.*, (2010) moreover argued that there was still a gap between climate-impacts research and adaptation planning and management. They observed that “recommendations for adaptation actions based on scientific research often fall short of providing information that can be directly useful in on-the-ground decision making”. As a response to this challenge, FRM, alongside other fields of environmental management, has identified stakeholder involvement as crucial for its successful and sustainable implementation (Evers *et al*., 2016). While participatory activities have become a common practice in FRM, it remains poorly understood what their impacts are on the production of knowledge on flooding and few studies have looked at the integration of stakeholder perspectives in the modelling of future flood risks.

In the context of growing pressures from climatic changes there has been a paradigm shift in FRM and flood policy towards integrated approaches. It is increasingly recognised that fragmented measures towards reducing flood risk are no longer viable and more holistic views are required (Merz *et al*., 2010). Broader catchment-scale processes relevant to flood risk reduction strategies should therefore be considered, alongside other river functions, such as water resource management (Rouillard *et al*., 2015). This shift towards integrated FRM in Europe is best represented by the European Union’s Water Framework Directive (2000) and Floods Directive (2007). The Directives moreover promote community engagement and stakeholder participation in the definition of flood policies as one of their core principles. There is a need for science and research on future flood risks to also incorporate the key concepts of this paradigm shift and align with the requirements of decision-making.

1.2. Aim and objectives

The overarching aim of this research is to assess the impact of climatic changes and SLR on future flood risks in a coastal region to inform flood risk management and adaptation responses.

Three specific objectives were identified to achieve the above stated research aim:

1) To assess the sensitivity of a coastal region to different sources of flooding by developing a catchment-to-coast hydraulic model.
2) To integrate local stakeholder perspectives with scientific model results in the assessment of future flood risk and definition of adaptation measures.
3) To analyse the impacts of climate change and SLR scenarios on flood risk and river salinity, and the implications of stakeholder-defined adaptation measures.

The Broads National Park (or the Broads) and its associated coastline were chosen as a study area in this research. As the largest protected wetland in Britain, this low-lying location is in a recurring struggle to protect internationally important socio-economic and environmental assets from diverse sources of flooding. As will be described in more detail in Chapter 3, the Broads’ complex hydrological features, low gradient and proximity to the North Sea, provide an ideal setting to test a catchment-to-coast hydraulic modelling approach. Moreover, the Broads are in a transitional period in their FRM and managing institutions are in the early phases of defining future adaptation strategies to cope with the threats posed by climate change and SLR. There is therefore not only a need for the latest scientific projections of future flood risk in the region, but also an opportunity to better understand stakeholder perspectives of flooding and adaptation.

The following research steps were undertaken to achieve the three specific objectives:

- construct a Digital Elevation Model of the Broads area, rivers and coastline
- assess the fitness-for-use for the study area of a 1D-2D hydraulic model design,
- determine the probability of extreme events to define synthetic river discharge and storm surge conditions,
- explore the role and potential interaction of different sources of flooding,
- incorporate local stakeholder perspectives of flood hazard, vulnerability and exposure in scientific modelling choices,
- define adaptation measures based on stakeholder interests and understand their implications for future flood risk management,
- bias correct regional UKCP18 projections of temperature and precipitation over the Broadland catchment,
- evaluate future changes in river discharge in the Broadland's river sub-catchments with a hydrological model,
- analyse future impacts on inundation extent, depth and river salinity.

1.3. Thesis structure

The thesis is structured in 6 chapters, the contents of which are described below. The first two of the three core chapters have been adapted from work published in peer-reviewed journals during the course of this PhD.

Chapter 2 provides an overview of the current state of knowledge and a review of the relevant literature used as background for this PhD study. Previous research and methods involved in the characterisation of flood risks in a changing climate are described. The status, opportunities and limits of different climate change adaptation approaches are moreover examined. Finally, previous attempts at engaging stakeholder knowledge in scientific endeavours are explored, particularly within the scope of integrated assessments.

Chapter 3 describes the study area, namely the Broads National Park and its coast. It provides an overview of the overarching methods used in this research. A description of the socio-economic and environmental features of the Broads is followed by a look at how floods have impacted the region in the past, how they are currently managed, and what future challenges they are expected to pose. The summary of methods is moreover accompanied by a description of the epistemological approach adopted as part of this research.

Chapter 4 presents an analysis of the study area's sensitivity to different sources of future flooding. This chapter's findings are based on the development of a preliminary hydraulic model, forced with long term deterministic scenarios of SLR, and addresses the potential impacts of compound events. The validation of a 1D-2D modelling approach, using fine resolution elevation data is discussed.

Chapter 5 focuses on the delivery and the outcomes of the central stakeholder engagement activity held in this research. A scientist-stakeholder workshop is presented as part of a collaborative approach to assess future flood risks and adaptation options. The chapter highlights key stakeholder perspectives held within the context of varied and competing interests. It also addresses how these perspectives influenced the model design and the definition of adaptation scenarios. An emphasis is put on the opportunities and challenges of stakeholder engagement in the co-production of knowledge.

Chapter 6 builds on from **Chapter 4** and **Chapter 5** to assess flood risks and stakeholder-defined adaptation measures throughout the 2030-2080 period, using the latest UKCP18 regional projections of temperature, precipitation and SLR. A catchment-to-coast approach is described in the definition of hydraulic boundary conditions, making use of bias-corrected climate projections as well as the joint probability analysis of tides and storm surges. The concept of flood hazard is expanded upon by looking not only at inundation but also river salinity concentration during extreme events. The implications of modelled adaptation measures are discussed, using stakeholder feedback, providing insights for future FRM.

Chapter 7 concludes this thesis by offering a summary of its key findings and overall contribution. How this research can be replicated in other contexts or different coastal regions is discussed. Finally, recommendations for future research are provided.

Chapter 2 – Background and Literature Review

2.1. Flooding risks in a changing climate

2.1.1. The properties of flood risk

Floods are natural phenomena that can bring both environmental and economic benefits (He *et al*., 2013). Settlements in floodplains have been common throughout human history to make use of their fertile soils for agriculture, flat terrain for building, or opportunities for leisure activities and transportation, among their other multiple functions (Di Baldassarre *et al*., 2013). Floodplains are moreover “biodiversity hotspots”, providing rich habitats for diverse species (Pander *et al*., 2018). The focus of this thesis is on hazardous – or damaging – floods, which can be defined as the excess of water that has adverse impacts on the social system, the natural system or the build environment (Merz *et al*., 2010). Flooding can be caused by water originating from a wide variety of sources, such as heavy rainfall (pluvial or surface flooding), rivers (fluvial or riverine flooding) and the sea (coastal or tidal flooding). Still, these hazards do not automatically lead to harmful outcomes and it is therefore important to differentiate between the notions of “hazard” and “risk”.

In the natural disaster management literature, the definitions for risk vary but many have followed the description of the “Risk Triangle” proposed by Crichton (1999). Risk in this case is characterised as the intersection of the three concepts of hazard, exposure and vulnerability. This approach has notably been incorporated into the IPCC terminology (Lavell *et al*., 2012), which provides the following definitions:

- Hazard: the potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources.
- Vulnerability: the susceptibility to the damaging effects of the hazard. This can be the result of social, economic or institutional circumstances, for example.

- Exposure: the presence of people, or assets (cultural, socio-economic or environmental) in places that could be affected by physical events. While exposure is a required pre-condition for vulnerability, it is possible to be exposed but not vulnerable to a particular hazard.

From these definitions, flood risk can be considered as the combination of a flood event and its potential impact on human and natural systems. Research in the field of flood risk assessment often relies on conceptual models to understand the processes related to flooding and its impacts. The Source-Pathway-Receptor-Consequence (SPRC) model is a popular approach to describe the interactions of different elements within the flood system (Evans *et al.*, 2004). This model has been applied in particular in previous studies on the appraisal of coastal flooding (Narayan *et al.*, 2012; Narayan *et al.*, 2014; Villatoro *et al.*, 2014). It describes the state of a flood system as the combination of a Source, or the origin of a hazard (e.g., a storm surge or river discharge), the Pathways through which that hazard propagates (e.g., flood defences) to reach Receptors, which refer to the entities that are harmed by the hazard (e.g., people, infrastructure or the environment). Finally, the SPRC model deals with Consequences of flooding events defined by their socio-economic or environmental impacts.

The SPRC model is usually nested within the broader Driver-Pressure-State-Impact-Response (DPSIR) framework. The DPSIR model further includes the influences of external Drivers such as climate change as well as the Responses put in place to adapt to – or mitigate the effects of – these Drivers (Narayan *et al.*, 2014; Sánchez-Arcilla *et al.*, 2016). FRM and adaptation planning have grown increasingly interlinked as all three components of the Risk Triangle can be expected to vary alongside socio-economic developments and climatic changes (Alfieri *et al.*, 2015).

2.1.2. Climate impacts on flooding and extreme events

It is now well understood that climate variability and long-term climate change play important roles in dictating flood risk (He *et al.*, 2013). The exact nature of this effect is however less clear as floods are complex processes confounded by site-specific factors such as land use or local engineering (Wilby and Keenan, 2012). The impact of climate change on flooding could occur through different pathways. There have been growing concerns that the intensification of the global water cycle, portrayed by an increase in the intensity and frequency of extreme precipitation, could lead to an increase in fluvial floods (Milly *et al.*, 2002). Some studies have argued that there has already been an anthropogenic contribution from climate change to increasing flood risk (e.g., Pall *et al.*, 2011). Hirabayashi *et al.*, (2018) found a large increase in 21st century flood frequency in many regions of the world, while decreasing in others, based on the outputs of climate model projections. In the context of the UK, most studies using model outputs show an increased risk of flooding under a changed climate (Wilby *et al.*, 2008). As the IPCC Fifth Assessment Report emphasised however, there is still limited evidence of observed climate-driven changes as well as low confidence in projections of future changes in the magnitude and frequency of fluvial floods (Seneviratne *et al.*, 2012).

On the other hand, there is greater confidence in the increased risk of coastal flooding as all climate models point towards rising sea levels (Wilby and Keenan, 2012). Although there are still uncertainties over the rate of increase in mean sea levels, SLR will exacerbate coastal flood patterns, causing more frequent extreme sea-level events (Hunter, 2009; Seneviratne *et al.*, 2012; Church *et al.*, 2013). While there has been a steady increase in the frequency of high water levels being exceeded due to climate change, this has not led to a corresponding increase in coastal flooding in the UK (Stevens *et al.*, 2016). This is largely due to developments in flood defences and flood forecasting (Haigh and Nicholls, 2017). This finding not only highlights the importance of FRM but also the need for a continuous reassessment of current practices as SLR is expected to continue throughout and beyond the 21st century (Church *et al.*, 2013). Considerable uncertainties moreover remain on the expected impacts of climate change on storm surge and wave conditions (Haigh and Nicholls, 2017), which are significant processes in coastal flooding.

Climatic changes and SLR have spurred the growing recognition that traditional engineering solutions founded on the assumption of stationarity are no longer applicable (Milly *et al.*, 2008). This shift has implications for the characterisation of flood risk as statistical models in the framework of Extreme Value Analysis (EVA) are often used to estimate annual probabilities of hydrological extreme events (Katz *et al.*, 2002). Statistical distributions can be used to determine the return period, or probability of occurrence, of events such as extreme discharge or sea level. For example, a “100-year flood” is associated to 1 in 100-year level event (noted as 1:100 going forward), which has a 1% probability of occurring in a given year. Commonly used methods in EVA include fitting a Generalised Extreme Value (GEV) function to annual maxima observation time series (e.g., Webster *et al*., 2014) or a Generalised Pareto (GP) function fitted to a Peaks-Over-Threshold (POT) series (e.g., Prosdocimi *et al*., 2015; Haigh *et al*. 2016). The POT method has been found to allow for more control over which events are included in the extreme value distribution and to perform better than the more traditional Annual Maxima method in previous flood frequency studies (Arns *et al.*, 2013, Bezak *et al.*, 2014).

Traditionally, these methods have been applied with stationary models, in which observations are assumed to be drawn from a probability distribution function with constant parameters and therefore statistics of extremes do not change over time (Ragno *et al.*, 2019). The potential impact of climate change on the frequency of extreme events has led to a shift to non-stationary methods that account for changes in distribution functions (Sadegh *et al*., 2015). Non-stationarity can be addressed by calling upon different approaches and tools. It can be modelled as a linear regression function of generic covariates (Gilleland and Katz, 2016). Collet *et al.* (2017) accounted for non-stationarity by comparing return levels of extreme discharge between two time periods – past and future – with each considered to be stationary.

2.1.3. Compound flooding

While extreme events are traditionally assessed independently, increasing attention has been dedicated to compound events (e.g., Kew *et al*. 2013). Zscheischler *et al.* (2018) defined compound events as “the combination of multiple drivers and/or hazards that contributes to societal or environmental risk”. Coinciding hazards, such as storm surges and river discharge, can lead to impacts that would otherwise not have been observed had they occurred separately and can therefore have significant implications for flooding risk (Ganguli *et al*., 2019). Compound flooding has only received increased attention in recent years with the recognition that discounting such processes has led to an underestimation of risk in a number of locations worldwide (Wahl *et al*., 2015).

There have been a number of examples of compound flooding in the past few years. Most notably in 2017, Hurricanes Harvey, Irma and Maria led to major floods in the US and Caribbean islands due to the combination of intense rainfall and storm surges (Dilling *et al.*, 2017; Wahl *et al.*, 2018; Zscheischler *et al.*, 2018). While Ward *et al.* (2018) assessed the dependence of river and coastal flooding in global deltas and estuaries, most studies on compound flooding have been conducted at a local (e.g., Kew *et al.*, 2013; Chen and Liu, 2014; Mazas and Hamm, 2017) or regional scale (e.g., Zheng *et al*., 2014; van den Hurk *et al*. 2015; Wahl *et al*., 2015; Wu *et al*., 2018a). These studies generally examine only two sources of flooding and more precisely combinations of storm surge with either river discharge, rainfall or waves.

Research has also assessed the dependence between river and coastal flooding along the UK coast (Svensson and Jones 2002; Hawkes and Svensson, 2003; Hawkes, 2005). Along with other larger scale studies also considering Europe and the UK (Paprotny *et al.*, 2018; Ward *et al*., 2018), these works have found that storm surges were more likely to coincide with high river discharge on the western coast than on the eastern coast of the UK. Looking specifically at the Broads, Mantz and Wakeling (1979) came to the same conclusion, considering these events as independent when assessing the risk of a compound event. More recently, Hendry *et al.* (2019) found that this spatial variability was driven by meteorological differences in storm characteristics. They argue that storms that typically generate storm surges are mostly distinct from the types of storms that tend to generate high river discharge.

While a significant dependence between different sources of flooding is not always found (Klerk *et al*. 2015), it remains highly uncertain how the climate will influence this relation in the future. Wahl *et al*. (2015) for example, observed in the US a change towards storms surges that also promote high rainfall. Bevacqua *et al*., (2019) also found higher probabilities of compound flooding along parts of the northern European coast under climate change projections. The threat posed by combined events from different sources underlines the importance of adopting a holistic stance in assessing flood hazard.

2.2. Future flood risk assessment and impact modelling

2.2.1. Top-down and. bottom-up approaches to risk assessment

Future projections of flood risk are needed to guide the definition and implementation of measures able to effectively mitigate flooding in a changing climate. The most common method to assess climate change impacts on hydrology is to use projections from GCMs, downscaled to a catchment scale, and subsequently run in rainfall-runoff (hydrological) and flood inundation (hydraulic or hydrodynamic) models (e.g., Rojas *et al.*, 2012; Ward *et al.*, 2014, Alfieri *et al.*, 2015; Roudier *et al.*, 2016). Relying on this model cascade (Figure 2.1), the method is referred to as a “top-down” or “scenario-led” approach (Prudhomme *et al.*, 2010). Generally motivated by economic goals and finding an optimal management strategy, this approach can also include the estimation of damage costs (e.g., Zhou *et al.*, 2012).

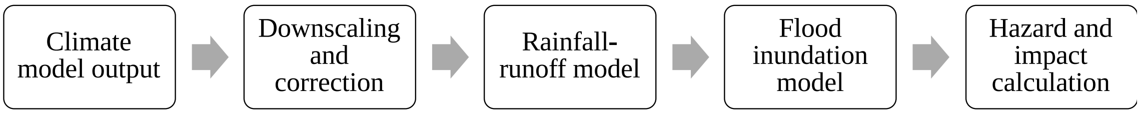

Figure 2.1 - Representation of the linear sequence of steps in the modelling cascade to assess future flood risk (adapted from He *et al.*, 2013)

While the risk-based top-down approach has dominated the field of future flood risk assessment, it is associated with significant limitations. Each modelling step represented in Figure 2.1 contains uncertainties that can accumulate and therefore widen the range of plausible futures (Rodríguez-Rincón *et al.*, 2015). Ranging from our limited knowledge of the climate system, to the choice hydrological model parameters and the numerical accuracy of model solvers, sources of uncertainty are numerous throughout the model cascade (Pappenberger *et al.*, 2012). This has led researchers to argue that these cascading uncertainties can explain the limited number of tangible examples of adaptation decisions derived from top-down future flood risk assessments (Prudhomme *et al.*, 2010; Wilby and Dessai, 2010).

A growing number of studies have favoured “bottom-up”, or “scenario-neutral”, approaches to model flood risk and vulnerability to climate change (Prudhomme *et al.*, 2010; Peel and Blöschl, 2011; Pielke and Wilby, 2012). As opposed to the top-down approach, the bottom-up approach to risk assessment does not take climate projections as the starting point but the vulnerabilities of the studied system instead (van Pelt and Swart, 2011). Starting at the local scale, this approach seeks to understand the processes linked with hydrological hazards and analyse the sensitivity to potential changes in flood risk over a range of plausible climatic changes (Tramblay *et al.*, 2014). While the top-down approaches can be described as motivated by an economic paradigm, bottom-up approaches follow a social paradigm (Blöschl *et al.*, 2013), and are better suited to the growing trend of stakeholder participation in adaptation science (Kuklicke and Demeritt, 2016).

Modelling methods tend to be less structured and more explorative in bottom-up approaches, taking into account the expertise of local stakeholders (Klinke and Renn, 2012). Adaptation measures derived from bottom-up approaches may not be optimal economically but can be considered as "low-regret" and "robust", as they are to perform well over a range of assumptions about the future (Wilby and Dessai, 2010). Blöschl *et al.* (2013) argued that the bottom-up approach should be the starting point in hydrological risk management, which may be complemented by climate scenarios.

2.2.2. Modelling the dynamics of flood inundation

The analysis and communication of flood inundation is an important aspect of both top-down and bottom-up approaches. A common practice for engineering and planning purposes is to combine hydrological and hydraulic models to develop flood hydrographs and represent areas susceptible to flooding (Gül *et al.*, 2009). This coupling is an integral part of the model cascade presented in Figure 2.1.

Hydrological models help understand the influence of weather events on catchment hydrology using mathematical calculations to represent the water cycle, from precipitation to discharge. There are a variety of hydrological models, which can be classified by their representation of these processes and their model inputs and parameters (Table 2.1). One way to categorise hydrological models is as empirical, conceptual and physically based models (Jajarmizad *et al.*, 2012).

Table 2.1 – Classification of hydrological models (adapted from Jajarmizad *et al.*, 2012; Devia *et al.*, 2015)

Model	Description	Examples

Empirical	Also called “black-box models”, they are purely mathematical and fitted directly to observed data.	Instantaneous Unit Hydrograph (IUH)
Conceptual	Uses simplified equations with a physical basis to conceptualise the process of runoff generation. Consists of interconnected reservoirs representing the physical elements in a catchment.	HBV (Bergström, 1992), TOPMODEL (Beven and Kirby, 1979)
Physically based	Simulates runoff processes explicitly in an idealised representation of real phenomena.	MIKE-SHE (Abbott *et al.*, 1986), SWAT (Neitsch *et al.*, 2011)

Different types of hydrological models, such as HBV (Hydrologiska Byrans Vattenbalansavdelning, developed by the Swedish Meteorological and Hydrological Institute) and MIKE-SHE (developed by the Danish Hydraulic Institute), have been used in climate change impact studies (Grillakis *et al.*, 2011; Janža, 2013). Physically based models such as MIKE-SHE can be more suitable for catchments with poor calibration data on discharge and can moreover represent changes in topography and land use (Ma *et al.*, 2016). On the other hand, comparisons between MIKE-SHE and HBV have found that HBV’s simpler structure allows for better predictions of peak discharge (Kalantari *et al.*, 2012). Conceptual models are also associated with moderate data requirements and are less computationally demanding. These are important considerations when choosing an appropriate hydrological model.

Representing the physics of water flow during flooding events is an important challenge for flood risk mapping and assessment. Advances in our understanding of floodplain flows has led to the use of hydraulic models in studies looking to serve to recreate past flood inundations (e.g., Quirogaa *et al.*, 2016; Patel *et al.*, 2017), to test the efficiency of flood control measures (e.g., Gül *et al.*, 2009), as well as to assess the flooding hazard in specific areas (e.g., Rojas *et al.*, 2012). These mathematical models that simulate fluid motion in river channels and in overbank flow conditions by solving equations formulated by applying the laws of physics. Hydraulic models can be grouped into one-dimensional (1D), two-dimensional (2D) or three-dimensional (3D) models

(Table 2.2) based on their level of detail in the spatial representation of floodplain flow (Teng *et al.*, 2017).

Table 2.2 – Classification of hydraulic modelling methods and examples (derived from Néelz and Pender, 2013)

Method	Description	Computational Time	Model examples (Developer)
1D	Solves the one-dimensional Saint-Venant equation	Minutes	MIKE 11/MIKE HYDRO (DHI), HEC-RAS (USACE), FloodModeller 1D (CH2M)
2D	Solves the two-dimensional Saint-Venant equations	Hours or days	MIKE 21 (DHI), FloodModeller 2D (CH2M), TELEMAC 2D (Électricité de France), LISFLOOD-FP (University of Bristol), HEC-RAS 2D (USACE)
3D	Predicts water levels and 3D velocity fields from 3D Reynolds-averaged Navier-Stokes equations	Days	MIKE 3 (DHI), TELEMAC 3D (Électricité de France)

The best currently conceivable representation of flow dynamics is to numerically model both the river channel and the floodplain in 3D, with solutions of the full Navier-Stokes equations that describe the motion of fluid substances (He *et al.*, 2013). This complex representation of flow is however prohibitively computationally expensive and is not considered a viable option at the scale of a river reach, let alone a river catchment (Teng *et al.*, 2017). In many cases, solutions with this level of detail are not necessary and treating flow as one-dimensional along the centreline of the river channel has been favoured in past research (e.g., Brunner, 2016). This assumption is appropriate in many situations but may not be suitable for flood mapping in areas where flow is expected to spread, such as in wide floodplains or urban areas (Néelz and Pender, 2013).

Alternatively, 2D models represent floodplain flow as a two-dimensional field across a continuous surface – rather than cross sections – made up of computational grid cells. While 2D models have different discretisation strategies (finite element, finite difference or finite volume), they have been reported to be able to simulate timing and duration of inundation with high accuracy (Horritt and Bates, 2002). These methods are highly dependent on accurate topographic data. Recent advances in remote sensing and Light Detection and Ranging (LiDAR) technology have however had significant implications for flood modelling by providing an unprecedented level of detail in digital elevation models (Costabile *et al.*, 2015; Mihu-Pintilie *et al.*, 2019). These high-resolution datasets have paved the way for new opportunities in flood hazard mapping. 2D models are moreover preferred in coastal environments as they can be used to simulate the overtopping or breaching of sea and flood defences (Wang *et al.*, 2012; Villatoro *et al.*, 2014; Wu *et al.*, 2015). Despite their growing popularity, 2D models remain less computationally efficient than 1D models and have been considered generally unviable for scenario-based approaches requiring many simulation runs (Teng *et al.*, 2017).

As a response to these challenges, methods to dynamically link 1D and 2D components have gained much momentum (Néelz & Pender, 2013). Where a 2D model needs to compute detailed data of the river channel, a 1D-2D framework can save significant computational time by only representing the floodplain in 2D, keeping the channel as a 1D system. Coupled 1D-2D models have been successfully used in research on flooding in coastal environments (Webster *et al.*, 2014; Liu *et al.*, 2015; Timbadiya *et al.*, 2015). Developed historically as a 1D software by the US Army Corps of Engineers (USACE), the Hydrologic Engineering Center – River Analysis System (HEC-RAS) model released in 2016 a 2D version of its model, which can be integrated dynamically in a 1D-2D set up.

2.2.3. Hydraulic modelling of river salinity

A number of hydraulic modelling suites allow for the representation of the concentration of salinity in rivers and estuaries alongside flow dynamics. Salinity transport models estimate advection-dispersion coefficients and can be integrated to hydraulic models. As for water flow, 3D models are available and provide the necessary detail to more comprehensively portray the processes governing salinity (e.g., Bricheno and Wolf, 2018). While this can be important as salinity tends to be stratified in the river water column, several studies have used 1D approaches to assess the impact of SLR on saline incursion (e.g., Etemad-Shahidi *et al.*, 2008; Hien *et al.*, 2010; Bhuiyan and Dutta, 2012). The HEC-RAS software is associated with a Water Quality Module, which is commonly used to simulate the transport of pollutants (Velísková *et al*., 2016). While it is possible to also model salinity by representing it as a conservative consitituent, as was shown by Haddout *et al.*, (2015), few studies have used it to assess the impact of SLR on salinity concentrations in a coastal zone. Integrating salinity assessments to hydraulic simulations can play an important role in deriving a more holistic view of flooding related risks to support decision making on adaptation.

2.3. Adaptation planning: linking science and policy

2.3.1. Adaptation strategies in the context of Flood Risk Management

In light of expected climatic trends, it has become increasingly clear that adaptation has a key role to play in limiting the impacts of climate change. Despite efforts to reduce and mitigate emissions of GHGs into the atmosphere, some degree of climate change is inevitable due to past emissions (Nauels *et al*., 2019). Adaptation involves taking measures that seek to manage the risks from the anticipated or potential effects of climate change on natural and human systems (Wong *et al.*, 2014). Planning these actions effectively is particularly significant for coastal and low-lying areas, which are intrinsically exposed and often vulnerable to extreme events. The potential increase in flood risks due to climate change makes FRM closely tied to adaptation.

One of the aims of adaptation is ensuring the resilience – or the ability to cope and bounce back from disturbances, such as floods – of socio-economic and environmental systems (Lavell *et al.*, 2012). In coastal regions, adaptation can be grouped into three main strategies: protect, accommodate and retreat (Table 2.3). An important distinction is that accommodation and retreat, as opposed to protection, allow the natural system to behave as it would without human intervention. Protection, by means of engineering solutions, remains the most common first response, in most coastal regions, including in the UK (Nicholls *et al.*, 2007).

Table 2.3 – Protect, accommodate, and retreat: non-exhaustive list of adaptation measures to SLR and flood risk in coastal regions (adapted from Nicholls *et al.*, 2007 and Wilby & Keenan, 2012)

Adaptation strategy	Objective	Examples
Protect	"Defend against the risk": Control natural systems to reduce impacts	*Hard structural options* Dikes, levees, floodwalls (Brown *et al.*, 2014) *Soft structural options* Beach nourishment *(Stive et al.*, 2013)
Accommodate	"Live with the risk": Adjust human activities and infrastructure to minimise impacts	*Behavioural change* Land use and agricultural practice (Parrott *et al.*, 2009) *Institutional and financial options* Hazard insurance (Keskitalo *et al.*, 2014) *Resilience systems* Early warning systems (Pathak & Eastaff, 2014) *Infrastructure* Flood-proof buildings (He *et al.*, 2013)
Retreat	"Withdraw from the risk": Pull back from the coast to avoid impacts	*Managed retreat* Managed realignment (French, 2006)

The prevailing complexities associated with climate change have contributed in the last decades to a paradigm shift, notably outlined by the EU Floods Directive (Hartmann and Juepner, 2013). In England for example, there has been a transition away from traditional structural and engineering-based flood protection policies to an integrated management of flood risk (Cumiskey *et al.*, 2019). Integrated FRM looks to recognise the interrelationships between risk management measures at the catchment level within changing social, economic and environmental contexts (Hall *et al.*, 2003). Under this new paradigm, “total safety” is no longer guaranteed and adaptation measures that account for extreme flooding scenarios are promoted (Löschner *et al.*, 2016).

2.3.2. Overcoming barriers to adaptation: the role of science

The array of options available to decision-makers cannot take away from the complex nature of adaptation processes. While the threat of potentially severe consequences of climate change and SLR has generated interest in adaptation, there are still significant limitations to its implementation which have attracted much research in recent years (Adger *et al.*, 2009; Moser and Boykoff, 2013). A number of these barriers challenge the role of science in its capacity to support decisions on adaptation.

Uncertainty over future risks and change is commonly regarded as a critical barrier to adaptation (e.g., Nicholson-Cole and O’Riordan, 2009). The probabilistic nature of science suggests it will never be possible to pinpoint the timing, scale, magnitude and type of impacts that coasts can expect in the future (McFadden, 2007). Still, the need for more “robust” science is emphasised throughout the adaptation literature (Dessai and Hulme, 2007; Wilby and Dessai, 2010). To move past underlying uncertainties, previous studies have rejected a “predictive” approach to science in favour of one that accounts for a range of plausible futures under which adaptation measures would be successful (Dessai *et al.*, 2009). Moser & Boykoff (2013) also argued that science plays a decision-support role, participating in the iterative process of evaluating future risks and adaptation goals. Nicholson-Cole & O’Riordan, (2009) moreover listed “strong science” as one of the conditions for adaptive coastal governance.

These views suggest the role of science is unilateral, occurring at isolated points to support the decision-making process, from which it is largely independent. Preston *et al.* (2013) however argued that not only can science serve to provide insights and knowledge, it can also facilitate adaptation by playing a more active role throughout the decision-making process. Vogel *et al.*, (2007) proposed an approach where science would engage within the adaptation process across multiple levels through two-way exchanges with practitioners. This has led to a need for a better understanding of stakeholder's perceptions of risk and scientific evidence. Yet, little is known on the relationship between practitioners' own knowledge and scientific information, or how one may impact the other. This is notably important because of increasing suggestions that trade-offs are needed between the complexity of scientific evidence on climate change and the needs of decision-makers for simplicity (Meyer, 2012).

The usefulness of science for adaptation has been found to be dependent on the values of local actors in a number of case studies (Preston *et al.*, 2013). Interviewing stakeholders in East Anglia from various environmental sectors, Shackley & Deanwood, (2002) suggested that recognising the importance of climate change issues relied on how well they fit into existing institutional frames of reference – giving the example of the Shoreline Management Plans. Adger *et al.* (2009) went on to argue that climate knowledge was associated with pre-existing social, organisational or individual understandings of "agents of adaptation", such as their perception of risk or of past weather events. Whether there are effective means by which science can align itself to these values remains largely unknown.

Previous work on overcoming the obstacles to adaptation has focused on the role played by institutions (Ekstrom and Moser, 2013). Gray *et al.*, (2014) however argued that individuals were key in facilitating adaptation and may not be detecting problems requiring action in part due to inconsistent communication of these issues. As a result of adaptation's sensitive nature, a lack of strategic communication may also hurt actors' willingness to act, even if they do know the problem exists (Moser and Boykoff, 2013). Lebel *et al.* (2013) argued that communication on risk should be multi-directional as different stakeholder may hold knowledge important to risk management and adaptation. They also found that action on adaptation is more likely when scientific predictions of future sources of flooding risk are framed alongside plausible response measures. In the context of the UK, Day *et al*. (2015) came to a similar conclusion, while emphasising the need to consider local perspectives in adaptation planning.

2.3.3. Integrated Assessment and stakeholder engagement

Research on flood risk has followed a similar paradigm shift to flood policy to examine the challenges introduced by climate change. Studies taking an interdisciplinary stance and drawing from different scientific fields to evaluate climate impacts and vulnerability have gained in popularity (e.g., Kaspersen and Halsnæs, 2017; Xie *et al.*, 2017). Many of these works are part of the now well-established methodological framework of Integrated Assessment (IA). Kloprogge and Sluijs (2006) defined IA as the "process of combining, interpreting and communicating knowledge from diverse scientific disciplines". The rationale for IA is that single-field assessments are inadequate to deal with global environmental risks and to provide useful information to decision makers (Rotmans, 1998). While IA is described as a "link between knowledge and action" (Farrell and Jäger, 2005), there is still concern over a gap between science and policy on climate adaptation (Mastrandrea *et al.*, 2010; Kirchhoff *et al.*, 2015). This has spurred recent efforts to expand the scope of IA towards sources of knowledge outside of scientific domains, notably with the participation of multiple stakeholders in the input of information (Kloprogge and Sluijs, 2006; Löschner *et al.*, 2016).

Participatory approaches have gained in popularity alongside a shift in the relation between science and policy. The rejection of science's traditional "top-down" stance to inform decision-making unilaterally (Pielke, 2007) has indeed been accompanied by efforts to make science more accountable and therefore more likely to be seen as acceptable (Voinov and Bousquet, 2010; Chilvers and Kearnes, 2019). Additionally, participation can be seen as a way to empower stakeholders, giving them a more central role in the generation of knowledge and therefore increasing their capacity to make use of that knowledge (Stringer *et al.*, 2006). Studies have moreover found that a participatory approach can lead to social learning (e.g., Steyaert *et al.*, 2007; Evers *et al.*, 2016), where stakeholders gain from each other, leading them to appreciate each other's views and develop valuable relationships or networks (Reed *et al.*, 2008). The trend for increased participation has also taken root in environmental modelling. Arguments have been made for a change in the traditional stance modellers take, including in FRM where computer programs typically take up an important role (Landström *et al.*, 2011). Krueger *et al.* (2012) argued that stakeholder scrutiny could not only be applied to model results, but also on the technical process of modelling itself to generate new knowledge.

Being closely linked to civil engineering, FRM remains a field where expert knowledge holds a significant role and in which stakeholder engagement may even be perceived as a threat, rather than the solution (Edelenbos *et al.*, 2016). Stakeholder engagement in general faces many challenges, which has led debates over its actual benefits (Reed, 2008). Tseng and Penning-Rowsell (2012) identified key barriers to stakeholder engagement in FRM ranging from the lack of an institutionalised and early engagement process to resistance experienced from stakeholders. Few *et al*. (2007) moreover described the challenges created by power dynamics, where leading authorities may use the pretence of participation as a way to steer outcomes to predefined goals in lieu of engaging with stakeholder perceptions or interests.

The potential gains from participation remain important in climate adaptation, as impacts are likely to be felt throughout society and experienced or perceived differently by various actors. Moreover, the effects of climate change may exacerbate cross-sectoral competition for resources and funding leading to different preferences for action. Coastal regions in particular are faced with the challenge of hosting greatly varying interests from a wide range of stakeholders (Tompkins *et al.*, 2008; Day *et al.*, 2015). The expansion of IAs to include stakeholders allows for new opportunities to produce knowledge in these areas through the collaboration of scientists, policy makers and other societal actors (Hegger *et al.*, 2012). In practice however, there are still few studies that attempt a participatory approach in the IA of flood risk to inform adaptation planning and develop response measures (Kettle *et al*., 2014; Löschner *et al*., 2016).

Chapter 3 – Study Area and Methodology

3.1. Introduction

This chapter provides a description of the area studied in this thesis, namely, the Broads National Park and its associated coastline. Information on past and future flood risk in the region, as well as on the current FRM strategy, is presented. The chapter goes on to define the overarching epistemological and methodological approaches followed in this research.

3.2. Study Area

3.2.1. The Broads, UK

Located on the eastern coast of England, the Norfolk and Suffolk Broads is Britain's largest designated wetland. This network of meandering rivers and shallow lakes—or "broads"—covers a total area of 303 km^2 at the downstream end of the 3200 km^2 Broadland Rivers Catchment (Figure 3.1). A predominantly freshwater ecosystem, the Broads are primarily made up of expansive floodplains, which also serve as diverse habitats for a number of rare plant and animal species (Panter *et al.*, 2011). It is the home of 28 Sites of Special Scientific Interest and is internationally recognised for its rich biodiversity, nature conservation, landscape and cultural features. The Broads executive area, which is closely drawn around the floodplains of its three main rivers, namely the Bure, Yare and Waveney, is managed by the Broads Authority (BA).

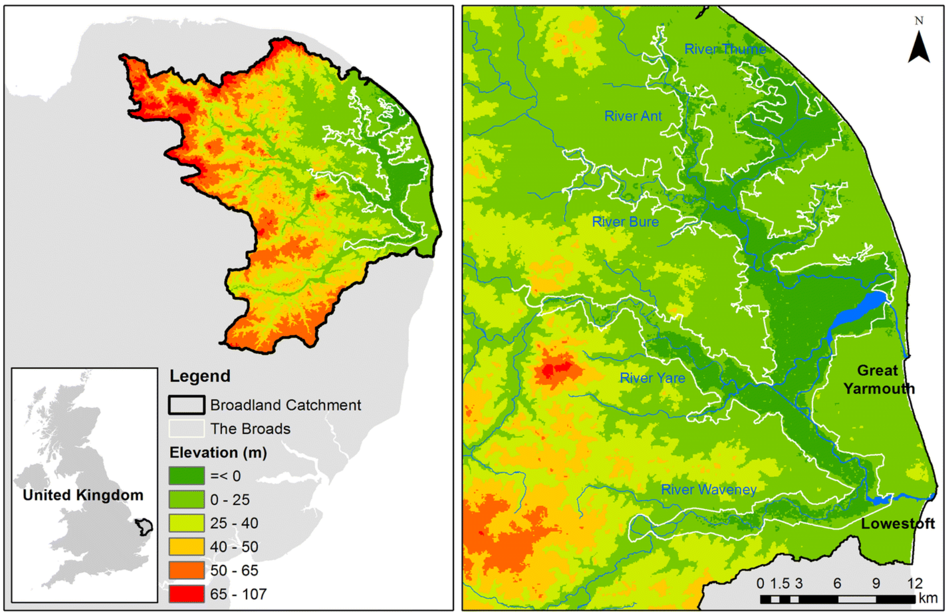

Figure 3.1 – The Broads National Park and the wider Broadland River Catchment in eastern England. The majority of the area within the Broads' administrative boundaries lies below sea level.

The Broads hold significant economic value both at the local and national level. Agriculture in the area represents an important contributor to both the region's and the country's economy. The agricultural landscape is primarily dominated by grazing marshes with some arable cropping, which result from a long history of drainage to benefit from fertile floodplains. Other important land cover types include fens near rivers and, to a lesser extent, broadleaved woodlands (Figure 3.2). This location is moreover a popular destination for over 7 million visitors a year with tourism contributing to approximately £568 million (Broads Authority, 2019a). Additionally, the area's unique hydrological features allow for many recreational or leisure activities, including boating and angling. While the population in the Broads is of low density and reaches just above 6000 residents, the National Park is bounded by important urban areas in Norwich, as well as the coastal towns of Lowestoft and Great Yarmouth.

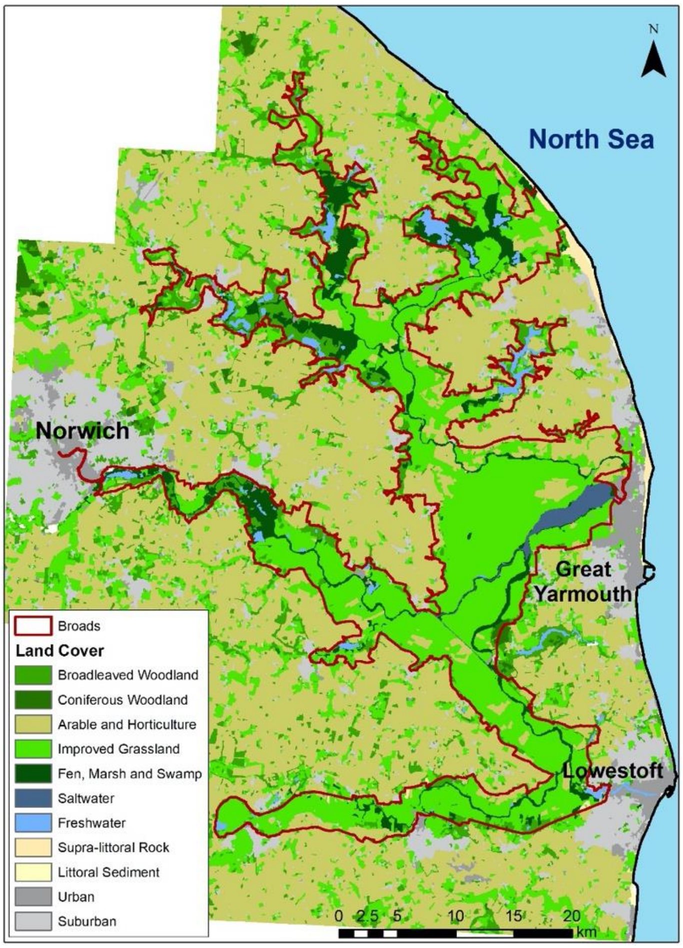

Figure 3.2 - Land cover in the Broads National Park (Land Cover data from CEH, 2015)

The Broads rivers are shallow, slow-flowing and primarily groundwater-fed streams. Their low gradients allow for the tidal influence to reach up to 40 km inland from the North Sea. Brackish waters can be found in lower reaches of this otherwise freshwater system. Observed increased salinity in the Broads has been a concern due to its ecological impacts. Many species in the Broads are intolerant to saline conditions (Panter *et al.*, 2011), while the saline flooding of agricultural land can cause long-lasting damage, as it notably did in 1953 (Cook, 2017). Moreover, rising salinity levels have been linked to the increased abundances of *Prymnesium parvum*, a microscopic biflagellate phytoplankton which has previously caused major fish kills during toxic blooms in the Broads (Wagstaff *et al.*, 2018; Roberts *et al.*, 2019).

Human activity has played a key role in shaping the Broads landscape and hydrology. While it has shifted from a commercial to a recreational role, navigation is an important activity in the region and many rivers have been modified to allow for boat traffic (Broads Authority, 2009). Land drainage, milling activities and the development of historic flood defences have also physically shaped the Broads.

3.2.2. Flood Risk Management in the Broads and its coast

The Broads have a long history of floods. Most notably, the storm of January 1953 had severe impacts in the North Sea region, with East Anglia being no exception. The storm surge led to loss of life and thousands of properties flooded in Great Yarmouth alone. Significant investments in flood protection and forecasting followed the event in the United Kingdom. The Broads today are highly engineered with over 240 km of earth embankments serving as flood defences alongside the rivers Bure, Wensum, Waveney, Yare and Ant. These structures have been maintained and strengthened as part of a 20-year strategy that began in 2001 and was implemented through the Broadland Flood Alleviation Project (BFAP). The goal of BFAP was to restore defences to a height that existed in 1995 with allowances for SLR. As such, the project's outlook was not to raise the long-term standard of protection of defences, and some level of overtopping is still expected during storm surge events.

Flood defences were severely tested in December 2013 by the largest storm surge since 1953 but were successful in minimising flooding on the coast and in the Broads. A comparison of the 1953 and 2013 surge events and their impacts was carried out by Wadey *et al*. (2015). Despite a return period for the surge on the east coast of the UK estimated at 1:188 in 2013, disruptions in Great Yarmouth and Lowestoft were low. Still, the 2013 event is qualified as a "near miss" in local reports and used to underline the need for better preparedness in the future (CH2M, 2016).

Much of the land in the Broads is either at or below sea level. The low-lying land in close proximity to the North Sea as well as its complex riverine system make this region at risk from tidal, coastal and fluvial sources of flooding. Approximately 95% of the area within the Broads National Park boundaries is at risk of flooding, which includes close to 2000 properties. Under the EA's Flood Maps for Planning, most of the Broads area falls under a Flood Zone 3 (Figure 3.3). This classification is defined as land with 1:100 (1%) or greater annual probability of river flooding or land having 1:200 (0.5%) or greater annual probability of sea flooding. The EA's flood risk maps depict the current likelihood of flooding without the consideration of existing defences. While they therefore provide an estimate of a "worst case scenario" flood, they do not take into account projections of climatic changes or SLR and therefore are not sufficient to plan for adaptation.

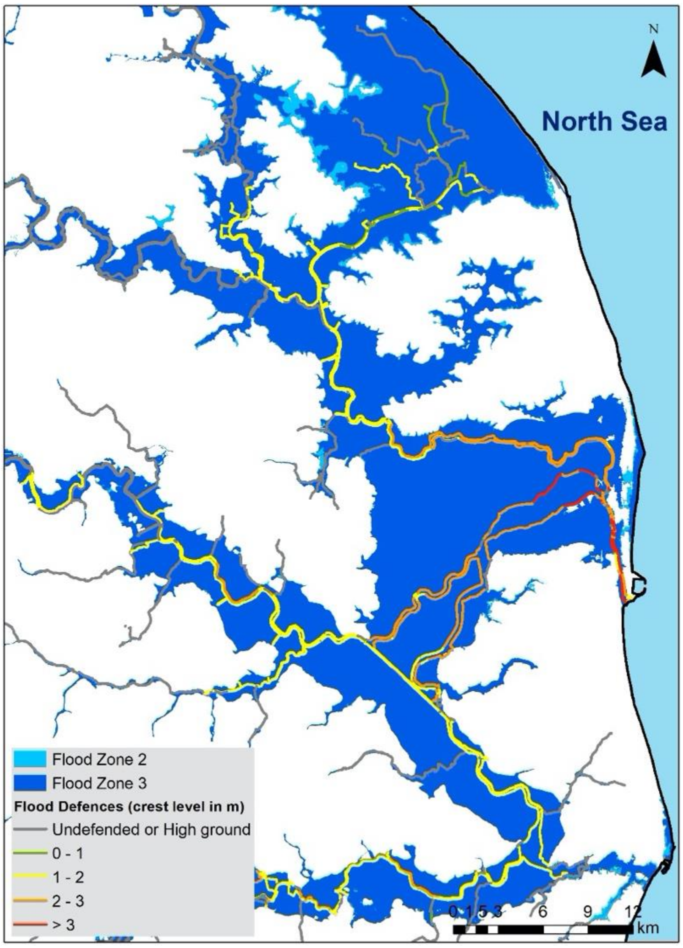

Figure 3.3 – Flood Zones as defined by the EA and status of flood defences in the Broads (data from EA, as of 5 August 2019)

A number of organisations play important roles in managing flood risk in the Broads and are listed in Table 3.1.

Table 3.1 – Organisations responsible for managing flood risk in the Broadland Catchment (adapted from Broads Climate Partnership, 2016)

Organisations	Role and responsibilities
Broads Authority (BA)	As the local planning authority, the BA can control development in floodplains and manages conservation, recreation and navigation in the Broads.

Environment Agency (EA)	Government agency managing flood risk from main rivers, estuary and the sea. Responsible for river and tidal defences.
County and District Councils	The County Councils are Lead Local Flood Authorities, managing flood risk from surface water, ordinary watercourses and groundwater. The District Councils on the coast take on a coastal erosion protection role.
Water and sewage companies	Manage the risk of flooding to water supply and sewerage facilities and the risk to others from the failure of their infrastructure.
Internal Drainage Board (IDB)	Manage land drainage in lowland areas and the many pumping stations that operate in the Broads.

The nature and condition of defences varies throughout the Broads (Figure 3.3). The standard of defence in upstream reaches are relatively low and typically equivalent to a 1:7 return period flood event for low density agricultural areas (Broads Authority, 2017). A study of flood risk in North Norfolk by JBA Consulting (2017) based their assessment on the Broads IDB target to maintain a general standard of protection against flooding of 1:10 with 600 mm of freeboard to agricultural land and 1:100 with 300 mm freeboard to developed areas. The standard of defence in Great Yarmouth is greater and consists primarily of flood walls. Important recent investments have been made to improve on the poor condition of these walls (Environment Agency, 2009) following the guidance from a Strategy Review outlining the preferred strategy to raise defences to a 1:300 standard (CH2M, 2016).

On the coastline, 14 km of sea defences extend between the villages of Eccles and Winterton to protect from coastal flooding. The current strategy for the length of the coastline set up by the Kelling to Lowestoft Shoreline Management Plan (SMP) adopted in 2012 is to “hold the existing defence line” for the short and medium term (up to 2055). It is worth noting that previous SMP proposal were met with negative reactions and concern from many local communities and organisations. Day *et al.* (2015) argued that the main reasons for the negative response were that scientific projections were made without associated management plans and with insufficient stakeholder input. Since then, while more emphasis has been put on stakeholder engagement in the region, finding ways to integrate the wide range of perspectives has remained a challenge.

As the current SMP points out, climatic changes and SLR are putting increasing pressure on the region and raising concern over the technical and economic sustainability of current structural approaches. Few studies have looked at the potential climatic changes, and their impacts, that the Broads will experience. A report by Price (2013) looked at the potential climate changes that could occur in the region containing the Broads using a 0.5° resolution climate model under IPCC emission scenarios. Future average temperatures were found to be closer to current average temperatures and precipitation increased in the winter while it decreased in summer months. More intense precipitation events over shorter periods were also found to be a likely change.

Recent research was conducted to better understand the impact of SLR on flood risk in East Anglia and the Broads as part of the Tyndall Coastal Simulator from the Tyndall Centre for Climate Change Research. Hall *et al.* (2015) and Wu *et al.* (2015) used a 2D hydraulic model, LISFLOOD-FP, to analyse current and future impacts of overtopping and breaching of coastal defences at Horsey, near the River Thurne. Mokrech *et al.* (2008) combined climate change scenarios with socio-economic scenarios and adaptation responses to assess future tidal and flooding risk for all of East Anglia. Hall *et al.* (2015) followed a similar approach using climate scenarios from the UKCP09 with shoreline management scenarios to also represent the impact of erosion and beach nourishment. The studies showed that SLR and urban development will play a major role in increasing future flooding risk. SLR has notably been found to increase extreme wave events in the region between Cromer and Lowestoft (Chini *et al.*, 2010). Another contributor to relative SLR that is specific to the region is the vertical movement of land caused by the response to melting ice sheets from the last ice age. This glacial isostatic adjustment has been found to cause land to subside by approximately 1 mm.a^{-1} in southern Britain (Bradley *et al.*, 2009).

There are still important knowledge gaps on the dynamic links between coastal and inland flooding, and how they will change in the future. Moreover, risk and damages in these studies are often restricted to residential properties, which could limit the relevance of such results for certain stakeholders with activities impacted by floods.

A high-level review of flood risk management in the region conducted in 2016 highlighted that climate impacts should be taken into account to consider a wider range of options in the future (CH2M, 2016). The high-level review emphasised the importance of interrelationships between tidal, coastal and fluvial flood risks, which have in the past been poorly considered. As a consequence, one of the main recommendations of the high-level review was to combine the separate management approaches in place for the Broads, the Eccles to Winterton coastline and Great Yarmouth into a single integrated FRM strategy.

With BFAP ending in 2021, an overarching plan for the Broadland area is yet to be agreed on, providing an opportunity to update the FRM strategy in the area. This thesis was included as one of the goals of the Broads Climate Adaptation Plan (Broads Climate Partnership, 2016) to inform on future flood risk in the Broads as well as on the implications of potential adaptation options. Composed of the organisations responsible for managing coastal and inland flood risk, the Broadland Futures Initiative (BFI) now looks to define a framework for FRM from the mid-2020s onwards.

3.3. Methodology

3.3.1. Epistemology: critical realism in interdisciplinary research

As this thesis deals with the integration of different knowledge domains, it is important to define the epistemological approach on which it rests to justify not only the adopted methodology, but also the claims made as a result of the research.

It is increasingly recognised that the complex nature of the issue of climate change adaptation requires an interdisciplinary approach. There is no single accepted definition of interdisciplinary research, with most attempts stating that the condition is the inclusion of two or more disciplines or area of knowledge (Danermark, 2019). As a philosophy of science, critical realism has embraced interdisciplinarity as an approach, notably within the context of sustainability and climate change (Bhaskar *et al.*, 2010). Developed by Bhaskar (1975), critical realism is characterised by several key principles.

The first is ontological realism, which argues that reality exists independently of its human conception, or our knowledge of it. Bhaskar (1975) proposed two dimensions of knowledge: (1) the intransitive dimension, which involves objects of scientific investigation and (2) the transitive dimensions, which consist in the socially produced knowledge of these objects. Critical realism also claims that reality is a complex open system, made of different layers and within which a multiplicity of mechanisms operates. This implies that a multiplicity of disciplines is needed to explain real phenomena (in both natural and social systems), as is done in IAs (Nastar *et al.*, 2018). Under this critical realist approach, combining scientific with local stakeholder knowledge can therefore improve understanding of complex issues.

The combination of different knowledge domains is further justified by the second core principle of critical realism, namely, epistemological relativism. Critical realism argues that all knowledge is socially produced and therefore that the world is known, interpreted and experienced differently by different people. Another implication of epistemological relativism is that critical realism, as opposed to positivism or interpretivism, contends that the combination of qualitative and quantitative methods can be beneficial in research (Porpora, 2015). The critical realist approach is therefore particularly appropriate for research relying on both natural and social scientific methods.

The third core concept of critical realist theory, judgmental rationality, states that although knowledge is fallible and socially mediated, it can be possible to rationally support one account of reality over another. It deviates from the positivist position of the existence of an absolute truth or the constructionist one that outright rejects the possibility of truth (Khazem *et al.*, 2018). Under this principle some constructions of reality or knowledge claims can therefore be epistemologically superior to others. As such, the presence of competing perspectives on an issue should not overrule what is understood as the best consensus of scientific understanding (Bhaskar *et al*., 2010).

3.3.2. Methodological framework: an iterative integrated assessment

The research design combined quantitative and qualitative analyses to assess future flood risks and adaptation in the Broads region. Local stakeholder perceptions of hazard, vulnerability and exposure were used as a starting point for the assessment of flood risk. As the goal of this research was not to identify the most economic strategy, but rather to inform on future hazards and the implications of measures looking to reduce vulnerabilities, risk was defined qualitatively throughout the project and not in monetary terms. The methods used here combined elements from both the top-down and bottom-up approaches to future flood risk assessment. The modelling of future flood risks was based on stakeholder inputs but was guided by climate scenarios derived from a model cascade.

Past research on the inclusion of stakeholders in IAs (Liu *et al.*, 2008) and scientific modelling (Voinov and Bousquet, 2010) make the case for an iterative process. Exchanges between scientists and stakeholders are moreover recommended to be held early in the research project. The co-production of knowledge on future flooding and adaptation in this research was carried through the iteration of stakeholder engagement activities and scientific modelling work (Figure 3.4).

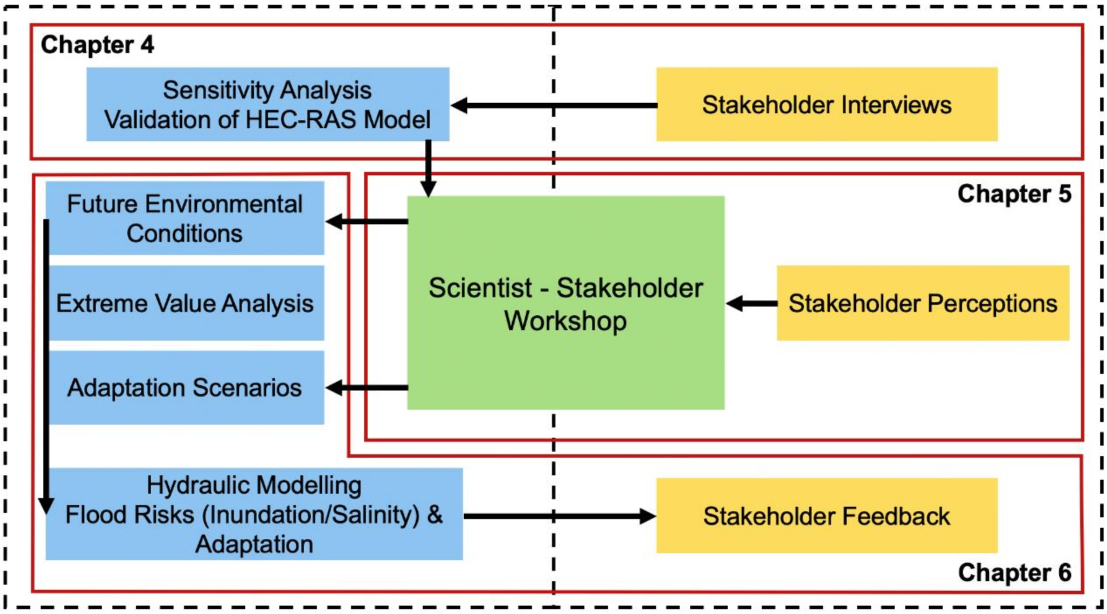

Figure 3.4 – Methodological framework. Yellow boxes represent stakeholder engagement activities. Blue boxes represent steps in the scientific modelling of flood risk. The green box represents the main interaction between both knowledge domain carried out during the research: a scientist-stakeholder workshop.

The flow of information (scientific results and stakeholder knowledge) was thereby arranged in both directions between the researcher and stakeholders. The iterative process defined to allow stakeholders to encourage modifications to the developed hydraulic model. A flexible approach to the model design was required to be able to account for stakeholder inputs. A prominent example for that was the expansion of explored hazards to account for river salinity, alongside inundation. A preliminary model was developed to provide a basis for discussion with stakeholders, help with problem setting, as well as to understand key flood risk processes in the study area. Deterministic scenarios were used to assess the sensitivity of the study area to different rates of 21-st century SLR. The participation of stakeholders throughout the study moreover helped to identify and analyse relevant local perspectives on flood risk and adaptation for decision-making, which was one of the aims of this research.

The central interaction between the knowledge domains in IA of future flood risk was a scientist-stakeholder workshop. Adapted from the methods described by Löschner *et al.* (2016), the purpose of this activity was to obtain stakeholder perspectives on hazard, vulnerability and exposure in the Broads, to obtain feedback on the hydraulic modelling design, as well as to define prioritised adaptation options to assess and incorporate in the model.

The scientific analysis of future flood risks and stakeholder-defined adaptation measures was based on a 1D-2D model set up with the HEC-RAS software. HEC-RAS is a freely-available modelling tool developed by USACE. Among its many applications, the software is well tested for flood mapping in both coastal (e.g., Ray *et al.*, 2011) and fluvial (e.g., Javaheri and Babbar-Sebens, 2014) environments as well as to assess the impacts of climate change (e.g., Shrestha and Lohpainsankrit, 2016). Previously limited to 1D models, a new version of HEC-RAS (version 5.0) was released in 2016 allowing for full 2D modelling and linkages between 1D and 2D features. While other tools such as Flood Modeller, developed by CH2M, or MIKE FLOOD, developed by the DHI, also offer the possibility to combine 1D and 2D models, HEC-RAS is a non-commercial software that has not previously been applied to the Broads. Moreover, although the new 2D capabilities of HEC-RAS offer opportunities for flood mapping, the model still requires testing for different applications (Vozinaki *et al.*, 2017). The new HEC-RAS version was used, for example, by Quirogaa *et al.* (2016) and Patel *et al.* (2017) to simulate past fluvial floods. Due to its recent release however, few studies have tested HEC-RAS version 5 in coastal regions. This project represented an opportunity to apply the latest software developments, for one of the most popular hydraulic modelling suites, in a coastal setting.

A catchment-to-coast modelling approach was adopted to integrate the interlinked coastal and inland processes affecting flood risk. As such, although coastal sources of flooding have historically been the most pressing concern for the studied low-lying area, fluvial processes were also included in the analysis of flood risk. Due to the region's unique landscape and river system, a differentiation between tidal and coastal flooding was necessary. Coastal flooding here was considered as the direct overtopping or breaching of sea defences, while tidal flooding was defined as the upstream ingress of seawater in a coastal river system such as the Broads. The hydraulic model's boundary conditions were derived from the results of a modelling chain and EVA, making use of the UKCP18 future projections of precipitation, temperature and SLR.

The specific methodologies used in each phase of the IA of future flood risk are further developed in their respective chapters.

Chapter 4 – Sensitivity analysis of a coastal region to interacting sources of flooding using a 1D-2D hydraulic modelling approach

This chapter was adapted from Pasquier *et al.* (2019) published in *Natural Hazards*, which can be found in Appendix 4.

4.1. Introduction: Integrated flood modelling

There has been in recent decades a paradigm shift towards a broader catchment-scale approach for flood risk management in Europe, as demonstrated by the European Union's Water Framework Directive (2000) and Floods Directive (2007). Integrated strategies that identify synergies at the river basin level, notably between rural and urban areas, have gained increasing support (Rouillard *et al.*, 2015). Isolated actions to mitigate flooding run the risk of leading to unwanted outcomes. For example, a flood alleviation measure taken at a location in a catchment can have downstream impacts that should be taken into account. An integrated approach is moreover justified when sources of flooding are varied, originate from different hydrological processes and interact with each other. The lack of adequate information on these interactions remains an important hurdle for decision-making.

There is a need for modelling methods to follow the above trends to be able to provide information required for planning. Recent computational advances and the shift from 1D to couple 1D-2D hydraulic models in flood risk research and assessment offer new opportunities to meet the goals of integrated approaches (Teng *et al.*, 2017). 1D–2D models can dynamically represent coastal, urban, river and floodplains interactions and are therefore well suited to assess the impact of flooding from compounding sources. While there has been an increasing number of studies looking at the impact of combined events on flooding, 1D–2D hydraulic models remain relatively new tools in this field that are subject to more investigation (Webster *et al.* 2014).

This chapter looks to present a modelling methodology to assess the sensitivity of the coastal region encompassing the Broads to the combination of fluvial, tidal and coastal sources of flooding. The fitness-for-use of an integrated 1D-2D hydraulic modelling approach is evaluated using a prototype modelling set up covering parts of the Broads National Park. The insights gathered from this analysis are to help understand the implications of portraying interacting sources of flooding at the catchment scale.

4.2. Data and methods

4.2.1. Environmental conditions

4.2.1.1. Sea level

Tide gauge data of sea level between 1964 and 2015 were obtained from the British Oceanographic Data Centre. The observations were made in Lowestoft (52°28′23.0556″N, 1°45′0.81″E), approximately 10 km south of Great Yarmouth. The east coast of England experiences a semidiurnal tidal regime. Chart datum at Lowestoft is located 1.50 m below ordnance datum (OD, at Newlyn). Sea level was recorded every 60 min prior to 1992 and every 15 min after 1992, with fewer than 3% missing data in the whole dataset.

A critical driver for flood hazard in coastal areas is peak sea level during extreme events that may occur, for instance, when a large storm surge coincides with high spring tide. The historical sea level data at Lowestoft were analysed with extreme value statistics using the POT method to determine the probability of occurrence of extreme sea levels. The mean residual life plot was used to identify an appropriate threshold for extreme value models in this study. This graphical method consists in plotting the mean excesses for a range of threshold values. The objective is to find the lowest possible threshold, subject to the constraint that the extreme value model must provide a reasonable fit to exceedances of this threshold. The use and interpretation of mean residual life plots in the choice of thresholds is described in more detail by Saeed Far and Abd. Wahab (2016). The 99.7th percentile of high tide peak sea levels was thereby chosen, extracting values exceeding a level of 1.90 m above Ordnance Datum (maOD) (Figure 4.1).

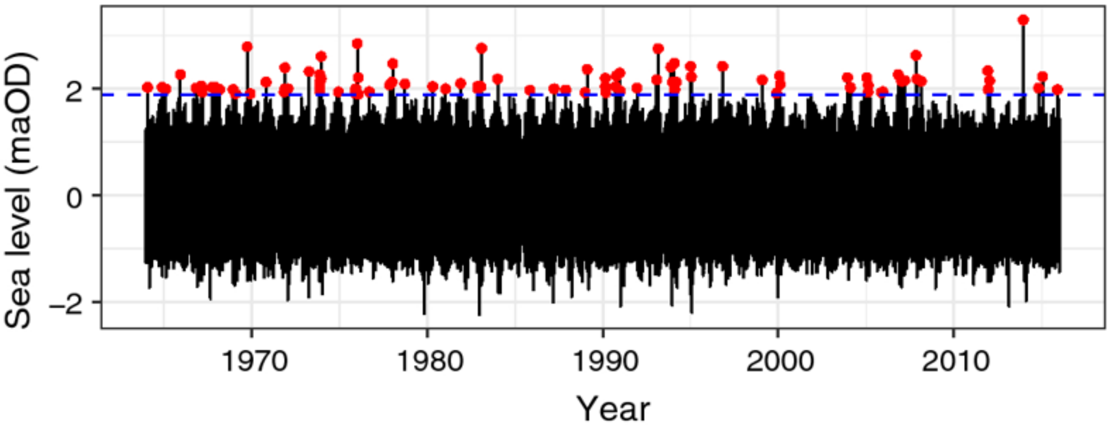

Figure 4.1 – Sea level relative to ordnance datum at Lowestoft, UK between 1964 and 2015. Red points represent sea level peaks above a defined threshold (blue, dashed horizontal line) chosen to fit a Generalised Pareto distribution and derive extreme return levels.

Due to the thermal expansion of water, melting glaciers and vertical land movement, relative sea level has been rising at Lowestoft at a rate of 2.70 ± 0.40 mm.a^{-1} in the second half of the twentieth century (Wahl *et al.*, 2013). A simple additive method was used to detrend the data and remove yearly changes in mean sea level with 2015 serving as the reference year. Moreover, the chosen peaks were declustered using a 48-h window to ensure only independent events were retained. A Generalised Pareto (GP) distribution was fitted to the remaining sea levels to determine return periods relative to the year 2015. The GP distribution has the distribution function:

$$F(x) = 1 - (1 - \frac{kx}{\alpha})^{1/k} \tag{4.1}$$

where the distribution's parameters α, the scale parameter, and k, the shape parameter, are determined with the maximum likelihood estimation method. The fit of the distribution was evaluated with plotting positions using the Gringorten formula, which is widely recognised for GP distributions (Chen and Singh, 2017).

4.2.1.2. River discharge

Daily mean river flow data at Horstead Mill (52°43′25.8672″N, 1°21′14.8745″E) on the River Bure between 1974 and 2015 were obtained from the National River Flow Archive. In the same way that sea levels were analysed, the POT method was used to determine the probability of extreme discharge. The GP distribution provided a better fit than a generalised extreme value distribution, which was tested using annual maxima of river flow. As for sea levels, a threshold for extreme river discharge was determined using the mean residual life plot. A threshold of 6.83 m^3.s^{-1} was selected, corresponding to the 99th percentile of river discharge levels (Figure 4.2). To insure the pre-requisite of independence between events, river discharge peaks were also declustered using a 48-hour window. An extreme value of 30.80 m^3.s^{-1} in 1981 particularly stood out from other peaks corresponding to an event that saw approximately 70 mm of rainfall in Norfolk between 25 April 1981 and 27 April 1981.

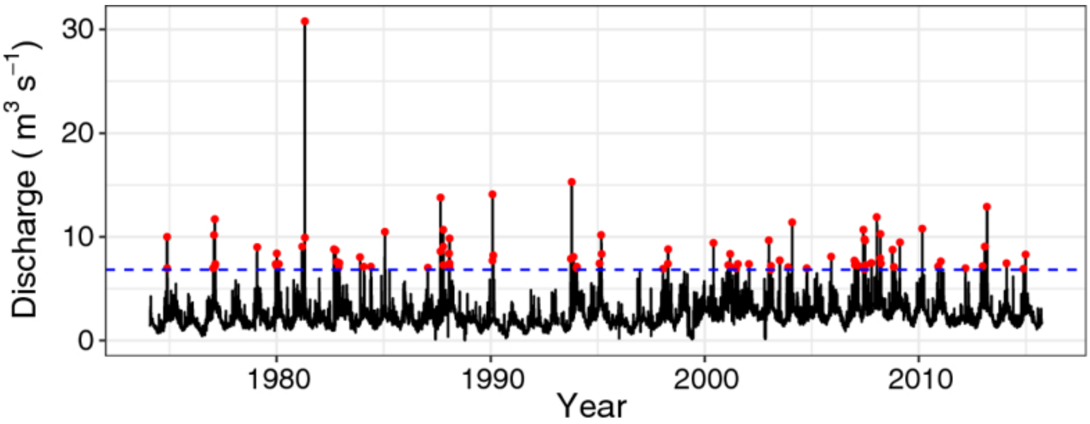

Figure 4.2 – River discharge at Horstead Mill between 1974 and 2015. The points represent discharge peaks above a defined threshold (blue, dashed horizontal line) chosen to fit a Generalised Pareto distribution and derive extreme return levels.

4.2.2. Hydrodynamic modelling: HEC-RAS

4.2.2.1. Model structure and domain

A 1D–2D hydraulic model was developed with the HEC-RAS software to map flooding extent and depth under different extreme scenarios. The Broads is a hydrologically complex and highly engineered area. The main rivers that make up the wetland—namely, the River Bure, River Yare and River Waveney—are narrow and constrained by high levees. These defences protect over 21,000 ha in the Broads and over 1700 properties. In many parts of the Broads, the flood banks are significantly higher than the wide floodplains they protect. Much of the Broads floodplain has a low elevation gradient and lies below sea level. A failure in the defences can therefore lead to widespread flooding. An accurate representation of the study area’s elevation is a fundamental requirement in hydraulic modelling. A composited DTM derived from light detection and ranging (LiDAR) data was obtained from the Environment Agency. The

DTM had a resolution of 2 m by 2 m with a vertical accuracy of ± 5 cm and provided a good coverage of the study area. River bathymetry is also an important input to the hydraulic model. As LIDAR data are poor at representing underwater elevations, river surveys from the Broads Authority conducted between 2011 and 2015 were used to correct the DTM within river channels. Moreover, information from the Environment Agency on flood defences in the area ensured that the latest levee heights were included in the DTM.

The 1D–2D hydraulic model shown in Figure 4.3 was built in HEC-GeoRAS, the ArcGIS extension for HEC-RAS. Cross sections of the river channels were drawn approximately every 30–50 m from one river bank to the other, forming the model's main 1D feature. A common method for out-of-bank flood modelling and mapping is to extend the model's cross sections into the floodplain. This technique is however not suitable for flood mapping in wide floodplains, which are common throughout the Broads. Instead, the floodplain is represented as a series of flood cells, called storage areas in HEC-RAS, where water can spill into from the rivers. The storage areas are separated by high ground and connected to the river cross sections in the HEC-RAS model with lateral structures, in this case, the flood defences on both sides of the rivers. Water will flow into the storage areas if the river level surpasses the corresponding height of the flood defence. Storage areas are 1D features represented using a volume-elevation table calculated with the DTM data and can provide satisfactory accounts of floodplain flow with little computational demands. More detail is however required in urban areas and where flow is likely to spread significantly as is the case at the downstream end of the study area. 2D flexible meshes were therefore set up and dynamically linked to the river cross sections in Great Yarmouth and the large low-lying area called the Halvergate Marshes. The mesh size varied between 10 m and 50 m and aligned to capture high ground features such as flood defences, roads, and railway tracks. A 2D domain is appropriate at the coast as it has the added benefit of being capable of portraying flooding occurring directly from the sea—in case of the overtopping of defences (coastal flooding)—and how it may interact with other sources of flooding.

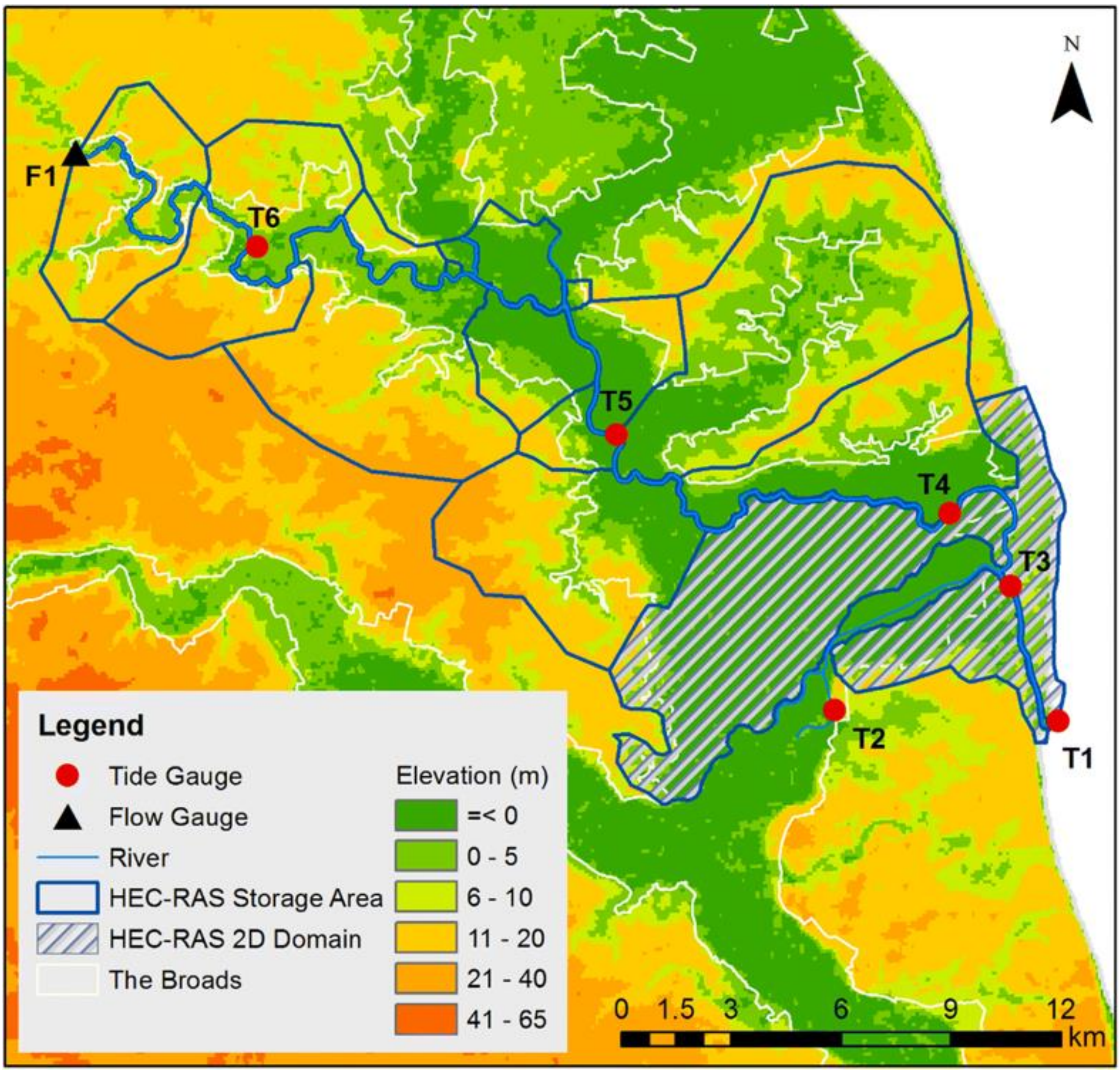

Figure 4.3 – HEC-RAS model domain. Storage areas and 2D areas are used to represent overbank flow in upstream and downstream portions of the model domain, respectively. Observations of river levels and discharge are available at different gauges: F1 (Horstead Mill), T1 (Great Yarmouth), T2 (Burgh Castle), T3 (Haven Bridge), T4 (Three Mile House), T5 (Acle Bridge) and T6 (Hoveton Broad).

The hydraulic model covers a 260 km area from the mouth of the River Yare in Great Yarmouth to Horstead Mill, approximately 40 km upstream on the River Bure. Portions of the River Bure’s tributaries – namely the River Ant and the River Thurne – are also included. The location of a flow gauge at Horstead Mill was chosen for the upstream boundary of the model. As a predominantly tidally influenced area, gauges in the Broads primarily measure river levels, and their locations are presented in Figure 4.3. Land-cover data were obtained from the EDINA Environment Digimap Service as supplied by the Centre for Ecology and Hydrology (CEH) for the year 2015 (Figure 4.4).

The original classification was simplified to represent the main land uses across the HEC-RAS 2D areas. The large floodplains of the Broads consist first and foremost of grassland and grazing marshes. Land used for arable crops and horticulture tends to be located on the higher ground and make up most of the rest of the area. The most significant urban area is Great Yarmouth on both sides of the River Yare.

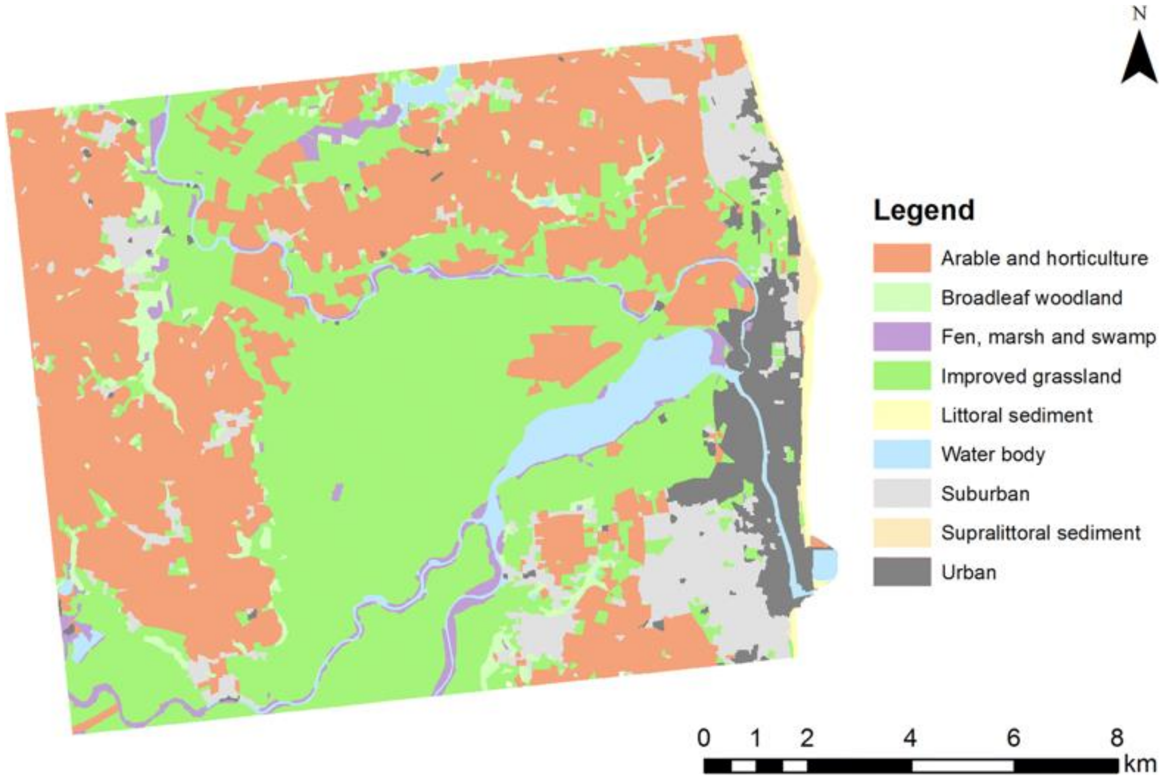

Figure 4.4 – Land-cover map of the downstream end of the Broads near Great Yarmouth in 2015 (Data obtained from EDINA Environment Digimap Services).

4.2.2.2. Unsteady flow analysis

Flood events were simulated in HEC-RAS under unsteady flow conditions. The HEC-RAS model solves the full Saint-Venant equations for the conservation of mass and momentum:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (4.2)$$

$$\frac{\partial u}{\partial t} + \frac{\partial}{\partial x}\left(\frac{u^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{uv}{h}\right) = -\frac{n^2 ug\sqrt{u^2+v^2}}{h^2} - gh\frac{\partial \zeta}{\partial x} + uf + \frac{\partial}{\rho \partial x}(h\tau_{xx}) + \frac{\partial}{\rho \partial y}(h\tau_{xy}) \qquad (4.3)$$

$$\frac{\partial v}{\partial t}+\frac{\partial}{\partial x}\left(\frac{v^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{uv}{h}\right)=-\frac{n^2 vg\sqrt{u^2+v^2}}{h^2}-gh\frac{\partial \zeta}{\partial y}+vf+\frac{\partial}{\rho\partial y}\left(h\tau_{yy}\right)+\frac{\partial}{\rho\partial x}\left(h\tau_{xy}\right) \tag{4.4}$$

where h is the water depth (m), u and v are the specific flow in the x and y directions ($m^2.s^{-1}$), ζ is the surface elevation (m), g is the gravitational acceleration ($m.s^{-2}$), n is the Manning's resistance, ρ is the water density ($kg.m^{-3}$), f is the Coriolis parameter and τ_{xx}, τ_{xy} and τ_{yy} are the components of the effective shear stress (Quirogaa *et al.*, 2016). While HEC-RAS offers the option of solving the diffusion-wave approximation of the equations in two dimensions, this method cannot be used for the propagation of waves in tidally influenced conditions. The full momentum equations were therefore chosen. A computational time step of 10 s was selected based on the guidelines proposed by the Courant–Friedrichs–Lewy condition:

$$C=\frac{V\Delta T}{\Delta x}\leq 1 \text{ Or } \Delta T\leq\frac{\Delta x}{V} \text{ (with C = 1)} \tag{4.5}$$

where C is the Courant Number, V is the flood wave velocity ($m.s^{-1}$), ΔT is the computational time step (s) and Δx is the average cell size (m).

The HEC-RAS model boundary conditions consisted of a stage hydrograph downstream and a flow hydrograph upstream. The observed sea level can be considered as the sum of the mean sea level, an astronomical tide component and a non-tidal residual (Pugh, 1996). The tidal component is the response of sea level to astronomical forces such as the relative position of the moon and the sun and can be isolated with a harmonic analysis of sea levels. What remains when the mean sea level is also removed is termed the non-tidal residual and primarily represents the meteorological impact on sea level from a surge.

An average storm surge shape was determined by identifying the 20 highest storm surges since 1964 at Lowestoft (Figure 4.5a). Ideally, local storm surge models can be used to reconstruct more physically realistic conditions in the definition of synthetic events (e.g., Villatoro *et al.*, 2014). The chosen method of generalisation was however described by the Environment Agency (McMillan *et al.*, 2011) as providing a reasonable means to derive a design surge profile. Although the averaging leads to a smoothed profile, the resulting storm surge shape is similar to the rest of the sample (Figure 4.5a) and can be considered representative of historical events. Moreover, by choosing the non-tidal residuals and not total sea level peaks to determine an average storm surge shape, large storm surges that may have occurred during low tide are also taken into account. An extreme sea level event for a target maximum level can thereby be recreated using this average surge shape, a base tidal prediction and the mean sea level (Figure 4.5b). A scaling factor was applied to the surge to stretch it to obtain the targeted total return sea level, when combined with the tide and the mean sea level. The base astronomical tidal cycle was derived such that the corresponding high tide level lied between highest astronomical tide (HAT) and mean high water springs (MHWS). At Lowestoft, HAT is equal to 1.48 maOD and the MHWS is equal to 1.08 maOD.

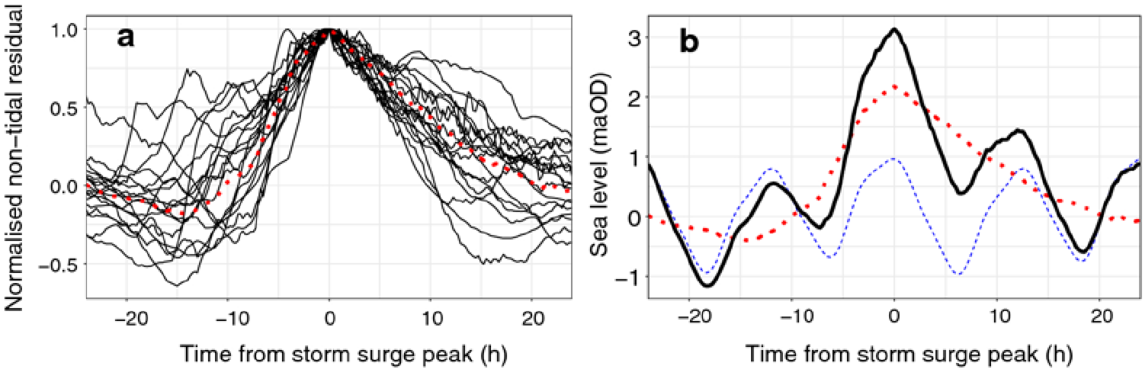

Figure 4.5 – **(a)** Average surge shape (red, dotted) estimated from the 20 largest surges at Lowestoft between 1964 and 2015. **(b)** Synthetic total sea level (black) derived from the surge residual (red, dotted) and the combination of a base astronomical tide) and the combination of a base astronomical tide) and the 2015 mean sea level (blue, dashed).

The skew surge is the difference between the predicted astronomical high tide and the nearest experienced high water. Since meteorological processes are independent of tidal forces, a surge can occur at any stage of the tide. Other studies have performed a joint probability analysis to form a probability distribution of total sea levels from the distribution of skew surges and peak tide levels (McMillan *et al.*, 2011). The assumption was made here that the storm surge peak coincided with the mean high predicted tide. This method, also used by Webster *et al.* (2014), was justified by analysing past extreme storm surge events that led to flooding concerns in the study area, which tended to occur at or near high tide.

An analogous method was applied to create synthetic flow hydrographs. The hydrograph shape of the last 20 most important storms in terms of flow at Horstead Mill on the River Bure was analysed to produce an average event shape. Figure 4.6 shows an example of a 100-year level synthetic hydrograph calculated for the River Bure and used as an upstream hydraulic boundary condition. Due to limited data availability, upstream boundaries at the River Yare and internal boundaries at the tributaries of the River Bure were assumed to be proportional to the discharge rate at Horstead Mill based on their relative drainage areas. This is a common method used for ungauged catchments (Webster *et al.*, 2014) that assumes similar hydrogeological characteristics. Drainage areas were determined in ArcGIS using 30 m by 30 m resolution Shuttle Radar Topography Mission (SRTM) data (Table 4.1). Initial conditions for both stage and discharge are taken directly from the boundary data.

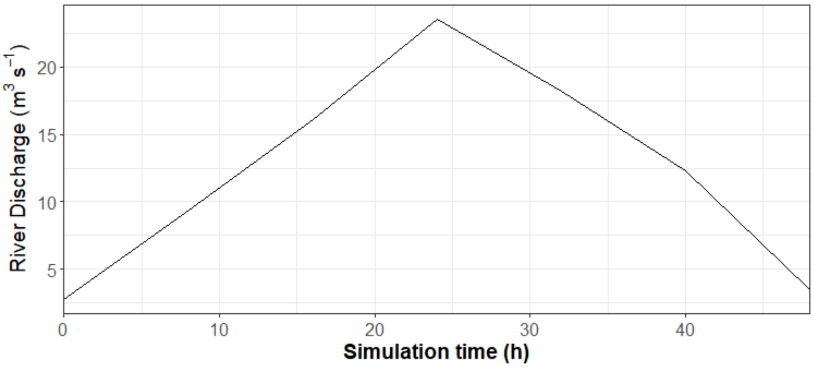

Figure 4.6 – Synthetic 100-year hydrograph for the River Bure derived from past observations of river discharge at Horstead Mill.

Table 4.1 – Drainage area of upstream and internal boundaries for the HEC-RAS model used to estimate flow hydrographs relative to the River Bure

River	Drainage area at model boundary (km^2)
Bure	336.54
Ant	145.24
Thurne	119.35
Spixworth Beck	59.94
Yare	1392.57
Waveney	891.43

4.3. Results and Discussion

4.3.1. EVA and Scenario Definition

Exploratory semi-structured interviews were conducted with a set of 11 stakeholders to identify priorities, interests and to help base the definition of scenarios on local knowledge. Stakeholders were chosen from professionals with extended knowledge of the Broads, and active residents with a long-lasting interest in the area's overall management. Specific experience in flood management varied greatly as participants covered a wide range of sectors such as farming, angling, environmental protection, engineering and coastal management. The interviews confirmed the importance of tidal and coastal sources of flooding in the Broads and highlighted vulnerable locations such as – but not limited to – Great Yarmouth or several protected areas. One of the main recurring statements emphasised in the interviews was a concern for the risk of combined events. More specifically, the occurrence of a storm surge during high river discharge was identified as a worry for different stakeholders. Although the small sample of participants does not allow for statistically significant conclusions, this information was used to guide modelling choices and define future scenarios.

A comparison of the available data on past peak sea levels, non-tidal residuals and river discharge shows that these events do not tend to occur simultaneously (Figure 4.7). While this research initially was based on the assumption that compound flooding was likely in the region, it became apparent not only that storm surge and extreme river discharge events could be considered independent on the eastern coast of the UK (Mantz and Wakeling, 1979) but that these events were generated by different meteorological characteristics (Hendry *et al.*, 2019). As stakeholders expressed concerns related to combined events, and there still exist uncertainties on the impacts of climatic changes on compound flooding (Bavacqua et al., 2019), it was deemed useful to keep such scenarios in model simulations.

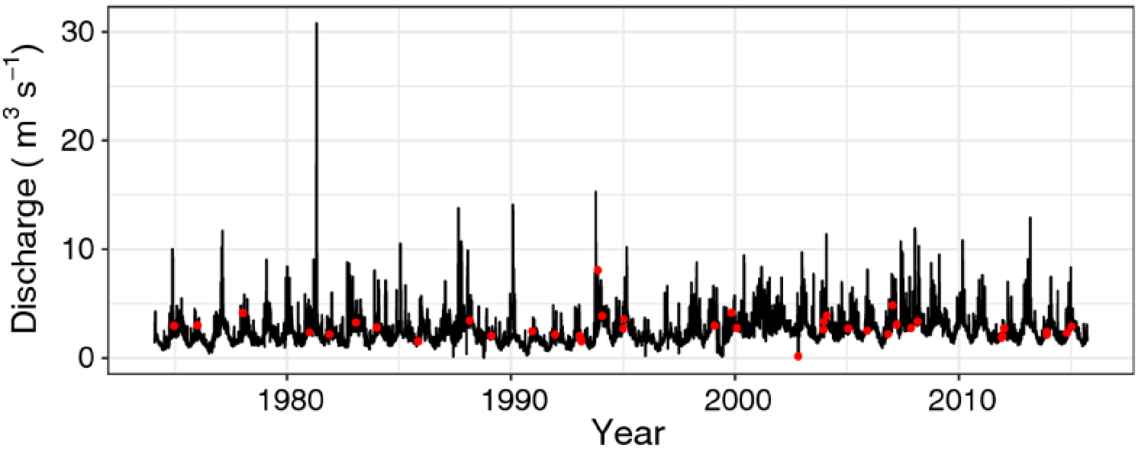

Figure 4.7 – The timing of the 40 highest non-tidal residuals (red points) decomposed from sea level data at Lowestoft, UK compared to river discharge at Horstead Mill between 1974 and 2015.

The EVA served to find return levels of both extreme sea level and extreme discharge to define representative downstream and upstream boundary conditions, respectively. The purpose of the EVA was not to provide a robust probabilistic assessment of flooding risk from different or combining sources. Without an analysis of the probability of joint occurrence of high tide and extreme storm surge, it was not possible to assign return levels to entire extreme sea level events. The EVA performed on total sea levels however did provide return levels for the peak of recreated extreme events.

The GP distribution performed relatively well to describe both extreme sea level (Figure 4.8a) and extreme discharge (Figure 4.8b). It should be noted that the most extreme values were found above the fitted distribution curves. These events corresponded to the December 2013 storm surge and a peak river flow in April 1981. Both occurrences were verified using data from other nearby gauges, and it was therefore decided not to discard them as recording errors. These points were by far the most extreme observations and did not provide strong evidence against the choice of the GP distribution function compared to other tested distribution functions. The lack of data is a common issue in EVA. More investigation using other sources of data (such as news reports if they exist) that extend past the recorded data period would allow for more confidence in this estimation.

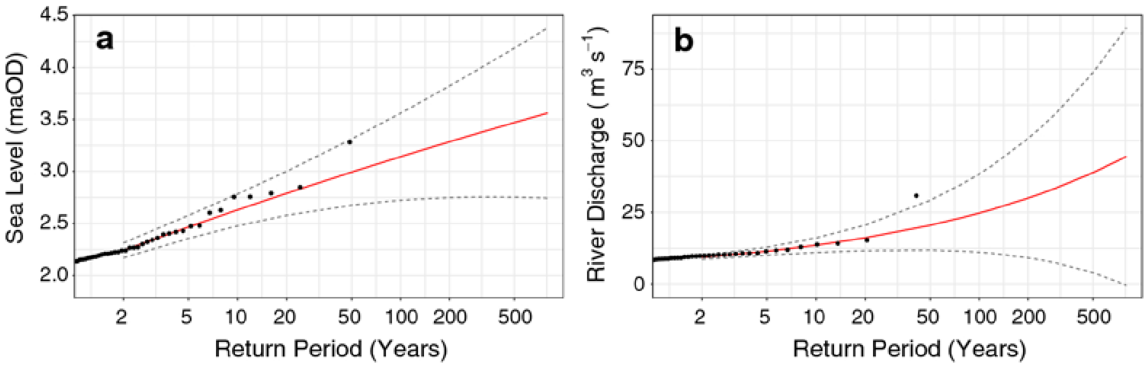

Figure 4.8 – Return levels at the reference year 2015 for **(a)** sea level at Lowestoft, UK expressed in relation to ordnance datum and **(b)** river discharge at Horstead Mill. The dashed lines represent the 95% confidence intervals.

Evidence suggests that changes in mean sea levels are the primary factor leading to an increase in extremes sea levels (Menéndez and Woodworth, 2010). Relative mean sea level is not only rising, but has also been found to accelerate at various rates around the world, with a trend of 4.4 ± 1.1 mm.a^{-1} estimated at Lowestoft from 1993 to 2011 by Wahl *et al.* (2013). It indeed remains highly uncertain how climate change will impact local storm surge patterns. A linear increase in relative mean sea level was assumed to determine future conditions and return levels up to the year 2100. Uncertainty moreover resides in current projections of the rate of SLR in the twenty-first century. Pfeffer *et al.* (2008) found that an accelerated rise between 0.8 m and 2 m up to 2100 was physically plausible depending on glaciological conditions. To account for such possibilities, extreme scenarios of 1 m and 2 m mean SLR by 2100 were also considered.

While seasonal precipitation changes are expected in the UK, notably with an increased proportion of heavy precipitation events occurring during winter months, current projections do not show significant changes in annual precipitation in East Anglia (Palmer *et al.*, 2018). Moreover, little is known on the intensity of extreme precipitation events in coming decades and therefore which trajectory river discharge will also follow. Patterns of extreme river discharge were therefore assumed to the same up to 2100 as in 2015 in the presented scenarios. This assumption is moreover warranted by the much greater influence of tidal processes in the Broads.

The chosen scenarios are presented in Table 4.2. They included three scenarios of 100-year return peak sea levels under different mean SLR pathways. As explained in Section 4.2.2.2, only the peak sea level is assigned a 100-year return period as opposed to the entire event. Each storm surge event was then also combined with a simultaneous 100-year return river discharge to test the sensitivity of the study area to coinciding extreme events. The timing of events can have significant impacts on flooding occurrence and extent. It is therefore important to note that previous studies have found it most likely for these types of events to not coincide with up to several days separating the different extremes (Klerk *et al.*, 2015). With these caveats taken into account, the proposed scenarios provide a basis to assess the sensitivity of the Broads to compound flooding.

Table 4.2 – Scenario names

Upstream boundary river discharge	**Downstream boundary sea level (1:100 peak sea level event)**		
	4 mm.a^{-1} mean SLR up to 2100	**1 m mean SLR**	**2 m mean SLR**
Base flow	2100Q0	1mQ0	2mQ0
1:100 return event	2100Q100	1mQ100	2mQ100

4.3.2. Calibration and validation

The HEC-RAS model was calibrated and validated with storm surge events from October 2014 and December 2013, respectively. The calibration parameter used was the Manning’s n roughness coefficient. Data on past flooding inundation extent in the Broads are lacking in both availability and accuracy. While there have not been major flooding events since 1953, localised defence failures have been observed during extreme storm surge events. Spencer *et al*. (2015) provided an account of the impact of the December 2013 storm surge along the Norfolk coast. Tidal flooding was however also observed further inland due to overtopping and reported in parts of the Broads (Broads Authority, 2014). As there is no record of the spatial footprint of this inundation, the validation process was carried out using river levels at different stations on the Bure and the Yare (Figure 4.3), as well as reports from the Broads Authority, news articles, dated photos, and local accounts of flooding.

Descriptions of the local environments and recommended ranges obtained from Chow (1959) served to make initial benchmarks for Manning’s n values. The model’s calibration was performed on the Manning's n within river channels to reach final values as shown in Table 4.3. A roughness coefficient was also applied to land classes out of the riverbanks in the 2D modelling domain. These values were not used during the model's calibration as flood extent data were not available (Table 4.4). In tidally influenced rivers, the inertial terms in the momentum equation are important and rivers levels are not highly sensitive to adjustments in the roughness coefficient (Brunner, 2016). Theta is a weighting factor that ranges between 0.6 (more accurate) and 1.0 (more computationally stable) applied to the finite difference approximations when solving the unsteady flow equations. A Theta value of 0.6 was used to improve the accuracy in the representation of the propagating tidal wave, which did not decrease the model's stability.

Table 4.3 – Manning's n in river channels after calibration

River reach	Manning's *n* roughness coefficient
River Bure	0.045
River Ant	0.045
River Thurne	0.045
River Yare—Great Yarmouth	0.04
River Yare—Breydon Water	0.025
River Yare—Upper	0.03
River Waveney	0.04

Table 4.4 – Manning's n for different land classes

Land cover	Manning's n roughness coefficient
Arable and horticulture	0.05
Broadleaf woodland	0.15
Fen, marsh and swamp	0.07
Improved grassland	0.035
Urban areas	0.2

The Nash-Sutcliffe model Efficiency coefficient (NSE) is used to assess the model. The NSE (Nash and Sutcliffe, 1970) is defined as:

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_m^t - Q_o^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q_o})^2} \tag{4.5}$$

where Q_m^t is modelled discharge over time t, Q_o^t is observed discharge over time t and $\overline{Q_o}$ is the mean of observed discharge.

As expected, the model performed well at recreating river levels near the model's downstream boundary condition in Great Yarmouth at Haven Bridge (Figure 4.8a) with an NSE of 0.92. The model also performed well upstream on both the River Bure and the River Yare, at the Three Mile House (Figure 4.9b) and Burgh Castle (Figure 4.9c) gauges, respectively. It should be noted that the instrument at Three Mile House was unable to measure the river level during the peak of the tide on 06/12/2013. The NSE remained relatively high at 0.84. The gauge at Burgh Castle is a flood warning monitoring station only and due to the position of its pressure sensor instrument, it therefore does not measure any levels below 0 maOD. Still, the model produced a good fit to both the level of the peaks and their timing at Burgh Castle.

The model's performance decreased upstream of the River Bure. At Acle, once the tidal wave had propagated, the NSE dropped to 0.67 and there was a slight shift in the timing of the tide (Figure 4.9d). The modelled peak river level remained within 0.03 m of the observed value. The error increased moving further upstream and away from the model's coastal boundary. The trends in simulated river levels at Hoveton Broad (Figure 4.9e), and, to a lesser extent, Acle suggest that tidal fluctuations were not propagating far enough upstream to match the observed amplitudes. A longer warm up time could improve model results leading up to the storm surge event. It is moreover possible that the influence of human activities such as pumping, which was disregarded in the presented model, could have had an uncaptured impact on water levels upstream on the River Bure. In Hoveton Broad, nearly 40 km from the mouth of the River Yare and the North Sea, the model overestimated peak river levels by a maximum of 0.1 m, which remained within an acceptable margin.

While river levels were high during this event, the defences were largely successful in holding back the water from the floodplains. This was also the case in the model’s recreation of the event, where only localised flooding was visible at moorings located near Berney Arms, which allowed water to flow into Halvergate Marshes.

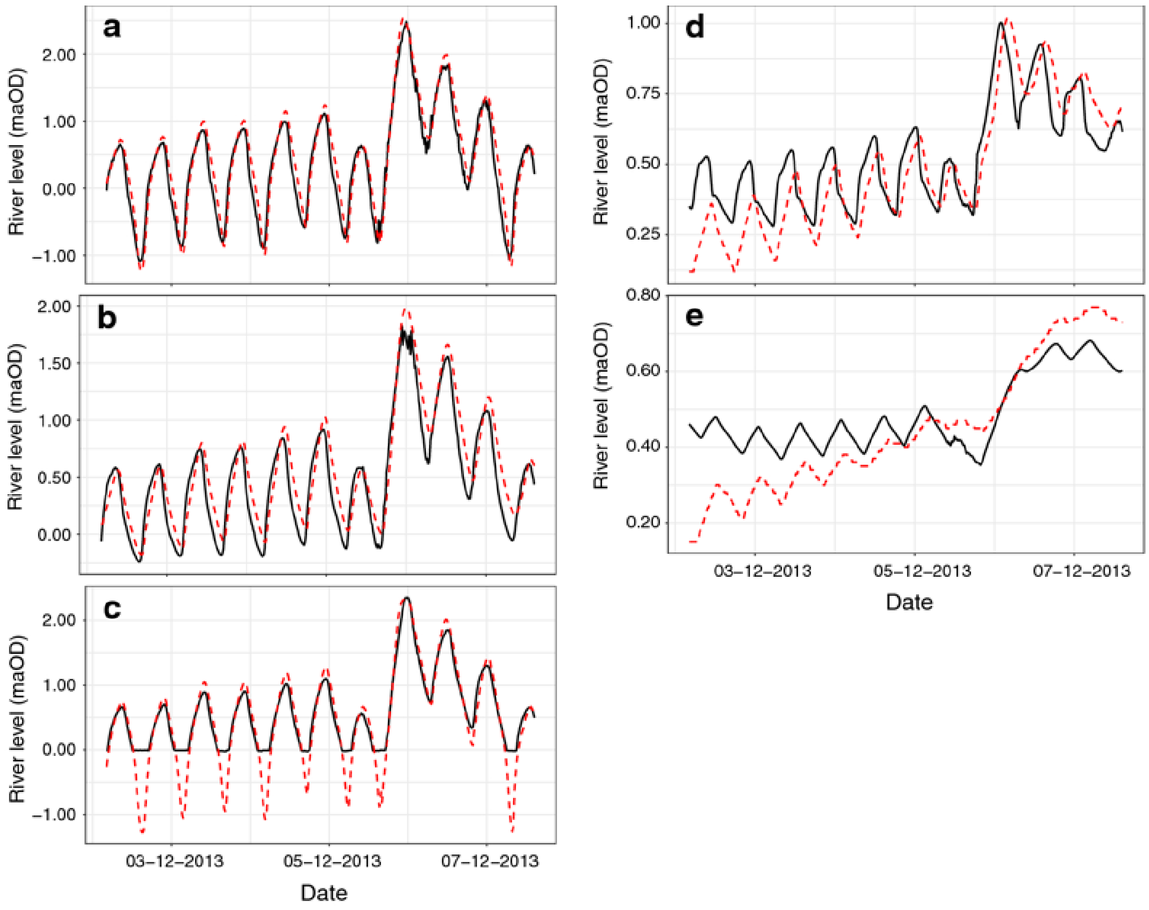

Figure 4.9 – Observed (black) and modelled (red dashed) river levels during the December 2013 storm surge at **(a)** Haven Bridge, **(b)** Three Mile House, **(c)** Burgh Castle, **(d)** Acle, and **(e)** Hoveton Broad.

4.3.3. Hydrodynamic simulations

4.3.3.1. Flooding impact

Model results derived from simulations in HEC-RAS were exported to ArcGIS and R for analysis. The maximum flooding depth from each simulation run can be found in Figure 4.9. The inundation extent shown in these profiles represents an aggregation of the overall runs rather than a specific simulation time. The profiles should therefore be differentiated with the extents occurring during maximum sea level, since flooding is dynamic, and its timing varies across various locations.

Extreme sea levels cause flooding both downstream and upstream in the Broads when assuming a linear mean SLR up to 2100 (Figure 4.10a). The largest affected area is Halvergate Marshes, where water is able to flow throughout the large floodplain located north of Breydon Water. Elevated roads and railway tracks are well captured by the model's 2D mesh and slow the propagation of the flood wave. Flooding is minimal in the more densely populated Great Yarmouth as there is almost no overtopping of high defences. With the exception of Halvergate Marshes, flood walls and levees are successful in preventing extensive flooding. Upstream of Ranworth Broads, the floodplains are unprotected and consist mostly of marshes that are well connected to the river. While buildings near the riverbanks in the towns of Horning and Hoveton are affected, the flood depth remains relatively low. As Figure 4.10b shows, combining this event with a 1:100 return river discharge has significant consequences on flooding on the upstream boundary of the tidal Bure. Impacts downstream remain limited. As SLR has been observed to accelerate in the last decades, a linear increase in relative mean sea level over the next century is a conservative assumption. Scenarios representing an accelerated rise leading up to 1 m and 2 m increase in mean sea level are shown in Figure 4.10c–f.

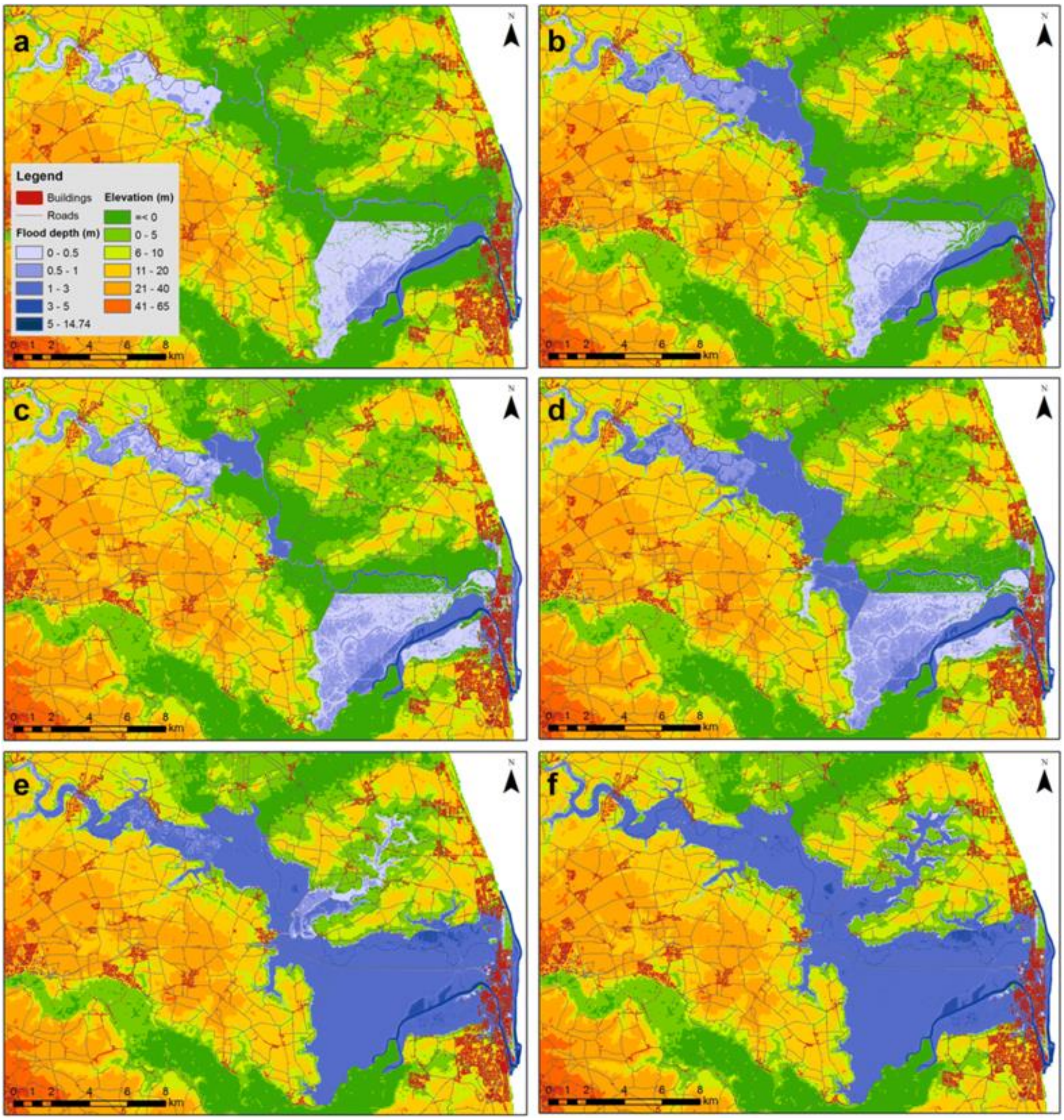

Figure 4.10 – Maximum flooding depth in the Broads between Great Yarmouth and Horstead Mill on the River Bure under different extreme scenarios (simulation names from Table 3). **(a)** 2100Q0, **(b)** 2100Q100, **(c)** 1mQ0, **(d)** 1mQ100, **(e)** 2mQ0, **(f)** 2mQ100.

The topology of the rivers and floodplains in the Broads causes flooding to occur rapidly and spread significantly when a defence is overtopped. Figure 4.10 shows that certain areas are susceptible to lower thresholds of embankment failure, thereby flooding first and highlighting potential vulnerabilities. A notable observation from the scenarios with a 1 m and 2 m mean SLR is the increased impact on Great Yarmouth. Not only are more tidal defences overtopped, but coastal waters are also able to flow into the town directly from the sea and cause more flooding at some simulation time steps. These interacting sources of flooding lead to an important increase in impacted buildings (Table 4.5). While a 2 m increase in mean sea level by 2100 is still considered unlikely and would require a drastic acceleration of SLR, this scenario is useful to highlight the area's sensitivity. For example, the model showed flooding outside of some of the left banks of the Bure only during scenarios 2mQ0 and 2mQ100. The main urban zone in the study area is Great Yarmouth, located near the coast. Sea level is therefore the main driver for the number of flooded buildings. Other towns located farther upstream in the Broads are also affected. Centres of activity for tourism and sailing in Horning and Hoveton lie in close proximity to the River Bure, and several buildings in both towns are susceptible to flooding in all scenarios.

Table 4.5 – Number of buildings affected by flooding under different extreme scenarios in the model study area

Scenario	Number of builds flooded	Proportion of buildings flooded
2100Q0	702	16.78
2100Q100	892	21.32
1mQ0	1285	30.72
1mQ100	1389	33.21
2mQ0	1635	39.09
2mQ100	1797	42.96

While flooding occurs in all the presented scenarios, both extent and depth vary greatly between the different simulations. Depth is important to consider for risk management as it is used in determining flood damage. Figure 4.11 shows the density of flooded 2-m cells by depth in all six scenarios. Although the flooding extent was already high in scenario 2100Q0, most of the flooding occurred at low depths between 0 m and 0.5 m, meaning actual damages would be limited or easier to cope with (Figure 4.11a). The maximum density shifts towards 0.5 m and 1 m for scenario 1mQ0 (Figure 4.11b) and increases considerably to over 2 m for scenario 2mQ0 (Figure 4.11c).

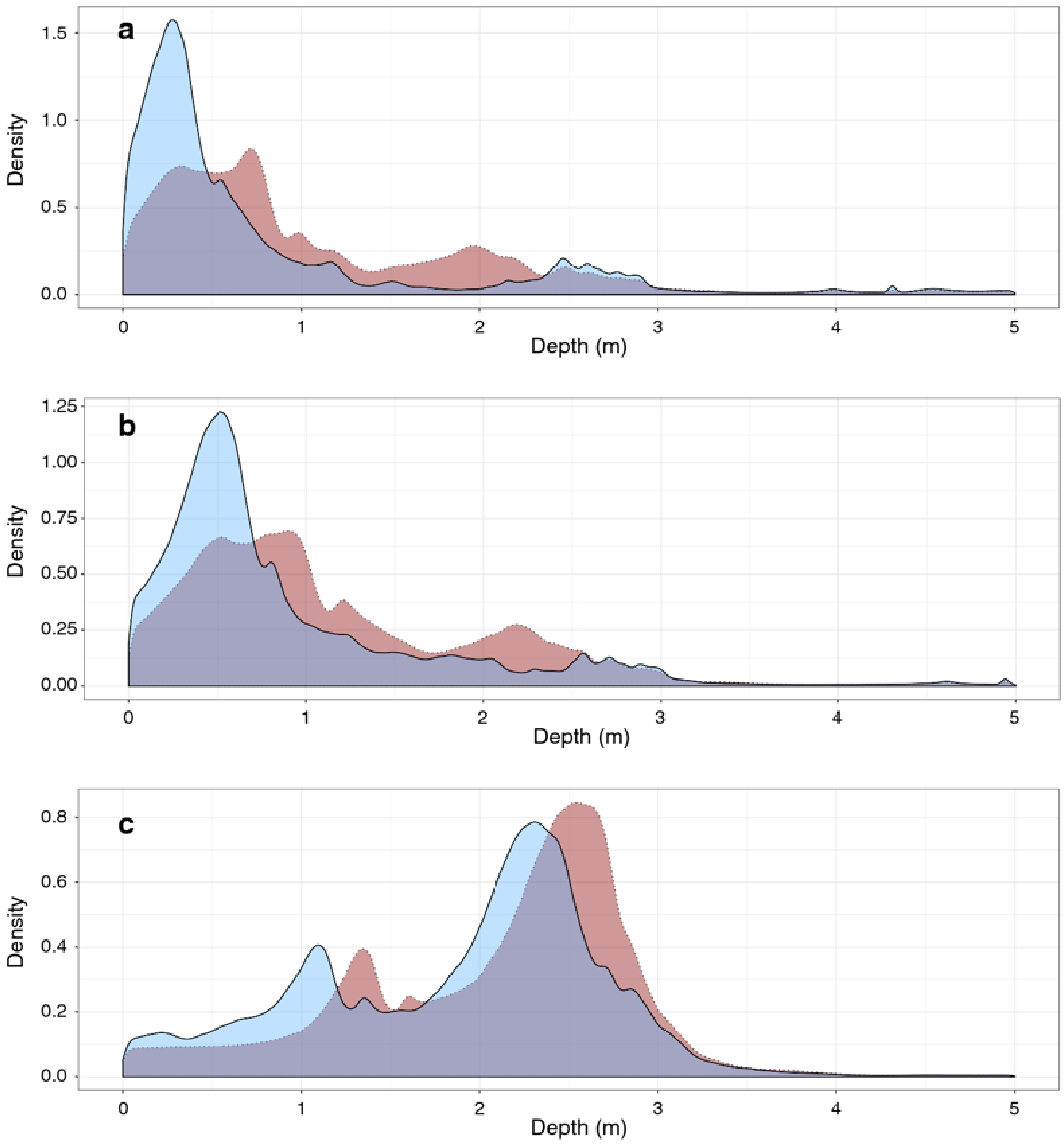

Figure 4.11 – Kernel density plots of flooded cells by depth for scenarios **(a)** 2100Q0 (blue), 2100Q100 (red, dotted line), **(b)** 1mQ0 (blue), 1mQ100 (red, dotted line) and **(c)** 2mQ0 (blue), 2mQ100 (red, dotted line). Y-axes represent probability densities (in m^{-1}).

Both Table 4.5 and Figure 4.11 emphasise that increasing relative mean sea levels have a significant impact on inundation extent and depth in the Broads. While sea level is indeed the main driver for flooding in the study area, the results also show that coinciding high river flows can exacerbate these impacts. The average depth of cells below 5 m in depth increased from 0.82 m to 1.08 m (Figure 4.11a), from 0.92 m to 1.16 m (Figure 4.11b) and from 1.9 m to 2.09 m (Figure 4.11c) for the three scenario pairs, respectively. A similar pattern can be observed for the total area of the flooding in each scenario. For both average depth and inundation area however, the influence of high discharge decreases as the maximum sea level increases. Average flood depth increases by 40% from scenarios 2100Q0 to 2100Q100, while it increases by 5% from scenarios 2mQ0 to 2mQ100. Similarly, total inundated area increases by 32% from scenarios 2100Q0 to 2100Q100 compared to a 10% rise from scenarios 2mQ0 to 2mQ100.

The simulated compound events did not have significant added consequences in Great Yarmouth on either flooding extent or depth, compared to unique events of extreme sea level. The longitudinal profile of the modelled rivers indeed shows that the influence of the combined extreme discharge decreases going downstream (Figure 4.12). Near the mouth of the River Yare, the extreme discharge has almost no impact on the water level in all three envisaged cases. Figure 4.12 also shows that the difference in water level between Q0 and Q100 events is greater for a lower mean sea level. Upstream areas are much more affected. The flooded area of broadleaf woodland, which occurs mostly upstream of Ranworth Broads along the River Bure, is highly influenced by the occurrence of a combined event (Figure 4.12, Table 4.6). The Bure Broads and Marshes are well connected to the river, and the encroachment of water is therefore not a direct concern or a rare occurrence.

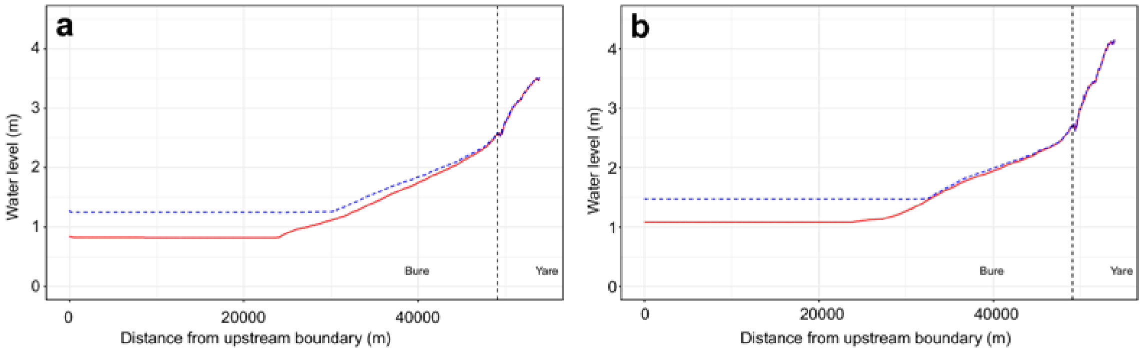

Figure 4.12 – Longitudinal profile view of maximum water levels along the River Bure and River Yare from the model's upstream boundary to its downstream boundary, the North Sea. **(a)** Maximum water levels for scenarios 2100Q0 (red) and 2100Q100 (blue, dashed). **(b)** Maximum water levels for scenarios 1mQ0 (red) and 1mQ100 (blue, dashed).

Table 4.6 – Area flooded by land-cover class (km^2)

Scenario	Broadleaf woodland	Arable and horticulture	Improved grassland	Fen, marsh and swamp	Urban	Sub-urban
2100Q0	6.31	1.01	23.27	6.92	1.45	0.16
2100Q100	8.91	2.16	33.14	8.65	1.60	0.31
1mQ0	7.93	3.34	35.86	8.08	4.59	0.56
1mQ100	10.41	6.73	47.89	9.14	4.69	0.74
2mQ0	12.83	14.22	61.52	10.02	6.73	1.58
2mQ100	14.22	15.92	63.26	10.09	6.77	1.86

The deeper upstream flooding observed in Figure 4.9b, c and d remains significant as it can lead to longer residence times of saline waters. Large areas of improved grassland, notably used for grazing, are predisposed to flooding under each scenario, with arable and horticulture land classes also highly impacted (Table 4.6). There are moreover several protected areas, such as Sites of Specific Scientific Interests (SSSI), located in the Broads. A topic for future research would be the impact of extreme events on salinity in the Broads. Salinity can cause damage to agricultural land and therefore lead to significant economic losses as well as representing a threat to sensitive species. Studying the impact of combined events may lead to counter-intuitive results as several processes affect salinity. Indeed, high river flows add freshwater to the system, while surges push saline water upstream into the Broads. River salinity and conductivity can be simulated in HEC-RAS's water quality module.

4.3.3.2. Implications of the modelling methodology

A significant benefit of the described 1D–2D approach in portraying overtopping is the use of specific lateral structures for flood defences to guarantee that maximum crest heights were accounted for, regardless of the chosen mesh resolution. It is a fundamental requirement for 2D cells in HEC-RAS to be set up such that cell edges (or "faces") align with high ground or structures impeding the movement of water. This task can be difficult for narrow flood defences, even with a relatively fine resolution of 2 m. Cells that are too large or that are not adequately oriented can cause issues with the model's calculations, leading water to incorrectly "leak" through natural or man-made barriers. The results in such cases are fragmented, do not respect hydraulic connectivity, and hence produce unrealistic outputs of flooding extents. The Broads is a highly engineered area with many embankments protecting large expanses of land from rivers. It was therefore essential to use lateral structures between 1D and 2D domains that capture the height of defences for their entire lengths. Until computational capabilities increase to allow for extremely fine mesh resolutions, this study finds that a 1D–2D method remains the most feasible approach for the geographical location in question.

The HEC-RAS 1D–2D model was able to highlight vulnerabilities and weak points within the study area as well as account for complex interactions between different sources of flooding. The model structure could still be improved by including building footprints in the 2D mesh to better represent the flow of water in urban areas. Such levels of accuracy were not necessary to assess the overall sensitivity of the case study area and the fitness for use of the HEC-RAS model version 5.0.

Several important considerations should be made when interpreting the results derived from the presented hydraulic model. The first is that while flood defence infrastructure can fail in a number of ways, only the overtopping of defences was considered here. The erosion and breaching of dunes, embankments and walls are a common concern in coastal regions (Hall *et al.*, 2015). Although these processes can be simulated in HEC-RAS and can be useful to represent catastrophic or "what if" scenarios, their impacts fell outside of the scope of this study.

A more comprehensive study of flooding risk would moreover look to incorporate processes of wind and waves, which were omitted in this simplified hydraulic modelling framework. Wind is a key parameter that plays a role in the dynamics of both waves and surges and can therefore have important consequences on coastal flooding. With the necessary data, the EVA and the scenarios used for simulations could therefore be refined by setting up local wave and storm surge models (e.g., Villatoro *et al*., 2014).

The presented results show the potential for multiple extreme events occurring at the same time to exacerbate flooding risk in the Broads. The assumption was made that peak river discharge and peak sea level occurred simultaneously in scenarios where both events were considered. This assumption may not be representative of likely events in the Broads. Past studies in other regions, such as the Netherlands, have, for example, shown a dependency between discharge peaks and water levels, but with a lag time of several days (Klerk *et al.*, 2015). Moreover, understanding the types of weather patterns associated with different events could provide useful insights into flooding hazard in the region. Hendry *et al.* (2019) found that storms on the east coast of the UK that tend to generate high skew surges are generally distinct from those that tend to generate high river discharge. Looking specifically at the Broads, Mantz and Wakeling (1979) found that extreme river discharge and surge events were independent and therefore their combined probability could be found as the product of their respective probabilities. Joint probabilities should be carefully considered to make robust planning recommendations on flood risk management.

4.4. Conclusions

This study has looked to evaluate the sensitivity of a complex coastal environment to different sources of flooding, using the new tools made available in HEC-RAS version 5.0. A 1D–2D approach was found to be appropriate for flood mapping in this context, accurately reproducing the flow of water in both large floodplains and urban areas while reducing computational requirements. Lower simulation run times moreover made it possible to cover a larger area from the coast and to 40 km inland where tidal and fluvial processes interact. The proposed approach is particularly relevant to low-lying and low-gradient regions like the Broads, which are prone to tidal flooding and where the tidal boundary extends far upstream. There will continue to be more opportunities for 2D modelling in the UK as the coverage of fine-resolution LIDAR data grows.

Hydraulic models are not only sensitive to topographical data but also to the choice and fundamental design of boundary conditions. With extremes being the primary cause of flooding in the Broads and in many regions around the world, it is important to capture the hydrological conditions occurring during these events. The GPD function was used to determine return levels of sea level and river discharge to create synthetic extreme events under future conditions of SLR. Important assumptions were made to create simplified synthetic events as the interest of this work was to assess the sensitivity of the

Broads to extreme flooding and the potential for the modelling framework to map out maximum flooding extents. Peak river discharge and sea level were thereby designed to occur at the same time. Similarly, the storm surge peak of synthetic scenarios coincided with the highest point in the tide cycle.

The insights from this case study informed a number of developments to the modelling methodology, which will be expanded upon in following Chapters:

- The expansion of the model domain to include other parts of the Broads, namely, the River Yare, the River Waveney, the River Thurne and the River Ant sub-catchments, as well as the coastal town of Lowestoft.
- The definition of a hydrological model for each river sub-catchment to determine more accurate upstream boundaries for the HEC-RAS hydraulic model.
- The inclusion of projected changes in temperature and precipitation in the Broadland catchment to better understand the impact of these climatic changes on flooding hazard.
- The consideration of the joint probability of occurrence of storm surges and high tides as well of extreme sea levels and extreme river discharge.

The proposed hydraulic modelling methodology contributes to improving our understanding of the Broads' sensitivity to different sources of flooding. Although storm surges are – and are likely to continue to be – the main drivers for flooding in the Broads with relative mean SLR over the next century, high river discharge has the potential to exacerbate flooding caused by extreme sea levels. This case study highlights the potential for 1D–2D modelling in assisting decision-making. This methodology indeed allows for the consideration of urban coastal areas, requiring a high amount of detail, as well as vast inland rural zones. It is moreover suited to dynamically represent interacting sources of flooding and potential combined extreme events. The presented approach is therefore a step towards helping meet the requirements of integrated catchment management as well as flood alleviation and adaptation.

Chapter 5 – Integrating stakeholder and scientific knowledge of future flood risk to inform climate change adaptation planning

This chapter was adapted from Pasquier *et al.* (2020) published in *Environmental Science & Policy*, which can be found in Appendix 5.

5.1. Introduction: Integrated Assessment in the Broads

Decision-makers face a particular challenge in planning for climate adaptation. The complexity of climate change's likely impacts, such as increased flooding, has widened the scope of information necessary to take action. This is particularly the case in valuable low-lying coastal regions, which host many competing interests, and where there is a growing need to draw from varied fields in the risk-based management of flooding. The rising scrutiny over science's ability to match expectations of policy actors has called for the integration of stakeholder and scientific knowledge domains.

The Broadland area is currently in a transition period and in the midst of redefining its FRM strategy for the mid-2020s onwards. This represents an ideal opportunity for stakeholders to reassess local flood risks and explore adaptation measures that better cope with a changing climate and rising sea levels. The goal of the research was to combine different knowledge domains to assess flood risk and consider potential adaptation measures for Broads. Stakeholders were engaged, most notably in a collaborative workshop, with scientific information derived from the sensitivity analysis presented in Chapter 4.

The aims of this research were to determine (1) how scientific information and stakeholder knowledge and perceptions on flood risk can be integrated, (2) how such a collaborative approach can translate risk-based management principles relevant for climate adaptation planning and (3) the lessons that can be derived from the participatory IA of flood risk to inform adaptation planning in the context of the Broads.

5.2. Methodology

5.2.1. Preliminary interviews and modelling

A combination of quantitative and qualitative methods was used both as a way to generate research material as well as to assess the knowledge generation process itself. The main sources of information on flood risk in this project originated iteratively from the development of the previously described hydraulic model and stakeholder engagement exercises. For this study, stakeholders were identified and recruited through different methods. This included presenting the research and handing out information leaflets at community meetings in the Broads, advertising stakeholder events on online BA newsletters and by snowball sampling. The different participatory activities in the research design received prior ethical approval from the General Research Ethics Committee of the University of East Anglia (Appendix 1).

Exploratory semi-structured interviews were first conducted between January 2017 and July 2017 to identify key overarching issues and interests related to flood risk. A total of 11 interviews were conducted with actors with various interests, namely farmers, conservationists, anglers, local elected officials, coastal managers and engineers.

Findings from the interviews guided the development of the first version of the hydraulic model of the River Bure sub-catchment in the Broads as presented in Chapter 4. The model as well as the previously described analysis of flooding sensitivity and derived flood maps served as the basis for discussions during a stakeholder workshop, the central engagement activity in this research.

5.2.2. Stakeholder workshop

The workshop design was loosely based on the “Scientific-Stakeholder Workshops” proposed by Löschner *et al*. (2016) but deviated from that approach in several ways. A method for stakeholder analysis in environment management studies (e.g., Reed *et al*., 2008; García-Nieto *et al.*, 2015) is to classify stakeholders based on their levels of influence in decision-making and interest, here in FRM. A balanced number of higher interest/higher influence (7) and higher interest/lower influence (7) stakeholders (Table 5.1) attended the workshop. Three individuals had previously participated in the exploratory interviews while the remainder were new to the project. The attendees were asked in the week prior to the workshop to respond to an online survey created with Lime Service[1]. A total of 9 responses were submitted. The survey was structured into 4 parts to (1) assess the participant's level of knowledge on flood risk and modelling, and to record their perceptions of (2) current flood risk and management, (3) future conditions and (4) possible adaptation measures in the Broads.

Table 5.1 – Workshop stakeholder affiliations grouped by individuals' levels of influence and interests in FRM.

Higher interest/Higher influence	Higher interest/Lower influence
Broads Authority	Norfolk Wildlife Trust
Internal Drainage Board	Royal Society for the Protection of Birds
Norfolk County Council, Suffolk County Council	National Farmers' Union, farmers
Broadland District Council	Broads Angling Services Group
Coastal engineers and managers	Broads Navigation

The workshop was held on July 10th 2018 at the Acle Recreation Centre in the Broads and was divided into three sessions, working under the basic instruction that all perceptions and opinions could be voiced.

Session I aimed to define and get a shared understanding of the problem at hand, using modelling results (i.e. flood maps as shown in Figure 5.2. derived from the results shown in Chapter 4) to spark discussions on hazard, vulnerability and exposure in the Broads. A presentation by the principal researcher explained the aims of the workshop and described the developed hydraulic model along with its results. An information sheet was provided to stakeholders with a summary of results from Chapter 4. The participants were prompted with non-exhaustive themes to drive the discussion on two interlinked questions: (1) *what are the key processes driving flood risk in the Broads?* and (2) *how can the presented model be used or improved to portray these processes?* It was made

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[1] https://broads-floodworkshop.limequery.com/911555?newtest=Y&lang=en

clear to the stakeholders that further modelling was to be done following the workshop and that they could therefore influence modelling choices and its overall methodology.

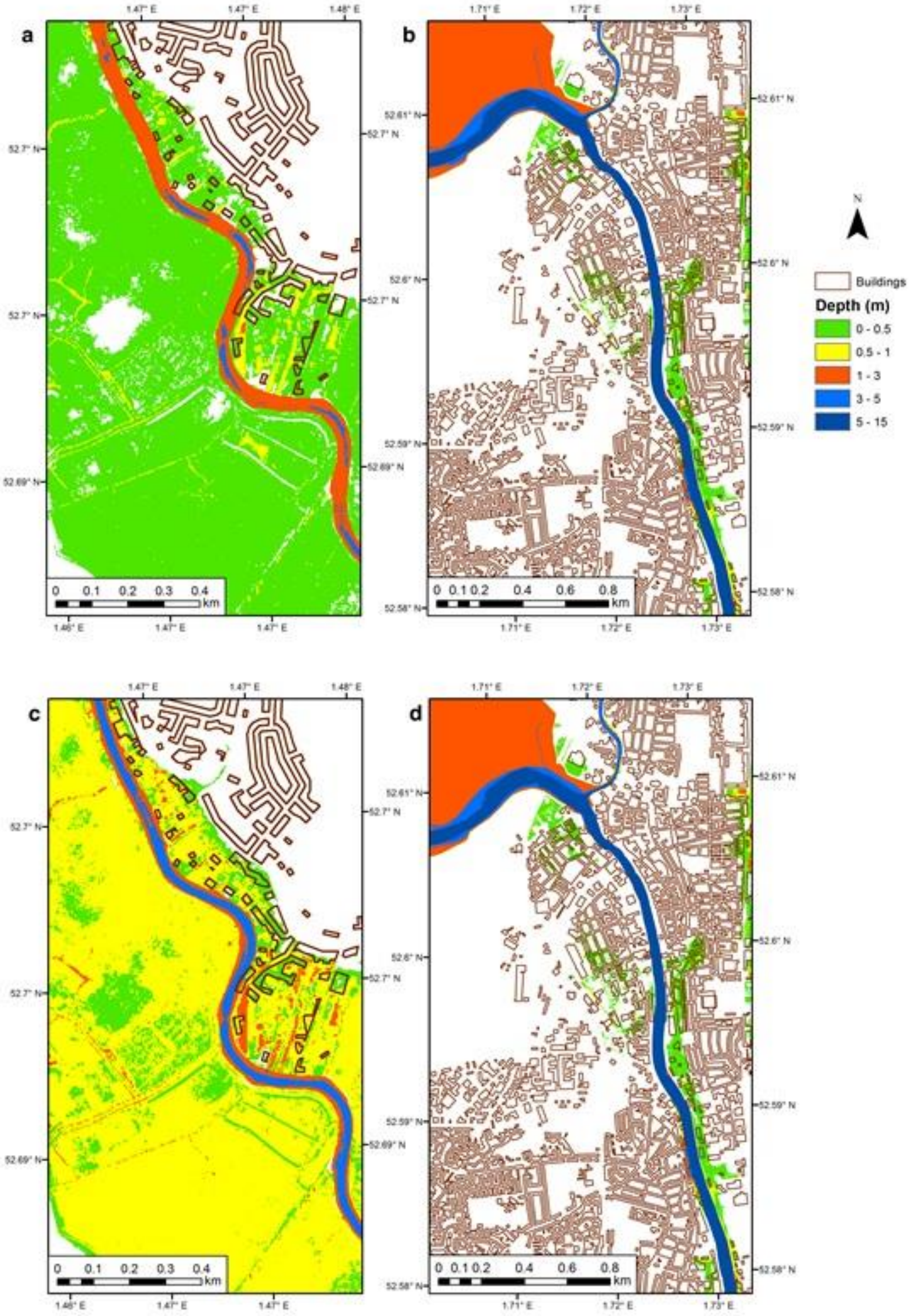


Figure 5.1 – Example of flood maps provided to stakeholders at the workshop showing flooding extent and depth upstream (a, c – near Hoveton) and downstream (b, d – in Great Yarmouth) of the Broads executive area respectively. Two scenarios are shown here, the first representing a 1:100 storm surge (**a**, **b** – scenario 2100Q0 from Table 4.2) and a second where the same 1:100 storm surge is combined to a 1:100 extreme discharge event

(**c**, **d** – scenario 2100Q100 from Table 4.2). Both scenarios are associated with a mean SLR of 38 cm from 2015 mean sea levels but no change in precipitation is considered. Modelled results adapted from Pasquier *et al.* (2019).

The stakeholders then separated into three groups of 4 to 5 participants to discuss potential adaptation strategies for Session II. Each group was moderated by a member of the research team and asked to use detailed A1-size paper maps to draw their proposed adaptation measures (Figure 5.2). While stakeholders were encouraged to be speculative and not to feel restricted by concerns over economic cost or political will, they were asked to discuss the feasibility of each measure. Indicators to assess these options were purposefully left undefined and open to stakeholder interpretation. The groups were aware that the researchers were interested in modelling the adaptation measures derived from the workshop in subsequent work. The participants were however advised not to limit the solutions they proposed to ones they thought were technically possible to model.

Figure 5.2 – Stakeholder discussions of potential adaptation measures for the Broads during Session II.

The outcomes from Session II were presented to the rest of the workshop participants during the final Session III. Stakeholders reflected on their respective discussions and lessons learned. Participants carried out a simple prioritisation task for the measures derived from Session II. Each individual had five votes to distribute to any number of options. The workshop ended with final comments, including reflections on the workshop itself. A survey was filled in by the stakeholders to obtain feedback on the workshop and its outcomes.

The workshop was recorded, and its transcription coded under the broad headings of vulnerability, exposure, hazard, modelling method, participation process, adaptation and FRM. The last heading referred to statements relevant to flood policy but not directly related to adaptation options, such as land ownership, funding, or the management of competing interests. The coded transcripts, in combination with other sources of data (i.e. the interviews and pre-workshop survey) were analysed to highlight the themes emerging from the stakeholders' perceptions of flood risk and adaptation in the Broads. Perceptions of the scientific information and method represented by the hydraulic model were also considered.

5.3. Results

The research results are divided into three sub-sections. The first describes the outcomes of the integration of stakeholder and scientific domains within the participatory process. The second focuses on the assessment of future flood risk in the Broads from different knowledge domains. The last sub-section focuses on stakeholder perceptions of adaptation drawn from their engagement and reactions to preliminary model results.

5.3.1. Outcomes of the participatory process

The participatory process allowed for multiple phases of interaction between different knowledge domains. The preliminary stakeholder interviews provided information on which to base early hydraulic modelling choices such as the geographic extent (from inland to the coast), processes to depict in scenarios (e.g., compounding events of simultaneous extreme river flow and sea level), model design (represent coastal urban areas in more detail), as well as the choice of modelling software itself (HEC-RAS). All stakeholders agreed (100%) that the flood maps resulting from this model were suitable materials on which to base discussions during the workshop (Figure 5.3).

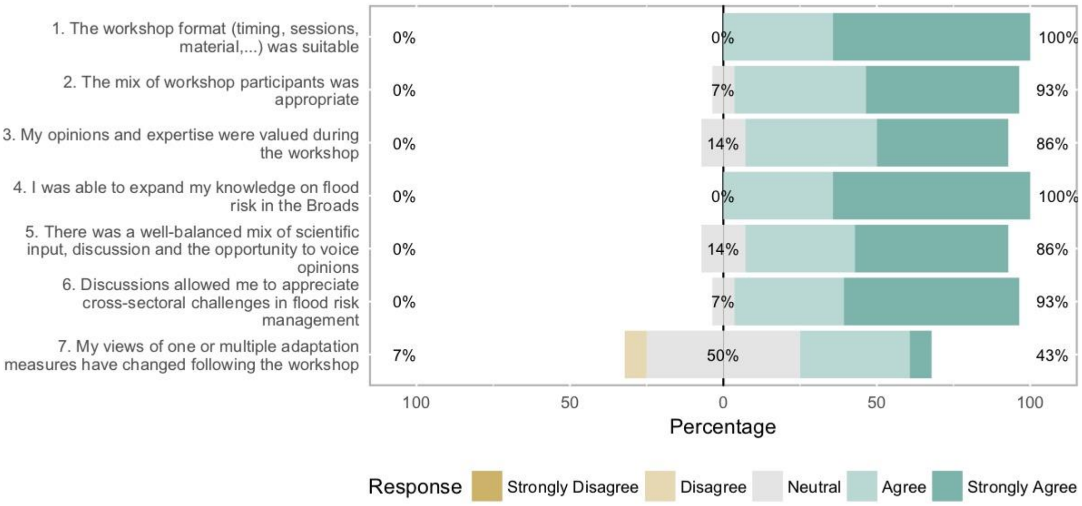


Figure 5.3 – Post-workshop stakeholder reflections and feedback (n = 14).

The workshop's format was deemed appropriate as the main interface between scientific and stakeholder knowledge, but it also brought together participants who had never met and who were not accustomed to exchanging knowledge in such a setting. Varying opinions and experiences were nevertheless represented. Stakeholders agreed (93%) that they were able to appreciate cross-sectoral challenges and competing interests (Figure 5.3). One of the workshop's concluding statements reinforced this finding:

> *"It's all about partnership working. We can't do it on our own! This is why these types of meetings are so important"* (Stakeholder 5, conservancy)

While the majority of responses (93%) found the mix of workshop participants to be appropriate, *lower influence* stakeholders expressed in written feedback and during discussions that they would have preferred to see the EA represented at the workshop. Only 43% of stakeholders agreed that their views of adaptation measures had changed from the workshop. Still, all participants (100%) found that the event allowed them to expand their knowledge of flood risk.

Based on the interest and knowledge of stakeholders, information was generated at the workshop that influenced scientific modelling choices. Recommendations were made to expand the model's coverage from the River Bure catchment to the rest of the Broads. Concerns were indeed raised – particularly from coastal managers – that flood alleviation measures implemented in one area could have unintended negative consequences in another. A more comprehensive model would therefore be able to capture interlinked processes leading to flooding. In another effort to facilitate their decision-making on actions to take, *higher influence* stakeholders requested to see scenarios in the short to medium term to show how risk will progress with time. Finally, stakeholders stressed the importance of assessing flooding risk alongside salinity issues. A water quality module, capable of simulating in-channel salinity concentration and its ingress within Broads Rivers during storm surges, was added to the hydraulic model as a consequence of the stakeholder engagement.

5.3.2. Flood risk assessment

Information used to assess flood risk in the Broads originated from both scientific findings and stakeholder input. The preliminary hydraulic modelling showed that SLR represents a considerable threat for the Broads and its flood defences under extreme storm surge conditions. Simultaneous extreme river discharge and sea level events were found to exacerbate flooding in upstream areas. Although urban areas, farmland, and protected areas were affected by flooding, the magnitude of impacts were highly dependent on the rate of SLR over the next decades (Pasquier *et al.*, 2019).

While stakeholders had varied backgrounds with different levels of expertise in FRM, the exploratory interviews as well as the pre-workshop survey emphasised the general agreement that flooding risk is a critical concern for the Broads (Figure 5.4) and is likely to increase in the future (89% of positive responses, Figure 5.5). Storm surge events were mostly perceived as the main cause for flooding in the Broads (67%), with compound events representing a particular concern (89%). These perceptions therefore aligned with the scientific information provided by the initial results of the hydraulic modelling as shown in Chapter 4.

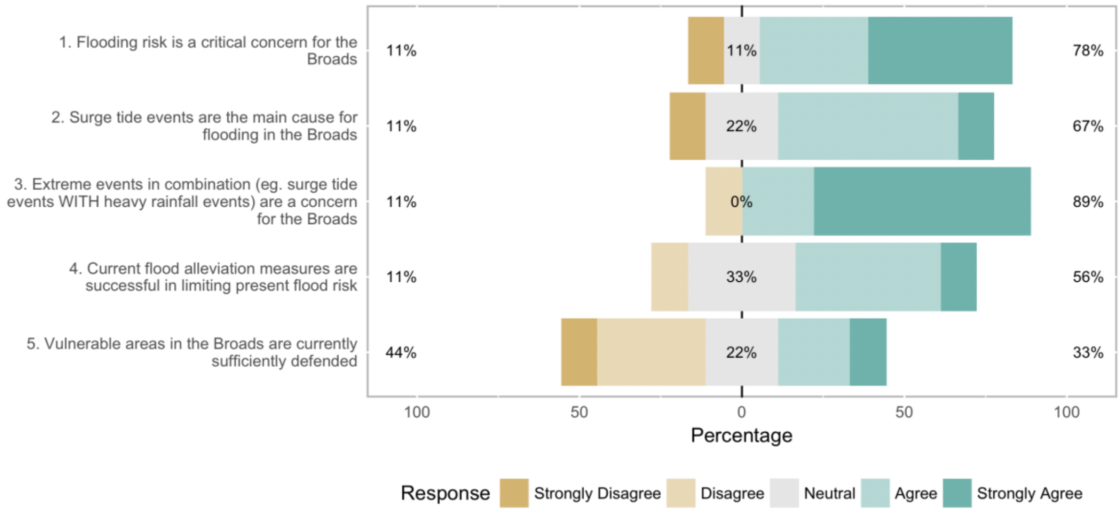


Figure 5.4 – Stakeholder perceptions of current flood risk and its management in the Broads (n = 9; 5 stakeholders present at the workshop did not submit responses). Data gathered from an online pre-workshop survey.

The 2013 “near miss” event was mentioned by two higher influence stakeholders as a reference for the type of hazard experienced in the Broads and to set the context during the workshop's Session I. Although both higher influence and lower influence stakeholders expressed concerns for compound events in the workshop's first two sessions, there were differences in the perception of such hazards:

> *“I’m very pleased that the problem of coinciding events is emphasised in the model. Tidal surges with high river flows. There isn’t really an issue without that coincidence.”* (Stakeholder 1, navigation)
>
> *“I don’t agree with that statement. We have had rainfall events, such as in 2012, that have had significant impacts.”* (Stakeholder 2, catchment engineer)

And:

> *"It's interesting to look at dual events, which we haven't faced so far."* (Stakeholder 3, local administration)
>
> *"I’m pleased that this has been brought in because it is something that has been overlooked. The [current strategy] didn’t really address that at all."* (Stakeholder 4, local administration)

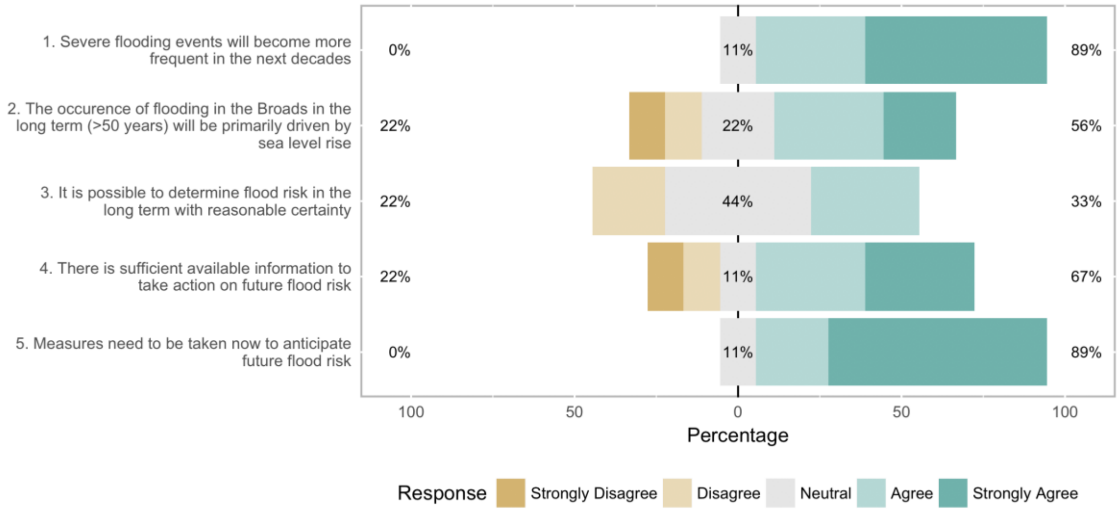


Figure 5.5 – Stakeholder perceptions of future flood risk in the Broads (n = 9; 5 stakeholders present at the workshop did not submit responses). Data gathered from an online pre-workshop survey.

The issue of salinity within the Broads system was raised during the workshop and was primarily brought forward from the perspective of angling interests. The view that there is a need to look at both flooding and salinity conjointly was strongly expressed. Stakeholders pointed out that high saline concentrations tend to occur in many parts of Broads system during extreme sea level events due to the rivers' low gradient allowing tidal waters to propagate upstream. In October 2013 for example, a storm surge event led to thousands of fish being found dead in the Broads' rivers.

The threat that encroaching saline waters pose to protected areas and farmland was also emphasised. Farmers pointed out the impact that salinity has on agricultural land in greatly increasing recovery time from flooding. The flooding from the December 2013 storm surge for instance impacted reclaimed saltmarsh developed for agriculture or nature conservation in North Norfolk (Spencer *et al.*, 2015). Despite the general agreement that — the Broads being a predominantly freshwater system — increased salinity due to SLR would challenge current management practices, workshop discussions highlighted differences between angling and conservation interests:

> *"I find it interesting that people are thinking that salt is necessarily bad. Salt is bad in a fresh system. But in an area dedicated as salty, it can be good. It's about making sure…"* (Stakeholder 5, conservancy)

> *"What we're talking about here is saline incursion going 18 miles from the sea. It's just not right, it's killing everything."* (Stakeholder 6, angling)

> *"No, it's not. But if there was an option to create an area to divert all the saltwater into. A system designed to cope with that saltwater. Then the system would eventually adapt to be able to cope with that saltwater. Then it becomes a positive."* (Stakeholder 5, conservancy)

Cross-sectoral interests were represented at the workshop in discussions of vulnerability and exposure. Stakeholders stressed the unique exposure that the Broads face due to their flat and low-lying landscape as well as their proximity to the sea. Close to equal attention was attributed to the vulnerability of freshwater habitats (located in "some of the most unsustainable locations in the long term" Stakeholder 2, catchment engineer), population centres, farming, tourism, fisheries and other businesses. The impact of flooding on key infrastructure such as important roads or power installations were mentioned in light of how it may affect the resilience of communities, in particular in Great Yarmouth on the coast.

Although only a small majority of stakeholders (56%) agreed that existing flood alleviation measures were successful in limiting present flood risk, the agreement was much less pronounced (33%) over whether the current level of defence provided to vulnerable areas in the Broads was sufficient (Figure 5.4). Finally, there was a general consensus (89%) among stakeholders that that actions should be taken now despite existing uncertainties or lack of available information (Figure 5.5).

5.3.2. Climate Change Adaptation

When asked in the pre-workshop survey to rate adaptation options from a list (or any other measures of their choice) stakeholders overwhelmingly rated "do nothing" as the least preferable. 89% of stakeholders either agreed or strongly agreed that measures should be taken to anticipate future flood risk. This view was represented during the workshop:

> *"We have choices, and they are all expensive, but unless we start planning for change, nature will take its course, change will be unplanned and that's not desirable either."* (Stakeholder 5, conservancy)

Three higher influence stakeholders from local public administration mentioned the economic constraints of adaptation at the workshop, referring to the cost of raising flood defences. While two of the three stakeholder groups in the workshop's Session II listed raising defences as an adaptation option, this measure received the least number of votes during the prioritisation exercise (Table 5.2) and was deemed the second least preferable (after "do nothing") in the pre-workshop survey.

Table 5.2 – Results of prioritisation exercise during stakeholder workshop.

Adaptation Measure	Number of attributed priority votes
Flood Storage Areas: dedicated to hold either fresh or saline water depending on their location in the catchment	16
Tidal Barrier: either a large structure near the mouth of the River Yare, or smaller structures on estuaries	15
Sustainable Drainage Systems (e.g., land use change: woodland creation)	13
Surveying floodplains	9
Communicate risks, inform and build community resilience	7
Put in place a water quality monitoring system	4
Re-site pumping stations	3
Migrate back from floodplains, creating new freshwater habitats	2
Raising defences	1

The most popular adaptation measure, which was mentioned in all three workshop groups by both *higher* and *lower influence* stakeholders, was to allow water to flood designated areas (referred to as "sacrificial land") to increase the Broads' storage capacity and therefore alleviate flooding in the rest of the system during extreme events. Although stakeholders were able to identify areas that could serve for flood storage, farmers and conservancy managers respectively stated that such efforts would require a plan to compensate landowners and create new habitat. The same stakeholders emphasised the need to consider the implications of storing saline or freshwater depending on the storage area’s location within the system as it would lead to important differences in land management. Uncertainty was expressed during the workshop’s mapping session over how much volume would be needed for flood storage to make a significant difference in reducing flood risk in the Broads.

The construction of a tidal barrier on the River Yare received attention at the workshop, as it has in the past in the Broads (CH2M, 2016). Several options were mapped out, such as putting up multiple smaller barriers on the River Yare’s tributaries upstream of Great Yarmouth. However, the most commonly proposed design remains a vertical gate in Great Yarmouth at Haven Bridge – approximately 4 km upstream from the North Sea – which would close off the river at high tide to prevent upstream flooding. As an important infrastructure, the issue of its financing was met with statements by engineers that this option "may become more cost effective than upgrading embankments" with climate change.

Other adaptation options also received attention during the workshop and should be mentioned (Table 5.2). The management of drainage in the wider Broadland catchment - or Sustainable Drainage Systems (SuDS) - was brought up from farmers and engineers in two out of the three groups in the second session and received the third highest number of votes in the final session. SuDS and other natural flood management techniques have gained popularity in decreasing flood risk by slowing the flow of water as it travels through the catchment. An example of such a measure discussed at the workshop was changing land use to include more vegetated areas in the hinterlands.

Final discussions during Session III highlighted fundamental diverging views regarding the management of rivers and embankments. Interest was expressed from some *lower influence* stakeholders to restore the natural flow of rivers in the Broads. Most rivers are indeed highly engineered and high flood defences restrict them to protect large surrounding floodplains. Rivers are also regularly dredged to facilitate navigation. The view was that setting back embankments would leave more space for water during extreme events and would forego of the risk of defences failing. Stakeholders argued that an added benefit of this approach would be the improvement of water quality by making use of the natural filtration capacity of bankside vegetation. The opposing perspective came from *higher influence* stakeholders and notably catchment engineers. The current strategy in the Broads is to contain water within river channels protecting surrounding land and protected areas. Letting rivers overtop and flow into floodplains would indeed require an expensive management plan to not only set defences back, but also to pump out water following extreme events.

5.4. Discussion

The iterative process underpinning this study allowed for both stakeholder and scientific domains of knowledge to influence the other. The inclusion of different perspectives was positively received by participants and led to knowledge exchange at multiple levels. Model results were used as a basis for workshop discussions and helped stakeholders connect future hazards to potential local impacts. The expression of, sometimes competing, interests facilitated not only the definition and prioritisation of adaptation scenarios (Maskrey *et al.*, 2016), but also the framing of the modelling methodology itself.

The engagement of stakeholders during the workshop on questions of hazard, vulnerability and exposure was an important condition for the IA of flood risk. The interaction between scientists and participants from a wide range of backgrounds led to the development of new modelling approaches. In particular, the workshop highlighted the interlinked nature of flooding and salinity for certain activities in the Broads including angling, farming and conservation. Stakeholders affirmed that modelling outputs that do not consider the relation between these processes would not match their needs for decision-making. As Landstrom *et al.* (2011) argued, knowledge on flood risk can be co-produced by allowing the initial framing of scientific modelling to be supplanted by stakeholder interests and expectations.

Scientific and local knowledge domains contributed to a shared understanding on the nature of flooding hazard in the Broads. Different stakeholders emphasised their concerns for compound flooding occurring as a result of the interaction of extreme river discharge and sea level. As was previously explained in Chapter 4, these events are independent in this region of the UK and do not tend to occur at the same time (Mantz and Wakeling, 1979; Hendry *et al.*, 2019). The quotes from Stakeholders 3 and 4 suggest that it is indeed a type of event that they have not had to respond to, but one that should nevertheless not be ignored in future flood risk planning. Despite the unlikelihood of such events occurring, as made evident by the scientific information, the demonstrated interest from stakeholders therefore guided the definition of worst-case scenarios, a common practice in FRM (e.g., Moftakhari *et al*., 2017; Ju *et al.*, 2019).

The high level of uncertainty with which future environmental conditions can be predicted is often listed as a primary barrier for climate change adaptation (Moser and Ekstrom, 2010). The results in this study nevertheless show that surveyed stakeholders perceived that action on future flood risk could be taken with the current level of available information (Figure 5.5). This position suggests a support among the present Broads stakeholders for a proactive, rather than reactive, approach to FRM (Tarrant and Sayers, 2012). Stakeholders however overwhelmingly rejected flood defences – upon which much of the current FRM strategy is reliant – as the measure to prioritise for future flood mitigation (Table 5.2). Levees, or dikes, have received much criticism in recent FRM literature due to their – sometimes irreversible – impacts on floodplains and low sustainability (Sayers *et al.*, 2013). A shared concern at the workshop among stakeholders was that raising or maintaining flood defences would no longer be economically feasible as sea levels rise. While interests in restoring the natural flow of rivers in the Broads were represented alongside other non-structural flood mitigation measures, structural options remained highly popular (i.e., setting up flood storage areas and a tidal barrier). The continued support for structural options has been explained in previous research by the fact that their benefits tend to be easier to visualise and quantify (Shah *et al*., 2015).

The workshop discussions matched the findings by Turner *et al.* (2016) that a point of contention in the Broads is the varying valuation of local ecosystem services and assets, which are to be protected from flooding. Competing interests represent a key hurdle for FRM and adaptation, but also for decision-support. The presented model outputs in this study were limited to showing the potential impacts of flooding on infrastructure and different types of land use. A deliberate choice was made not to provide stakeholders with other indicators related to expected economic costs. The aim was to avoid providing cost estimates that would not only influence discussions but also be perceived as biased or contestable. The approach was appropriate since the goal of the workshop was to draw out stakeholder perceptions and knowledge, and not to carry out a cost-benefit analysis of adaptation measures. Disagreements that arose during this study were more dictated by individual interests rather than stakeholders' relative levels of influence in decision making. A more comprehensive analysis of future options should take into consideration the diverging interests of concerned parties.

The composition of actors involved is a key criterion for the success of knowledge production (Hegger *et al.*, 2012). The presence of exclusively *higher interest* stakeholders at the workshop facilitated discussions. Participants were indeed already sensitised to flooding issues in the Broads. While they represented different fields of expertise, they were able to quickly understand and react to model outputs as well as to come up with adaptation measures with few prompts. The absence of EA representatives at the workshop — who were interviewed before and after the workshop but not present on the day — was seen negatively by *lower influence* stakeholders. The EA plays a critical role in the definition of FRM policy at the national level. The traditionally top-down FRM process in England, led by the EA, can explain the stakeholders' expectations (Thaler and Hartmann, 2016). Limiting the workshop to local actors however represented an opportunity for discussions to be less constrained by the national context. Few *et al.* (2011) found that conflicts between scales of interests can lead to managerialist stances where agency may steer stakeholder participation toward support for predetermined goals. FRM is prone to this "containment" of participation (Few *et al.*, 2011) due to its reliance on a high level of technical expertise, generally provided by the EA. Although scientist-stakeholder workshops provide an opportunity to explore responses to flood risk outside of a managerial context, they should still consider intrinsic power dynamics and levels of influence.

Löschner *et al.*, (2016) argued that scientist-stakeholder workshops on flood risk are unlikely to become institutionalised, despite their usefulness. These types of activities indeed require considerable resources and planning. Due to time and funding restrictions, only one workshop with 14 stakeholders was held as part of this research. A better representation of perceptions of flood risk in the Broads could have been obtained by including a wider range of stakeholder interests. The multiplication of participatory events can however lead to stakeholder fatigue, which Turner *et al*. (2016) has already previously shown to be an issue in the Broads.

5.5. Conclusion

The presented collaborative approach carried out in the Broads National Park highlighted some of the benefits and challenges of integrating scientific and stakeholder knowledge to generate information on flood risk and adaptation. As previous work has shown, the early and iterative exchange between these domains increases the likelihood of improving the value and usefulness of scientific results (e.g., Aytur *et al.*, 2015; Schinko *et al.*, 2017). The co-production of knowledge, as presented here, not only builds mutual trust and fosters the empowerment of stakeholders, it also helps to better understand the links between future risks and societal pressures (Löschner *et al.*, 2016). As such, participatory IAs of future flood risks can contribute to addressing critical institutional and societal barriers to adaptation.

Several conditions played a role in guaranteeing the intended outcome of the stakeholder engagement, which can be used as recommendations for future projects. The majority of participants were familiar with the research before the workshop, either through interviews or presentations made in various forums. This helped to build trust and for stakeholders to quickly understand research objectives. Workshop discussions were moreover facilitated by the choice of participants. Selecting participants with a high interest in flooding risk as well as a comprehension of local issues allowed them to easily discuss adaptation options and their potential implications. Finally, model results and maps were designed to be easily understood by a wide range of backgrounds.

The sample of stakeholders participating in this study was relatively small and while it did not allow for a statistically significant representation of opinions held in the Broads, some conclusions can be made on local perspectives coming from varied interests. A shared understanding among stakeholders emerged from this study showing a collective concern for flood risk alongside a notable interest in a potential change in FRM practices. It moreover became clear that salinity, and its excess during extreme events, is very much a concern for different activities in the Broads and can be a key factor in how flooding is perceived. A fundamental management question in the Broads, when dealing with both future flood risk and saline incursion due to SLR, is whether to protect and keep the area as it is (i.e, predominantly freshwater and highly engineered) or to allow for a controlled change to cope with rising environmental pressures.

The contextualisation of scientific results by practitioners on such questions contributes to bridging the gaps between science and policy on adaptation. As the Broads enter a new phase of FRM, there is an opportunity to gain from bringing together different knowledge domains to plan adaptation going forward.

Chapter 6 – Assessment of future flood risk and river salinity under UKCP18-derived climate change scenarios and stakeholder-defined adaptation measures

6.1. Introduction

Future flood risk projections are essential for decision-making on adaptation but are often characterised by high uncertainty (Muis *et al.*, 2015). The consideration of a range of possible future scenarios can help to better cope with these uncertainties (Smid and Costa, 2017). The IA of flood risk in coastal areas requires taking into account changes at different timeframes both in meteorological conditions as well as in SLR. The temporal scope of projections is important to support adaptation planning. Vautard *et al.* (2012) argued that a medium-term outlook of 2050 corresponded to the societal demand of climatic projections for adaptation purposes. Shorter- and longer-term 21st century time scales remain relevant in impact studies to ensure a sustainable planning (Carter *et al.*, 2015). This reinforces the need for up-to-date risk assessments using the latest climate projections.

This chapter draws from the findings of the previous Chapter 4 and Chapter 5 to assess the impacts of projected climatic changes and SLR on future risks of flooding and extreme river salinity in the Broads. The hydraulic model design from Chapter 4 informed the development of an expanded HEC-RAS model, covering all rivers in the Broads National Park. Stakeholder perspectives described in Chapter 5 also guided the modelling methodology as well as the definition of adaptation measures to simulate under future scenarios of SLR. The Broadland area is entering a new phase of FRM and the IA of future risk and adaptation options can provide useful knowledge to guide decision-making.

6.2. Methodology and Data

The assessment of future flood hazard commonly follows the modelling chain shown in Figure 6.1 (e.g., Ward *et al.*, 2013; Alfieri *et al.*, 2015). This study followed a similar approach. Projections of bias-corrected future climate variables, such as precipitation and temperature, were used in a hydrological model to derive future river discharge at the sub-catchment scale. Probabilistic scenarios were defined from the EVA of river discharge and extreme sea level, taking into account projections of SLR. The final step was to obtain corresponding inundation extents and depth from a hydraulic model, similarly to the methods presented in Chapter 4. The solutions from the HEC-RAS hydraulic model simulations were dynamically linked to a Water Quality Module to calculate river salinity concentrations. The derived future scenarios were combined with adaptation scenarios determined from the stakeholder engagement described in Chapter 5. The associated flooding impacts were assessed from data of building footprint and land use.

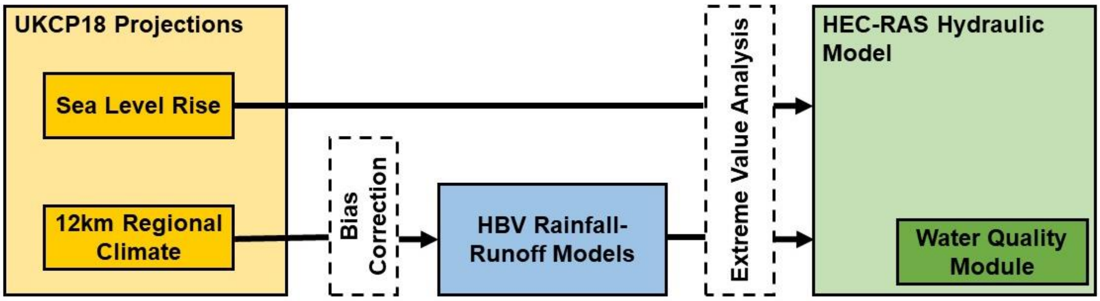


Figure 6.1 – Future flood risk assessed by combining a chain of modelling methods and EVA to derive future scenarios from climate and SLR projections.

6.2.1. UKCP18 data and bias correction

Future scenarios were based on the most up-to-date assessment of how the climate of the UK may change over the 21st century provided by the UK Climate Projections (UKCP). The UKCP18 provides a set of projections from the latest Met Office Hadley Centre climate model (HadGEM3-GC3.05). Its simulations were produced by generating a Perturbed Parameter Ensemble (PPE) to obtain different plausible variants of the model. Twelve members of the GC3.05 simulations were downscaled from the global model scale of 60 km to a finer scale using a 12 km regional climate model (Lowe *et al.*, 2018).

Murphy *et al.* (2018) found that the 12 km regional model was better at simulating some of the more extreme daily rainfall events, particularly during winter months, where the GCM tends to underestimate their frequency in the UK region. The regional climate projections are therefore useful to assess the impacts of climate change of future flood risk.

For this study, regional projections of mean air temperature (at 1.5 m) and precipitation rate from 1980 to 2080 were obtained from the UKCP18 dataset (*2019/07/31 version*). The projections are currently only available under the Representative Concentration Pathway (RCP) 8.5. RCPs represent the concentration of greenhouse gases that will results in total radiative forcing increased by a target amount by 2100, relative to pre-industrial levels. RCP8.5 is most comparable to a high emissions scenario in UKCP09, with a warming of 4.3 °C by 2081-2100 compared to the pre-industrial period (Stocker *et al*., 2013).

The projected temperature and precipitation are provided on a 360-day year within the UKCP18 dataset. They needed to be converted a Gregorian calendar format. The method for this was based on Dobor *et al*. (2015). Additional days were created for the months of January, March, May, July, August, October, and December. In the temperature dataset, the average temperature of the previous and following days was used for these additional days. Dry days were added in the case of precipitation. Either the last, or the two last days of the 30-day February month were removed to match the Gregorian calendar, taking leap years into account.

UKCP18 data are provided without bias correction. As Eden *et al*. (2012) argued, although GCMs perform reasonably well in capturing large-scale mean precipitation patterns, regional details can often be poorly represented and often deviate from observations. It is therefore necessary to correct the datasets to account for these systematic differences. Temperature and precipitation were bias corrected independently following the method used by Prudhomme *et al*. (2012). A linear additive transfer function was applied to the regional projections of temperature for each month resulting in a set of 12 transfer functions for each PPE member and sub-catchment, which were then applied to each day in the data. In the case of precipitation, Prudhomme *et al*. (2012) used a parametric quantile-mapping method based on the gamma distribution, described in more detail by Piani *et al*. (2009). As for temperature, transfer functions for precipitation were estimated on a monthly basis for each PPE member and sub-catchment. In both cases, historical meteorological data from 1981-2000 from the Centre of Ecology and Hydrology (CEH) CHESS dataset (Robinson *et al.*, 2017) were used to estimate the parameters of the transfer functions and to assess the results of the bias correction.

Projections of 21st century SLR near the UK coastline were also obtained from the UKCP18 datasets. Mean SLR projections are based on those in the IPCC 5th assessment (Stocker *et al.*, 2013) but takes 1981-2000 as a baseline period and includes updated estimates of the contribution from the Antarctic ice. Projections are provided for low (RCP 2.6), medium (RCP 4.5) and high (RCP 8.5) emissions scenario (Figure 6.2).

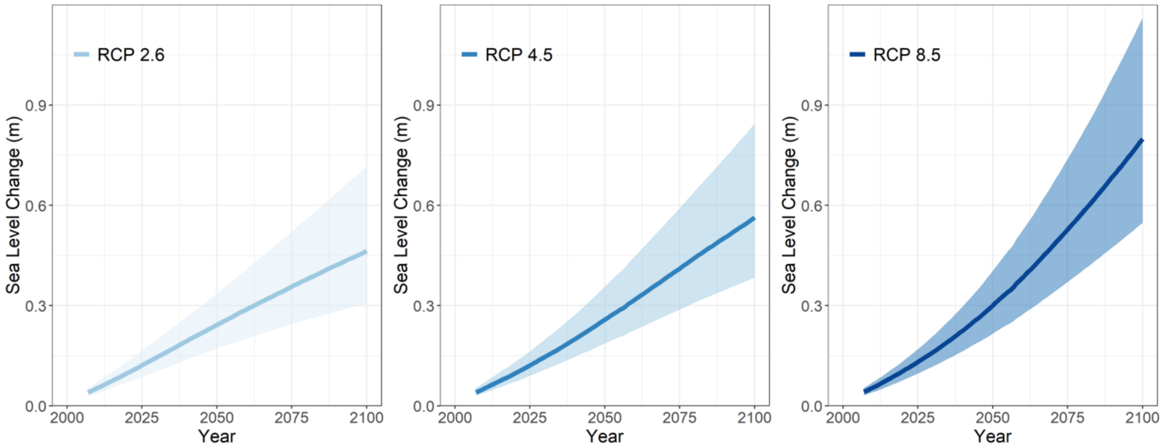


Figure 6.2 – Mean sea level change compared to 1981-2000 near Lowestoft for different RCP emission scenarios. The solid line and shaded regions represent the central estimate and 5th -95th range respectively for each RCP scenario.

6.2.2. Defining hydraulic model boundary conditions

6.2.2.1. River discharge: HBV hydrological model

The UKCP18 data were used to force an HBV hydrological model to generate projections of daily river discharge up to 2080. The HBV model was calibrated for each Broadband river sub-catchment (Figure 6.3) and was forced by the outputs of the 12 PPE members to represent the range of meteorological projections. The inputs to the HBV model are temperature, precipitation and potential monthly evapotranspiration. Historical observations of these input variables were obtained from the CHESS dataset to calibrate the HBV models. The observations of daily river discharged used to calibrate the HBV model were obtained from the National River Flow Archive (NRFA). The river gauges used in this study are listed in Appendix 2.

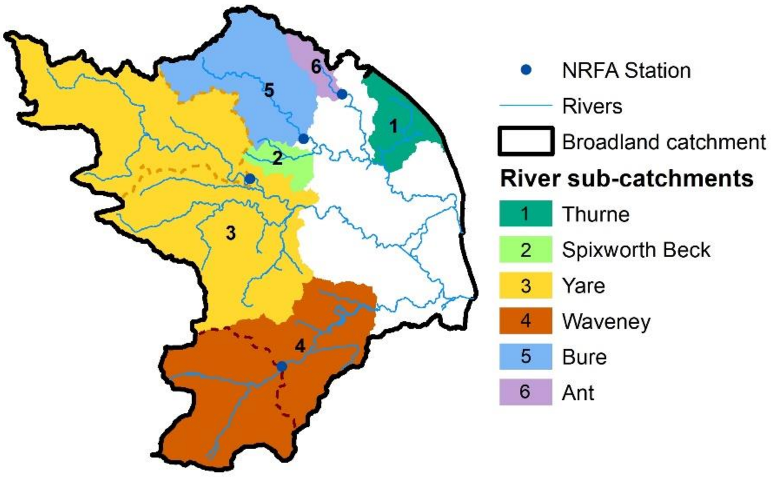


Figure 6.3 – Broadland river sub-catchments located at the upstream boundary of the HEC-RAS hydraulic model and used to create HBV hydrological models. The dotted lines show the catchments at NRFA gauges for the Yare and Waveney sub-catchments, where the gauge is further upstream from the HEC-RAS model boundary.

In the case of the River Waveney and the River Yare, the flow gauges were located further upstream from the hydraulic model boundary. In such cases the HBV models were calibrated using the gauge as the outlet point for the catchment. The sub-catchment area was then adjusted to represent the greater drainage area at the boundary location. Due to the absence of flow data for Spixworth Beck and the River Thurne, parameters from the calibrated HBV models of the River Bure and the River Ant were used, respectively. Since the Broadland Rivers catchment has a low elevation gradient and both the Spixworth Beck and Thurne sub-catchments cover relatively small areas (Table 6.1), these assumptions do not have a large impact on river flow simulations. Catchment areas for the Bure and the Ant were obtained directly from the NRFA. Other catchments areas were determined by calculating the flow accumulation and directions in the Broadland area using 1-arc second resolution (approximately 30 m) SRTM elevation data in the ArcGIS Hydrology Toolbox.

Table 6.1 – Surface area of Broadland river sub-catchments used in HBV hydrological models

River sub-catchment	Calibration area (km^2)	Simulation area (km^2)
Waveney	378	683
Yare	565	1171
Bure	334	334
Ant	50	50
Spixworth Beck	NA	59
Thurne	NA	119

The NSE coefficient is used to assess the HBV model performance for the Waveney and the Yare catchments. Due to the importance of extreme conditions for the assessment of flooding impact, the Peak-Error (PE) (defined in Equation 6.1) was used to assess model performance.

$$PE = \frac{\overline{Q_{m(\max)}} - \overline{Q_{o(\max)}}}{\overline{Q_{o(\max)}}} \tag{6.1}$$

where $\overline{Q_{m(\max)}}$ is the mean annual simulated peak discharge and $\overline{Q_{o(\max)}}$ is the mean annual observed peak discharge.

As climate changes are likely to affect the frequency of future extreme events, a similar approach to Collet *et al.* (2017) was carried out to account for this non-stationarity. Return levels for a baseline (1961-2015) and a future time period (2020-2080) were compared, with each individual period considered to be stationary. Probabilities of extreme discharge were determined with the POT method, as previously described in Chapter 4. Respective thresholds were determined using the Mean Residual Plot approach for each catchment. The GP distribution was fit to extreme river discharge to obtain return levels. This procedure was carried out for the 12 HBV model outputs for each catchment resulting from the RCM ensemble. The mean 1:100 event in the ensemble was then calculated along with the 5th and 95th quantiles.

Synthetic triangular hydrographs for each upstream boundary condition were generated from the return levels, using the values as the peak river discharge. Past hydrographs for each gauged catchment was analysed to derive a rising limb of 20 hours for a 60-hour event, matching previous similar work in the Broadland Rivers catchment (Mantz & Wakeling, 1979).

6.2.2.2. Sea level: Joint Probability Analysis

There are various methods used to estimate probabilities of extreme sea levels. Among the most common are *direct* and *indirect* methods, as described by Haigh *et al.* (2010). Direct methods analyse extremes of observed sea levels. There are limitations to such methods as they do not account for the complex combination of components making up total sea levels. In the sensitivity analysis shown in Chapter 4, the high tide and the peak of the storm surge were assumed to occur simultaneously without account of joint probabilities. Indirect methods, as used here, offer an improvement on the characterisation of extreme sea levels.

The Joint Probability Method (JPM) proposed by Pugh and Vassie (1978) looks at astronomical tide and storm surge separately. The probability density function (PDF) of total sea level is found by the convolution of the distinct empirically determined PDFs of tide and storm surge respectively. The Revised Joint Probability Method (RJPM) by Tawn and Vassie (1989) offers another improvement to the JPM in modelling the upper tail of the non-tidal distribution by fitting it to a parametric distribution (e.g., Generalised Extreme Value or GP). The methodology presented here to determine the probability of total sea levels follows the RJPM, as described by the Environment Agency (2011) for the UK coast.

The pre-processing of sea level data followed similar steps to the ones described in Chapter 4. A simple additive method was used to detrend tide gauge data from the BODC at Lowestoft between 1964 and 2018 to remove yearly changes in mean sea level with 2018 serving as the reference year. For each high-water event, following the semi-diurnal tidal period of 12.42 hours, the nearest predicted high tide was identified with a harmonic analysis of sea levels. This allowed for the estimation of the difference between the predicted astronomical high tide and the nearest experienced high water (i.e., the skew surge).

A semi-parametric (or piecewise) distribution was constructed for skew surge peaks by parametrically modelling the tails of the distribution with a GP distribution. The parameters of shape and scale that define the GP distribution were determined using the maximum likelihood method. The 97.5th percentile of skew surge values was used as a threshold for the GP distribution fit. Below that threshold the rest of the distribution was determined using the kernel density method (Figure 6.4).

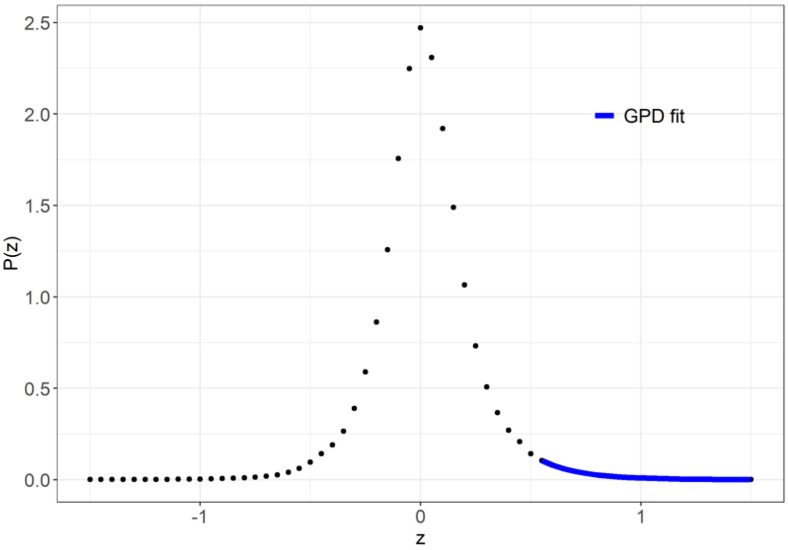


Figure 6.4 – Piecewise PDF of skew surges with an upper-tail GP distribution fit. z represents skew surge height (m) and P(z) is the probability density (m^{-1}).

The joint probability distribution of all possible total sea levels derived from the combination of skew surge and peak tide levels can be found such as for a total water level x, the probability function $F(x)$ is:

$$F(x) = (\prod_{n=1}^{N} F_{SS}(x - X_n))^{1/N} \tag{6.2}$$

where X is the peak tide level, N is the total number of peak tide levels, and F_{SS} is the probability function of skew surge, expressed for a level z.

The return period $T(x)$ is calculated such that

$$T(x) = \frac{1}{N(1 - F(x))} \tag{6.3}$$

where N is the number of tides per year. Surges vary in behaviour depending on the location of interest along the coast. The final synthetic events to use as the hydraulic model boundary conditions were generated to last 48 hours (centred on the surge peaks) using a normalised surge shape at Lowestoft (Figure 6.5) obtained from the Environment Agency (2011). Where an average surge shape was found in Chapter 4, the EA developed "time-integrated" surge shapes using a different method. The duration of each of the 15 largest surges in Lowestoft at particular levels in the surge column was calculated and the maximum duration at each level was then determined. These maximum durations were arranged to form the surge shape by determining the relative proportions of the duration expected on the rising and falling limbs of the surge. The EA argues that this method provides the best representation of the largest surges, both in terms of shape and duration. It should be noted that it is common at Lowestoft and in the North Sea for positive storm surges to be preceded by a negative surge as can be seen in Figure 4.5. However, this feature was not captured in the EA methodology.

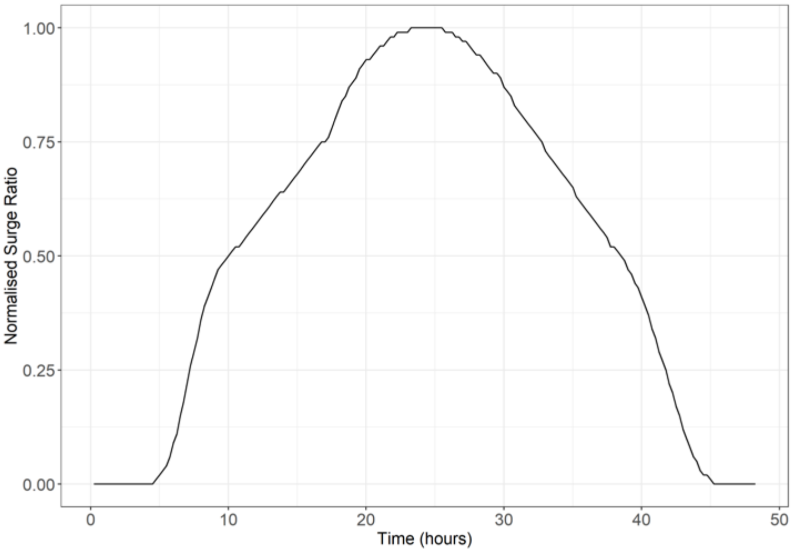


Figure 6.5 – Normalised surge shape at Lowestoft obtained from the Environment Agency (2011) practical guidance for coastal design sea levels.

6.2.2.3. Compound flooding

As discussed in previous chapters, the coincidence of peak river flows and extreme sea levels can lead to compound flooding, where the resulting impact is worse than if the two events were to occur individually. It is therefore important to understand the relationship between such processes. Looking specifically at the Broads, Mantz and Wakeling (1979) found that river discharge and surge events were independent, and their joint probability could therefore be derived from the product of their respective probabilities. More recently, Hendry *et al*. (2019) found that storms on the east coast of the UK that tend to generate high skew surges are generally distinct from those that tend to generate high river discharge. While some studies have reported a change towards storm surges that also promote high rainfall in the US (Wahl *et al.*, 2015) and in Europe (Bevacqua *et al.*, 2019), the impact of climate change on storm surges in the North Sea is still uncertain. The UKCP18 findings suggested there were no significant changes projected in future storm surges in the North Sea (Palmer *et al.*, 2018). For this study it is hence assumed that high river discharge events and storm surges will continue to be independent.

6.2.3. HEC-RAS hydraulic modelling

6.2.3.1. Model design

The hydraulic model used in this study was derived from the model described in Chapter 4 and improved upon based on stakeholder inputs presented in Chapter 5. The improved model follows the same 1D-2D integrated design but was expanded to cover the rest of the Broads (Figure 6.6). Additional 1D and 2D compartments were added and dynamically linked with river channels. The 2D areas were chosen based on the previous identification of locations exposed to coastal flooding in a high-level review of flood management in the Broads by CH2M (2016). The new model expands on 2D areas from Chapter 4 by adding the Eccles to Winterton area in the northern part of the Broads and the coastal town of Lowestoft to the already existing area in Great Yarmouth. The boundaries of both 1D and 2D areas follow terrain and structures such that overbank flow is expected to be restricted to individual compartments.

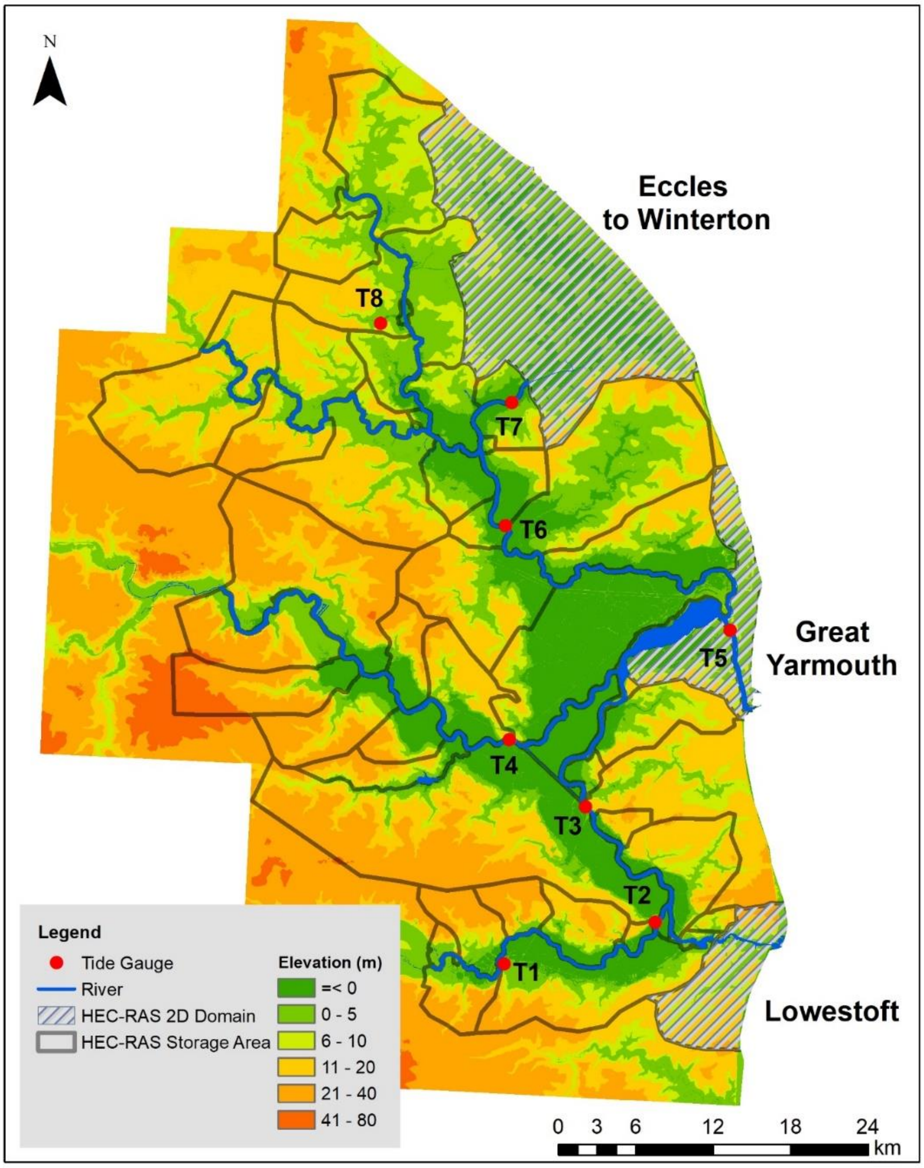


Figure 6.6 – Structure of the 1D-2D integrated HEC-RAS hydraulic model. Data from several tide gauges across the Broads' Rivers were obtained at: (T1) Beccles Quay, (T2) Burgh St. Peter, (T3) Haddiscoe, (T4) Reedham, (T5) Haven Bridge, Great Yarmouth, (T6) Acle, (T7) Repps and (T8) Barton Turf.

Just over 3000 cross-sections were drawn at irregular intervals to represent the meandering rivers in the Broads. Data from a set of 10 river gauges were obtained from the EA with historical records of river levels at a 15-minute temporal resolution. The model was first tested under steady conditions and all subsequent simulations were run in an unsteady state. Calibration and validation runs were based on river levels from the same extreme events as the ones used for the previous model version (i.e., October 2014 and December 2013 respectively). As in Chapter 4, Manning's n roughness coefficient was used as the calibration parameter.

The assessment of flooding impacts was also estimated in a similar fashion, using a simple GIS analysis of land cover and buildings affected by the inundation extent. The land cover map was obtained from a 25 m resolution dataset from the CEH (Rowland *et al.*, 2017). Building footprints were obtained from Ordnance Survey data.

6.2.3.2. Analysis of salinity concentrations in river channels

A significant addition to the model was the use of a Water Quality Module, within the HEC-RAS software, to assess river salinity. The module is linked to the results of velocity and water levels from the HEC-RAS 1D hydraulic model. Outputs of river salinity concentration are based on the Quickest-Ultimate explicit numerical scheme (Leonard, 1991) to solve the one-dimensional transport (advection-dispersion) equation of a conservative constituent (Haddout *et al.*, 2015):

$$\frac{\partial(AC)}{\partial t} + \frac{\partial(QC)}{\partial x} = \frac{\partial}{\partial x}\left[D.A\frac{\partial C}{\partial x}\right] \tag{6.4}$$

where C is the salinity concentration (‰), A is the cross-sectional area (m^2), Q is the river flow (m^3.s^{-1}) and D is the longitudinal dispersion coefficient (m^2.s^{-1}). Dispersion coefficients were computed by the model with hydraulic variables at each cross-section, based on the equation by Fischer *et al.* (1979):

$$D = 0.011\frac{u^2w^2}{yu^*} \tag{6.5}$$

where u is the face velocity (m.s^{-1}), w (m) is the average channel width, y (m) is the average channel depth and u^* (m.s^{-1}) is the shear velocity.

Despite the considerable impacts that salinity can have in the Broads, continuous river salinity data remain scarce. Continuous observations of Electrical Conductivity (EC) in rivers between 2013 and 2016 were obtained from the Environment Agency. EC is the ability of 1 cm^3 of water to conduct an electric current at 25°C and is dependent of the total amount of soluble salts as charged particles. EC observations of conductivity (in µS.cm^{-1}) were converted to mg.L^{-1}, where 1000 µS.cm^{-1} = 640 mg.L^{-1} (Dahaan *et al.*, 2016). Data were obtained from probes, set at a minimum of a meter in depth, at Cantley (River Yare), Acle (River Yare) and Repps (River Thurne), as shown in Figure 6.7 (S1, S2, S3 respectively). These probes are used by the EA to detect saline incursions in the

Broads. Discrete measurements – which were mostly taken during surge events, such as December 2013 – were also used to help calibrate, validate and set salinity boundary conditions for, the Water Quality Module. Due to the absence of available salinity data, the River Waveney was excluded from salinity simulations. The hydraulic model was adjusted to represent this change by moving the location of the model upstream boundary at the Waveney. The previous steps described to calculate return levels of river discharge were repeated for the now larger Waveney catchment (895 km^2). A salinity of 35000 $mg.L^{-1}$ was assigned to the downstream boundary condition at the North Sea.

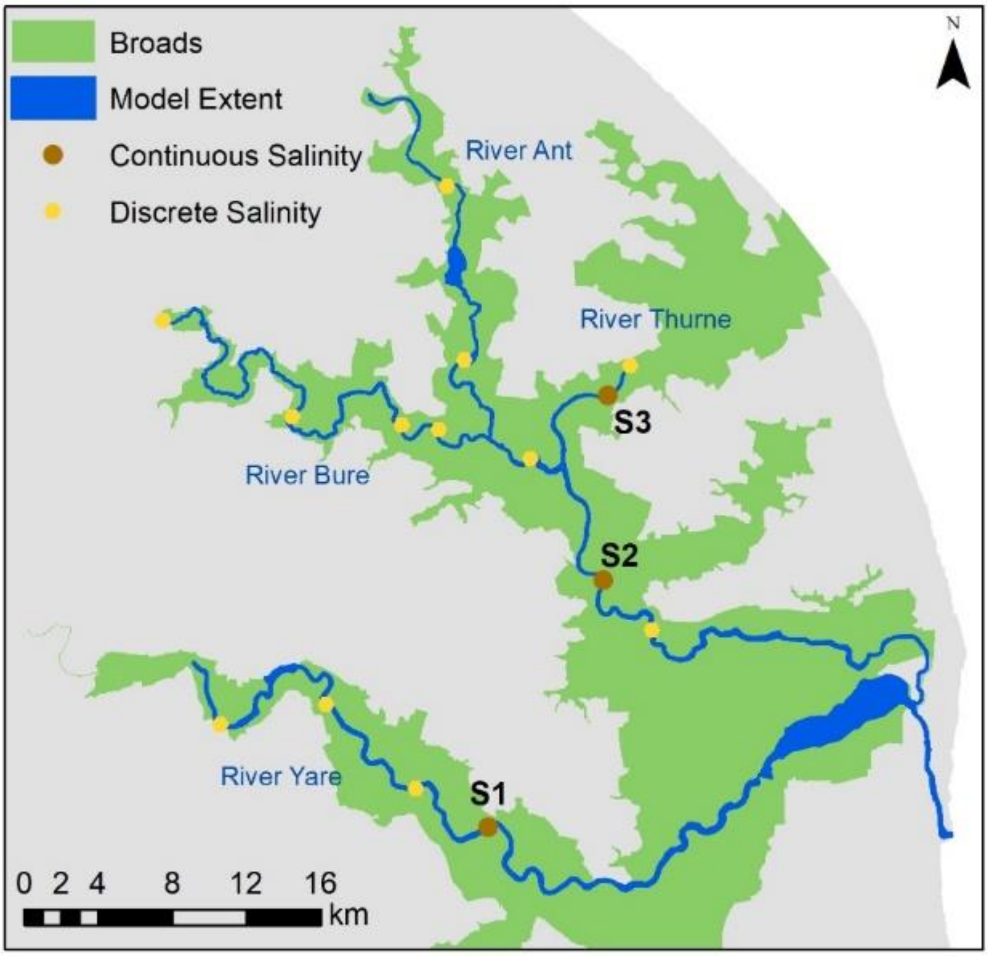


Figure 6.7 – Water Quality Module domain and location of observational data of conductivity in the Broads Rivers. S1-3 are locations where salinity is monitored.

6.2.3.3. Modelling stakeholder-defined adaptation options

The two measures defined in Chapter 5 at the stakeholder workshop were incorporated into the model design to simulate adaptation scenarios.

Haddiscoe Island was chosen as the location for the flood storage area (not to be confused with HEC-RAS's terminology designing compartments) based on discussions and map drawings at the workshop. Haddiscoe is located between the River Yare and River Waveney upstream of Breydon Water (Figure 6.8). With a surface area of 8 km^2, this relatively large isolated compartment is mostly used for grazing marshes and has only five dwellings with its other buildings being owned by boating businesses. Flood storage area vary in nature and the EA classifies them as "online" or "offline". Online flood storage temporarily stores flood water within the river channel and its floodplain using an impounding or flow control structure. Offline flood storage divert water to an area when the river level exceeds a pre-determined value. Haddiscoe Island was defined as the latter.

The model DTM was edited to lower the elevation of the terrain of Haddiscoe Island by 3 m to represent the engineering work that would take place to increase its storage capacity if it was designated as a flood storage area. Consulted local catchment engineers confirmed that this would be an extensive project but that material from Haddiscoe could then be used to strengthen river embankments. Following test simulation runs, embankments on the south-western end of the Island were raised by 0.5 m to prevent the storage area from overflowing into other compartments when full. Two sluice gates were put in place in the model on the River Yare and the River Waveney that would open when river levels reached 1 maOD to let water flow into the storage area as the tide comes in.

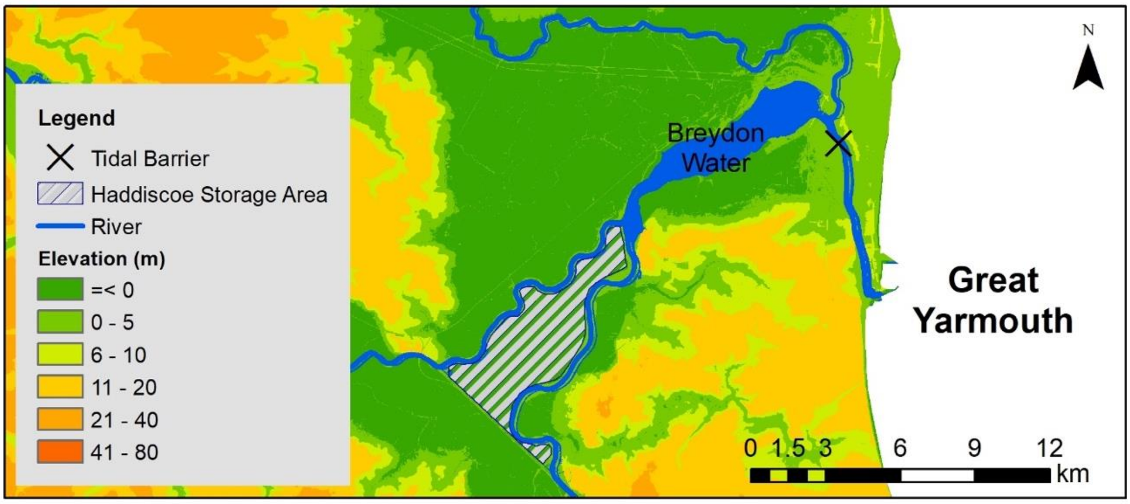


Figure 6.8 – Location of proposed adaptation measures in the HEC-RAS hydraulic model.

The second adaptation option was modelled separately. A tidal barrier was set up at Haven Bridge on the River Yare in Great Yarmouth (Figure 6.8). The design of the barrier was inspired by the Hull Tidal Surge Barrier, which was finalised in 1980. Modelled as an inline structure in HEC-RAS, the barrier is a large vertical gate that closes down to the riverbed during extreme sea level events. The operation of the barrier was also based on the Hull Barrier such that the gate rests outside of the water and can be shut within 30 minutes after the river level at the downstream cross-section reaches 2 maOD.

As a final step in this project, the outputs derived from the modelling presented above were presented in one-on-one interviews with stakeholders who attended the workshop described in Chapter 5. These interviews were held between June and October 2019. The results shown included flooding and river salinity maps, with and without the proposed adaptation measures, for different hazard and climate change scenarios. The purpose of the interviews was to obtain stakeholders' feedback on the final results of the hydraulic modelling and on the effects and implications of modelled adaptation measures. Eight out of the 14 stakeholders were able to attend the interviews, which included emergency planners, farmers, conservationists and engineers. The EA were also presented the results as part of the on-going Broadland Futures Initiative.

6.3. Results and Discussion

6.3.1. Projected climatic changes and their impacts on river discharge

6.3.1.2. Changes in temperature and precipitation

Both the projected temperatures and precipitation data were extracted and spatially averaged over the Broadland catchment for the 12 members of the PPE. Temperature is projected to increase by up to 4.55 °C by 2080 compared to the average of the 1981-2000 period (Figure 6.9a). On the other hand, yearly precipitation is not projected to follow a noticeable trend throughout the 21st century, with a low decrease in average yearly precipitation (Figure 6.9b). Winter precipitation however is projected to increase by up to almost 1 mm.day^{-1} by 2080. This is consistent with the findings that the UK is likely to experience drier summers and wetter winters (Lowe *et al.,* 2018).

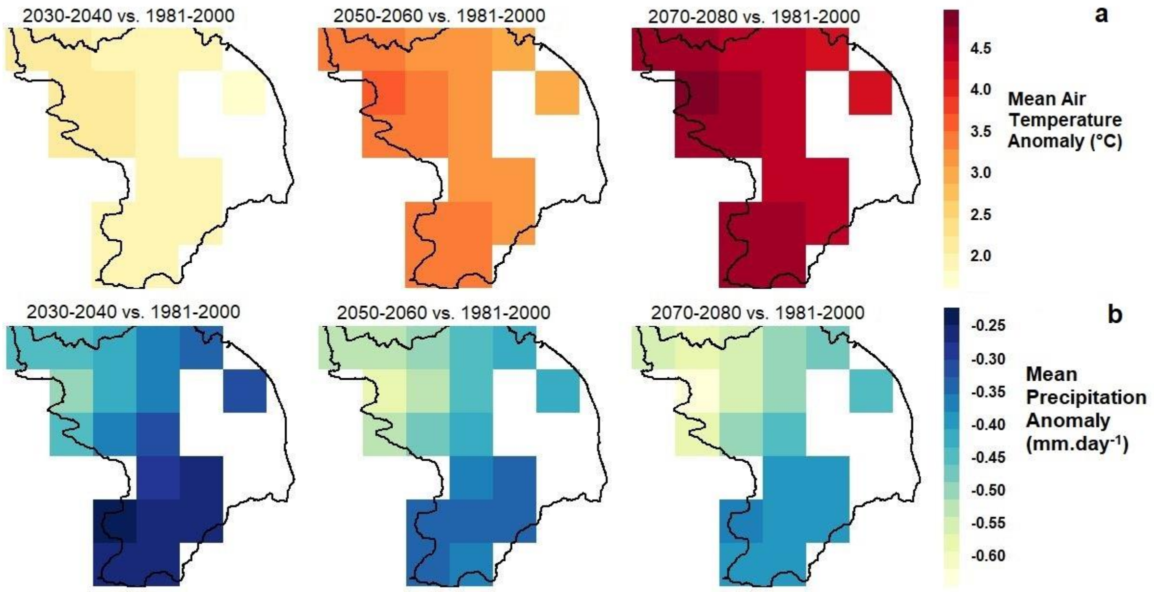


Figure 6.9 – Bias-corrected UKCP18 RCM PPE projections compared to the 1981-2000 baseline for **(a)** mean air temperature anomaly and **(b)** mean annual precipitation rate anomaly. Only cells over Broadland sub-catchments of interest were extracted and bias-corrected.

While there exists various statistical bias corrections methods, the quantile mapping method minimizes the difference between the cumulative density function of the climate model output and that of the observations. It is therefore commonly used for precipitation in the context of extreme events and has been shown to outperform other methods such as linear or variance scaling (Cannon *et al.*, 2015). More recently, quantile mapping methods have however been shown to affect projected long-term trends and thereby potentially altering the climate change signal in modelled precipitation series (Grillakis *et al.*, 2017). Uncorrected mean daily precipitation over the study area was 2.11 mm.day^{-1}, 2.01 mm.day^{-1}, 1.98 mm.day^{-1} for 2030-2040, 2050-2060 and 2070-2080 respectively. This compared to mean daily precipitation rates of 1.81 mm.day^{-1}, 1.72 mm.day^{-1} and 1.68 mm.day^{-1} for 2030-2040, 2050-60 and 2070-2080 respectively after bias correction by quantile mapping. As an answer to this issue, trend-preserving methodologies have been proposed that are designed to preserve the relative changes in monthly mean values of precipitation, while correcting daily variability by quantile mapping (Hempel *et al.*, 2013). Further work should look to compare the viability of different bias-correction methods with UKCP18 climate projections.

The Broadland catchment is not highly influenced by snow and snowmelt. Temperature is therefore not as important as precipitation in dictating the catchment's hydrology. Figure 6.10 shows that the UKCP18 PPE performs better when recreating past temperature than precipitation in the Broadland region. This is also the case when looking at the distribution of precipitation. Precipitation is overall overestimated and most notably so during winter months. A correction that preserves the climate signal is therefore necessary.

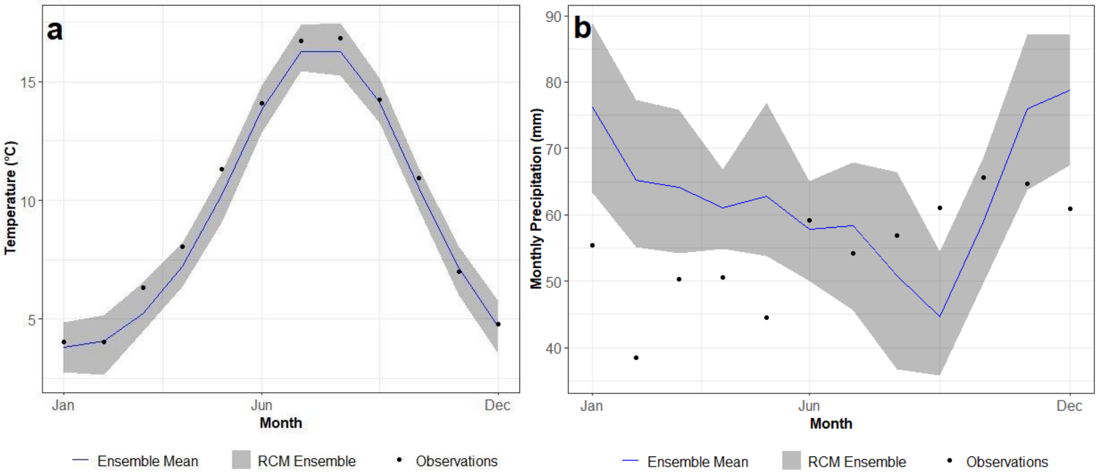


Figure 6.10 – Comparison of **(a)** temperature and **(b)** precipitation from the UKCP18 RCM PPE hindcast with observations for the 1981-2000 baseline period.

Both bias correction methods were able to provide a closer fit to the observed data of average temperature (Figure 6.11a) and monthly precipitation (Figure 6.11b). The cumulative distribution function shows the effect of the bias correction for both past (Figure 6.12a) and future (Figure 6.12b) simulated annual precipitation. The change in distribution is important in both cases and shows a bias for larger precipitation values overall. Figure 6.11b also shows the climate signal and the intensification of precipitation. There is indeed a visible increase in the proportion of extreme precipitation events for the 2020-2080 period compared to the baseline period.

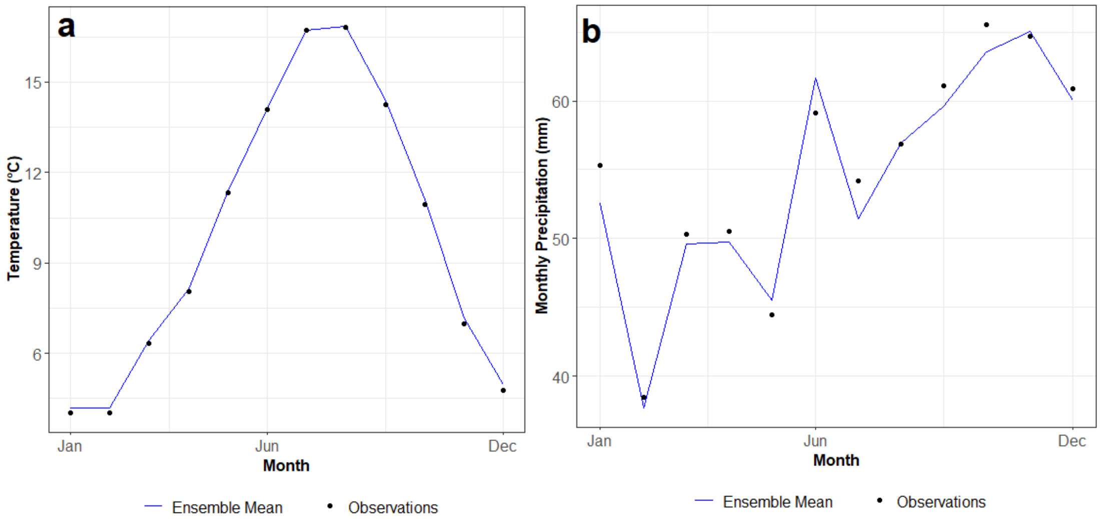


Figure 6.11 – Comparison between observations and bias corrected hindcast of monthly variation in **(a)** temperature and **(b)** precipitation in the Broadland catchment for the control period (1981-2000).

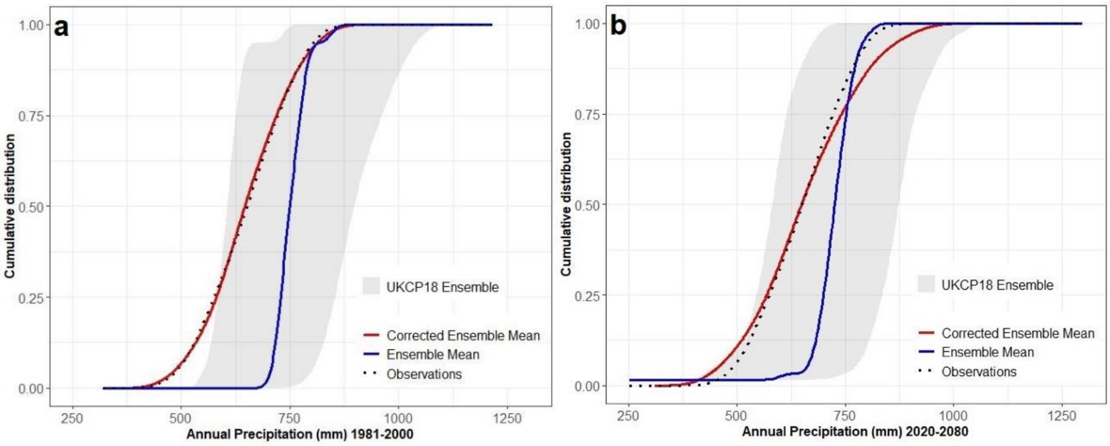


Figure 6.12 – Annual precipitation cumulative distribution functions from the UKCP18 RCM. **(a)** shows the control period (1981-2000) while **(b)** shows future projections (2020-2080). Observations from the control period are kept in both graphs as a reference.

The bias corrected UKCP18 projections for the RCP8.5 show an increase in average monthly temperature in the Broadland catchment, with little variation between individual PPE members (Figure 6.13a). While the mean of the PPE ensemble shows an increase in winter precipitation and a decrease over the summer months compared to the 1981-2000 baseline period, the range of possibilities is greater for projections of future precipitation than for temperature (Figure 6.13b). The increase in average annual winter precipitation shown by the bias-corrected projections is homogeneous spatially across the Broadland river sub-catchments (Table 6.2). The highest change occurs in the Waveney sub-catchment with a 16% increase in winter precipitation compared to 1981-2000. These findings are consistent with previous studies looking at 21st century changes in the Broads region (Price, 2013).

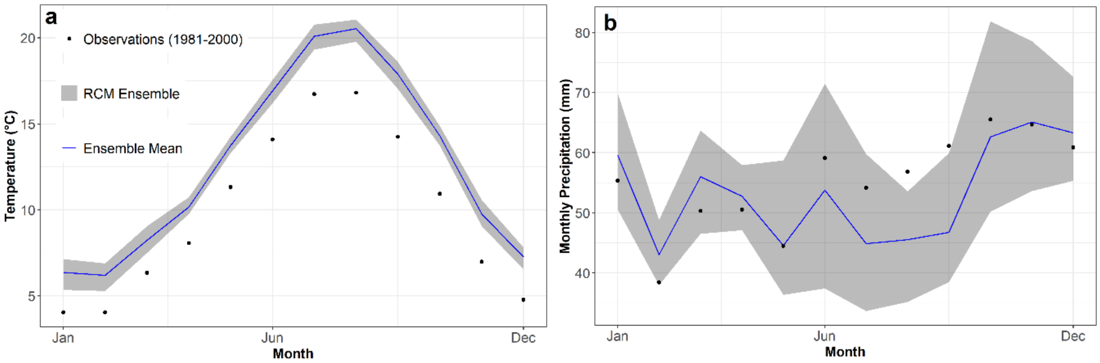


Figure 6.13 – Climatic changes in monthly **(a)** temperature and **(b)** precipitation in the Broadland catchment for RCP8.5 over the 2020-2080 period compared to the baseline period (1981-2000).

Table 6.2 – Comparing average annual winter precipitation (mm) between the bias-corrected projections of 2020-2080 and the baseline period (1981-2000) observations in Broadland sub-catchments.

River sub-catchment	Observations (1981-2000)	5th Percentile (2020-2080)	Mean (2020-2080)	95th Percentile (2020-2080)
Waveney	145.16	152.00	168.43	183.33
Yare	157.26	148.20	166.75	181.41
Bure	157.49	146.22	163.83	180.63
Ant	152.05	148.79	164.26	179.40
Spixworth Beck	151.57	145.30	164.45	180.17
Thurne	144.92	145.77	164.52	179.54

Many bias-correction methods exist with their own set of assumptions. The Gamma Quantile Mapping method used here assumes that RCM-simulated projections and observations approximate the Gamma distribution. This technique is nonetheless often considered appropriate for the distribution of precipitation. Studies have found it to perform better than other bias-correction methods, including at the tail end of the distribution, which is of particular concern for flood risk assessment (Luo *et al.*, 2018). A potential limitation in this analysis is the use of a 20-year baseline period to generate the transfer functions, as opposed to 30 years of data, which is more commonly used. A shorter period of time may indeed not represent the error linked to decadal variability (Dosio *et al.*, 2012). Other studies (e.g., Chen *et al.*, 2011) have however found that uncertainty in hydrological projections from the choice of the baseline period was negligible compared to other sources of uncertainty such as the choice of GCM or RCP. Since RCP8.5 is the higher end of warming among IPCC pathways, further research should moreover incorporate other RCPs, as they continue to be made available in the UKCP18, to account for a wider range of socio-economic and mitigation trajectories.

6.3.1.2. Hydrological modelling of future river discharge

The parameters of the HBV hydrological models for the Broadland catchments were estimated based on the availability of observations of daily river flow. The Waveney and Yare models were calibrated from 01/12/1963 – 01/12/1993 and 01/01/1961 – 01/01/1981 respectively. With NSE values of 0.73 and 0.60, the Waveney and Yare models were able to recreate daily river discharge at an acceptable level when validated from 01/01/1994 – 31/12/2015 and 01/01/1984 – 31/12/2000 respectively. Simulated mean annual river discharge shows a close fit to observations in both catchments (Figure 6.14).

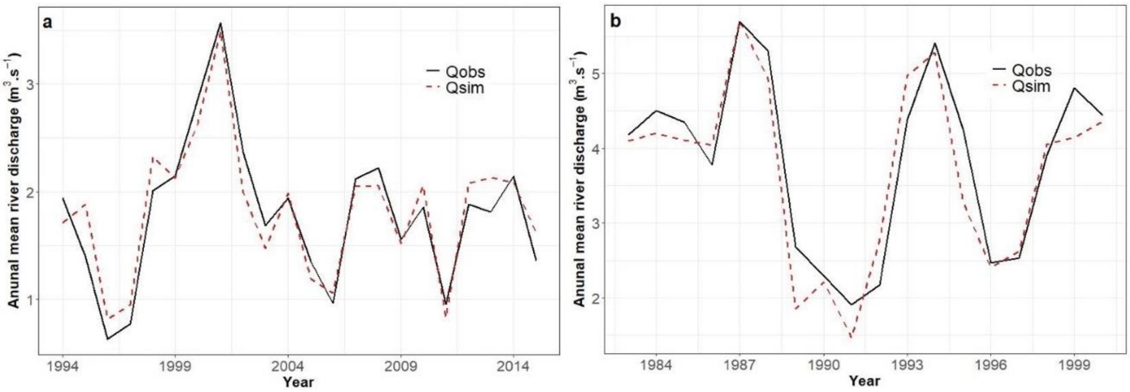


Figure 6.14 – Comparison of observed (red, dashed) and simulated (black, solid) river discharge, validating the HBV hydrological models for the **(a)** Waveney River and the **(b)** Yare river.

The rivers of the Broadlands catchment are often highly influenced by artificial sources resulting from human activities, such as land drainage and water abstraction

(Hiscock *et al.*, 2001). As the NRFA describes at the Bure Horstead Mill station, "the flow records are significantly affected by flow control operations" (NRFA, 2019). This makes daily river discharge difficult to reproduce from meteorological data without a more comprehensive consideration of local water management. The interest of this study lies in assessing flooding events, which occur during extreme conditions. For the Bure and Ant catchments, which are smaller in area compared to the Waveney and Yare catchments, a good model performance at peak discharge was therefore considered satisfactory. For the 01/01/1996 – 31/12/2006 validation period, the Ant catchment HBV model simulated discharge had a PE of -2% compared to observations. Similarly, for the 01/01/1984 – 31/12/1993 validation period, the Bure catchment HBV model simulate discharge had a PE of -9% compared to observations. This indicated a slight underestimation of simulated peaks, while the model overall tends to overestimate daily discharge in both catchments (Figure 6.15). For reference, Rabuffetti *et al*. (2008) found that a mean peak relative error below ±10% could be considered as a good model performance for peak values.

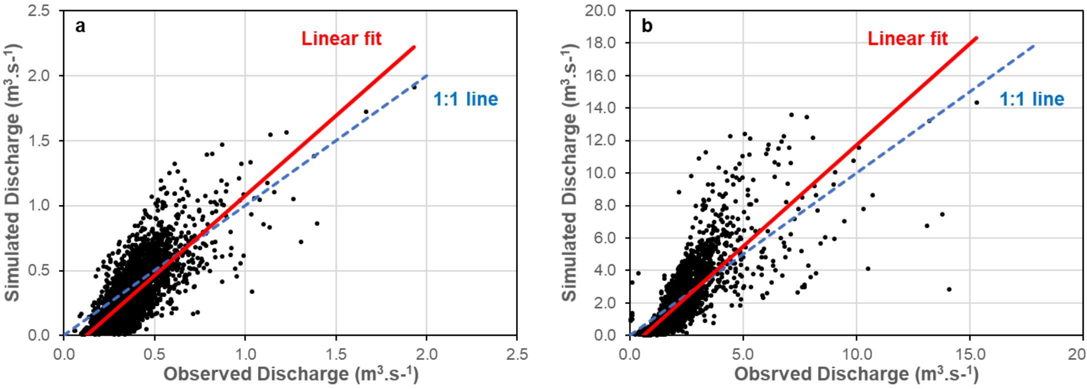


Figure 6.15 – Comparison between observed and simulated daily outflow during validation for **(a)** the River Ant ($R^2 = 0.80$) and **(b)** the River Bure ($R^2 = 0.79$).

The results of the hydrological simulations for 2020-2080 using the bias corrected UKCP18 projections of precipitation and temperature are shown in Figure 6.16 for each Broadland river sub-catchment studied. Averaging by year, river discharge is expected to decrease marginally throughout the next decades in the Broadland catchment. This is consistent with the expected increase in projected annual temperatures and the slight decrease in projected annual precipitation as shown in Figure 6.9. Decreasing river flows and water scarcity are a concern for water resource management in the East Anglian region (Spraggs *et al.*, 2015), alongside a potential intensification of the hydrological cycle leading to flooding during extreme events. Seasonally over the 2020-2080 period, summer flows in Broadland catchments are expected to lower slightly compared to the baseline period, while winter flows are expected to slightly increase. This finding is consistent with previous studies using UKCP09 in UK catchments (Christierson *et al.*, 2012). As can be seen for the Waveney catchment, which is representative of the other studied Broads rivers, the range of river flows derived from the 12 PPE members is wider in winter than in the summer (Figure 6.17).

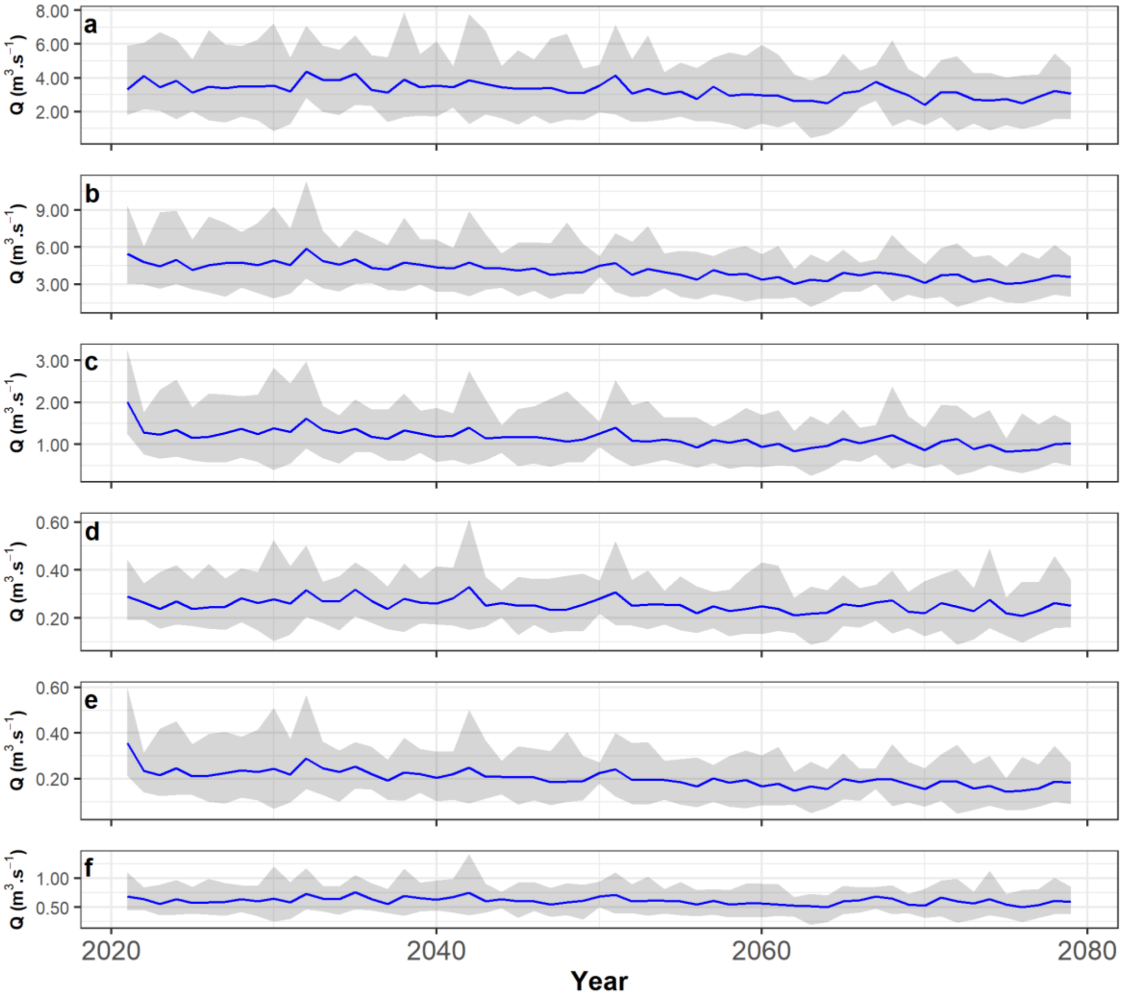


Figure 6.16 – Mean annual river discharge (Q) from HBV simulations for the 2020-2080 period in **(a)** the Waveney, **(b)** the Yare, **(c)** the Bure, **(d)** the Ant, **(e)** the Spixworth Beck and **(f)** the Thurne river catchments. The blue line represents the mean of the 12 UKCP18 PPE members, while the grey shaded area represents the 5th-95th percentile range.

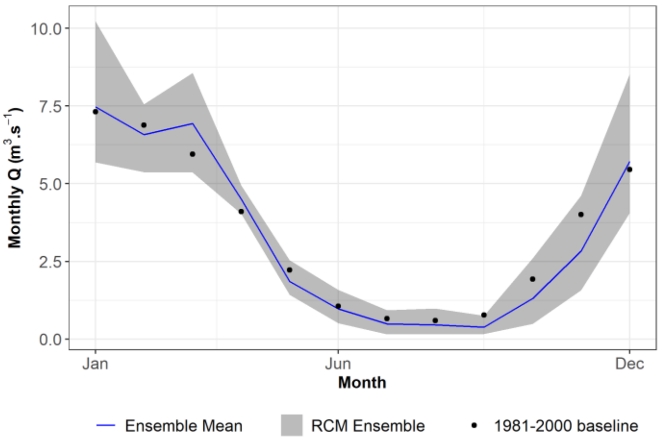


Figure 6.17 – Change in monthly average river discharge (Q) at the River Waveney for the 2020-2080 period modelled from the UKCP18 RCM PPE compared to the 1981-2000 baseline period.

The conceptual hydrological model used in this study provides an assessment of the impact of climatic changes on river discharge. The assumption was made in this study that land use would not change significantly. It should however be noted that land use changes can also have important effects on hydrology. Looking at land-vegetation-atmosphere feedbacks using other physically based hydrological models (Jones *et al.*, 2006) can be an area of future research for the Broadland catchment.

The lack of flow data in some of the Broads rivers, due to their primarily tidal nature, represents a challenge for calibrating and validating a hydrological model. Despite the assumptions made in the development of the HBV models, the presented methods offer a significant improvement to the characterisation of river discharge as an input for hydraulic modelling. The HBV models moreover allow for the assessment of the impact of climatic changes on river discharge, using the most recent projection for the UK, which was not possible using the previous methods described in Chapter 4. The derived time series of future daily river discharge allow for an analysis of trends in extremes and peak flows, which are essential in determining flooding impact.

6.3.2. EVA and scenario definition

6.3.2.1. Extreme river discharge

The EVA of future river discharge was carried out with the POT method for each HBV output resulting from the set of UKCP18 PPE members for each catchment. The derived 1:100 return river discharge levels for the simulated period of 2020-2080 were compared to past discharge modelled with HBV for the period of 1961-2015 (Table 6.3). On average, the river flows derived from the 12 PPE members shows an increase in the 1:100 return level across the Broadland catchments. There remains a high variability among the PPE members and in most sub-catchments the 5th percentile shows a decrease in extreme river discharge compared to 1961-2015.

Table 6.3 – 1:100 return River Discharge levels.

River sub-catchment	1:100 River Discharge (1961-2015) in $m^3.s^{-1}$	1:100 River Discharge (2020-2080) in $m^3.s^{-1}$		
		5th	Mean	95th
Waveney	72.96	82.36	131.36	198.53
Yare	47.24	32.89	57.60	101.40
Bure	16.61	10.54	27.30	55.23
Ant	2.15	1.77	3.92	7.01
Spix	2.50	1.87	3.70	7.00
Thurne	5.20	4.57	8.98	14.97

The frequency of extreme events is likely to increase with climate change (Stocker *et al.*, 2013). It is therefore necessary to account for the non-stationarity of hydrological extremes. As shown by Collet *et al.* (2017), non-stationarity induced by climate change can be explored by comparing past and future time periods. An important assumption however with this methodology is that each time period is considered stationary. An improvement to this work could therefore be to incorporate statistical EVA methods that deal with non-stationary extremes. Parameters of fitted distributions can, for example, be made to vary with time to obtain “effective return levels” and capture the changing properties of extremes (Gilleland and Katz, 2016). While flood and precipitation frequency analyses in the past have traditionally adopted stationary models, a growing number of studies have used nonstationary approaches (e.g, Ragno *et al.*, 2019).

6.3.2.2. Extreme sea level and SLR

Sea levels are projected to continue to rise throughout the 21st century in all the scenarios considered by the UKCP18. Projections vary however depending on the geographical location and the scenario (Figure 6.18). There is a north-south divide when looking at relative SLR across the UK coastline. Greater anomalies are found in the south, which is primarily due to vertical land movement. On the East Anglian coast, Bradley *et al.*, (2009) found that land subsides at a rate of 0.6 to 0.9 mm.a^{-1}. At Lowestoft, sea levels are projected to rise by 0.46 m, 0.56 m and 0.80 at the 50th percentile estimate for RCP2.6, RCP4.5 and RCP8.5 respectively.

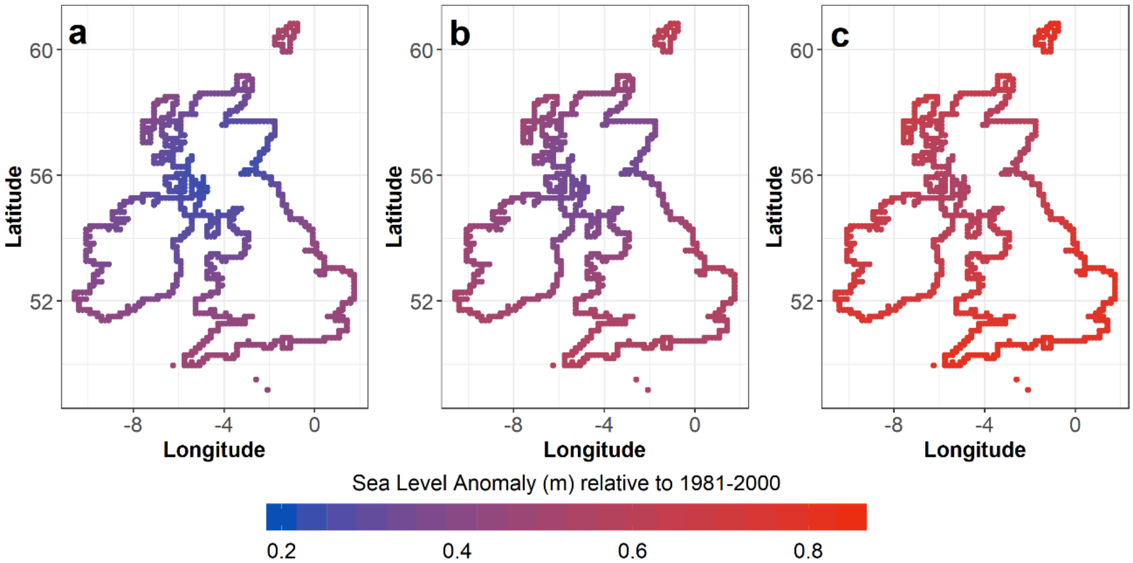


Figure 6.18 – UKPC18 projections of time-mean SLR by 2100 relative to 1981-2000 at the 50th percentile of **(a)** RCP2.6, **(b)** RCP4.5 and **(c)** RCP8.5

The convolution of the tide and surge density functions provides an improved characterisation of extreme sea levels through the RJPM. Previous comparison between the direct and indirect methods have found the former to underestimate resulting probabilities (Haigh *et al*., 2010; Mazas *et al*., 2014). A return sea level of 3.27 maOD was estimated for a 1:100 event using the RJPM method at Lowestoft with data from 1964 to 2018. For reference, a return sea level of 3.49 maOD was estimated in Chapter 4, with 3 years less data and without considering joint probabilities of tides and surges. The impact of SLR means a 1:100 event in 2018 could have a 1:20 return period by 2080 (Figure 6.19).

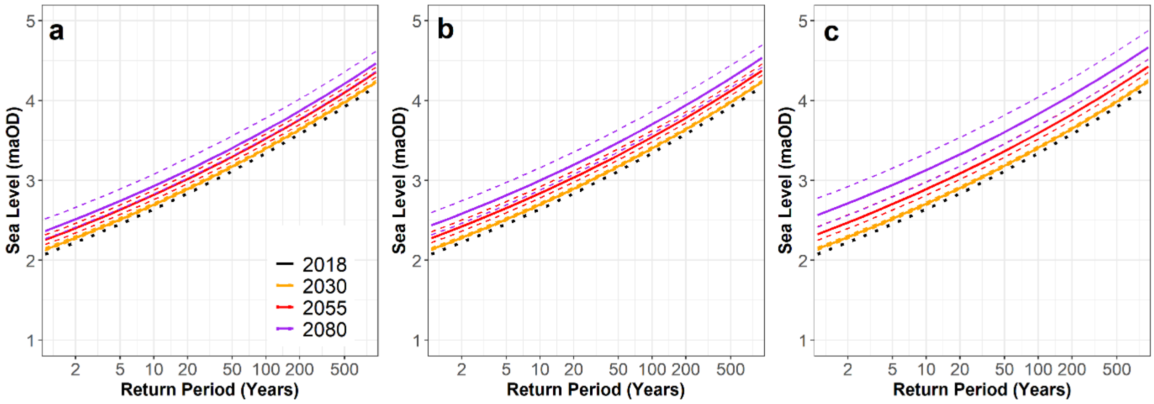


Figure 6.19 – Impact of relative mean SLR up to the years 2030, 2055 and 2080 on return sea levels at Lowestoft for **(a)** RCP2.6, **(b)** RCP4.5 and **(c)** RCP8.5. For each RCP and year, 5th and 95th percentiles (dashed line) are shown with the 50th percentile (solid line).

It should be noted that in shallow water areas, tides and surges can interact leading to dependency between the two components. This is the case for the Thames estuary for example and should be taken into consideration in the RJPM. However, the area near Lowestoft was previously found not to display tide-surge interactions by examining the standard deviation of the surge conditional on the tidal level (Environment Agency, 2005). The two processes can therefore be considered to be independent. Synthetic storm events, as shown in Figure 6.20, could hence be created to be used as inputs for the HEC-RAS hydraulic model.

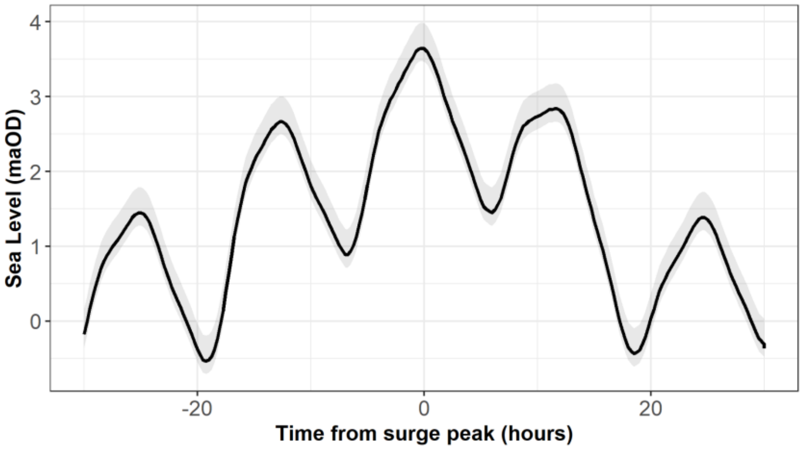


Figure 6.20 – Synthetic storm surge events are created from a representative surge shape and the results of the EVA of tides and surges. This figure shows a 1:100 extreme sea level event associated to RCP4.5 (50th) projections of SLR up to 2080. The shaded area represents the lower (RCP2.6, 5th) and upper (RCP8.5, 95th) UKCP18 SLR projections at Lowestoft.

6.3.2.3. Hydraulic model scenarios

The full list of scenarios run in the HEC-RAS hydraulic model are available in this thesis’ Appendices. Scenarios were defined based on three categories of downstream and upstream boundary conditions: (1) events with an extreme sea level and a base river flow (Appendix 3.1), (2) events with a base tide (no surge) and an extreme river flow (Appendix 3.2), and (3) worst case scenario events with the association of a 1:100 sea level to a 1:100 river flow for a combined 1:10,000 return event (Table Appendix 3.3). The different emission pathways were represented in the scenarios as well as the range of uncertainties carried on from the UKPC18 climate and marine projections. Modelled extreme sea level events covered RCP2.6, RCP4.5 and RCP8.5, while modelled extreme river discharge events only represented RCP8.5. To match stakeholder expectations described in Chapter 5, the evolution of the impacts of SLR throughout the 21st century was portrayed. Stakeholder-defined adaptation options were modelled under the conditions of scenarios listed in Appendix 3.1.

6.3.3. Future flood hazard and impacts in the Broads

6.3.3.1. Flooding hazard

The HEC-RAS hydraulic model performed well in recreating river levels when forced with past river flow and sea level conditions (Figure 6.21). As for Chapter 4, model performance decreased going upstream from the mouth of River Yare. The model achieved better results in the northern half of the Broads in recreating the river levels at low and high tide. It should be noted that the model slightly underestimated the amplitude of tidal river levels for the River Waveney and the River Yare. The correlation coefficients between modelled and observed values remained high, with R^2 values above 0.80. Final Manning’s n values were the same as the ones chosen in Chapter 4 (Table 4.3 and Table 4.4).

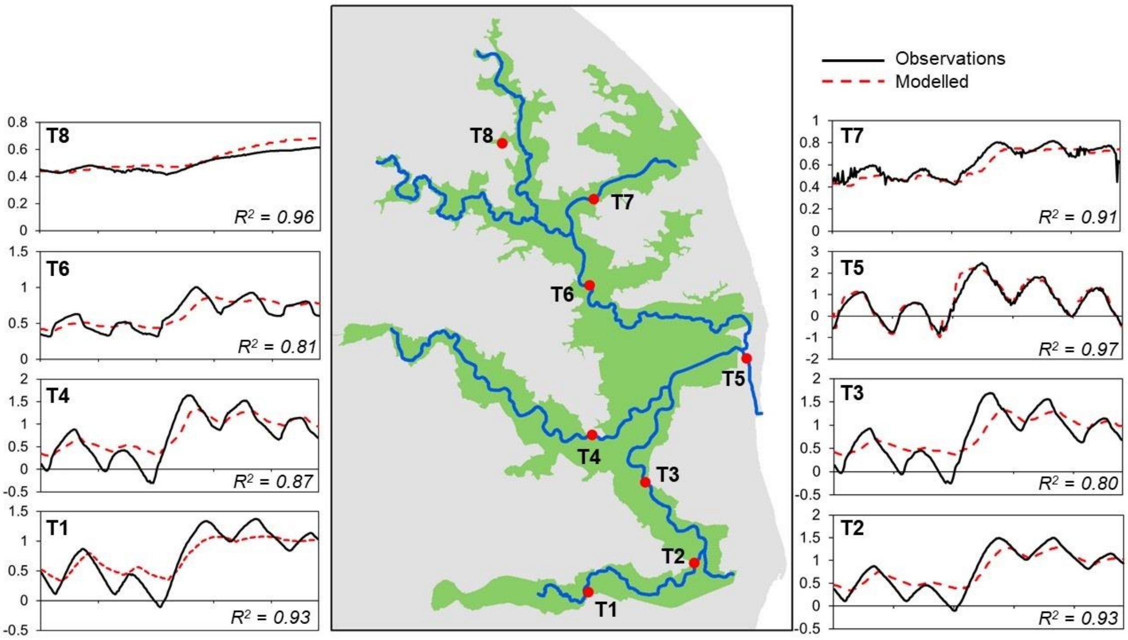


Figure 6.21 – Validation of the HEC-RAS model for the 04/12/2013-07/12/2013 period. River levels (in maOD) are shown for the 8 river gauges in the Broads (same locations as in Figure 6.6). NSE values: T1 (0.77), T2 (0.8), T3 (0.62), T4 (0.7), T5 (0.93), T6 (0.65), T7 (0.75), T8 (0.6).

Resulting flood extent and depth maps show the progression of flood hazard from 2030 to 2055 and 2080 under different 1:100 events. Figure 6.22 shows the flood extent resulting from storm surge under increments of SLR. The low, middle and high ranges of RCP2.6, RCP4.5 and RCP8.5 respectively are provided to account for the range of uncertainty stemming from emission scenarios and projections of future SLR. Since UKCP18 projections of climatic changes are, at this time, only provided for RCP8.5, extreme river discharge and combined events also only represent RCP8.5.

In 2030, flooding is limited to Haddiscoe Island and some part of Great Yarmouth in all scenarios (Figure 6.22). While upstream parts of the Bure and the Yare show some flooding, these areas are mostly undefended fens and marshes with out-of-channel flow therefore to be expected. By 2030, projections of SLR among RCPs does not vary greatly and therefore differences in flooding extent are minimal. These differences are more pronounced by 2055, where Halvergate Marshes, north of Breydon Water, as well as the compartment south of Haddiscoe Island, flood under the RCP8.5 (95th percentile) scenario. The A47 road and the railway connecting Norwich to Great Yarmouth are important infrastructural assets located in Halvergate. These areas also flood in the RCP4.5 (50th) in 2080. The upstream Waveney River only experiences flooding from a

1:100 extreme sea level in 2080 and under RCP8.5 (95th). Flooding depth, which is an important indicator of potential impacts, also increases with time (Figure 6.23). Under the RCP4.5 (50th) scenario, depths up to 2 m are visible in Great Yarmouth. Flooding depth is greater in Haddiscoe Island compared to surrounding marshes, which themselves experience up to 0.5 m of flooding in 2055 and between 1 m and 2 m in 2080

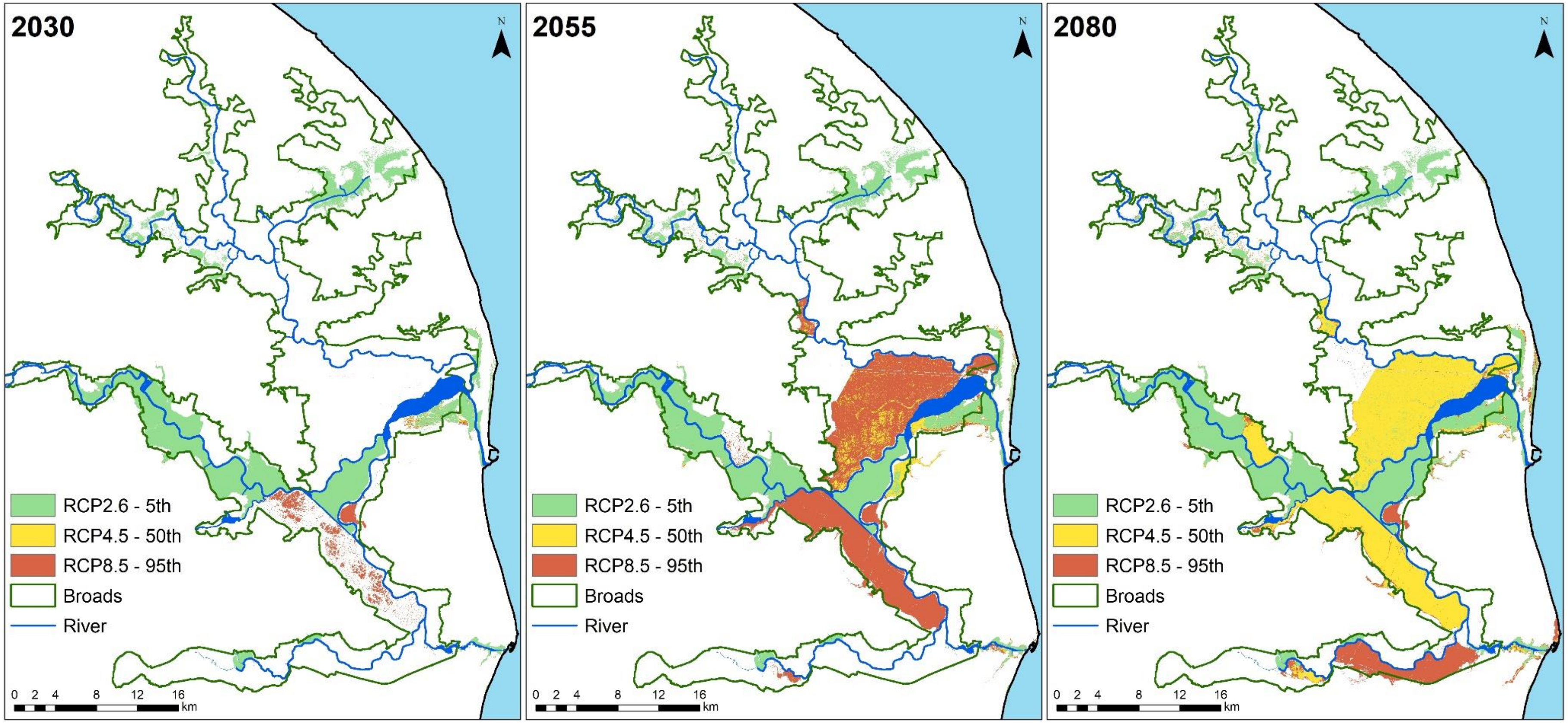


Figure 6.22 – Flooding extent resulting from the hydraulic modelling in HEC-RAS of 1:100 extreme sea level events using UKCP18 projections of SLR in 2030, 2055 and 2080. The name of each category represents the minimum SLR projection (of the three shown) at which the area floods: areas under the "RCP8.5 – 95th" heading flood only in the RCP8.5 scenario at the 95th percentile and areas under the "RCP2.6 – 5th" heading flood in all three scenarios shown.

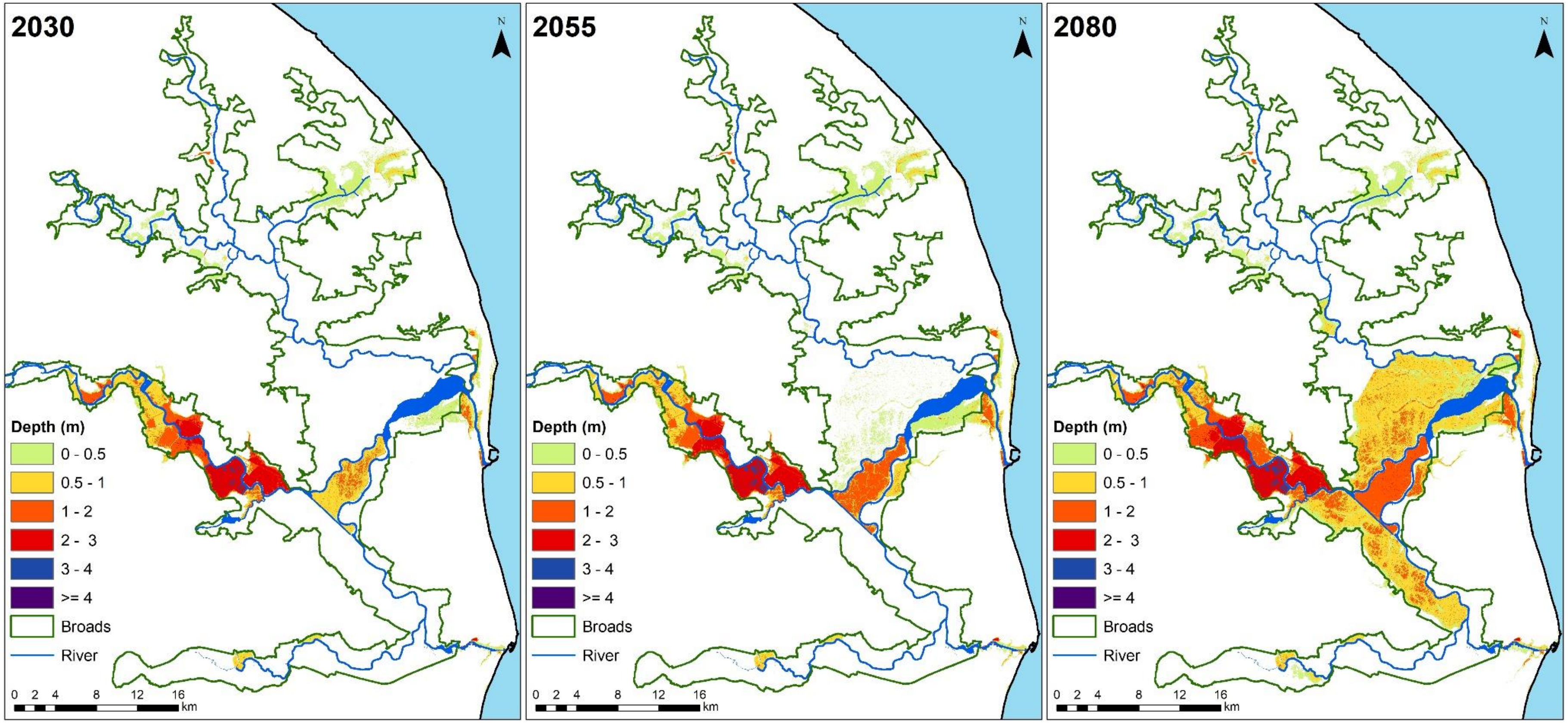


Figure 6.23 – Flooding depth resulting from the hydraulic modelling in HEC-RAS of 1:100 extreme sea level events using UKCP18 projections of SLR in 2030, 2055 and 2080 under RCP4.5 (50th).

There is a noticeable divide between the northern and southern rivers when looking at the impact of extreme sea level on the Broads. Despite some isolated flooding in the Thurne and Bure, current levels of defences are better able to limit flooding in the north than in the south. This finding aligned with expectations from stakeholders (farmers, conservationists and catchment engineers) as well as the Environment Agency during final feedback meetings, that the southern part of the National Park is more exposed to flooding. Comparing to results from the sensitivity analysis in Chapter 4, the Bure River experiences far less overtopping of defences. This is indeed due to the definition of scenarios, as Chapter 4 looked at the impact of extreme SLR of up to 1 m and 2 m, which is greater than the expected rise in RCP8.5 by 2080. The two models remain consistent in showing Halvergate Marshes and the compartment on the right bank of Acle as the areas that flood first on the Bure.

The HEC-RAS model is also consistent in showing that the extreme sea level events, on their own, are a more important threat to the Broads than extreme river discharge events of the same probability (Figure 6.24). Future fluvial events under RCP8.5 affect upstream areas of the Broads but have little impact on the rest of the model domain. On the other hand, the combination of the same 1:100 extreme river discharge events with a 1:100 extreme sea level event exacerbates flooding throughout the Broads (Figure 6.25). The extent of flooding in these “worst-case” scenarios are larger than in the equivalent extreme sea level scenarios under RCP8.5 at the 95th percentile starting in 2030. Halvergate Marshes and the upper Waveney being examples of areas that flood, which did not without the combined river discharge. With much of the floodplains already flooded, the main difference from year to year is an increase in flooding depth, which affects areas like the right-bank in Great Yarmouth.

Modelled flooding was primarily tidal in nature and resulting from the overtopping of river embankments. On the other hand, coastal flooding was minimal in all scenarios, including the upper estimates of RCP8.5 in 2080. The 14 km long length of coastline between Eccles and Winterton in particular is threatened by coastal flooding, which occurred during the 1953 storm surge. It is currently defended by a concrete sea wall, as well as sand dunes and the beach itself, which are depicted in the model topography. While model results show that the current standard of defence is successful is preventing widespread flooding from the coast, a more in-depth and localised analysis of the integrity and stability of defences is required.

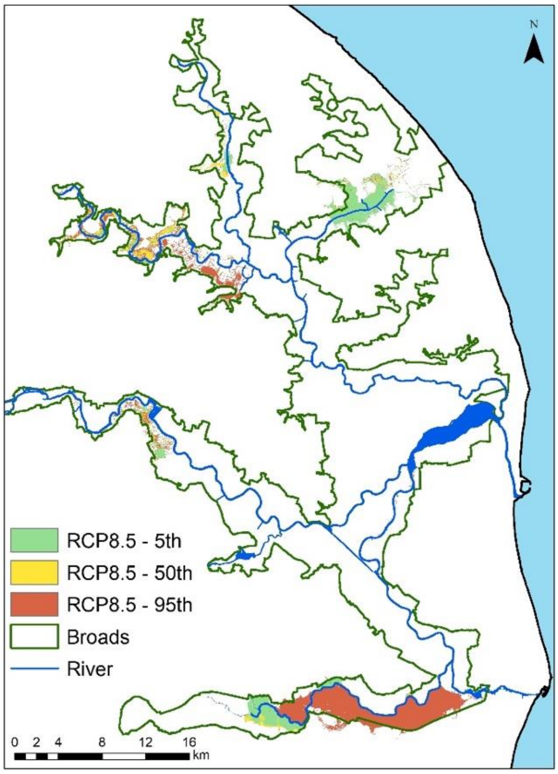


Figure 6.24 – Flooding extent resulting from the hydraulic modelling in HEC-RAS of 1:100 extreme river discharge events using UKCP18-derived projections. The UKCP18 has only provided climatic projections for RCP8.5 at this time. The name of each category on the map represents the minimum future projection (of the three shown) at which the area floods.

The inclusion of the latest UKCP18 projections in forcing the hydraulic model provides an estimate of how climate change and SLR will affect the Broads in the coming decades. Many of the same assumptions that were discussed in Chapter 4 remain in the modelling design and are important to note. The model indeed does not consider the influence of waves and wind on flooding hazard. Moreover, only the overtopping of defences and embankments is represented, and other types of failures, such as breaches, are not studied. In the definition of upstream boundary conditions, it was moreover assumed that all rivers in the Broads experience the same probability peak discharge simultaneously. Since the Broads rivers are slow-flowing and their catchments are relatively homogenous, this assumption was deemed acceptable. Further research should look at the varying response of each sub-catchment to specific weather patterns, and how that relationship affects river discharge into the Broads. As UKCP18 projections continue to be released, the inclusion of a wider range of RCPs in the definition of extreme river discharge scenarios is an area of improvement to this work.

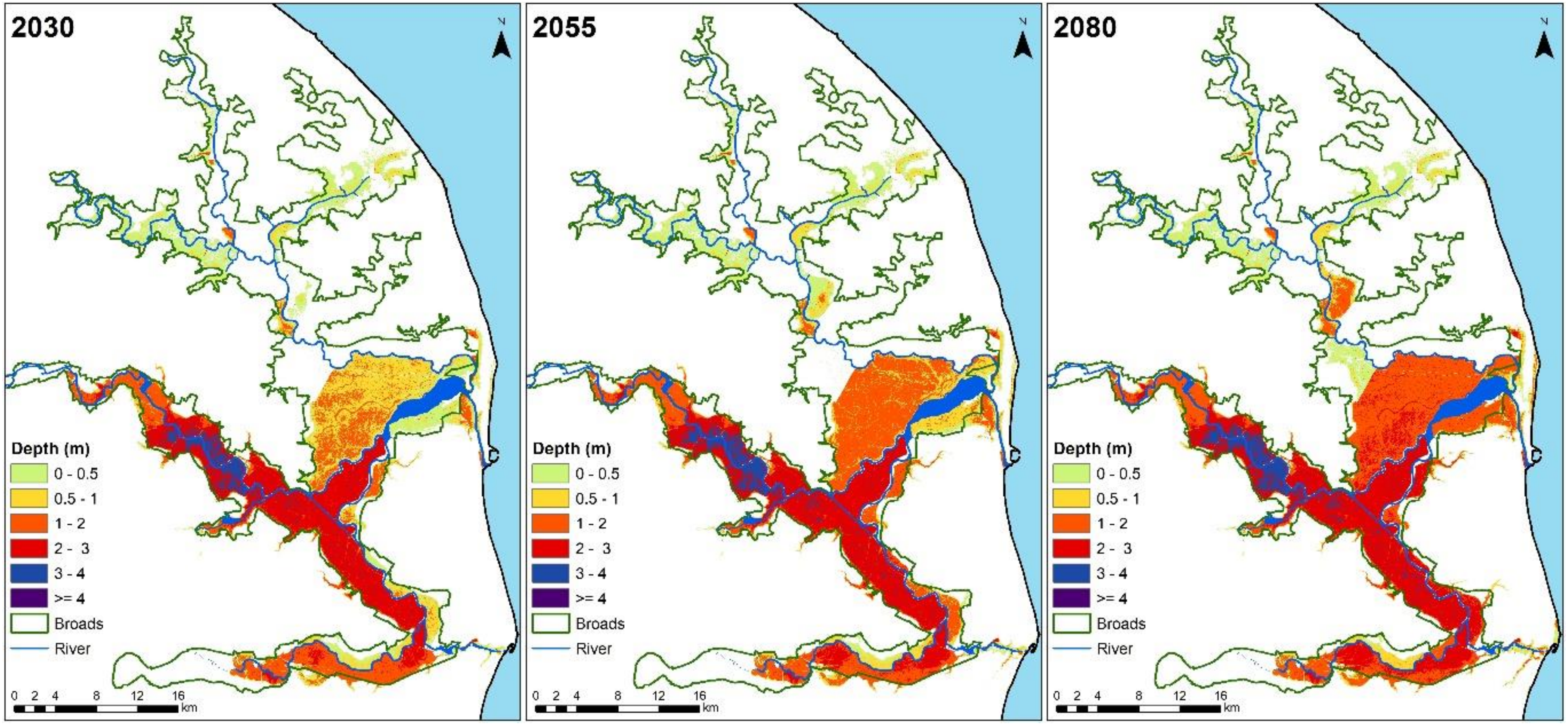
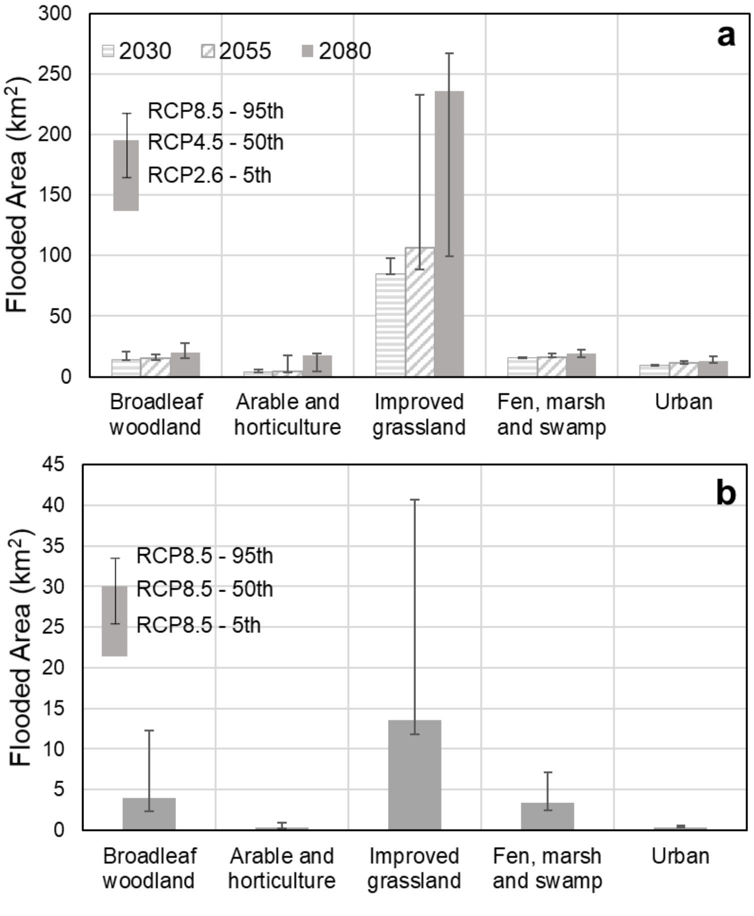


Figure 6.25 – Flooding depth resulting from the hydraulic modelling in HEC-RAS of 1:10,000 “worst-case” scenario events combining a 1:100 extreme sea level event with a 1:100 extreme river discharge event, using UKCP18 projections of SLR in 2030, 2055 and 2080 under RCP8.5 at the 95th percentile.

6.3.3.2. Flooding impact

The modelled flooding scenarios can be expected to have varied impacts on human and natural systems in the Broads. Approximately 40% of the Broads is made up of grassland, which primarily consists in drained land used as grazing marshes. As the dominant feature in the Broads floodplains, grasslands are also the most affected land cover type in terms of area of flooding in the modelled scenarios (Figure 6.26). These marshes are composed of a large network of drainage dykes, which provide freshwater habitats for wildlife and plant communities (Broads Authority, 2009). Some of these areas, such as Halvergate Marshes or Cantley Marshes along the Yare River, are designated as SSSI and are currently protected by flood defences. These defences are overtopped under RCP4.5 (50th) by 2055. The average flooding depth is also the highest than any other land cover (1.20 m under RCP4.5), which can be significant for response measures and lead to complications in pumping out floodwater from these expansive areas.



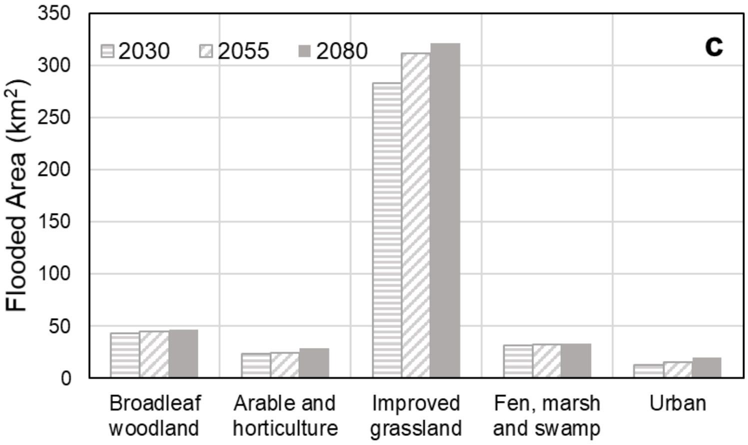


Figure 6.26 – Flooded area by land cover type. **(a)** 1:100 storm surge event with SLR up to 2030, 2055 and 2080 for RCP4.5 at the 50th percentile with error bars showing the spread of possible futures depicted by RCP scenarios. **(b)** 1:100 extreme river discharge event for the period 2020-2080 under RCP8.5. **(c)** 1:10,000 event combining a 1:100 extreme river discharge and a 1:100 storm surge event with SLR up to 2030, 2055 and 2080 for RCP8.5 at the 95th percentile.

The flooding occurring in extreme discharge events (Figure 6.26b) mostly affected grassland, woodland and fens, while having negligible impacts on arable land and urban areas. Located near the coast, Lowestoft and Great Yarmouth are primarily at risk from extreme sea level events. Flooding in these scenarios was more important in Great Yarmouth than in Lowestoft and was caused by an overtopping of the River Yare. The flooded urban area increases from 8.76 km^2, to 10.09 km^2 and 11.59 km^2 in 2030, 2055 and 2080 respectively, during a 1:100 extreme sea level event under RCP4.5 (50th). This goes along with an increase in the average depth of urban flooding from 0.75 m, to 0.84 m and 0.88 m, as well as greater numbers of buildings and properties within the inundation extent (Table 6.4).

Table 6.4 – Number of buildings within the modelled inundation extent for different scenarios.

Type of event	Year	Number of buildings
1:100 extreme sea level	2030	(2111) – 2162 – (2230)
(RCP2.6, 5th) - RCP4.5, 50th - (RCP8.5, 95th)	2055	(2288) - 2468 – (2857)
	2080	(2466) - 2914 – (3784)
1:10,000 combined event	2030	3579
RCP8.5, 95th	2055	4109
	2080	4952

Although the combination of an extreme river discharge event to an extreme sea level event did not have a large impact on urban areas (compared to an extreme sea level event on its own), it did exacerbate flooding for all other land cover types (Figure 6.26c). Figure 6.26a moreover shows that there is a large level of uncertainty in total flooded area my land cover type due the range of SLR projections from different RCPs. The same can be said for differences resulting from the consideration of the spread of UKP18 RCM PPE members in the characterisation of fluvial extremes (Figure 6.27c).

The presented GIS analysis shows some of the physical impacts of the modelled probabilistic future flooding scenarios on different activities, interests and environments in the Broads. More can be done to infer the full range of impacts of flooding to assist decision making, which fell outside of the scope of this study. Much research has been dedicated at determining damage caused by projected future flooding and related economic costs to support risk assessments (e.g., de Moel *et al.*, 2015; Kaspersen and Halsnæs, 2017; Rehan, 2018). The valuation of assets or ecosystem services can be a contentious issue in the Broads, which requires the input of varied stakeholders (Turner *et al.*, 2016).

6.3.3.3. Impacts of SLR on river salinity during extreme surge events

Considering the little available data, the HEC-RAS Water Quality Module was able to able to recreate river salinity during extreme sea level events reasonably well. NSE values of 0.97 and 0.96 were obtained at Cantley (Figure 6.27 – S1) and Acle (Figure 6.27 – S2) respectively during model validation for the December 2013 storm surge. While background river salinity was well represented, the response to the tidal surge was less accurately estimated by the salinity model. This was particularly the case at Cantley on the River Yare, where the model was slower to reach peak river salinity levels than observations.

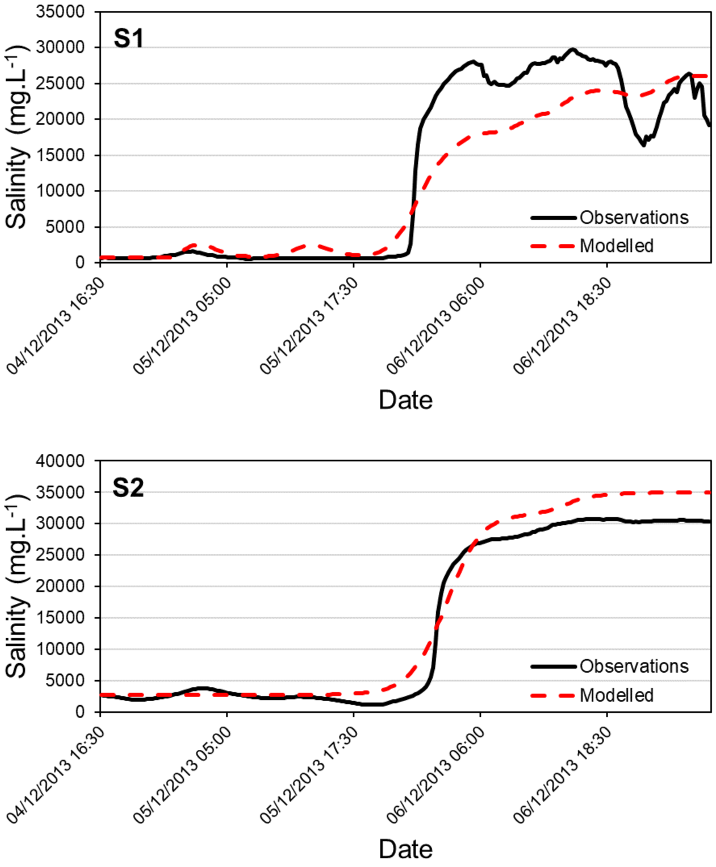


Figure 6.27 – Validation of the HEC-RAS salinity model for the 04/12/2013-07/12/2013 period. River salinity concentrations are shown for the two continuous probes in the Broads (same locations as in Figure 6.7).

The low gradient of the Broads allows saline waters to flow far upstream into its river system during episodes of high sea level. There are concerns in the Broads that salinity will reach higher up the Broads waterways with SLR as tidal surge events intensify. This poses a challenge for water management, agriculture and freshwater biodiversity. A classification of saline waters from the Food and Agriculture Organisation (FAO) was used as a reference to assess the potential impact of saline incursion during a flood (Table 6.6).

Table 6.5 – Classification of saline waters (adapted from Rhoades *et al.*, 1992).

Water class	Salt concentration (mg.L^{-1})	Type of water
Non-saline	< 500	Drinking water
Slightly saline	500 – 1500	Irrigation water
Moderately saline	1500 – 7000	Primary drainage
Highly saline	7000 – 15000	Secondary drainage water and groundwater
Very highly saline	15000 – 35000	Very saline groundwater / Seawater

While the Broads are a primarily freshwater system, some of the lower valleys and the upper Thurne are highly influenced by saline conditions. This is the case, for example, in the saline grasslands adjacent to Breydon Water. Salinity can however pose a threat to freshwater species. Panter *et al.*, (2011) found that 63% of “priority species” in the Broads required fully freshwater conditions and were unlikely to tolerate brackish influence. Under the different modelled scenarios of SLR, salinity was shown to affect rivers up to Brundall on the Yare, Hoveton on the Bure, upstream of Barton Turf on the Ant and all of the River Thurne (Figure 6.28). Concentrations greater than 7000 mg.L^{-1} reach the River Ant and key areas for conservation such as, the Strumpshaw Fen and Surlingham Church Marsh RSPB sites.

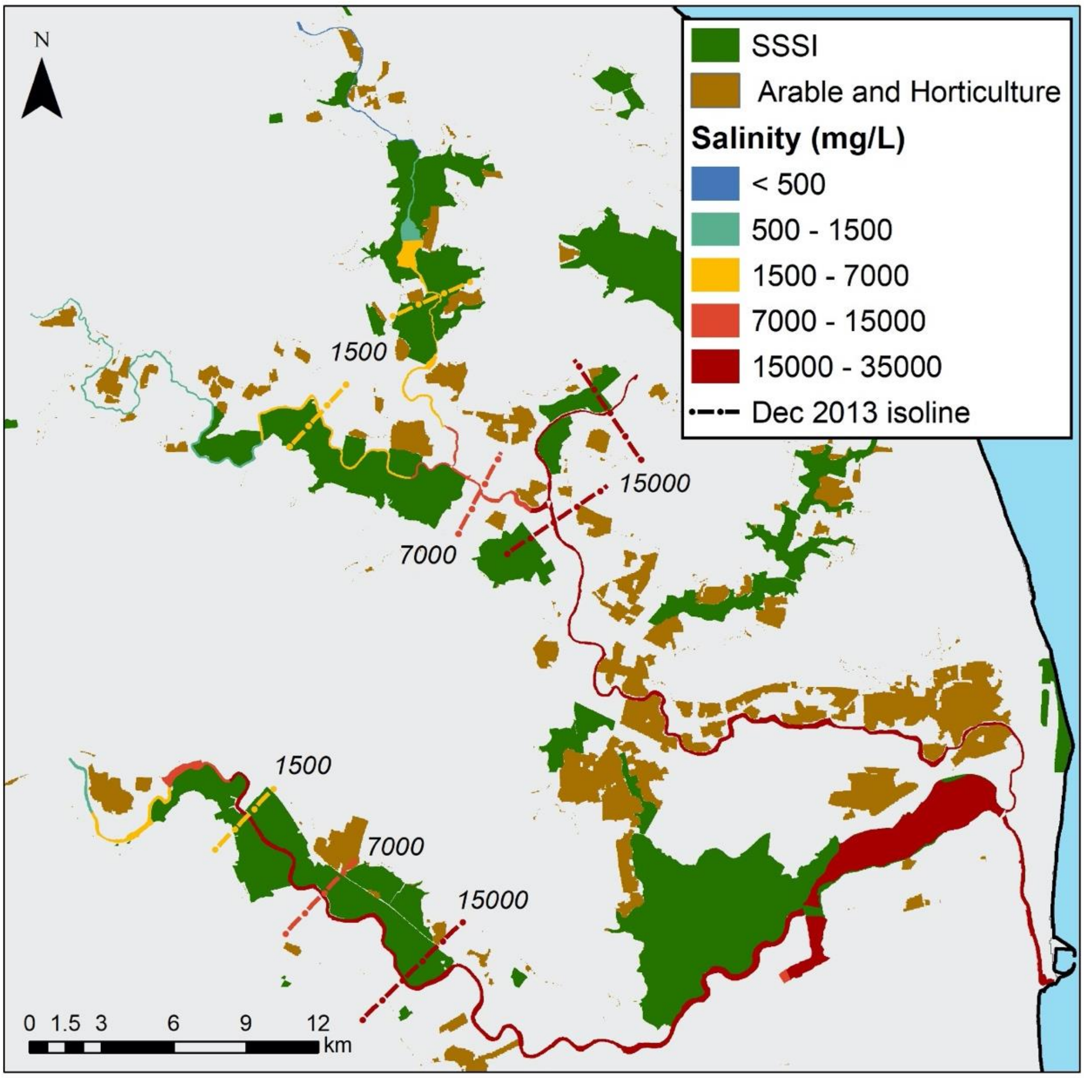


Figure 6.28 – River salinity concentrations modelled during a 1:100 extreme sea level event under RCP4.5 (50th) projections of SLR up to 2080. Isohalines (lines of equal salinity) from the modelled December 2013 storm surge are shown for comparison. Overbank flow of saline waters can have significant impacts on areas designated for conservation, such as SSSI, as well as agriculture.

Figure 6.28 shows the difference in saline incursion between the recreated December 2013 conditions and a 1:100 extreme sea level event under RCP4.5 (50^{th}) projections of SLR up to 2080. Saline water at the highest threshold (> 15000 mg.L^{-1}) reached approximately 10 km further upstream on the River Yare in the future scenario. The difference was less pronounced on the River Bure with high levels of salinity (> 7000) encroaching approximately 3 km further upstream. The comparison of the model outputs from other future scenarios under different RCPs however showed that the salinity results were not highly sensitive to changes in sea level. The choice of RCP, reference year, or confidence level in sea level projections only changed the reach of the salinity by 300 to 500m, depending on the scenario. The return level (i.e. the peak sea level) of the extreme event was also not the dominant driver for salinity. The large differences with the December 2013 event suggest that the shape of the surge and its interaction with the tide is more important in determining the extent of saline incursion in the Broads. For instance, the December 2013 surge was characterised by a negative storm surge residual in the lead up to the peak water levels (Spencer *et al.*, 2015), which is not represented in the synthetic storms derived from the EA surge shape. Further research should therefore look at the effect of different surge shapes on salinity levels in the Broads.

The HEC-RAS simulations assumed that the model's upstream boundaries on the Rivers Yare, Bure and Ant were not affected by the saline incursion. As sea levels rise however, salinity can be expected to have a greater range of influence. In such cases it would therefore be necessary to push back model boundaries or obtain sufficient observational data to define appropriate boundary conditions. An important omission in the model, was not only the River Waveney due to lack of data, but also of the Upper Thurne. While the salinity probe on the River Thurne provided an appropriate model boundary condition, salinity in the rest of the Thurne system requires a more detailed analysis.

Previous attempts at modelling the salinity in the Thurne system have also mentioned the difficulties in calibrating salinities in parts of the Broads, indicating that factors controlling the hydraulics of the system vary in space and time (Holman and White, 2008). Such studies have also found that pumping operations, which play an important role in that area, can have a significant impact in either reducing or increasing river salinity concentrations. Salinity in the Thurne moreover originates directly from the sea through groundwater (Simpson *et al.*, 2011), which is also omitted from the presented hydraulic model.

Despite the simplistic representation of salinity, the presented modelling can help assess the drivers of future river salinity concentrations in the Broads during extreme events. Few studies have looked at salinity and flooding in an integrated hydraulic modelling design, which can help better understand the complex risks that coastal regions face. Still, as the last link in the modelling chain, much uncertainty applies to the salinity model. There is a need for more systematic and widespread observations of EC in the Broads, which would play an important role in reducing these uncertainties and help better plan for the challenges that increasing salinity poses.

6.3.3.4. Discussion on the model cascade and uncertainty

Projections of flood extent and depth and river salinity concentrations are the results of a complex multi-step analysis, from the modelling of future climatic changes, to the assessment of hydrological and hydraulic trends. This process is often referred to in the literature as a modelling "chain", in which uncertainties are introduced at each modelling step and adding up, leading to a "uncertainty cascade" (Mitchell and Hulme, 1999). While probabilistic projections of future flooding and flood hazard mapping are becoming increasingly essential for decision-making, it is important to consider these uncertainties (Dittes *et al.*, 2018). Pappenberger *et al.* (2012) listed the sources of uncertainty within the physical modelling chain and ranked them by importance, as shown in Table 6.6.

Table 6.6 – Sources of uncertainty in the modelling chain of future flood hazard (adapted from Pappenberger *et al.*, 2012)

Source of uncertainty	Qualitative ranking of importance
Meteorological forcing	High
Model structure (hydrological, hydraulic), factors and parameters	Medium
Numerical accuracy and solver	Medium
Other boundary conditions (e.g., topography, river geometry)	High
Post-processing and re-mapping of results	Low
Observation dataset for comparison (e.g., historical inundation maps)	High

Uncertainties can be stochastic, resulting from the intrinsic variability in the climate system, or they can be epistemic (Döll and Romero-Lankao, 2017). There is ample literature on the latter, which can arise from our limited knowledge of socio-economic and environmental systems (e.g., Prudhomme and Davies, 2008; van Vuuren *et al.*, 2011). In the case of SLR different RCPs provided by the IPCC were used to highlight the range of possible future scenarios of anthropogenic emission and their varied impacts on flooding. As was shown, the range of uncertainty in SLR between RCPs increases with time and can lead to important differences in future flooding. While this approach is often recommended to deal with the uncertainties of future projections of climate change (Smid and Costa, 2017), local impact assessment studies also require techniques to obtain projections at spatial scales that are relevant for decision-making.

Uncertainties can indeed also stem from the dynamical downscaling of GCMs to obtain finer-resolution climate model outputs (Mirdashtvan *et al.*, 2017), as was done for the UKCP18 12-km RCM. While RCMs are better able to represent mesoscale atmospheric processes that are particularly important in portraying precipitation (Turco *et al.*, 2017), a bias correction was required to align projections with past observations. Still, previous studies have found that uncertainty in GCMs were greater than the uncertainty resulting from downscaling processes (Déqué *et al.*, 2012). The spread in projections of temperature and precipitation from the UKCP18 RCM PPE was taken into account in this study and carried over to the hydrological modelling and analysis of extreme events. The results shown are however only based on the HadGEM3-GC3.05 climate model. A comparison of projections from a multi-model ensemble, would help assess uncertainties from the selection of GCM, which Her *et al.* (2019) found to be more important than the uncertainties from hydrological model parameters in hydrological analyses of climate change.

As shown in Table 3, the quality of data used as inputs in the hydraulic model structure can be important sources of uncertainty. The best available fine-resolution LiDAR data from the EA combined with river bathymetry surveys were used to limit the influence of these uncertainties. Rodríguez-Rincón *et al.* (2015) indeed argued that the precise characterisation of rivers and floodplains is critical in predicting inundation extent. While the continued development and coverage of LiDAR data represents a significant opportunity for 2D hydraulic modelling (Mihu-Pintilie *et al.*, 2019), there remains a need to regularly update this data and test it with on-site surveys. The EA indeed states that the vertical accuracy of the LiDAR is no greater than ± 5 cm. Still, this level of error can make for important differences in flood extents, particularly in the Broads, where high defences protect large flat floodplains. For these reasons, the reliability of such data for flood mapping was expressed as a concern by a stakeholder with farming interests during final feedback meetings.

Finally, the lack of available historical inundation maps was a significant hurdle in this study. The hydraulic model was calibrated based on observed river levels, which is an acceptable proxy in a tidally driven system (Vidal *et al*., 2007). In most flat compartments within the 1D HEC-RAS model domain the use of river levels is moreover justified as flooding extent are dictated by the overtopping of defences rather than local topography. This is less the case in urban areas and areas affected by coastal flooding (modelled in 2D), which could be improved with detailed inundation maps.

6.3.4. Effect of stakeholder-defined adaptation measures on flooding hazard

The cascading scientific and socioeconomic uncertainties that lie behind climate change impact assessments are a critical hurdle for action on adaptation (Dessai and van der Sluijs, 2007, Moser and Ekstrom, 2010). The range of possible future outcomes expands at each step in the modelling chain, which can make decision-making particularly difficult (Refsgaard *et al.*, 2013). Still, the plausible impacts of climate change, as well as the potential cost of inaction, mean that societal actors must consider adaptation options despite this uncertainty (Vermeulen *et al*., 2013). A number of researchers have moreover suggested the need for the identification of robust, rather than optimal, adaptation measures, which are able to perform under a range of future scenarios (Lempert *et al.*, 2004, Dessai and Hulme, 2007). Under such a paradigm, Wilby and Dessai (2010) argued that even uncertain projections of future risk can provide boundaries for the testing of adaptation options over decadal timeframes.

6.3.4.1. Flood storage area: Haddiscoe Island

Under the modelled extreme sea level events, setting up Haddiscoe Island as an offline flood storage area had a visible impact of flooding (Figure 6.29). Overtopping of embankments in surrounding compartments was considerably reduced and the effect of the flood area on flooding extent increased with time from 2030, to 2055 and 2080 under RCP4.5 (50th).

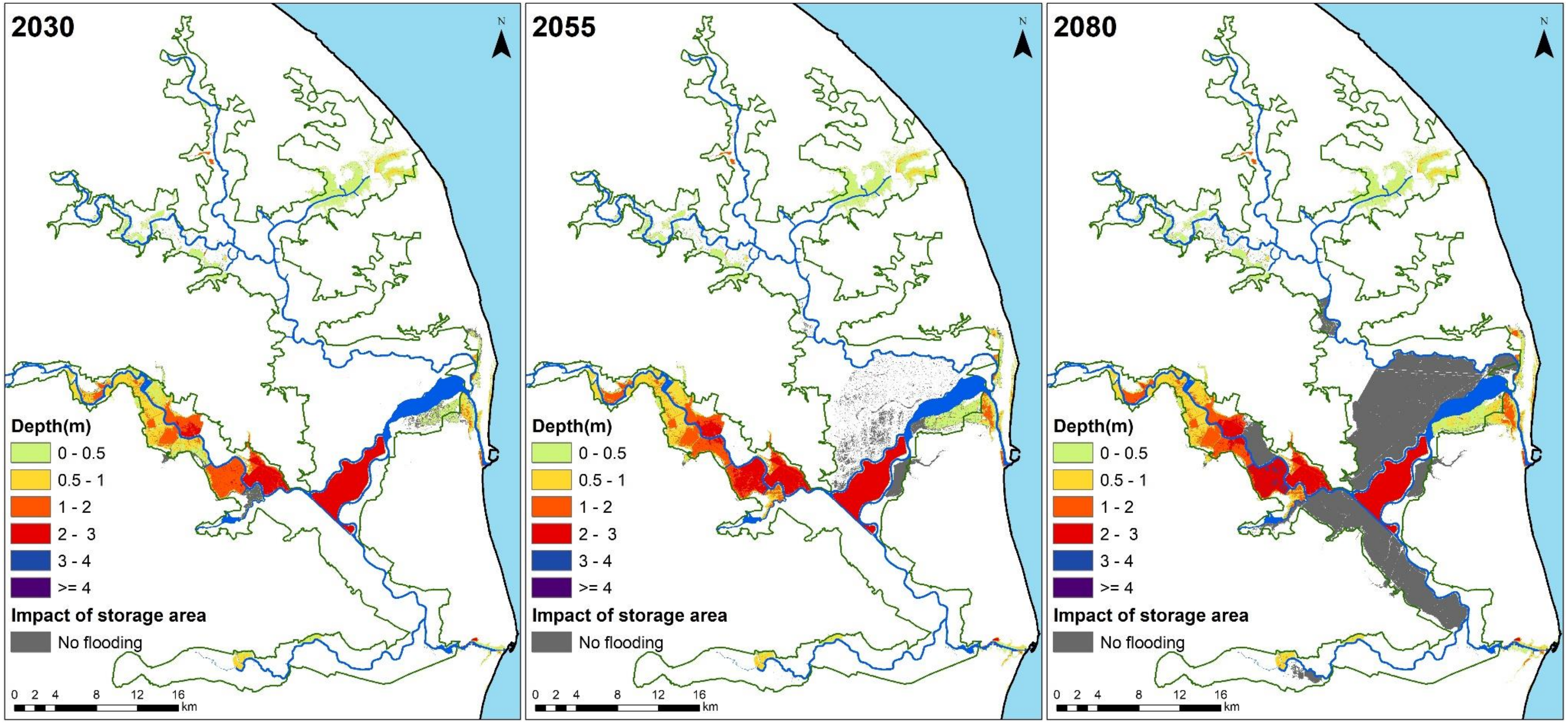


Figure 6.29 – Impact of setting up Haddiscoe Island as a flood storage area on inundation extent under RCP4.5 (50th) during a 1:100 extreme sea level event in 2030, 2055 and 2080. Grey areas represent zones that would otherwise flood under the same scenario and without the flood storage area.

The model results showed that while dedicating a large area of close to 8 km^2 to store water could have local advantages in protecting surrounding land, it could not on its own prevent flooding across the Broads. The model outputs show flooding continuing to occur in Great Yarmouth as well as undefended parts of the upper River Yare. While offline storage areas can be a metre to several metres deep (Environment Agency, 2015), a 3 m depth for a total storage volume of 5×10^7 m^3 would require not only a substantial engineering project to set up the area and dispose of material, but also extensive pumping operations to remove water after an extreme event. Further research is required to test the sensitivity of the adaptation scenario to the depth (and therefore volume) of the storage area.

As discussed in Chapter 5, stakeholders' primary concern with this adaptation measure was the compensation of landowners. During final feedback meetings, stakeholders (conservancies, farmers and catchment engineers) noted that the consideration of salinity in the hydraulic model was an important addition to support decision making on this measure. Due to its location near the coast and judging by the results of the salinity model, it can be expected that a storage area at Haddiscoe Island would primarily store saline water. Areas flooded with saline water as opposed to fresh water would indeed require a prompt pumping scheme following an extreme event to prevent long lasting damages to the land.

6.3.4.2. Tidal Barrier: Great Yarmouth

As opposed to the flood storage area, a tidal barrier at Haven Bridge in Great Yarmouth would successfully prevent flooding across the Broads during an extreme sea level event. Assuming that the barrier holds and operates as expected, it is able to prevent the tidal wave from the storm surge to spread into the Broads Rivers and raise river levels. Despite the interest it generated during the workshop, concerns about the barrier were raised by emergency planners and local officials as a response to model results. The simulated impact of the tidal barrier indeed showed that while it would be able to limit flooding in the Broads, it would also increase river levels in Great Yarmouth (Figure 6.30), a key population centre, and therefore require engineering works to raise flood walls in the coastal town. The river level downstream of the barrier were raised in 1:100 scenarios above the current level of defences for all RCPs. The River Yare level in 2080 reaches 3.65 maOD and 3.99 maOD for RCP4.5 (50^{th}) and RCP8.5 (95^{th}), respectively. Downstream river levels increase by 1.32 m, 1.40 m and 1.45 m in 2030, 2055 and 2080 respectively under RCP4.5 (50^{th}) due to the tidal barrier. The tidal barrier raises downstream river levels by 1.32 m, 1.41 m and 1.67 m in 2030, 2055 and 2080 respectively under RCP8.5 (95^{th}).

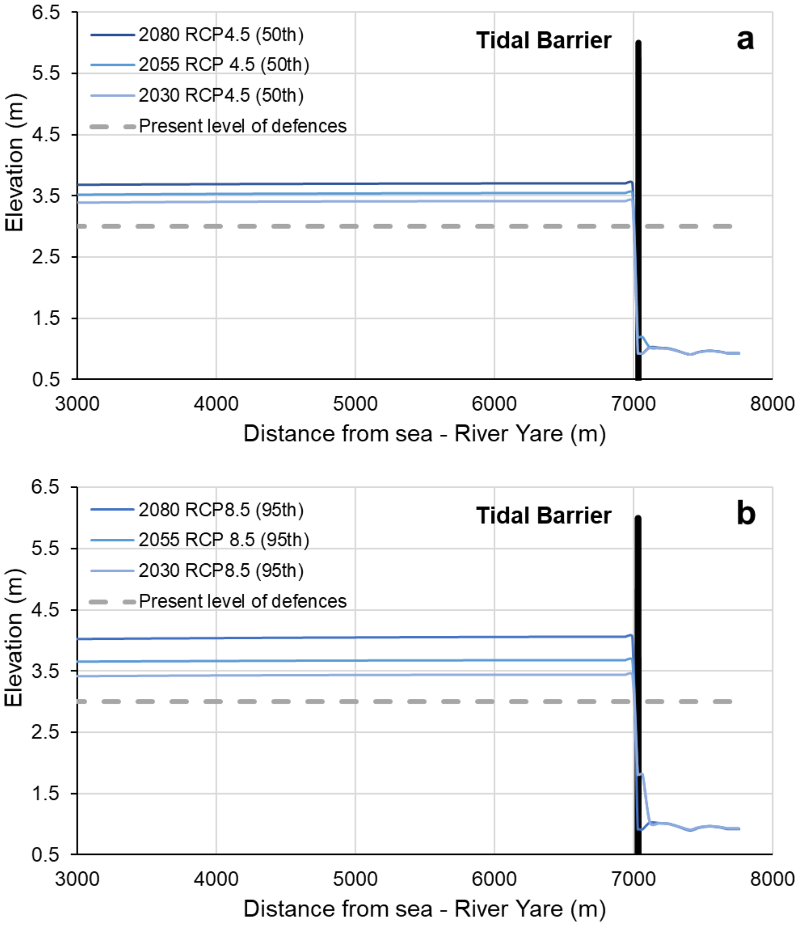


Figure 6.30 – Longitudinal profile of the River Yare in Great Yarmouth. The impact of the tidal barrier on downstream river levels are shown for the years 2030, 2055 and 2080 under **(a)** RCP4.5 (50th) and **(b)** RCP8.5 (95th).

As an important infrastructure, the cost of a tidal barrier has been its main deterring factor in the past in the Broads. The high-level review by CH2M estimated that the capital cost for the barrier could be in the order of “£50 - £55 million” as a high-end estimate, excluding any other defence raising works (CH2M, 2016). As a comparison, the Hull Barrier equivalent present-day capital cost over its first 10 years of operation was estimated at approximately £25 to £30 million. Some costs could be saved by the lower maintenance requirements of upstream embankments due to the protection provided by the barrier. Another benefit of the barrier would be its capacity to limit the impact of extreme events on river salinity, blocking off the Broads from the effects of a storm surge. At the same time, the high-level review found that an open vertical gate design would not have significant impacts on salinity distribution under normal tidal conditions (CH2M, 2016), which is important for the protection of salinity-dependent species in the Broads.

The economic analysis of flood damage is a common practice in the assessment of flooding impacts as well as to support the appraisal of adaptation options (e.g., Thorarinsdottir *et al.*, 2017). While a cost-benefit analysis is an important tool to make final decisions on flood mitigation, it fell outside of the scope of this research. The stakeholder feedback nonetheless showed that the model results provided insights into the implications of adaptation measures, which are useful in the early stages of the policy making process. Further work should look into the more specific economic impacts of other adaptation measures, including non-structural solutions.

The complexity of decision-making on adaptation can be accentuated by the presence of varied interests from stakeholders who may not have the same perceptions of future risk or uncertainty (Collet *et al.*, 2018). Refsgaard *et al*. (2013) argued that stakeholder dialogue and knowledge sharing can help reduce the impact of such ambiguities. The two modelled adaptation measures in this study were defined in a collaborative approach, representing stakeholder interests. The feedback on the model results showed an understanding among different stakeholders that the Broads' future adaptation strategy could not rely on a single measure. Stakeholders showed a willingness for action and to see a shift in FRM away from traditional measures (i.e. maintaining and raising flood defences). The main interest was still to rely on a protective approach to FRM, with the type of structural and engineering-based solutions that were modelled in this study. The stakeholder feedback on the model results however also brought up opposing perspectives interested in a shift towards softer adaptation measures and the restoration of the natural conditions of the highly engineered rivers in the Broads. Diverging expectations for the management of the Broads is an important hurdle for climate adaptation.

The expansion of the hydraulic model and its added consideration of salinity were choices made that were directly derived from stakeholder interests and helped to overcome some of these hurdles. These results provide a case for a flexible modelling stance and the inclusion of stakeholder knowledge to co-produce information that is more relevant for decision making (Landström *et al.*, 2011; Krueger *et al.*, 2012). The high-level review of flood management by CH2M (2016) moreover concluded that there was a need for “an integrated strategy, combining the strategies in place” on the coast from Eccles to Winterton, at Great Yarmouth and in the Broads to account for “all impacts” and “avoid incompatible approaches”. The 1D-2D modelling methodology combined to a salinity model presented in this study are compatible with this new outlook on FRM and should be considered for future assessments.

The study however also highlighted the limits to which scientific modelling alone can promote adaptation planning. Measures such as increasing flood storage or constructing tidal barriers can be successful in reducing flood hazard while coming at a cost for certain stakeholders. Stakeholder reiterated that a flood storage area would require a comprehensive compensation plan for landowners. On the other hand, local officials pointed out that a large infrastructure in Great Yarmouth would change the landscape and perhaps not be acceptable by local inhabitants. These implications represent another argument for the engagement of stakeholders in such studies as they should be carefully understood for adaptation to be possible.

6.4. Conclusion

While adaptation planning and FRM are often required to move forward within the scope of much uncertainty, an understanding of future environmental conditions can support decisions on a range of appropriate and effective actions. The newly released UKCP18 projections of temperature, precipitation and SLR were used in this research as the main input for the IA of future flood risk in the Broads. Following the bias correction of meteorological variables, the 12 members of the UKCP18 RCM PPE (derived from the HadGEM3-GC3.05) showed the Broadland Catchment was expected to experience wetter winters, drier summers and an overall increase in monthly temperatures throughout the 21st century. The modelling in HBV and subsequent EVA of extreme river discharge showed the hydrological response to this change: slightly decreasing annual river flows with more intense extremes.

Future flood risk was assessed by expanding the Broads HEC-RAS model to the full extent of the National Park's rivers and surrounding floodplains. Extreme sea level events were compared to extreme river discharge events as well as events combining both sources of flooding. Different projections of SLR under RCP2.6, RCP4.5 and RCP8.5, were also assessed to highlight the range of possible futures. The model results were consistent with those presented in Chapter 4 while providing more realistic scenarios, constrained by projections of SLR and a more detailed characterisation of hydrological conditions in river sub-catchments. The expansion of the model allowed for the identification of varying responses to extreme events throughout the study area. While extreme discharge events had a greater impact inland, they were overall considerably less important as a cause of flooding in the Broads compared to extreme sea level events. The latter represented a threat to Great Yarmouth and were also found to have a greater effect on flooding extent and depth on the River Yare and River Waveney floodplains than the northern parts of the Broads. In all scenarios, coastal flooding did not occur, although the breaching of defences was not modelled. As was found in Chapter 4, the combination of extreme river discharge to extreme sea levels exacerbated flooding, but this was most apparent again in the southern half of the Broads. Despite the unlikely occurrence of combined events in this region, these findings reinforce the need for an integrated approach to coastal and riverine flood management, as has been recognised by the Broads Authority (2019b).

Due to interests from stakeholders in its inter-linked relationship with flooding, river salinity was modelled as a conservative constituent in the HEC-RAS model. Although important factors driving salinity, such as groundwater sources and pumping activities, were omitted, the model showed that potentially dangerous levels of salinity (for freshwater species and farmland) could spread into the upstream parts of the Broads rivers. While SLR was shown to increase the upstream reach of salinity, a comparison with the December 2013 event suggested that the total volume of water coming into the system, as dictated by the shape of the storm surge in relation to the tide, remained a more important factor.

Finally, the modelling of stakeholder-defined adaptation options provided insight into their capacity to reduce flooding under extreme sea level scenarios. A flood storage area at Haddiscoe Island was able to reduce flooding locally but could not on its own completely eliminate the risk in flooding and had very limited effects on Great Yarmouth.

A tidal barrier River Yare, on the other hand, was able to hold back tidal surges from entering the Broads system but would increase downstream river levels during extreme sea level events. The assessment of the adaptation options benefited from the expansion of the model, as it was possible to capture the implications of their development on the rest of the Broads. Still, this represents only a first step in their evaluation, and it should be combined to more detailed and localised studies as well as cost analyses. The feedback from stakeholders showed that their engagement with modelling design choices and in the definition of adaptation scenarios had a positive effect on their ability to use the results to enhance their understanding of the problem at hand. Decision making on adaptation and FRM remains dependent of factors outside the scope of scientific modelling, such as the ability to reconcile diverging visions of the desired future for the Broads.

Chapter 7 – Summary and Conclusions

7.1. Key findings and contribution

As coastal regions increasingly face critical challenges brought on by a changing climate and SLR, there has been a growing need for integrated approaches to flood risk assessments. This research made use of advances in hydraulic modelling, as well as the latest regional projections of 21st-century climate and sea level, to help enhance our understanding of future flooding in the Broads National Park. With the aim to inform, and therefore support adaptation planning, an iterative approach to stakeholder input was adopted. The IA resulted not only provided substantive information on perceptions of hazard, exposure and vulnerability to help the analysis and management of risk, it also offered insights into the potentially beneficial role of stakeholder engagement within flood modelling studies.

While the Broads are primarily tidal, sources of flooding can be varied, and few studies had previously explored their potential interaction in the region. One of the first hydraulic models to be based on the recently released version 5 of the HEC-RAS software and 2 m resolution LiDAR data was developed and tested in **Chapter 4**. This new version allowed for the design of a 1D-2D model structure, which matched the framing of a catchment-to-coast approach as it allowed the detailed representation of coastal areas and coastal flooding, while covering a large inland system of rivers and their floodplains. The sensitivity of the Broads to a combination of fluvial, tidal and coastal sources of flooding was assessed under deterministic scenarios of SLR. Future flooding was found to be more extensively caused by extreme sea levels than extreme river discharge, but the combination of these events could exacerbate flooding extent and depth (Pasquier *et al.*, 2019).

Interactions with stakeholders were carried out early on and throughout the course of this project. The goal was less to get a representative set of opinions in the Broads, and more to identify key local perspectives on flood risk and adaptation. A wide range of stakeholders with interests in FRM and varied levels of influence in decision-making were included in, and allowed to shape, the modelling methodology. The central participatory activity was a stakeholder-scientist workshop, where preliminary model results were used to discuss future flooding risks as well as to define and prioritise adaptation options for the Broads. The results from the stakeholder engagement reported in **Chapter 5** highlighted key perceptions of risk and adaptation, which will be important to consider and can help frame future planning, such as through the ongoing Broadland Futures Initiative. The findings showed a shared recognition of the rising concern that flooding represents for the Broads, as well as a willingness to act on it. There was also a widespread perception that the current FRM strategy based on the maintenance and raising of flood defences was the least desirable option for the future (after no action) due to its decreasing economic feasibility. Preference was still given to protective measures, namely, flood storage areas and tidal barriers, over softer adaptation options (Pasquier *et al.*, 2020).

A significant output of this research was the demonstrated importance for stakeholders in the Broads to see the assessment of flood risk integrated with the issue of salinity. There was moreover a reiterated necessity expressed by stakeholders to look at different sources of flooding over the whole area covered by the Broads. These interests shaped the design of subsequent modelling choices and helped produce information that was closer to stakeholder expectations. The feedback from stakeholders supported the conclusion that such a collaborative approach made results derived from scientific models more relevant for planning. This supports a case for a flexible modelling stance, as opposed to the top-down approach traditionally employed in flood modelling.

Chapter 6 drew from the results of the previous two chapters to provide an assessment of future flood risks and stakeholder-defined adaptation measures in the Broads. UKCP18 projections of temperature and precipitation up to 2080 were bias corrected and used to force HBV rainfall-runoff models to estimate future daily discharge in the Broads sub-catchments. Drier summers and wetter winters are to be expected in the Broadland Catchment, putting further pressures on water resource management and FRM. Cascading uncertainties in the modelling chain represent a significant challenge for decision-making. Projections from 12 members of a PPE from the UKCP18's RCM were considered to take into account our limited knowledge of the climate system. SLR projections for different RCPs were used to create synthetic extreme level events. EVA and the POT method helped to estimate the probabilities of specific extreme events and the definition of hydraulic boundary conditions. An indirect method was used to determine the probabilities of extreme sea levels off the coast of East Anglia by estimating the joint probability of astronomical tide and non-tidal residuals.

Expanded to cover all of the Broads and its nearby coastline, the 1D-2D model structure helped to match stakeholder interests, to represent the inter-connected hazards and to identify key vulnerabilities. Tidal flooding can be expected to remain the main source of inundation while minimal coastal flooding impacted the study area in the simulations. Great Yarmouth was found to be impacted by flooding from a 1:100 event by 2030. A north-south divide was moreover made evident by the model results, with the Yare and Waveney experiencing more flooding than other rivers during extreme events under SLR scenarios up to 2080. The impact of flooding on grazing marshes, protected areas and arable land can be exacerbated by the salinity of overflowing waters. Although the model showed the potential for salinity to spread far upstream into the Broads system during extreme events, a more detailed analysis supported by additional data is still required to fully understand this process.

The interdisciplinary methods adopted in this research provided insights that can help identify, and therefore surpass, hurdles to the implementation of adaptation measures in future FRM strategies. Stakeholder-defined adaptation measures were modelled under extreme sea level events and SLR scenarios. The modelled flood storage area at Haddiscoe Island was able to reduce flooding in nearby floodplains, although it was not able to stop flooding downstream, in Great Yarmouth for example. Moreover, as the results of the salinity model showed, water stored in the dedicated area during a storm surge would be saline and would therefore have to be pumped quickly after the event to prevent long lasting damage to the land. As significant would be the need for a compensation plan for landowners. A tidal barrier in Great Yarmouth on the other hand was found to successfully prevent flooding in the Broads, while considerably increasing downstream river levels in the coast town and therefore requiring further investments in raising flood defences. Stakeholder feedback and scientific information complemented each other in this process and their interaction promoted the understanding of important conditions for success of individual adaptation measures. This research’s findings as well as the proposed integrated approach can contribute to future FRM in the Broads as well as in other coastal areas.

7.2. Replicability of the research methods and implications for other coastal areas

Coastal areas across the world face different hazards, under varying levels of vulnerability and exposure. This represents a challenge for the replicability of hydraulic model designs, which are highly dependent on local topography as well as existing physical or hydrological features. Assuming that sufficient data is available, the described modelling chain can nevertheless be applied to other regions and at different scales. Computational resources are a limiting factor in hydraulic models. Still, as was demonstrated in this research, models can be adapted to the required level of detail to match specific interests. The combination of 1D and 2D features can help improve the transferability of hydraulic modelling approaches by reducing computational requirements while increasing the range of processes represented.

Although this study was set mostly in a rural context, the increasing pressures that coastal cities face due to climate change and SLR is a growing concern. Densely-populated urban areas are potential hotspots for climate and coastal risks. Studies have shown that the added implementation of 2D models significantly improved results of hydraulic simulations in cities (Vojinovic & Tutulic, 2008; Timbadiya *et al.*, 2015). Models in larger cities may however require more detailed representations of urban infrastructures and drainage systems. In this case for example, 2D surface flow models can be coupled to a 1D sewer models (Leandro *et al.*, 2009).

Specific model choices moreover had to be made due to the studied-area's highly-engineered characteristics. Despite being a low-lying area, the Broads and its coastline are heavily drained and protected by flood defences, and only directly connected to the North Sea through the River Yare's relatively narrow channel. Many coastal regions around the world are made up of large estuaries and deltas, leading to more complex nearshore hydraulic properties. In such cases, a nearshore model taking into account the generation of waves and storm surges is necessary and can be coupled to surface flow models. Such work has been carried out for example in Bangladesh (Deb and Fereira, 2016) and China (Song *et al*., 2020).

Modelling is only part of the IA process, and the overarching methodology presented here can serve to inform similar approaches in other coastal regions. While there is a growing recognition for the need to engage stakeholders in flood risk assessments, few flood modelling studies integrate stakeholder knowledge in their designs. Stakeholder input played an important role in this research in identifying the specificities (and their implications) of the studied coastal region. Modelling methodologies that engage with stakeholder interests are therefore more likely to be robust and replicable. As was discussed in Chapter 5 however, stakeholder-scientist exchanges face hurdles such as stakeholder fatigue or resource requirements that can make them difficult to institutionalise (Löschner *et al.*, 2016). IAs are more likely to offer an added value in areas that face multiple pressures and have to manage trade-offs and cross-sectoral interests (Nicholls *et al.*, 2015). Finally, this research was set within the scope of FRM in the UK. Other studies focusing on developing countries (Spires *et al.*, 2014) have shown that the poor coordination between organisations responsible in implementing adaptation measures can present a major challenge to effective stakeholder engagement.

This study assessed stakeholder-derived adaptation options, namely a flood storage area and a tidal barrier. Universal solutions to flood risk however do not exist and adaptation strategies can also rely on national policies, funding schemes, and historical management legacies. Context-specific social, resource and physical barriers to adaptation can be significant (Moser and Ekstom, 2010). Tailored approaches to FRM and adaptation are therefore required to address these specificities. The overarching methodology presented in this thesis can nevertheless be recommended for a wide range of contexts. Small islands and low-lying deltas often face not only high flood risks but also geographical and socio-economic factors that may limit the range of available FRM options compared to the eastern coast of the UK. Still, an iterative and collaborative approach between scientists and practitioners can help to bridge gaps between coastal science and effective policy, engaging stakeholders that have interests in the long-term management of flood risks (Nicholls *et al.*, 2015). As such, the presented method can offer opportunities for collective learning and consensus-building, even in data-scarce regions.

7.3. Recommendations for future research

7.3.1. Technical opportunities

A number of developments can be carried out on the modelling of future flood risks in the Broads. More research is needed to understand future changes in wind, waves, and storm surges. Coupling storm surge models (e.g., Wu *et al.*, 2018b) with hydraulic models would help to assess how these changes affect flooding hazard. Simulating breaches (e.g., Villatoro *et al.*, 2014) of flood defences under extreme conditions can also be important to identify areas exposed to potentially catastrophic flooding. Erosion represents an added threat to the coastline and communities in Norfolk alongside flooding and the integrated analysis of these processes can support decision-making (Walkden *et al.*, 2015). While a basic salinity model was developed in this study, a more detailed analysis of saline incursion that includes the representation of groundwater and pumping is required. Most of the existing research on the question of salinity in the Broads has focused the Thurne catchment (Simpson *et al.*, 2011) and little attention has been given to other rivers.

The inputs to the presented hydraulic model can be improved in several ways. As one of the main drivers of results of flooding extent, developments in the accuracy and coverage of elevation data will continue to be important for hydraulic simulations. Projections of 21st century changes in temperature and precipitation were only considered under a high emission RCP8.5 scenario and for 12 members of a PPE of a single climate model. A better understanding of the range of potential futures and uncertainty would be obtained by including other RCPs as well as projections from an ensemble of GCMs. Land cover was assumed to remain constant in this work. Changes in land cover can however have significant repercussions on local hydrology, potentially increase flooding risks, and should therefore be considered in future work in the Broads.

7.3.2. Stakeholder engagement

Constraints in time and resources limited the number of participatory activities in this project as well as the number of stakeholders involved. Further assessments of flood risk would benefit from a larger set of stakeholders. Some interest groups, such as local businesses or members of the general public, were not represented in this study and would offer new perspectives. Collaborative flood modelling methods vary greatly are still a relatively new area of research. There remains many unknowns on their applicability and impact. An area of future research would be to expand on studies such as Landström *et al.* (2011) on the comparison of different modelling methods looking to coproduce knowledge on flood risk. Evers *et al.* (2016) also pointed out it remains unclear whether these techniques lead to changes in perceptions or attitudes towards adaptation. As flood maps are still the most popular tool to communicate on flooding issues, a growing field of study is exploring how their visualisation affects the perception of risk (Jude *et al.*, 2015). Online resources present opportunities to improve the communication of scientific results, for example on complex topics such as the representation of uncertainty.

7.3.3. Flooding impact and adaptation

The assessment of the consequences of future flooding in this research was mostly qualitative and did not include an economic analysis. Flood depths can be tied to a calculation of associated damage to obtain the monetary cost of flooding under different future scenarios (e.g., Wagenaar *et al*., 2019). This analysis is also necessary to perform a cost-benefit analysis of possible adaptation measures. As was discussed in this thesis, the valuation of assets and ecosystem services in the Broads can be a contentious issue (Turner *et al*., 2016) and should therefore consider diverging stakeholder perspectives.

Only two adaptation measures were simulated in this study, namely, a flood storage area and a tidal barrier. However, these measures can vary greatly in design, operation and scale. The developed hydraulic model could be adjusted to represent a wider range of options. Other more extensive changes to the model would allow the portrayal of other types of solutions. For example, a detailed representation of terrestrial and groundwater processes would allow the modelling of the improvement of drainage within the Broadland catchment. There was interest expressed in measures seeking to restore catchment processes that have been affected by human intervention. While Natural Flood Management approaches have gained momentum in recent years in the UK (Dadson *et al*., 2017), they have still received little attention in research in the Broads.

The opportunities listed above can not only guide future academic research, but also benefit the BFI project as the Broadland area enters a new phase of FRM.

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Appendices

Appendix 1 – Ethics Approval Form

University of East Anglia

Research and Innovation Services

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Ulysse Pasquier
School of Environmental Sciences

23rd April 2018

Dear Ulysse,

I am writing to you on behalf of the University of East Anglia's General Research Ethics Committee, in response to your request for ethical approval for your project '*Modelling future flood risk for coastal and inland adaptation planning: a case of the Broads'.*

Having considered the information that you have provided in your correspondence I am pleased to confirm that your project has been approved on behalf of the Committee.

You should let us know if there are any significant changes to the proposal which raise any further ethical issues.

Please let us have a brief final report to confirm the research has been completed.

Yours sincerely,

Victoria Hamilton

pp. Polly Harrison, Secretary
General Research Ethics Committee

Appendix 2 – NFRA river gauges

River sub-catchment	Gauge name	NRFA River Gauge
Waveney	Needham Mill	34006
Bure	Horstead Mill	34019
Ant	Honing Lock	34008
Yare	Costessey Mill	34004

Appendix 3.1 – List of 1:100 scenarios of extreme sea level

ID	Reference year for sea level rise	RCP	Percentile
1	2030	2.6	5th
2	2030	4.5	50th
3	2030	8.5	95th
4	2055	2.6	5th
5	2055	4.5	50th
6	2055	8.5	95th
7	2080	2.6	5th
8	2080	4.5	50th
9	2080	8.5	95th

Appendix 3.2– List of 1:100 scenarios of extreme river discharge

ID	Period	RCP	Percentile
10	2020-2080	8.5	5th
11	2020-2080	8.5	50th
12	2020-2080	8.5	95th

Appendix 3.3 – List of 1:10,000 scenarios combining a 1:100 extreme sea level event to a 1:100 extreme river discharge

ID	Reference year for sea level rise	RCP	Percentile (for both sea level rise and river discharge)
13	2030	8.5	95th
14	2055	8.5	95th
15	2080	8.5	95th

Appendix 4 – Pasquier *et al.* (2019)

Natural Hazards (2019) 98:915–937
https://doi.org/10.1007/s11069-018-3462-1

ORIGINAL PAPER

An integrated 1D–2D hydraulic modelling approach to assess the sensitivity of a coastal region to compound flooding hazard under climate change

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Abstract
Coastal regions are dynamic areas that often lie at the junction of different natural hazards. Extreme events such as storm surges and high precipitation are significant sources of concern for flood management. As climatic changes and sea-level rise put further pressure on these vulnerable systems, there is a need for a better understanding of the implications of compounding hazards. Recent computational advances in hydraulic modelling offer new opportunities to support decision-making and adaptation. Our research makes use of recently released features in the HEC-RAS version 5.0 software to develop an integrated 1D–2D hydrodynamic model. Using extreme value analysis with the Peaks-Over-Threshold method to define extreme scenarios, the model was applied to the eastern coast of the UK. The sensitivity of the protected wetland known as the Broads to a combination of fluvial, tidal and coastal sources of flooding was assessed, accounting for different rates of twenty-first century sea-level rise up to the year 2100. The 1D–2D approach led to a more detailed representation of inundation in coastal urban areas, while allowing for interactions with more fluvially dominated inland areas to be captured. While flooding was primarily driven by increased sea levels, combined events exacerbated flooded area by 5–40% and average depth by 10–32%, affecting different locations depending on the scenario. The results emphasise the importance of catchment-scale strategies that account for potentially interacting sources of flooding.

Keywords Flooding · Hydraulic modelling · Storm surge · Sea-level rise · Compound hazard · Extreme value analysis

1 Introduction

1.1 Flooding hazard in a changing climate

Floods are significant and regular threats to a great number of people worldwide. In Europe, flooding represents the most costly natural hazard (Whitfield 2012) with damages on the rise as population grows in flood-prone areas (Barredo 2009) and human activities

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Extended author information available on the last page of the article lead to land-cover changes (He et al. 2013). Recent severe disruptions in the UK during the 2013/2014 and 2015/2016 winters were reminders of the devastating potential of such extreme floods. While there is still much uncertainty in attributing a climate signal to a possible trend in extreme events (Wilby et al. 2008), climate models suggest that climate change could lead to more frequent and intense precipitation in certain regions (Wang et al. 2017), thereby increasing flood hazard. On the other hand—as the Intergovernmental Panel on Climate Change (IPCC) reported (Church et al. 2013)—there is a high level of confidence that sea levels will continue to rise throughout and beyond the next century. Moreover, changes in mean sea level (MSL) are fundamental drivers for extreme sea levels (Menéndez and Woodworth 2010), thereby putting further pressure on coastal regions. While the development of flood defences and forecasting has prevented a significant increase in coastal flooding (Stevens et al. 2016), these trends highlight the need for better preparedness and an improved understanding of future hazards.

Coastal environments are vulnerable systems that can act as the interface for different hazards. Groundwater, pluvial (surface water), fluvial (river), tidal and coastal sources of flooding can all exist in areas near the sea, which also often host dense population centres. As presented by Wong et al. (2014) there is ample research on the risks coastal regions face and therefore the importance of adaptive measures. More recently, increasing attention has been dedicated to compounding extreme events (e.g. Kew et al. 2013; van den Hurk et al. 2015). Coinciding hazards, such as storm surges and precipitation, can lead to impacts that would otherwise not have been observed had they occurred separately and can therefore have significant implications for flooding risk. A number of studies have looked to determine the dependence between these hydrological extremes (e.g. Zheng et al. 2014), including in the UK (Svensson and Jones 2002). While a significant dependence is not always found (Klerk et al. 2015), it remains highly uncertain how the climate will influence this relation in the future. Wahl et al. (2015) for example, observed in the USA a change towards storms surges that also promote high rainfall. The threat of combined events from different origins underlines the importance of adopting a holistic stance in assessing flood hazard.

1.2 Integrated flood modelling

There has been in recent decades a paradigm shift towards a broader catchment-scale approach for flood risk management in Europe, as demonstrated by the European Union's Water Framework Directive (2000) and Floods Directive (2007). Integrated strategies that identify synergies at the river basin level, notably between rural and urban areas, have gained increasing support (Rouillard et al. 2015). Isolated actions to mitigate flooding run the risk of leading to unwanted outcomes. For example, a flood alleviation measure taken at a location in a catchment can have downstream impacts that should be taken into account. An integrated approach is moreover justified when sources of flooding are varied, originate from different hydrological processes and interact with each other. The lack of adequate information on these interactions remains an important hurdle for decision-making.

There is a need for modelling methods to follow the above trends to be able to provide information required for planning. Hydrodynamic models solve equations of fluid motion to replicate the movement of water and are widely used to assess flooding risk. The simplest and most common practice is to use one-dimensional (1D) models that treat flow one-dimensionally along the river channel. This assumption is appropriate in many situations but may not be suitable for flood mapping in areas where flow is expected to spread, such as in wide floodplains (Néelz and Pender 2009). Alternatively, while two-dimensional (2D) models can provide more detailed results and have gained in popularity, they remain computationally and data intensive and therefore difficult to apply to large areas. Recent advances and software developments offer new opportunities to help meet the goals of integrated approaches by allowing for linkages between 1D and 2D models (Teng et al. 2017). Coupled 1D–2D models can dynamically represent coastal, urban, river and floodplains interactions and are therefore well suited to assess the impact of flooding from different sources. While—as was shown in the previous section—there has been an increasing number of studies looking at the impact of combined events on flooding, 1D–2D hydraulic models remain relatively new tools in this field that are subject to more investigation (Webster et al. 2014).

This paper aims to present a modelling methodology to assess the sensitivity of a coastal area to the combination of fluvial, tidal and coastal sources of flooding. The fitness for use of an integrated 1D–2D hydraulic modelling approach is to be evaluated in the context of the Broads National Park in the UK. The aim of this study is to provide a modelling framework for simulating compound modelling scenarios. In this study, we are not providing a comprehensive probabilistic flood risk assessment framework. Finally, an aim of the modelling design is to understand the implications of portraying interacting sources of flooding from opposite ends of a river sub-catchment.

2 Study area: the Broads, UK

Located on the eastern coast of England, the Norfolk and Suffolk Broads is Britain's largest designated wetland. The network of rivers and shallow lakes—or "broads"—covers a total area of 303 km^2 at the downstream end of the 3200 km^2 Broadland Rivers Catchment (Fig. 1). The low-lying national park holds importance for natural conservation, navigation, recreation and tourism, as well as for its cultural features. Land use is mostly shared between coastal and floodplain grazing marshes, fens and arable land. The Broads are bounded by several urban centres, namely, Norwich, Lowestoft and Great Yarmouth, where the River Yare flows into the North Sea.

The Broads Authority was established in 1988 to coordinate the management of land and water in the Broads because of its special landscape. While offering many economic and environmental opportunities, water also presents considerable risks. The Broads have a long history of flooding driven by its low elevation and proximity to the sea. The 1953 storm had severe impacts in East Anglia, as it did throughout much of the North Sea coasts. The event led to significant investments in flood protection and forecasting. Most recently, the Broads Flood Alleviation Project has been responsible for the improvement and maintenance of the 240 km of flood defences that exist in the Broads. The scheme has been successful in limiting inundation, and defences coped well during the largest storm surge since 1953 in December 2013. As climatic conditions change and sea level rises, the Broads are however anticipated to face further pressures and there remains uncertainty over the best strategic line to follow to manage flood risk.

Flood management in the Broads is a challenging task due to the area's complex hydrology and range of potential flooding sources. In the context of the Broads, coastal flooding—or the ingress of water inland directly from the sea—is differentiated from tidal flooding, caused by the propagation of the tidal wave upriver. Although coastal flooding can have devastating consequences (Wu et al. 2015), tidal flooding is still the main concern

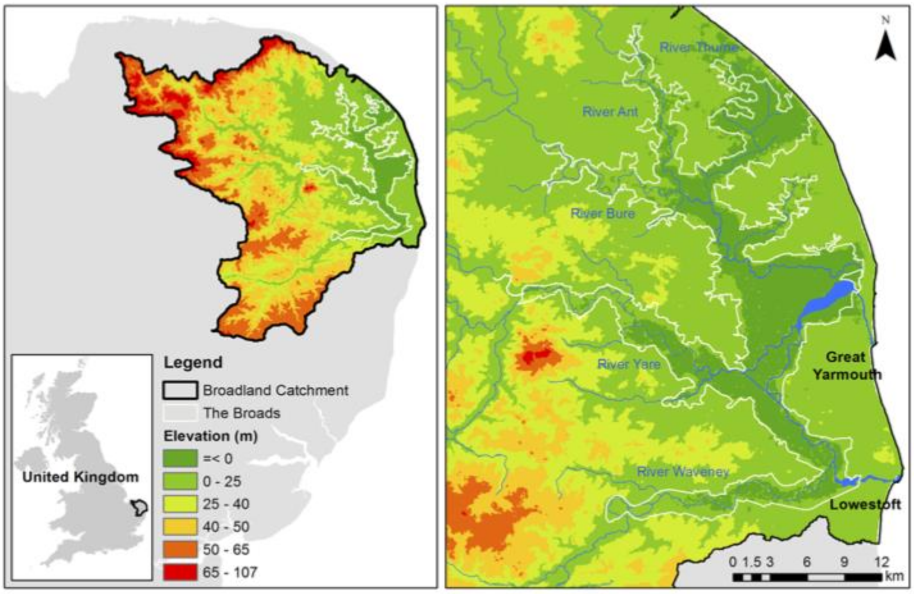

Fig. 1 The Broads National Park is part of the Broadland River Catchment in eastern England. The majority of the area within the Broads' administrative boundaries lies below sea level

in many parts of the Broads as low gradients along the key rivers allow the tidal influence to travel throughout much of the area. Major floods have also occurred due to heavy rainfall, for example in 1959 and 1968. Past studies in the catchment have found that fluvial floods and surge events occurred independently (Mantz and Wakeling 1979). There remains however a risk of combined river and tidal flooding in the Broads. Extreme sea levels can indeed coincide with high river flows or prevent proper drainage to cause flooding, for example on the River Bure (Environment Agency 2009). While they can exacerbate the impact of inundation, little research has focused on combined events and how they could affect the Broads in the future with projections of climate change and sea-level rise (SLR).

3 Data and methods

3.1 Environmental conditions

3.1.1 Sea level

Tide gauge data of sea level between 1964 and 2015 were obtained from the British Oceanographic Data Centre. The observations were made in Lowestoft (52°28′23.0556″N, 1°45′0.81″E), approximately 10 km south of Great Yarmouth. The east coast of England experiences a semidiurnal tidal regime. Chart datum at Lowestoft is located 1.50 m below ordnance datum (OD, at Newlyn). Sea level was recorded every 60 min prior to 1992 and every 15 min after 1992, with fewer than 3% missing data in the whole dataset.

A critical driver for flood hazard in coastal areas is peak sea level during extreme events that may occur, for instance, when a large storm surge coincides with high spring tide. The historical sea level data at Lowestoft were analysed with extreme value statistics to determine the probability of occurrence of extreme sea levels. Block maxima and Peaks Over Threshold (POT) are the primary approaches for extreme value analysis (EVA), and both have been used in the past to analyse sea levels (Webster et al. 2014; Haigh et al. 2016). POT however allows for more control over which events are included in the extreme value distribution and has been found to perform better than the more traditional Block Maxima method in previous flood frequency studies (Arns et al. 2013, Bezak et al. 2014). An average of 1.92 extreme values per year were thereby extracted that exceeded a level of 1.90 m above ordnance datum (maOD), corresponding to the 99.7th percentile of high tide peak sea levels (Fig. 2).

Due to the thermal expansion of water, melting glaciers and vertical land movement, relative sea level has been rising at Lowestoft at a rate of 2.70 ± 0.40 mm a^{-1} in the second half of the twentieth century (Wahl et al. 2013). A simple additive method was used to detrend the data and remove yearly changes in MSL with 2015 serving as the reference year. Moreover, the chosen peaks were declustered using a 48-h window to ensure only independent events were retained. A Generalised Pareto (GP) distribution was fitted to the remaining sea levels to determine return periods relative to the year 2015. The GP distribution has the distribution function

$$F(x) = 1 - \left(1 - \frac{kx}{\alpha}\right)^{1/k} \tag{1}$$

where the distribution's parameters α, the scale parameter, and k, the shape parameter, are determined with the maximum likelihood estimation method. The fit of the distribution was evaluated with plotting positions using the Gringorten formula, which is widely recognised for GP distributions (Chen and Sign 2017).

3.1.2 River discharge

Daily mean river flow data at Horstead Mill (52°43′25.8672″N, 1°21′14.8745″E) on the River Bure between 1974 and 2015 were obtained from the National River Flow Archive. In the same way that sea levels were analysed, the POT method was used to determine the probability of extreme discharge. The GP distribution provided a better fit than a generalised extreme value distribution, which was tested using annual maxima of river flow. The mean residual life plot, an exploratory technique described by Saeed Far and Abd. Wahab (2016), here helped identify an appropriate threshold. An average of 2.20 extreme values

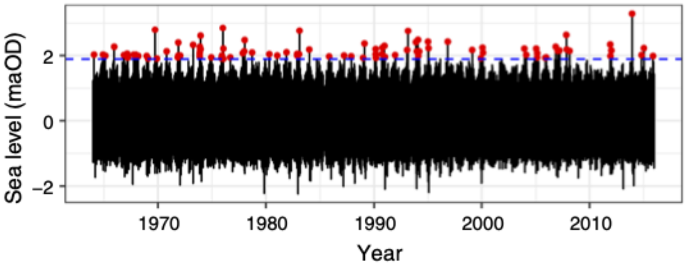

Fig. 2 Sea level relative to ordnance datum at Lowestoft, UK between 1964 and 2015. Red points represent sea level peaks above a defined threshold (blue, dashed horizontal line) chosen to fit a Generalised Pareto distribution and derive extreme return levels

per year were extracted that exceeded a level of 6.83 $m^3\ s^{-1}$, corresponding to the 99th percentile of river discharge levels (Fig. 3). An extreme value of 30.80 $m^3\ s^{-1}$ in 1981 particularly stood out from other peaks corresponding to an event that saw approximately 70 mm of rainfall in Norfolk between 25 April 1981 and 27 April 1981.

3.2 Hydrodynamic model: HEC-RAS

3.2.1 Model structure and domain

A 1D–2D hydraulic model was developed with the HEC-RAS software to map flooding extent and depth under different extreme scenarios. HEC-RAS is a free modelling tool developed by the United States Army Corps of Engineers (USACE). Among its many applications, the software is well tested for flood mapping in both coastal (e.g. Ray et al. 2011) and fluvial (e.g. Javaheri and Babbar-Sebens 2014) environments as well as to assess the impacts of climate change (e.g. Shrestha and Lohpainsankrit 2016). Previously limited to 1D models, a new version of HEC-RAS (version 5.0) was released in 2016 allowing for full 2D modelling and linkages between 1D and 2D features. While other tools such as Flood Modeller, developed by CH2 M, or MIKE FLOOD, developed by the Danish Hydraulic Institute (DHI), also offer the possibility to combine 1D and 2D models, HEC-RAS is the non-commercial software that has not previously been applied to the Broads. Moreover, although the new 2D capabilities of HEC-RAS offer opportunities for flood mapping, the model still requires testing for different applications (Vozinaki et al. 2017). The new HEC-RAS version was used, for example, by Quiroga et al. (2016) and Patel et al. (2017) to simulate past fluvial floods. Due to its recent release however, few studies are yet to apply HEC-RAS version 5 in coastal regions.

The Broads is a hydrologically complex and highly engineered area. The main rivers that make up the wetland—namely, the River Bure, River Yare and River Waveney—are narrow and constrained by high levees. These defences protect over 21,000 ha in the Broads and over 1700 properties. In many parts of the Broads, the flood banks are significantly higher than the wide floodplains they protect. Much of the Broads floodplain has a low elevation gradient and lies below sea level. A failure in the defences can therefore lead to widespread flooding. An accurate representation of the study area’s elevation is a fundamental requirement in hydraulic modelling. A composited digital terrain model (DTM) derived from light detection and ranging (LIDAR) data was obtained from the Environment Agency. The DTM had a resolution of 2 m by 2 m with a vertical accuracy

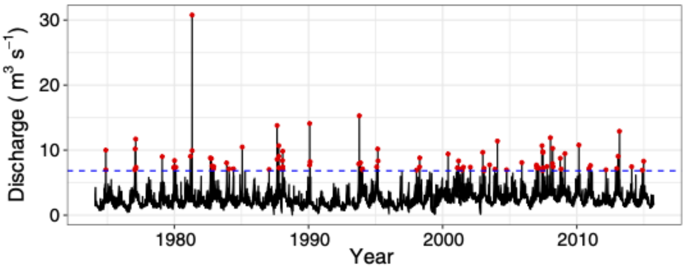

Fig. 3 River discharge at Horstead Mill between 1974 and 2015. The points represent discharge peaks above a defined threshold (blue, dashed horizontal line) chosen to fit a Generalised Pareto distribution and derive extreme return levels

of ± 5 cm and provided a good coverage of the study area. River bathymetry is also an important input to the hydraulic model. As LIDAR data are poor at representing underwater elevations, river surveys from the Broads Authority conducted between 2011 and 2015 were used to correct the DTM within river channels. Moreover, information from the Environment Agency on flood defences in the area ensured that the latest levee heights were included in the DTM.

The 1D–2D hydraulic model shown in Fig. 4 was built in HEC-GeoRAS, the ArcGIS extension for HEC-RAS. Cross sections of the river channels were drawn approximately every 30–50 m from one river bank to the other, forming the model's main 1D feature. A common method for out-of-bank flood modelling and mapping is to extend the model's cross sections into the floodplain. This technique is however not suitable for flood mapping in wide floodplains, which are common throughout the Broads. Instead, the floodplain is represented as a series of flood cells, called storage areas in HEC-RAS, where water can spill into from the rivers. The storage areas are separated by high ground and connected to the river cross sections in the HEC-RAS model with lateral structures, in this case, the

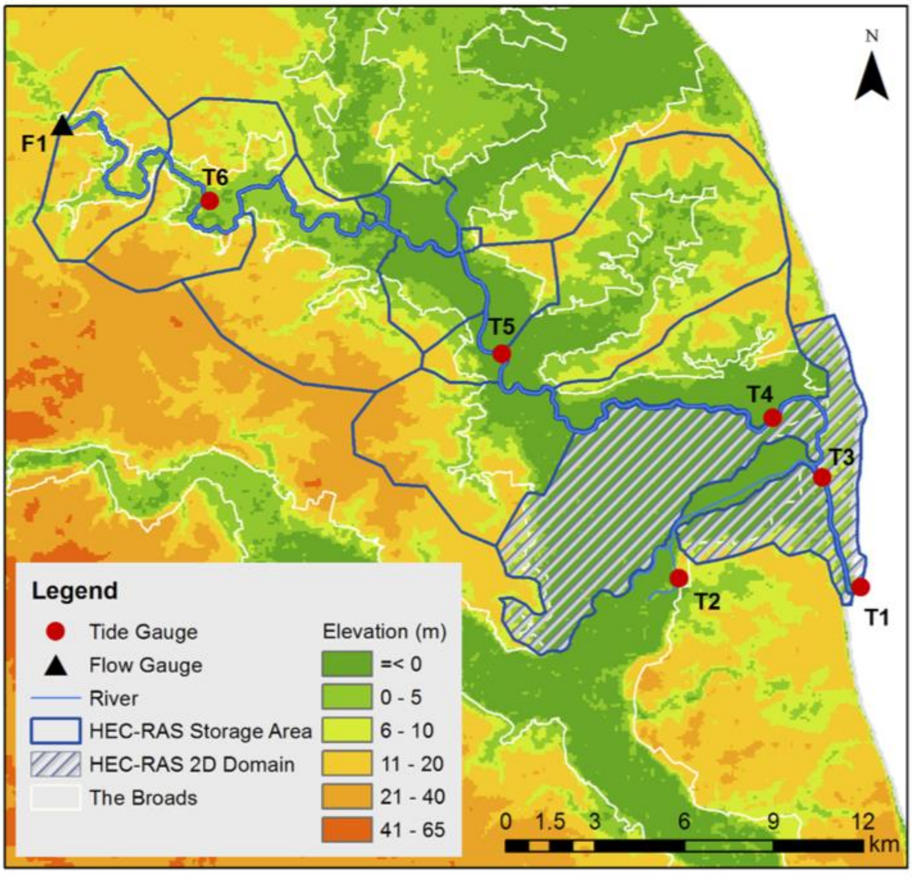

Fig. 4 HEC-RAS model domain. Storage areas and 2D areas are used to represent overbank flow in upstream and downstream portions of the model domain, respectively. Observations of river levels and discharge are available at different gauges: F1 (Horstead Mill), T1 (Great Yarmouth), T2 (Burgh Castle), T3 (Haven Bridge), T4 (Three Mile House), T5 (Acle Bridge) and T6 (Hoveton Broad)

flood defences on both sides of the rivers. Water will flow into the storage areas if the river level surpasses the corresponding height of the flood defence. Storage areas are 1D features represented using a volume-elevation table calculated with the DTM data and can provide satisfactory accounts of floodplain flow with little computational demands. More detail is however required in urban areas and where flow is likely to spread significantly as is the case at the downstream end of the study area. 2D flexible meshes were therefore set up and dynamically linked to the river cross sections in Great Yarmouth and the large low-lying area called the Halvergate Marshes. The mesh size varied between 10 m and 50 m and aligned to capture high ground features such as flood defences, roads, and railway tracks. A 2D domain is appropriate at the coast as it has the added benefit of being capable of portraying flooding occurring directly from the sea—in case of the overtopping of defences (coastal flooding)—and how it may interact with other sources of flooding.

The hydraulic model covers a 260 km area from the mouth of the River Yare in Great Yarmouth to Horstead Mill, approximately 40 km upstream on the River Bure. Portions of the River Bure’s tributaries—namely the River Ant and the River Thurne—are also included. The location of a flow gauge at Horstead Mill was chosen for the upstream boundary of the model. As a predominantly tidally influenced area, gauges in the Broads primarily measure river levels, and their locations are presented in Fig. 4. Land-cover data were obtained from the EDINA Environment Digimap Service as supplied by the Centre for Ecology and Hydrology (CEH) for the year 2015 (Fig. 5). The original classification was simplified to represent the main land uses across the HEC-RAS 2D areas. The large floodplains of the Broads consist first and foremost of grassland and grazing marshes. Land used for arable crops and horticulture tends to be located on the higher ground and make up most of the rest of the area. The most significant urban area is Great Yarmouth on both sides of the River Yare.

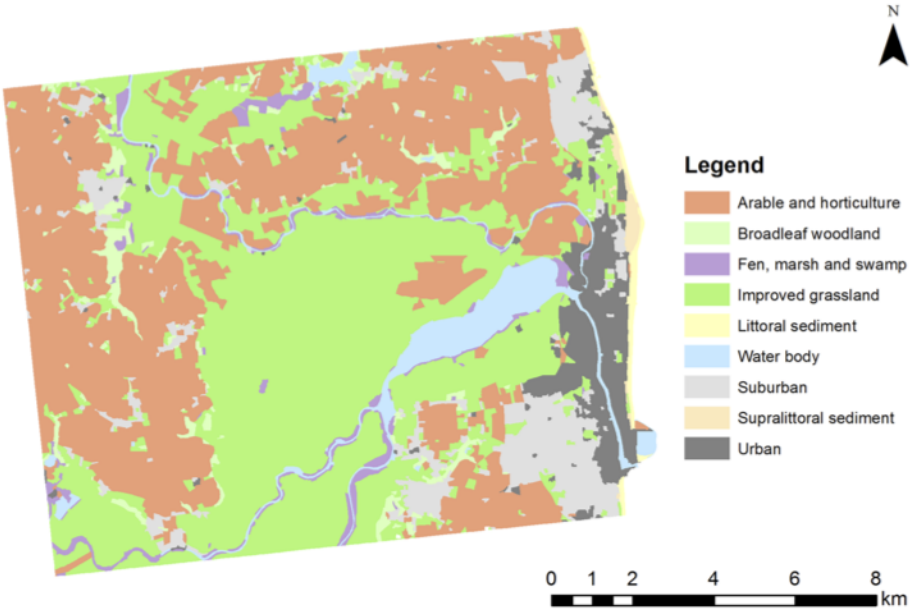

Fig. 5 Land-cover map of the downstream end of the Broads near Great Yarmouth in 2015 (Data obtained from EDINA Environment Digimap Services)

3.2.2 Unsteady flow analysis

Flood events were simulated in HEC-RAS under unsteady flow conditions. The HEC-RAS model solves the full Saint-Venant equations for the conservation of mass and momentum:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{2}$$

$$\frac{\partial u}{\partial t} + \frac{\partial}{\partial x}\left(\frac{u^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{uv}{h}\right) = -\frac{n^2 ug\sqrt{u^2+v^2}}{h^2} - gh\frac{\partial \zeta}{\partial x} + uf + \frac{\partial}{\rho \partial x}\left(h\tau_{xx}\right) + \frac{\partial}{\rho \partial y}\left(h\tau_{xy}\right) \tag{3}$$

$$\frac{\partial v}{\partial t} + \frac{\partial}{\partial x}\left(\frac{v^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{uv}{h}\right) = -\frac{n^2 vg\sqrt{u^2+v^2}}{h^2} - gh\frac{\partial \zeta}{\partial y} + vf + \frac{\partial}{\rho \partial y}\left(h\tau_{yy}\right) + \frac{\partial}{\rho \partial x}\left(h\tau_{xy}\right) \tag{4}$$

where h is the water depth (m), u and v are the specific flow in the x and y directions ($\mathrm{m}^2\ \mathrm{s}^{-1}$), ζ is the surface elevation (m), g is the gravitational acceleration ($\mathrm{m\ s}^{-2}$), n is the Manning's resistance, ρ is the water density ($\mathrm{kg\ m}^{-3}$), f is the Coriolis parameter and τ_{xx}, τ_{xy} and τ_{yy} are the components of the effective shear stress (Quiroga et al. 2016). While HEC-RAS offers the option of solving the diffusion-wave approximation of the equations in two dimensions, this method cannot be used for the propagation of waves in tidally influenced conditions. The full momentum equations were therefore chosen. A computational time step of 10 s was selected based on the guidelines proposed by the Courant–Friedrichs–Lewy condition:

$$C = \frac{V\Delta T}{\Delta x} \leq 1 \quad \text{Or} \quad \Delta T \leq \frac{\Delta x}{V} (\text{with } C = 1.0) \tag{5}$$

where C is the Courant Number, V is the flood wave velocity ($\mathrm{m\ s}^{-1}$), ΔT is the computational time step (s) and Δx is the average cell size (m). The performance of the model was tested with the Nash–Sutcliffe Efficiency (NSE) coefficient defined as:

$$1 - \frac{\sum_{t=1}^{n}\left(Q_m^t - Q_o^t\right)^2}{\sum_{t=1}^{n}\left(Q_o^t - \overline{Q_o}\right)^2} \tag{6}$$

where Q_o^t are observations at time t and Q_m^t are modelled values.

The HEC-RAS model boundary conditions consisted of a stage hydrograph downstream and a flow hydrograph upstream. The observed sea level can be considered as the sum of MSL, an astronomical tide component and a non-tidal residual (Pugh 1996). The tidal component is the response of sea level to astronomical forces such as the relative position of the moon and the sun, and can be isolated with a harmonic analysis of sea levels. What remains when the MSL is also removed is termed the non-tidal residual and primarily represents the meteorological impact on sea level from a surge.

An average storm surge shape was determined by identifying the 20 highest storm surges since 1964 at Lowestoft (Fig. 6a). Ideally, local storm surge models can be used to reconstruct more physically realistic conditions in the definition of synthetic events (e.g. Villatoro et al. 2014). The chosen method of generalisation was however described by the Environment Agency (McMillan et al. 2011) as providing a reasonable means to derive a design surge profile. Although the averaging leads to a smoothed profile, the resulting

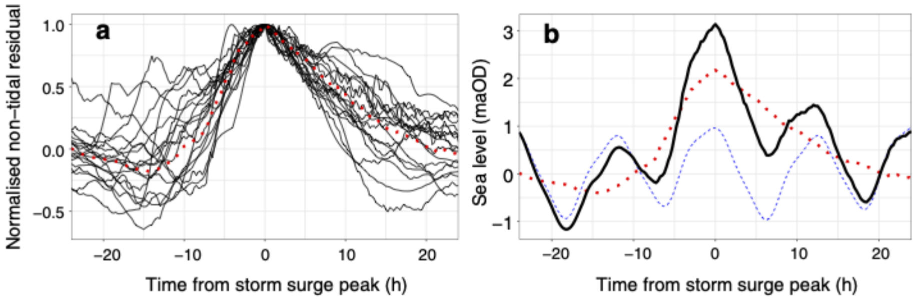

Fig. 6 **a** Average surge shape (red, dotted) estimated from the 20 largest surges at Lowestoft between 1964 and 2015. **b** Synthetic total sea level (black) derived from the surge residual (red, dotted) and the combination of a base astronomical tide) and the 2015 mean sea level (blue, dashed)

storm surge shape is similar to the rest of the sample (Fig. 6a) and can be considered representative of historical events. Moreover, by choosing the non-tidal residuals and not total sea level peaks to determine an average storm surge shape, large storm surges that may have occurred during low tide are also taken into account. An extreme sea level event stage hydrograph for a target maximum level can thereby be recreated using this average surge shape, a base tidal prediction and MSL (Fig. 6b).

The skew surge is the difference between the predicted astronomical high tide and the nearest experienced high water. Since meteorological processes are independent of tidal forces, a surge can occur at any stage of the tide. Other studies have performed a joint probability analysis to form a probability distribution of total sea levels from the distribution of skew surges and peak tide levels (McMillan et al. 2011). The assumption was made here that the storm surge peak coincided with the mean high predicted tide. This method, also used by Webster et al. (2014), was justified by analysing past extreme storm surge events that led to flooding concerns in the study area, which tended to occur at or near high tide.

An analogous method was applied to create synthetic flow hydrographs. The hydrograph shape of the last 20 most important storms in terms of flow at Horstead Mill on the River Bure was analysed to produce an average event shape. Due to limited data availability, upstream boundaries at the River Yare and internal boundaries at the tributaries of the River Bure were assumed to be proportional to the discharge rate at Horstead Mill based on their relative drainage areas. This is a common method used for ungauged catchments (Webster et al. 2014) that assumes similar hydrogeological characteristics. Drainage areas were determined in ArcGIS using 30 m by 30 m resolution Shuttle Radar Topography Mission (SRTM) data (Table 1). Initial conditions for both stage and discharge are taken directly from the boundary data.

4 Results and discussion

4.1 EVA and scenario definition

Exploratory semi-structured interviews were conducted with a set of 11 stakeholders to identify priorities, interests and to help base the definition of scenarios on local knowledge. Stakeholders were chosen from professionals with extended knowledge of the Broads, and

Table 1 Drainage area of upstream and internal boundaries for the HEC-RAS model used to estimate flow hydrographs relative to the River Bure

River	Drainage area at model boundary (km^2)
Bure	336.54
Ant	145.24
Thurne	119.35
Spix	59.94
Yare	1392.57
Waveney	891.43

active residents with a long-lasting interest in the area's overall management. Specific experience in flood management varied greatly as participants covered a wide range of sectors such as farming, angling, environmental protection, engineering and coastal management. The interviews confirmed the importance of tidal and coastal sources of flooding in the Broads and highlighted vulnerable locations such as—but not limited to—Great Yarmouth or several protected areas. One of the main recurring statements emphasised in the interviews was a concern for the risk of combined events. More specifically, the occurrence of a storm surge during high river discharge was identified as a worry for different stakeholders. Although the small sample of participants does not allow for statistically significant conclusions, this information was used to guide modelling choices and define future scenarios.

A comparison of the available data on past peak sea levels, non-tidal residuals and discharge shows that these events do not tend to occur simultaneously (Fig. 7). However, Fig. 7 also shows that it is physically possible for the peak of the storm surge to occur during a high discharge event and therefore near peak flow.

The EVA served to find return levels of both extreme sea level and extreme discharge to define representative downstream and upstream boundary conditions, respectively. The purpose of the EVA was not to provide a robust probabilistic assessment of flooding risk from different or combining sources. Without an analysis of the probability of joint occurrence of high tide and extreme storm surge, it was not possible to assign return levels to entire extreme sea level events. The EVA performed on total sea levels however did provide return levels for the peak of recreated extreme events.

The GP distribution performed relatively well to describe both extreme sea level (Fig. 8a) and extreme discharge (Fig. 8b). It should be noted that the most extreme values were found above the fitted distribution curves. These events corresponded to the December 2013 storm surge and a peak river flow in April 1981. Both occurrences were

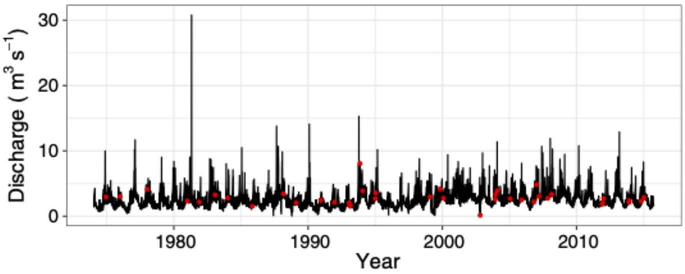

Fig. 7 The timing of the 40 highest non-tidal residuals (red points) decomposed from sea level data at Lowestoft, UK compared to river discharge at Horstead Mill between 1974 and 2015

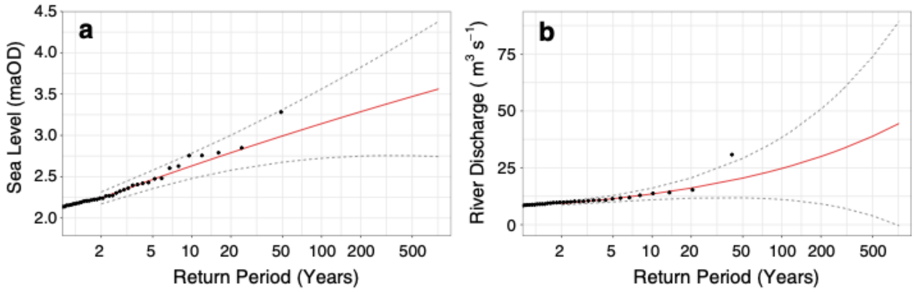

Fig. 8 Return levels at the reference year 2015 for **a** sea level at Lowestoft, UK expressed in relation to ordnance datum and **b** river discharge at Horstead Mill. The dashed lines represent the 95% confidence intervals

verified using data from other nearby gauges, and it was therefore decided not to discard them as recording errors. These points were by far the most extreme observations and did not provide strong evidence against the choice of the GP distribution function compared to other tested distribution functions. The lack of data is a common issue in EVA. More investigation using other sources of data (such as news reports if they exist) that extend past the recorded data period would allow for more confidence in this estimation.

Evidence suggests that changes in MSL are the primary factor leading to an increase in extremes sea levels (Menéndez and Woodworth 2010). Relative MSL (RMSL) is not only rising, but has also been found to accelerate at various rates around the world, with a trend of 4.4 ± 1.1 mm a^{-1} estimated at Lowestoft from 1993 to 2011 by Wahl et al. (2013). It indeed remains highly uncertain how climate change will impact local storm surge patterns. A linear increase in RMSL was assumed to determine future conditions and return levels up to the year 2100. Uncertainty moreover resides in current projections of the rate of SLR in the twenty-first century. Pfeffer et al. (2008) found that accelerated sea-level rise between 0.8 m and 2 m up to 2100 was physically plausible depending on glaciological conditions. To account for such possibilities, extreme scenarios of 1 m and 2 m MSL rise by 2100 were also considered.

While seasonal precipitation changes are expected in the UK, notably with an increased proportion of heavy precipitation events occurring during winter months, current projections do not show significant changes in annual precipitation in East Anglia (Jenkins 2009). Moreover, little is known on the intensity of extreme precipitation events in coming decades and therefore which trajectory river discharge will also follow. Patterns of extreme river discharge were therefore assumed to the same up to 2100 as in 2015 in the presented scenarios. This assumption is moreover warranted by the much greater influence of tidal processes in the Broads.

The chosen scenarios are presented in Table 2. They included three scenarios of 100-year return peak sea levels under different MSL rise pathways. As explained in Sect. 3.2.2, only the peak sea level is assigned a 100-year return period as opposed to the entire event. Each storm surge event was then also combined with a simultaneous 100-year return river discharge to test the sensitivity of the study area to coinciding extreme events. The timing of events can have significant impacts on flooding occurrence and extent. It is therefore important to note that previous studies have found it most likely for these types of events to not coincide with up to several days separating the different extremes (Klerk et al. 2015). With these caveats taken into account, the proposed scenarios provide a basis to assess the sensitivity of the Broads to compound flooding.

Table 2 Scenario names

Upstream boundary—river flow	Downstream boundary—sea level		
	2100–4 mm a^{-1} MSL rise 1:100 peak sea level event	1 m MSL rise 1:100 peak sea level event	2 m MSL rise 1:100 peak sea level event
Base	2100Q0	1mQ0	2mQ0
1:100 event	2100Q100	1mQ100	2mQ100

4.2 Calibration and validation

The HEC-RAS model was calibrated and validated with storm surge events from October 2014 and December 2013, respectively. The calibration parameter used was the Manning's *n* roughness coefficient. Data on past flooding inundation extent in the Broads are lacking in both availability and accuracy. While there have not been major flooding events since 1953, localised defence failures have been observed during extreme storm surge events. Spencer et al. (2015) provided an account of the impact of the December 2013 storm surge along the Norfolk coast. Tidal flooding was however also observed further inland due to overtopping and reported in parts of the Broads (Broads Authority, 2014). As there is no record of the spatial footprint of this inundation, the validation process was carried out using river levels at different stations on the Bure and the Yare (Fig. 6), as well as reports from the Broads Authority, news articles, dated photos, and local accounts of flooding.

Descriptions of the local environments and recommended ranges obtained from Chow (1959) served to make initial benchmarks for Manning's *n* values. The model's calibration was performed on the Manning's *n* within river channels to reach final values as shown in Table 3. A roughness coefficient was also applied to land classes out of the river banks in the 2D modelling domain. These values were not used during the model's calibration as

Table 3 Manning's *n* in river channels after calibration

Land cover	Manning's *n* roughness coefficient
River Bure	0.045
River Ant	0.045
River Thurne	0.045
River Yare—Great Yarmouth	0.04
River Yare—Breydon Water	0.025
River Yare—Upper	0.03
River Waveney	0.04

Table 4 Manning's *n* for different land classes

Land cover	Manning's *n* roughness coefficient
Arable and horticulture	0.05
Broadleaf woodland	0.15
Fen, marsh and swamp	0.07
Improved grassland	0.035
Urban areas	0.2

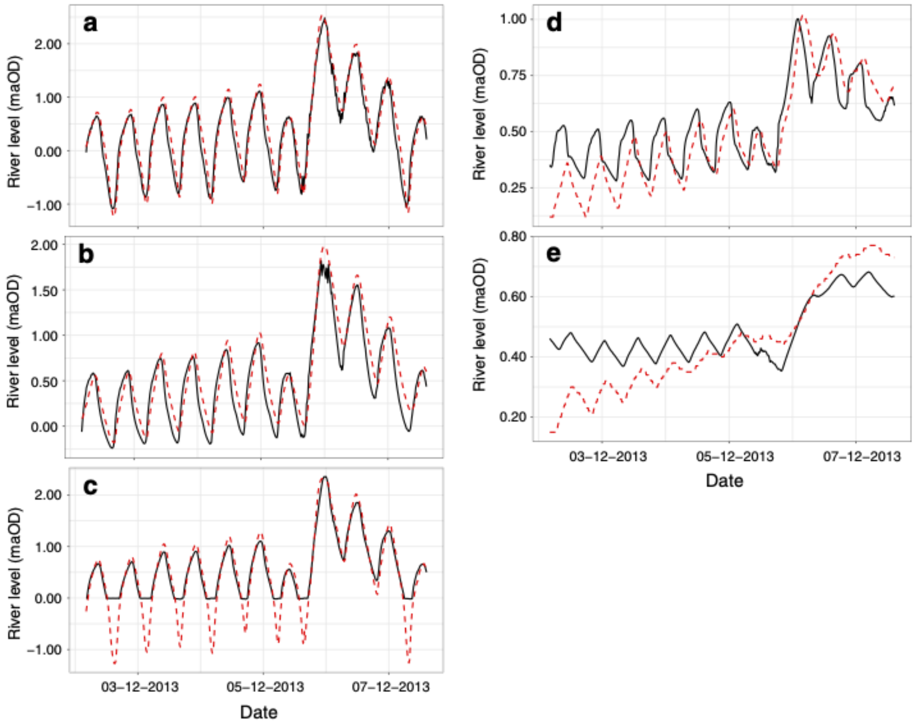

Fig. 9 Observed (black) and modelled (red dashed) river levels during the December 2013 storm surge at **a** Haven Bridge, **b** Three Mile House, **c** Burgh Castle, **d** Acle, and **e** Hoveton Broad

flood extent data were not available (Table 4). In tidally influenced rivers, the inertial terms in the momentum equation are important and rivers levels are not highly sensitive to adjustments in the roughness coefficient (USACE 2016). Theta is a weighting factor that ranges between 0.6 (more accurate) and 1.0 (more computationally stable) applied to the finite difference approximations when solving the unsteady flow equations. A Theta value of 0.6 was used to improve the accuracy in the representation of the propagating tidal wave, which did not decrease the model's stability.

As expected, the model performed well at recreating river levels near the model's downstream boundary condition in Great Yarmouth at Haven Bridge (Fig. 9a) with an NSE of 0.92. The model also performed well upstream on both the River Bure and the River Yare, at the Three Mile House (Fig. 9b) and Burgh Castle (Fig. 9c) gauges, respectively. It should be noted that the instrument at Three Mile House was unable to measure the river level during the peak of the tide on 06/12/2013. The NSE remained relatively high at 0.84. The gauge at Burgh Castle is a flood warning monitoring station only and due to the position of its pressure sensor instrument, it therefore does not measure any levels below 0 maOD. Still, the model produced a good fit to both the level of the peaks and their timing at Burgh Castle. The model's performance decreased upstream of the River Bure. At Acle, once the tidal wave had propagated, the NSE dropped to 0.67 and there was a slight shift in the timing of the tide (Fig. 9d). The modelled peak river level remained within 0.03 m of the observed value. Nearly 40 km from the sea, the error increased further upstream towards Hoveton Broad, where the model overestimated the river level by a maximum of 0.1 m. While river levels were high during this event, the defences were largely successful in holding back the water from the floodplains. This was also the case in the model's recreation of the event, where only localised flooding was visible at moorings located near Berney Arms, which allowed water to flow into Halvergate Marshes.

4.3 Hydrodynamic simulations

Model results derived from simulations in HEC-RAS were exported to ArcGIS and R for analysis. The maximum flooding depth from each simulation run can be found in Fig. 10. The inundation extent shown in these profiles represents an aggregation of the overall runs rather than a specific simulation time. The profiles should therefore be differentiated with the extents occurring during maximum sea level, since flooding is dynamic and its timing

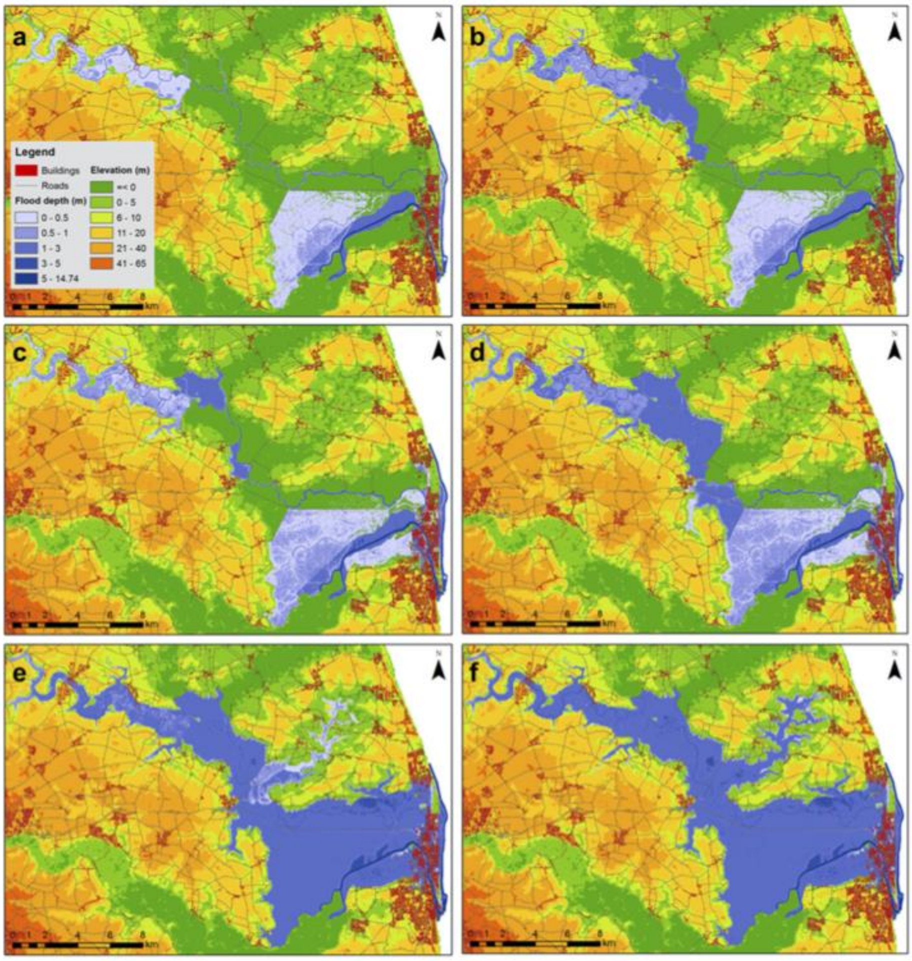

Fig. 10 Maximum flooding depth in the Broads between Great Yarmouth and Horstead Mill on the River Bure under different extreme scenarios (simulation names from Table 3). **a** 2100Q0, **b** 2100Q100, **c** 1mQ0, **d** 1mQ100, **e** 2mQ0, **f** 2mQ100

varies across various locations. Extreme sea levels cause flooding both downstream and upstream in the Broads when assuming a linear mean SLR up to 2100 (Fig. 10a). The largest affected area is Halvergate Marshes, where water is able to flow throughout the large floodplain located north of Breydon Water. Elevated roads and railway tracks are well captured by the model's 2D mesh and slow the propagation of the flood wave. Flooding is minimal in the more densely populated Great Yarmouth as there is almost no overtopping of high defences. With the exception of Halvergate Marshes, flood walls and levees are successful in preventing extensive flooding. Upstream of Ranworth Broads, the floodplains are unprotected and consist mostly of marshes that are well connected to the river. While buildings near the riverbanks in the towns of Horning and Hoveton are affected, the flood depth remains relatively low. As Fig. 10b shows, combining this event with a 1:100 return river discharge has significant consequences on flooding on the upstream boundary of the tidal Bure. Impacts downstream remain limited. As SLR has been observed to accelerate in the last decades, a linear increase in RMSL over the next century is a conservative assumption. Scenarios representing an accelerated rise leading up to 1 m and 2 m increase in MSL are shown in Fig. 10c–f.

The topology of the rivers and floodplains in the Broads causes flooding to occur rapidly and spread significantly when a defence is overtopped. Figure 10 shows that certain areas are susceptible to lower thresholds of embankment failure, thereby flooding first and highlighting potential vulnerabilities. A notable observation from the scenarios with a 1 m and 2 m RMSL rise is the increased impact on Great Yarmouth. Not only are more tidal defences overtopped, but coastal waters are also able to flow into the town directly from the sea and cause more flooding at some simulation time steps. These interacting sources of flooding lead to an important increase in impacted buildings (Table 5). While a 2 m increase in MSL by 2100 is still considered unlikely and would require a drastic acceleration of SLR, this scenario is useful to highlight the area's sensitivity. For example, the model showed flooding outside of some of the left banks of the Bure only during scenarios 2mQ0 and 2mQ100. The main urban zone in the study area is Great Yarmouth, located near the coast. Sea level is therefore the main driver for the number of flooded buildings. Other towns located farther upstream in the Broads are also affected. Centres of activity for tourism and sailing in Horning and Hoveton lie in close proximity to the River Bure, and several buildings in both towns are susceptible to flooding in all scenarios.

While flooding occurs in all the presented scenarios, both extent and depth vary greatly between the different simulations. Depth is important to consider for risk management as it is used in determining flood damage. Figure 11 shows the density of flooded 2-m cells by depth in all six scenarios. Although the flooding extent was already high in scenario 2100Q0, most of the flooding occurred at low depths between 0 m and 0.5 m, meaning actual damages would be limited or easier to cope with (Fig. 11a). The maximum density

Table 5 Number of buildings affected by flooding under different extreme scenarios in the model study area

Scenario	Number of buildings flooded	Proportion of buildings flooded (%)
2100Q0	702	16.78
2100Q100	892	21.32
1mQ0	1285	30.72
1mQ100	1389	33.21
2mQ0	1635	39.09
2mQ100	1797	42.96

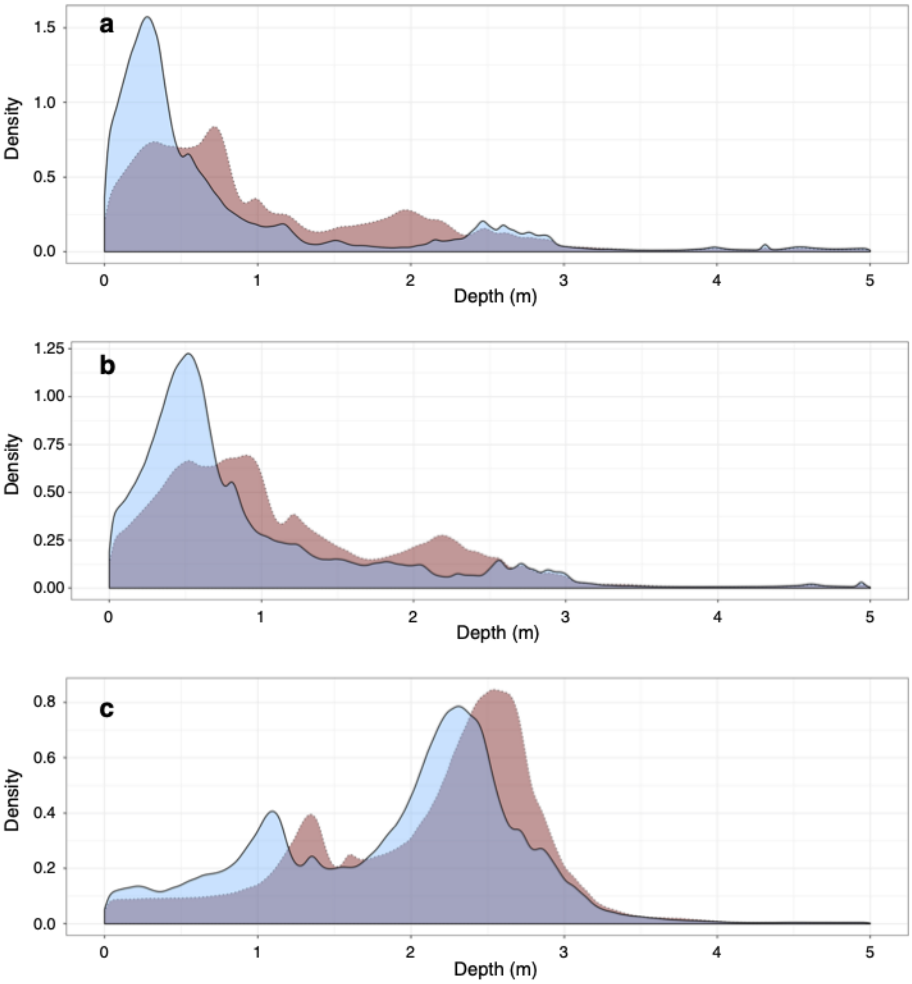

Fig. 11 Kernel density plots of flooded cells by depth for scenarios **a** 2100Q0 (blue), 2100Q100 (red, dotted line), **b** 1mQ0 (blue), 1mQ100 (red, dotted line) and **c** 2mQ0 (blue), 2mQ100 (red, dotted line)

shifts towards 0.5 m and 1 m for scenario 1mQ0 (Fig. 11b) and increases considerably to over 2 m for scenario 2mQ0 (Fig. 11c).

Both Table 5 and Fig. 11 emphasise that increasing RMSL has a significant impact on inundation extent and depth in the Broads. While sea level is indeed the main driver for flooding in the study area, the results also show that coinciding high river flows can exacerbate these impacts. The average depth of cells below 5 m in depth increased from 0.82 m to 1.08 m (Fig. 11a), from 0.92 m to 1.16 m (Fig. 11b) and from 1.9 m to 2.09 m (Fig. 11c) for the three scenario pairs, respectively. A similar pattern can be observed for the total area of the flooding in each scenario. For both average depth and inundation area however, the influence of high discharge decreases as the maximum sea level increases. Average flood depth increases by 40% from scenarios 2100Q0 to 2100Q100, while it increases by 5% from scenarios 2mQ0 to 2mQ100. Similarly total inundated area increases

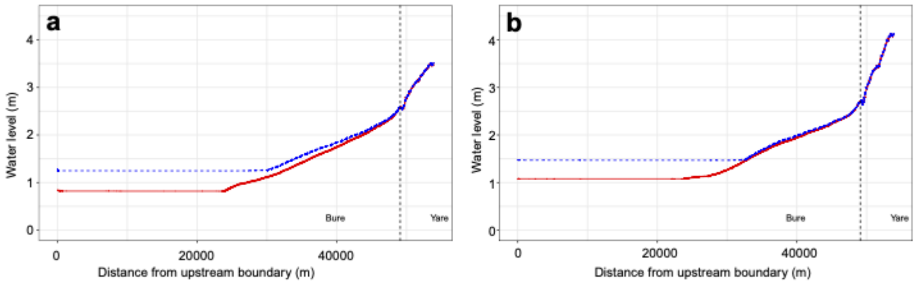

Fig. 12 Longitudinal profile view of maximum water levels along the River Bure and River Yare from the model's upstream boundary to its downstream boundary, the North Sea. **a** Maximum water levels for scenarios 2100Q0 (red) and 2100Q100 (blue, dashed). **b** Maximum water levels for scenarios 1mQ0 (red) and 1mQ100 (blue, dashed)

by 32% from scenarios 2100Q0 to 2100Q100 compared to a 10% rise from scenarios 2mQ0 to 2mQ100.

The simulated compound events did not have significant added consequences in Great Yarmouth on either flooding extent or depth, compared to unique events of extreme sea level. The longitudinal profile of the modelled rivers indeed shows that the influence of the combined extreme discharge decreases going downstream (Fig. 12). Near the mouth of the River Yare, the extreme discharge has almost no impact on the water level in all three envisaged cases. Figure 12 also shows that the difference in water level between Q0 and Q100 events is greater for a lower MSL. Upstream areas are much more affected. The flooded area of broadleaf woodland, which occurs mostly upstream of Ranworth Broads along the River Bure, is highly influenced by the occurrence of a combined event (Fig. 12, Table 6). The Bure Broads and Marshes are well connected to the river, and the encroachment of water is therefore not a direct concern or a rare occurrence.

The deeper upstream flooding observed in Fig. 10b, c and d remains significant as it can lead to longer residence times of saline waters. Large areas of improved grassland, notably used for grazing, are predisposed to flooding under each scenario, with arable and horticulture land classes also highly impacted (Table 6). There are moreover several protected areas, such as sites of specific interests (SSSI), located in the Broads. A topic for future research would be the impact of extreme events on salinity in the Broads. Salinity can cause damage to agricultural land and therefore lead to significant economic losses as well as representing a threat to sensitive species. Studying the impact of combined events may lead to counter-intuitive results as several processes affect salinity. Indeed, high river flows

Table 6 Area flooded by land-cover class (km^2)

Scenario	Broadleaf woodland	Arable and horticulture	Improved grassland	Fen, marsh and swamp	Urban	Sub-urban
2100Q0	6.31	1.01	23.27	6.92	1.45	0.16
2100Q100	8.91	2.16	33.14	8.65	1.60	0.31
1mQ0	7.93	3.34	35.86	8.08	4.59	0.56
1mQ100	10.41	6.73	47.89	9.14	4.69	0.74
2mQ0	12.83	14.22	61.52	10.02	6.73	1.58
2mQ100	14.22	15.92	63.26	10.09	6.77	1.86

add freshwater to the system, while surges push saline water upstream into the Broads. River salinity and conductivity can be simulated in HEC-RAS's water quality module.

A significant benefit of the described 1D–2D approach in portraying overtopping is the use of specific lateral structures for flood defences to guarantee that maximum crest heights were accounted for, regardless of the chosen mesh resolution. It is a fundamental requirement for 2D cells in HEC-RAS to be set up such that cell edges (or "faces") align with high ground or structures impeding the movement of water. This task can be difficult for narrow flood defences, even with a relatively fine resolution of 2 m. Cells that are too large or that are not adequately oriented can cause issues with the model's calculations, leading water to incorrectly "leak" through natural or man-made barriers. The results in such cases are fragmented and therefore produce unrealistic outputs of flooding extents. The Broads is a highly engineered area with many embankments protecting large expanses of land from rivers. It was therefore essential to use lateral structures between 1D and 2D domains that capture the height of defences for their entire lengths. Until computational capabilities increase to allow for extremely fine mesh resolutions, this study finds that a 1D–2D method remains the most feasible approach for the geographical location in question.

The HEC-RAS 1D–2D model was able to highlight vulnerabilities and weak points within the study area as well as account for complex interactions between different sources of flooding. The model structure could still be improved by including building footprints in the 2D mesh to better represent the flow of water in urban areas. Such levels of accuracy were however not necessary to assess the overall sensitivity of the case study area and the fitness for use of the HEC-RAS model version 5.0. Further developments for the model could moreover be to include other parts of the Broads that currently lie outside the modelling domain. Areas in the River Yare, Waveney, Thurne and Ant basins, as well as in Lowestoft have experienced flooding in the past.

Several important considerations should be made when interpreting the results derived from the presented hydraulic model. The first is that while flood defence infrastructure can fail in a number of ways, only the overtopping of defences was considered here. The erosion and breaching of dunes, embankments and walls are a common concern in coastal regions (Hall et al. 2015). Although these processes can be simulated in HEC-RAS and can be useful to represent catastrophic or "what if" scenarios, their impacts fell outside of the scope of this study.

A more comprehensive study of flooding risk would moreover need to incorporate processes of wind and waves, which were omitted in this simplified hydraulic modelling framework. Wind is a key parameter that plays a role in the dynamics of both waves and surges and can therefore have important consequences on coastal flooding. With the necessary data, the EVA and the scenarios used for simulations could therefore be refined by setting up local wave and storm surge models (e.g. Villatoro et al. 2014). Similarly, the lack of available discharge data was also a limitation for this work. A hydrological model could be used in future research to determine more accurate upstream boundaries for the HEC-RAS hydraulic model. A hydrological model would moreover make it possible to account for projected changes in temperature and precipitation in the Broadland catchment to better understand the impact of these climatic changes on flooding hazard.

This study highlighted the potential for multiple extreme events occurring simultaneously to exacerbate flooding risk in the Broads. Validating the proposed modelling framework to assess the sensitivity of the Broads, the aim of this research was however not to understand the probabilities of co-occurrence of these events. The assumption was made that peak river discharge and peak sea level occurred simultaneously in scenarios where both events occurred. While it helped in interpreting the created scenarios, this assumption may not be representative of likely events in the Broads. Past studies in other regions, such as the Netherlands, have, for example, shown a dependency between discharge peaks and water levels, but with a lag time of several days (Klerk et al. 2015). More analysis should be performed to determine the dependency between discharge peaks and sea levels in the East coast of England. Moreover, understanding the types of weather patterns associated with different events could provide some useful insights into flooding hazard in the region. As the timing of events can have significant consequences not only of flooding extent but also on the usefulness of flood mitigation strategies, joint probabilities should be carefully considered to make robust planning recommendations on flood risk management.

5 Conclusions

This study has looked to evaluate the sensitivity of a complex coastal environment to different sources of flooding, using the new tools made available in HEC-RAS version 5.0. A 1D–2D approach was found to be appropriate for flood mapping in this context, accurately reproducing the flow of water in both large floodplains and urban areas while reducing computational requirements. Lower simulation run times moreover made it possible to cover a larger area from the coast and to 40 km inland where tidal and fluvial processes interact. The proposed approach is particularly relevant to low-lying and low-gradient regions like the Broads, which are prone to tidal flooding and where the tidal boundary extends far upstream. There will continue to be more opportunities for 2D modelling in the UK as the coverage of fine-resolution LIDAR data grows.

Hydraulic models are not only sensitive to topographical data but also to the choice and fundamental design of boundary conditions. With extremes being the primary cause of flooding in the Broads and in many regions around the world, it is important to capture the hydrological conditions occurring during these events. The GPD function was used to determine return levels of sea level and river discharge to create synthetic extreme events under future conditions of SLR. Important assumptions were made to create simplified synthetic events as the interest of this work was to assess the sensitivity of the Broads to extreme flooding and the potential for the modelling framework to map out maximum flooding extents. Peak river discharge and sea level were thereby designed to occur at the same time. Similarly, the storm surge peak coincided with the highest point in the tide cycle. For a more comprehensive assessment of flood risk, further research should look into the significance of the timing of these events as well as the joint probability of their occurrence. The proposed model however helps to understand the Broads' sensitivity to different sources of flooding. Storm surges are, and are likely to continue to be, the main drivers for flooding in the Broads as RMSL rises over the next century. While there is still uncertainty in the pattern of future precipitation with climate change, this study has shown that high discharge could exacerbate the flooding caused by storm surges.

While the described hydraulic model can be expanded to cover a larger portion of the Broads, this case study highlights the potential for 1D–2D modelling in assisting decision-making. This methodology indeed allows for the consideration of urban coastal areas, requiring a high amount of detail, as well as vast inland rural zones. It is moreover suited to dynamically represent interacting sources of flooding and potential combined extreme events. The presented approach is therefore a step towards helping meet the requirements of integrated catchment management as well as flood alleviation and adaptation.

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"We can't do it on our own!"—Integrating stakeholder and scientific knowledge of future flood risk to inform climate change adaptation planning in a coastal region

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ABSTRACT

Decision-makers face a particular challenge in planning for climate adaptation. The complexity of climate change's likely impacts, such as increased flooding, has widened the scope of information necessary to take action. This is particularly the case in valuable low-lying coastal regions, which host many competing interests, and where there is a growing need to draw from varied fields in the risk-based management of flooding. The rising scrutiny over science's ability to match expectations of policy actors has called for the integration of stakeholder and scientific knowledge domains. Focusing on the Broads — the United Kingdom's largest protected wetland — this study looked to assess future flood risk and consider potential adaptation responses in a collaborative approach. Interviews and surveys with local stakeholders accompanied the development of a hydraulic model in an iterative participatory design, centred on a scientist-stakeholder workshop. Knowledge and perspectives were shared on processes driving risk in the Broads, as well as on the implications of adaptation measures, allowing for their prioritisation. The research outcomes highlight not only the challenges that scientist-stakeholder integrated assessments of future flood risk face, but also their potential to lead to the production of useful information for decision-making.

1. Introduction

Climate change poses a particular challenge due to the significant uncertainties that exist over its timing, magnitude and impacts. These impacts, such as the potential increase in flood risk, are likely to have widespread and disastrous effects without the adaptation of human and natural systems (IPCC, 2014). The prevailing complexities associated with climate change have contributed in the last decades to a paradigm shift in both flood policy and flood risk research. In England for example, there has been a transition away from traditional structural and engineering-based flood protection policies to an integrated management of flood risk (Environment Agency, 2000). Integrated Flood Risk Management (FRM) looks to recognise the interrelationships between risk management measures at the catchment level within changing social, economic and environmental contexts (Hall et al., 2003). The trend for more risk-based management emphasises the need in climate change adaptation planning not just to look at environmental hazard, but also to account for vulnerability and exposure (IPCC, 2012).

Research on flood risk has followed a path that is parallel to flood policy to examine the challenges introduced by climate change. Studies taking an interdisciplinary stance and drawing from different scientific fields to evaluate climate impacts and vulnerability have gained in popularity (e.g., Kaspersen and Halsnæs, 2017; Xie et al., 2017). Many of these works are part of the emerging methodological framework of Integrated Assessment (IA). Kloprogge and Sluijs (2006) defined IA as the "process of combining, interpreting and communicating knowledge from diverse scientific disciplines". The rationale for IA is that single-field assessments are inadequate to deal with global environmental risks and to provide useful information to decision makers (Rotmans, 1998). While IA is described as a "link between knowledge and action" (Farrell and Jäger, 2005), there is still concern over a gap between science and policy on climate adaptation (Mastrandrea et al., 2010; Kirchhoff et al., 2015). This has spurred recent efforts to expand the scope of IA towards knowledge claims other than from just scientific domains, notably with participation of multiple stakeholders in the input of information (Kloprogge and Sluijs, 2006).

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Participatory approaches have gained in popularity alongside a shift in the relation between science and policy. The rejection of science's traditional "top-down" stance to inform decision-making unilaterally (Pielke, 2007) has indeed been accompanied by efforts to make science more accountable and therefore more likely to be seen as acceptable (Voinov and Bousquet, 2010; Chilvers and Kearnes, 2016). Additionally, participation can be seen as a way to empower stakeholders, giving them a more central role in the generation of knowledge and therefore increasing their capacity to make use of that knowledge (Stringer et al., 2006). Studies have moreover found that a participatory approach can lead to social learning (e.g., Steyaert et al., 2007; Evers et al., 2016), where stakeholders gain from each other, leading them to appreciate each other's views and develop valuable relationships or networks (Reed et al., 2010). The trend for increased participation has also taken root in environmental modelling. Arguments have been made for a change in the traditional stance modellers take, including in FRM where computer programs typically take up an important role (Landström et al., 2011). Krueger et al. (2012) argued that stakeholder scrutiny could not only be applied to model results, but also on the technical process of modelling itself to generate new knowledge.

Being closely linked to civil engineering, FRM remains a field where expert knowledge holds a significant role and in which stakeholder engagement may even be perceived as a threat, rather than the solution (Edelenbos et al., 2016). Stakeholder engagement in general faces many challenges, which has led debates over its actual benefits (Reed, 2008). Tseng and Penning-Rowsell (2012) identified key barriers to stakeholder engagement in FRM ranging from the lack of an institutionalised and early engagement process to resistance experienced from stakeholders. Few et al. (2007) moreover described the challenges created by power dynamics, where leading authorities may use the pretence of participation as a way to steer outcomes to predefined goals in lieu of engaging with stakeholder perceptions or interests.

The potential gains from participation remain important in climate adaptation, as impacts are likely to be felt throughout society and experienced or perceived differently by various actors. Moreover, the effects of climate change may exacerbate cross-sectoral competition for resources and funding leading to different preferences for action. Coastal regions in particular are faced with the challenge of hosting greatly varying interests from a wide range of stakeholders (Tompkins et al., 2008; Day et al., 2015). The expansion of IAs to include stakeholders allows for new opportunities to produce knowledge in these areas through the collaboration of scientists, policy makers and other societal actors (Hegger et al., 2012). In practice however, there are still few studies that attempt a participatory approach in the IA of flood risk to inform adaptation planning (Kettle et al., 2014; Löschner et al., 2016).

This paper describes the work that was carried out in the Broads wetland in the United Kingdom (UK). The goal of the research was to combine different knowledge domains to assess flood risk and consider potential adaptation measures for the study area. Stakeholders were engaged, most notably in a collaborative workshop, with information from a scientific analysis of flood risk from a hydraulic model developed as part of this project. The aims of this research were to determine (1) how scientific information and stakeholder knowledge and perceptions on flood risk can be integrated, (2) how such a collaborative approach can translate risk-based management principles relevant for climate adaptation planning and (3) the lessons that can be derived from the participatory IA of flood risk to inform adaptation planning in the context of the Broads.

1.1. Study area

1.1.1. The Broads, UK

Located on the eastern coast of England, the Norfolk and Suffolk Broads form Britain's largest designated wetland (Fig. 1). This network of interconnected rivers and shallow lakes – or "broads" – covers a total area of 303 km^2 at the downstream end of the Broadland Rivers catchment. A predominantly freshwater ecosystem, the Broads is a low-lying area that covers more than 30,000 ha of floodplain. It is the home of 28 Sites of Special Scientific Interest and is internationally recognised for its rich biodiversity, nature conservation, landscape and cultural features. The Broads executive area, closely drawn around the floodplains of its three main rivers, namely the Bure, Yare and Waveney, is managed by the Broads Authority (BA).

The Broads also hold significant economic value both at the local and national level. Agriculture in the area, which primarily consists of livestock grazing and arable cropping, represents an important contributor to the economy. This location is moreover a popular destination for over 7 million visitors a year with tourism contributing to approximately £568 million (Broads Authority, 2019). Additionally, the area's unique hydrological features allow for many recreational or leisure activities, including boating and angling. While the population count in the Broads reaches just above 6000 residents, the National Park is bounded by large urban areas in Norwich, as well as the coastal towns of Lowestoft and Great Yarmouth.

1.1.2. Flood risk management

Much of the land in the Broads is either at or below sea level. The close proximity to the North Sea as well as a complex riverine system leads this area to be at risk from both tidal and fluvial sources of flooding. The Broads have a long history of floods. Most notably, the storm of January 1953 had severe impacts in East Anglia and led to significant subsequent investments in flood protection and forecasting in the country. Several institutional bodies hold a role in the management of flood risk in the Broads as shown in Table 1.

The Broads today are highly engineered with over 240 km of earth embankments serving as flood defences alongside the rivers Bure, Wensum, Waveney, Yare and Ant. These structures have been maintained and strengthened as part of a 20-year strategy that began in 2001 and is being implemented through the Broadland Flood Alleviation Project (BFAP). Flood defences were severely tested in December 2013 by the largest storm surge since 1953, but were successful in minimising flooding in the Broads. Still, the 2013 event is often qualified as a "near miss" and underlined the need for better preparedness.

On the coastline, 14 km of sea defences extend between the villages of Eccles and Winterton to protect the region from coastal flooding. The current strategy for the length of the coastline set up by the Shoreline Management Plan (SMP) adopted in 2012 is to "hold the existing defence line" for the short and medium term (up to 2055). It is worth noting that previous SMP proposal were met with negative reactions and concern from many local communities and organisations. Day et al. (2015) argued that the main reasons for the negative response were that scientific projections were made without associated management plans and with insufficient stakeholder input. Since then, emphasis has been put on stakeholder engagement, but findings ways to integrate the wide range of perspectives remains a challenge.

As the current SMP points out, climatic changes and sea level rise are putting increasing pressure on the region and raising concern over the technical and economic sustainability of current structural approaches. A high level review of flood risk management on the coast and inland conducted in 2016 highlighted that climate impacts should be taken into account to consider a wider range of options in the future (CH2M, 2016). With BFAP ending in 2021, an overarching plan for the Broads is yet to be agreed on, providing an opportunity to update the FRM strategy in the area.

2. Methods

2.1. Preliminary interviews and modelling

A combination of quantitative and qualitative methods were used both as a way to generate research material as well as to assess the

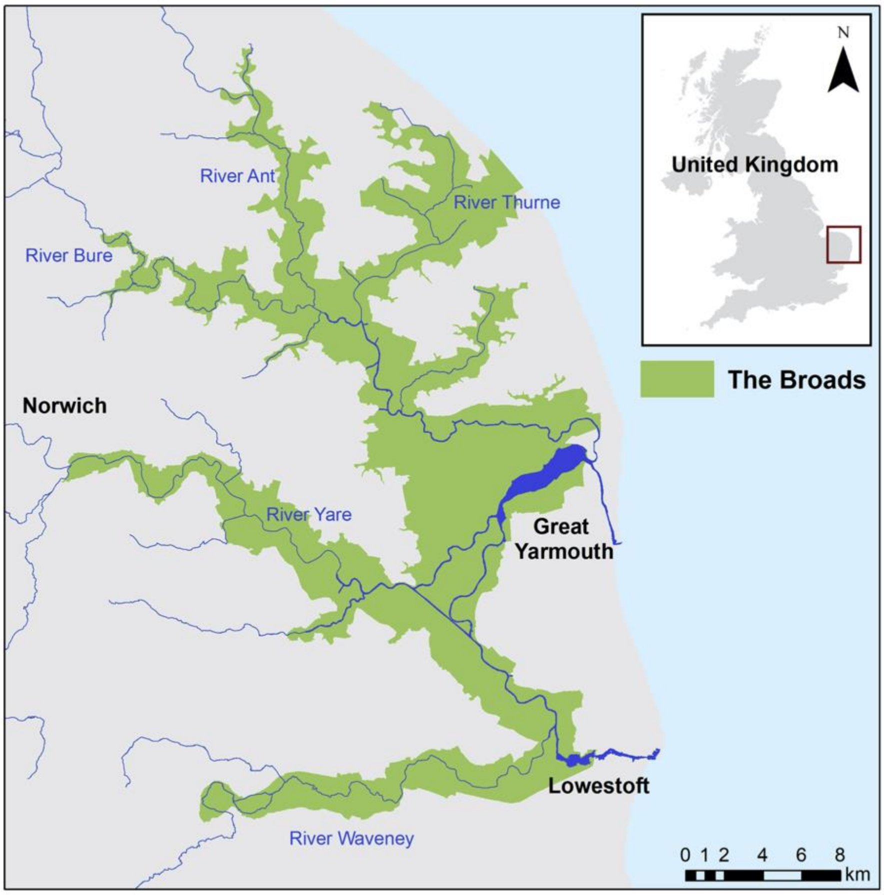

Fig. 1. The Norfolk and Suffolk Broads National Park.

knowledge generation process itself. The main sources of information on flood risk in this project originated iteratively from the development of a hydraulic model and stakeholder engagement exercises (Fig. SM1). For this study, stakeholders were identified and recruited through different methods. This included presenting the research and handing out information leaflets at community meetings in the Broads, advertising stakeholder events on online BA newsletters and by snowball sampling. The different participatory activities in the research design received prior ethical approval from the General Research Ethics Committee of the University of East Anglia.

Exploratory semi-structured interviews were first conducted to identify key overarching issues and interests related to flood risk. A total of 11 interviews were conducted with actors with various interests, namely farmers, conservationists, anglers, local elected officials, coastal managers and engineers.

Findings from the interviews guided the development of the first version of a hydraulic model of the River Bure sub-catchment in the Broads. The model, described by Pasquier et al. (2018) was used to assess the sensitivity of the Broads to fluvial, tidal and coastal sources of flooding under different rates of sea level rise throughout the 21 st

Table 1
Organisations responsible for managing flood risk in the Broadland Catchment (adapted from Broads Climate Partnership, 2016).

Organisations	Role and responsibilities
Broads Authority (BA)	As the local planning authority, the BA can control development in floodplains and manages conservation, recreation and navigation in the Broads.
Environment Agency (EA)	Government agency managing flood risk from main rivers, estuary and the sea. Responsible for river and tidal defences.
County and District Councils	The County Councils are Lead Local Flood Authorities, managing flood risk from surface water, ordinary watercourses and groundwater. The District Councils on the coast take on a coastal erosion protection role.
Water and sewage companies	Manage the risk of flooding to water supply and sewerage facilities and the risk to others from the failure of their infrastructure.
Internal Drainage Board (IDB)	Manage land drainage in lowland areas and the many pumping stations that operate in the Broads.

century. Simple deterministic ("what if") long-term scenarios of extreme storm surges and river discharge were designed to create maps of flooding extent and depth. The flooded area of different land use types was calculated along with the number of flooded buildings by depth to provide a basic comparison of impact. The model as well as the derived analysis and maps served as the foundation for discussions during a stakeholder workshop, the central engagement activity in this research.

2.2. Stakeholder workshop

The workshop design was loosely based on the “Scientific-Stakeholder Workshops” proposed by Löschner et al. (2016) but deviated from that approach in several ways. A method for stakeholder analysis in environment management studies (e.g., Reed et al., 2009; García-Nieto et al., 2015) is to classify stakeholders based on their levels of influence in decision-making and interest, here in FRM. A balanced number of *higher interest/higher influence* (7) and *higher interest/lower influence* (7) stakeholders (Table 2) attended the workshop. Three individuals had previously participated in the exploratory interviews while the remainder were new to the project. The attendees were asked in the week prior to the workshop to respond to an online survey created with Lime Service[1] . A total of 9 responses were submitted. The survey was structured into 4 parts to (1) assess the participant’s level of knowledge on flood risk and modelling, and to record their perceptions of (2) current flood risk and management, (3) future conditions and (4) possible adaptation measures in the Broads.

The workshop was divided into three sessions, working under the basic instruction that all perceptions could be shared. Session I aimed to define and get a shared understanding of the problem at hand, using modelling results (i.e. flood maps as shown in Fig. SM2) to spark discussions on hazard, vulnerability and exposure in the Broads. The stakeholders then separated into three groups to discuss potential adaptation strategies for Session II. Each group was moderated by a member of the research team and asked to use detailed A1-size paper maps to draw their proposed adaptation measures. While stakeholders were encouraged to be speculative and not to feel restricted by concerns over economic cost or political will, they were asked to discuss the feasibility of each measure. Indicators to assess these options were purposefully left undefined and open to stakeholder interpretation. The groups were aware that the researchers were interested in modelling the adaptation measures derived from the workshop in subsequent work. The participants were however advised not to limit the solutions they proposed to ones they thought were technically possible to model.

The outcomes from Session II were presented to the rest of the workshop participants during the final Session III. Stakeholders reflected on their respective discussions and lessons learned. Participants carried out a simple prioritisation task for the measures derived from Session II. Each individual had five votes to distribute to any number of options. The workshop ended with final comments, including reflections on the workshop itself. A survey was filled in by the stakeholders to obtain feedback on the workshop and its outcomes.

The workshop was recorded and its transcription coded under the broad headings of vulnerability, exposure, hazard, modelling method, participation process, adaptation and FRM. The last heading referred to statements relevant to flood policy but not directly related to adaptation options, such as land ownership, funding, or the management of competing interests. The coded transcripts, in combination with other sources of data (i.e. the interviews and pre-workshop survey) were analysed to highlight the themes emerging from the stakeholders’ perceptions of flood risk and adaptation in the Broads. Perceptions of the scientific information and method represented by the hydraulic model were also considered.

Table 2
Workshop stakeholder affiliations grouped by individuals' levels of influence and interests in FRM.

Higher interest/Higher influence	Higher interest/Lower influence
Broads Authority	Norfolk Wildlife Trust
Internal Drainage Board	Royal Society for the Protection of Birds
Norfolk County Council, Suffolk County Council	National Farmers' Union, farmers
Broadland District Council	Broads Angling Services Group
Coastal engineers and managers	Broads Navigation

2.3. Modelling adaptation measures and final feedback

Outputs from the workshop were used to refine the modelling methodology and define future scenarios. The adaptation measures which received the most votes during Session III of the workshop were implemented within the hydraulic model. The ensuing simulations showed the impact of these measures on flooding extent and depth in the Broads under future scenarios of climate change and sea level rise up to 2080. The resulting flood maps were finally presented individually to stakeholders who had participated to the workshop, to obtain their feedback on the proposed adaptation measures and future flooding risk.

3. Results

The research results are divided into three sub-sections. The first describes the outcomes of the integration of stakeholder and scientific domains within the participatory process. The second focuses on the assessment of future flood risk in the Broads from different knowledge domains. The last sub-section focuses on stakeholder perceptions of adaptation drawn from their engagement and reactions to model results.

3.1. Outcomes of the participatory process

The participatory process allowed for multiple phases of interaction between different knowledge domains. The preliminary stakeholder interviews provided information on which to base early hydraulic modelling choices such as the geographic extent (from inland to the coast), processes to depict in scenarios (e.g., compounding events of simultaneous extreme river flow and sea level), model design (represent coastal urban areas in more detail), as well as the choice of modelling software itself (HEC-RAS, a freely available online software). All stakeholders agreed (100%) that the flood maps resulting from this model were suitable for stimulating discussions during the workshop (Fig. 2).

The workshop’s format was deemed appropriate as the main interface between scientific and stakeholder knowledge, but it also brought together participants who had never met and who were not accustomed to exchanging knowledge in such a setting. Still, varying opinions and experiences were represented. Stakeholders agreed (93%) that they were able to appreciate cross-sectoral challenges and competing interests (Fig. 2). One of the workshop’s concluding statements reinforced this finding:

“It’s all about partnership working. We can't do it on our own! This is why these types of meetings are so important” (Stakeholder 5, conservancy)

While the majority of responses (93%) found the mix of workshop participants to be appropriate, *lower influence* stakeholders expressed in written feedback and during discussions that they would have preferred to see more representation from the EA. Only 43% of stakeholders agreed that their views of adaptation measures had changed from the workshop. Still, all participants (100%) found that the event allowed them to expand their knowledge of flood risk.

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[1] https://broads-floodworkshop.limequery.com/911555?newtest=Y&lang=en

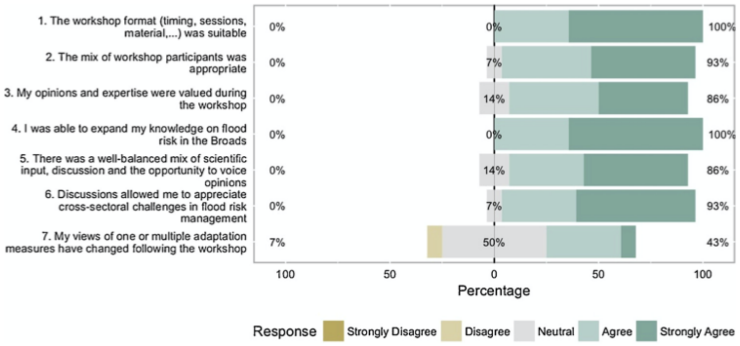

Fig. 2. Post-workshop stakeholder reflections and feedback (n = 14).

Based on the interest and knowledge of stakeholders, information was generated at the workshop that influenced scientific modelling choices. Recommendations were made to expand the model's coverage from the River Bure catchment to the rest of the Broads (Fig. SM3). Concerns were indeed raised – particularly from coastal managers – that flood alleviation measures implemented in one area could have unintended negative consequences in another. A more comprehensive model would therefore be able to capture interlinked processes leading to flooding. In another effort to facilitate their decision-making on actions to take, *higher influence* stakeholders requested to see scenarios in the short to medium term to show how risk will progress with time. Finally, as will be discussed further, stakeholders stressed the importance of assessing flooding risk alongside salinity issues. A water quality module was therefore added to the hydraulic model, capable of simulating in-channel salinity concentration and its ingress within Broads Rivers during storm surges.

3.2. Risk assessment

Information used to assess flood risk in the Broads originated from both scientific findings and stakeholder input. The preliminary hydraulic modelling showed that sea level rise represents a considerable threat for the Broads and its flood defences under extreme storm surge conditions. Simultaneous extreme river discharge and sea level events were found to exacerbate flooding in upstream areas. While urban areas, farmland, and protected areas were affected by flooding, the magnitude of impacts were highly dependent on the rate of sea level rise over the next decades (Pasquier et al., 2018).

While stakeholders had varied backgrounds with different levels of expertise in FRM, the exploratory interviews as well as the pre-workshop survey emphasised the general agreement that flooding risk is a critical concern for the Broads (Fig. 3) and is likely to increase in the future (89% of positive responses, Fig. SM4). Storm surge events were mostly perceived as the main cause for flooding in the Broads (67%), with compound events representing a particular concern (89%). These perceptions therefore aligned with the scientific information provided by the hydraulic model, though a more detailed analysis is required to understand the physical processes behind compound events.

The 2013 “near miss” event was mentioned by two *higher influence* stakeholders as a reference for the type of hazard experienced in the Broads and to set the context during the workshop's Session I. Although both *higher influence* and *lower influence* stakeholders expressed concerns for compound events in the workshop's first two sessions, there were differences in the perception of such hazards:

“I'm very pleased that the problem of coinciding events is emphasised in the model. Tidal surges with high river flows. There isn't really an issue without that coincidence.” (*Stakeholder 1*, navigation)

“I don't agree with that statement. We have had rainfall events, such as in 2012, that have had significant impacts.” (*Stakeholder 2*, catchment engineer)

And:

"It's interesting to look at dual events, which we haven't faced so far." (*Stakeholder 3*, local administration)

"I'm pleased that this has been brought in because it is something that has been overlooked. The [current strategy] didn't really address that at all." (*Stakeholder 4*, local administration)

The issue of salinity within the Broads system was raised during the workshop and was primarily brought forward from the perspective of angling interests. The threat that encroaching saline waters pose to protected areas and farmland was also emphasised. Farmers pointed out the impact that salinity has on agricultural land in greatly increasing recovery time from flooding. Despite the general agreement that — the Broads being a predominantly freshwater system — increased salinity due to sea level rise would challenge current management practices, workshop discussions highlighted differences between angling and conservation interests:

“I find it interesting that people are thinking that salt is necessarily bad. Salt is bad in a fresh system. But in an area dedicated as salty, it can be good. It's about making sure…” (*Stakeholder 5*, conservancy)

“What we're talking about here is saline incursion going 18 miles from the sea. It's just not right, it's killing everything.” (*Stakeholder 6*, angling)

“No it's not. But if there was an option to create an area to divert all the salt water into. A system designed to cope with that salt water. Then the system would eventually adapt to be able to cope with that salt water. Then it becomes a positive.” (*Stakeholder 5*, conservancy)

Cross-sectoral interests were represented at the workshop in discussions of vulnerability and exposure. Stakeholders stressed the unique exposure that the Broads face due to their flat and low-lying landscape as well as their proximity to the sea. Close to equal attention was attributed to the vulnerability of freshwater habitats (located in *“some of the most unsustainable locations in the long term” Stakeholder 2, catchment engineer*), population centres, farming, tourism, fisheries and other businesses. The impact of flooding on key infrastructure such as important roads or power installations were mentioned in light of how it may affect the resilience of communities, in particular in Great Yarmouth on the coast.

Finally, while a small majority of stakeholders (56%) agreed that existing flood alleviation measures were successful in limiting present flood risk, the agreement was much less pronounced (33%) over whether the current level of defence provided to vulnerable areas in the Broads was sufficient (Fig. 3). Following the workshop, model outputs showed that the southern parts of the Broads (e.g. Yare and Waveney catchments) were more exposed to flooding than northern catchments.

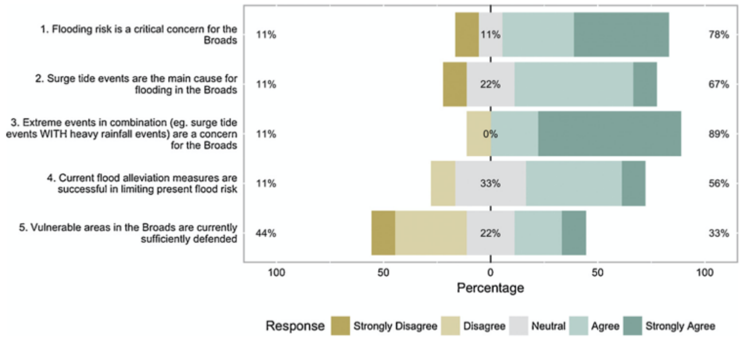

Fig. 3. Stakeholder perception of current flood risk and its management in the Broads (n = 9; 5 stakeholders present at the workshop did not submit responses). Data gathered from an online pre-workshop survey.

Local stakeholders from farming, conservation and engineering positions confirmed this finding met their expectations, indicating the model was performing as intended.

3.3. Climate change adaptation

When asked in the pre-workshop survey to rate adaptation options from a list (or any other measures of their choice) stakeholders overwhelmingly rated “do nothing” as the least preferable. 89 % of stakeholders either agreed or strongly agreed that measures should be taken to anticipate future flood risk. This view was represented during the workshop:

“We have choices, and they are all expensive, but unless we start planning for change, nature will take its course, change will be unplanned and that’s not desirable either.” (*Stakeholder 5*, conservancy)

Three *higher influence* stakeholders from local public administration mentioned the economic constraints of adaptation at the workshop, referring to the cost of raising flood defences. While two of the three stakeholder groups in the workshop's Session II listed raising defences as an adaptation option, this measure received the least number of votes during the prioritisation exercise (Table 3), and was deemed the second least preferable (after "do nothing") in the pre-workshop survey.

The most popular adaptation measure, which was mentioned in all three workshop groups by both *higher* and *lower influence* stakeholders, was to allow water to flood designated areas (referred to as "sacrificial land") to increase the Broads' storage capacity and therefore alleviate flooding in the rest of the system during extreme events. Although stakeholders were able to identify areas that could serve for flood storage, farmers and conservancy managers respectively stated that such efforts would require a plan to compensate land owners and create new habitat. The model results showed that while dedicating a large area of close to 8 km^2 to store water could have local advantages in protecting surrounding land, it could not on its own prevent flooding across the Broads. The consideration of salinity in the hydraulic model was considered an important addition to support decision making on this measure. Land flooded with saline water as opposed to fresh water would indeed require a prompt pumping scheme following an extreme event to prevent long lasting damages.

The construction of a tidal barrier on the River Yare received attention at the workshop, as it has in the past in the Broads (CH2M, 2016). The most commonly proposed design is a vertical gate in Great Yarmouth – approximately 4 km upstream from the North Sea – which would close off the river at high tide to prevent upstream flooding. As an important infrastructure, the issue of its financing were met with statements by engineers that this option "may become more cost effective than upgrading embankments" with climate change. Despite the interest it generated during the workshop, concerns about the barrier were raised by emergency planners and local officials as a response to model results. The simulated impact of the tidal barrier indeed showed that while it would be able to limit flooding in the Broads, it would also increase risk for Great Yarmouth, a key population centre, and would require substantive engineering work to raise flood walls in the coastal town.

The feedback on the model results showed an understanding among different stakeholders that the Broads’ future adaptation strategy could not rely on a single measure. Both during the workshop and final feedback exchanges, there were interests expressed in moving away from hard engineering options to more natural management strategies. Environmental managers brought forward the idea of sustainable management of drainage and water flows in upstream parts of the catchment, which received a high number of votes at the workshop (Table 3). Discussions however also highlighted two fundamental contrasting stances around floodplain management. While farmers expressed their desire to restore the natural flow and connectivity of rivers with surrounding floodplains, catchment engineers pointed out that letting water flow out-of-bank would infringe on other interests

Table 3
Results of prioritisation exercise during stakeholder workshop.

Adaptation Measure	Number of attributed priority votes
Flood Storage Areas: dedicated to hold either fresh or saline water depending on their location in the catchment	16
Tidal barrier: either a large structure near the mouth of the River Yare, or smaller structures on estuaries	15
Sustainable Drainage Systems (e.g. woodlands to slow upstream flow of water into the system)	13
Surveying floodplains	9
Communicate risks, inform and build community resilience	7
Put in place a water quality monitoring system	4
Re-site pumping stations	3
Migrate back from floodplains, creating new freshwater habitats	2
Raising defences	1

and require expensive pumping operations.

4. Discussion

The iterative process underpinning this study allowed for both stakeholder and scientific domains of knowledge to influence the other. The inclusion of different perspectives was positively received by participants and led to knowledge exchange at multiple levels. Model results were used as a basis for workshop discussions and helped stakeholders connect future hazards to potential local impacts. The expression of, sometimes competing, interests facilitated not only the definition and prioritisation of adaptation scenarios (Maskrey et al., 2016), but also the framing of the modelling methodology itself.

While stakeholders showed a willingness for action and to see a shift in FRM away from traditional measures (i.e. maintaining and raising flood defences), discussions still highlighted important hurdles for climate adaptation. The expansion of the hydraulic model and its added consideration of salinity are examples of outcomes that were directly derived from stakeholder interests and helped to overcome some of these hurdles. These results provide a case for a flexible modelling stance and the inclusion of stakeholder knowledge to co-produce information that is more relevant for decision making (Landström et al., 2011; Krueger et al., 2012). The study however also highlighted the limits to which scientific modelling alone can drive adaptation planning. Measures such as increasing flood storage or constructing tidal barriers can be successful in reducing flood hazard while coming at a cost for certain stakeholders. This cost must be carefully understood and managed for adaptation to be possible. Therefore there is a need to not only include stakeholders in the assessment of flood risk, but also to involve those affected or providing the resources necessary to make these options possible.

The composition of actors involved is a key criteria for the success of knowledge production (Hegger et al., 2012). The presence of exclusively *higher interest* stakeholders at the workshop facilitated discussions. Participants were indeed already sensitised to flooding issues in the Broads. While they represented different fields of expertise, they were able to quickly understand and react to model outputs as well as to come up with adaptation measures with few prompts. The absence of EA representatives at the workshop — who were interviewed before and after but not present on the day — was seen negatively by *lower influence* stakeholders. The EA plays a critical role in the definition of FRM policy at the national level. The traditionally top-down FRM process in England, led by the EA's technical expertise, can explain the stakeholders' expectations (Thaler and Hartmann, 2016). Limiting the workshop to local actors however represented an opportunity for discussions to be less constrained by the national context.

Löschner et al. (2016) argued that scientist-stakeholder workshops on flood risk are unlikely to become institutionalised, despite their usefulness. These types of activities indeed require considerable resources and planning. Due to time and funding restrictions, only one workshop with 14 stakeholders was held as part of this research. A better representation of perceptions of flood risk in the Broads could have been obtained by including a wider range of stakeholder interests. The multiplication of participatory events can however lead to stakeholder fatigue, which Turner et al. (2016) has already previously shown to be an issue in the Broads.

5. Conclusion

The presented collaborative approach carried out in the Broads National Park highlighted some of the benefits, potential and challenges of integrating scientific and stakeholder knowledge to generate information on flood risk and adaptation. As previous work has shown, the early and iterative exchange between these domains increases the likelihood of improving the value and usefulness of scientific results. A shared understanding among stakeholders emerged from this study showing a collective concern for flood risk alongside an interest in a potential change in FRM practices. As the Broads area enters a new phase of FRM, there is an opportunity to gain from bringing together different knowledge domains to plan adaptation going forward.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found in the online version at doi:https://doi.org/10.1016/j.envsci.2019.10.016.

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List of abbreviations

aOD – above Ordnance Datum

BA – Broads Authority

CEH – Centre for Ecology and Hydrology

DTM – Digital Terrain Model

DPSIR – Driver-Pressure-State-Impact-Response

EA – Environment Agency

EC – Electrical Conductivity

EVA – Extreme Value Analysis

FRM – Flood Risk Management

GCM – Global Climate Model

GP – Generalised Pareto

HAT – Highest Astronomical Tide

HBV – Hydrologiska Byråns Vattenbalansavdelning

HEC-RAS – Hydrologic Engineering Center-River Analysis System

IA – Integrated Assessment

IDB – Internal Drainage Board

IPCC – Intergovernmental Panel on Climate Change

JPM – Joint Probability Method

LiDAR – Light Detection And Ranging

MHWS – Mean High Water Springs

NSE – Nash-Sutcliffe Efficiency

PDF – Probability Density Function

PE – Peak Error

POT – Peaks Over Threshold

PPE – Perturbed Parameter Ensemble

RCM – Regional Climate Model

RCP – Representative Concentration Pathway

RJPM - Revised Joint Probability Method

SLR – Sea Level Rise

SPRC – Source-Pathway-Receptor-Consequence

SMP – Shoreline Management Plan

SSSI – Sites of Special Scientific Interest

UKCP – United Kingdom Climate Projections

USACE – United States Army Corps of Engineers