UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

Energy and Climate Change Division

A Conceptual Model and Rapid Appraisal Tool for Integrated Coastal Floodplain Assessments

by

Siddharth Narayan

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ABSTRACT

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Low-lying coastal zones are high-risk areas threatened by flooding due to extreme coastal events and rising sea-levels. The coastal floodplain system includes elements such as near-shore waves and water levels, inter-tidal beaches and coastal habitats, natural and artificial sea defences and multiple inland floodplain features. Flood risk studies generally achieve an integrated assessment of these elements using multiple numerical models for different floodplain elements. However fundamental choices of floodplain description and the appropriate data, methods and models can vary widely between different sites and flood risk studies. A comprehensive conceptual model is needed to describe the floodplain system and help inform these choices in each site. However a descriptive conceptual model for coastal floodplain systems does not exist at present. There is a bias in flood risk studies towards the direct use of numerical models with limited use of conceptual models – existing models are implicit and do not describe the coastal floodplain system.

This thesis addresses this gap by developing, applying and testing a rapid appraisal tool that conceptually describes the coastal floodplain as a system of interacting elements. The tool is developed in two parts – i) a quasi-2D Source – Pathway – Receptor (SPR) model that provides a comprehensive qualitative description of the floodplain; and ii) a Bayesian network model that uses this description to quantify individual elements as sources, pathways and receptors of flood propagation. The quasi-2D SPR is applied in 8 diverse coastal zones across Europe 4 of which include nested case-studies. It is an effective way of gathering and describing information about the floodplain from stakeholders across multiple disciplines. The Bayesian network model is applied to two contrasting floodplain systems in England – Teignmouth and Portsmouth. The network model is effective in pinpointing critical flood pathways and identifying key knowledge gaps for further analyses. The two models together provide a comprehensive understanding of the coastal floodplain system that can be used to inform and target the use of more detailed numerical models. Hence this thesis provides a conceptual model and tool to improve flood risk assessment. It makes conceptual understanding of the floodplain explicit and stratifies quantitative analysis by application of a rapid assessment tool before the use of detailed numerical models.

Table of Contents

ABSTRACT i

List of tables vii

List of figures ix

DECLARATION OF AUTHORSHIP xiii

Acknowledgements xv

Abbreviations and Glossary xvi

1 Introduction 1

1.1 Coastal Flooding and Floodplain Systems 1
1.2 Problem Statement 3
1.3 Research Aims and Objectives 5
1.4 Thesis Structure 6

2 Literature Review: Challenges to Effective Integrated Flood Risk Management 9

2.1 Introduction 9
2.2 Estimation of Risk in Coastal Flood Risk Studies 10
2.3 Evolution of Integrated Risk-based Approaches for Coastal Floodplains 13
2.4 Conceptual Models and Frameworks in Flood Risk Studies 17
2.5 Numerical Models and Methods in Flood Risk Studies 23

2.5.1 Coastal Hydraulic Parameters (Flood Source) 23

2.5.2 Structural and other Flood Defences (Flood Pathway) 26

2.5.3 Floodplain Inundation (Flood Receptor) 28

2.5.4 Uncertainties in Model Simulations 30

2.6 Outputs and Utility of Flood Risk Studies 32
2.7 Extreme Coastal Flood Events and Lessons for Flood Risk Management 34

2.7.1 Weak Links and Critical Elements 35

2.7.2 Diversity in Floodplain Elements and Management 35

2.7.3 Developing a Quantitative Systems Understanding of Coastal Floodplains 36

2.8 Integrated Flood Risk Management: Challenges and Requirements 37

3 The quasi-2D SPR Conceptual Model for Integrated Coastal Floodplain Assessments 39

3.1 Introduction 39
3.2 Quasi – 2D SPR: Objectives 42
3.3 Quasi – 2D SPR: Selection of Participatory Process 42
3.4 Quasi – 2D SPR: Construction Methodology 44
3.5 Quasi – 2D SPR: Case-Studies 53
3.5.1 Hel Peninsula, Gdansk, Poland 53
3.5.2 Medoc Region, Gironde Estuary, France 57
3.5.3 Teign Estuary, South Devon, UK 63
3.5.4 Description of Complex Coastal Floodplains 69
3.5.5 Participatory Construction Methodology 71
3.5.6 Model Limitations 72
3.5.7 Scale Issues in the Quasi-2D SPRs 73

4 Development of a Quantitative Model for Rapid Integrated Floodplain Assessments 77

4.1 Introduction 77
4.2 Quantitative Model: Aims and Objectives 78
4.3 Quantitative Model: Considerations 78
4.4 Network and Systems Models: A mini-review 80
4.4.1 Introduction 80
4.4.2 Coupled Component Models 81
4.4.3 System Dynamics 81
4.4.4 Graph-theoretic Models (GMs) 82
4.4.5 Bayesian Networks 83
4.4.6 Agent-Based Models 84
4.5 Selection of Modelling Approach 85
4.6 Quantitative Model: Description 88
4.7 Bayesian Network Model: Construction 95

4.8 Quantitative Model: Illustrative Example 99
4.9 A Bayesian Network Model for Rapid Integrated Floodplain Assessments 102
5 Application of a Bayesian Network Model for Rapid Integrated Floodplain Assessments 103
5.1 Introduction 103
5.2 Case-Study: Teignmouth, England 105
5.2.1 Site Description and Quasi-2D SPR 105
5.2.2 Stage II: Bayesian Network Model 109
5.2.3 Teignmouth Model: Initial Runs and Validation............117
5.2.4 Teignmouth Model: Analyses of Flood Extents 120
5.2.5 Teignmouth Model: Floodplain Response to Uncertain Inputs 124
5.2.6 Teignmouth Model: Uncertainty in Model Simulations .129
5.2.7 Teignmouth Model: Lessons Learnt.............................132
5.3 Case-Study: Portsmouth, England..134
5.3.1 Site Description 134
5.3.2 Stage 1: Quasi-2D SPR 135
5.3.3 Stage II: Bayesian Network Model 138
5.3.4 Portsmouth Model: Evaluation and Analyses of Flood Extents...144
5.3.5 Portsmouth Model: Floodplain Response to Uncertain Inputs 151
5.3.6 Portsmouth Model: Lessons Learnt and Model Uncertainties 155
5.4 Bayesian Network Model: Discussions 156
5.4.1 Network Model Application 156
5.4.2 Network Model Construction 157
5.4.3 Modelling Approach 157
5.4.4 Use of Quasi-2D SPR System Diagrams 158

6 Discussion ... 160

6.1 Introduction ... 160

6.2 *Where?* A Rapid Appraisal Tool for Integrated Flood Risk Studies ... 161

6.3 *When?* Positioning the Rapid Appraisal Tool within a Flood Risk Study ... 162

6.4 *How?* Applying the Rapid Appraisal Tool within a Flood Risk Study ... 163

6.5 *What?* Outcomes of the Rapid Appraisal Tool ... 165

6.6 *Why?* Utility of the Rapid Appraisal Tool ... 167

6.6.1 Use in Multiple-Scale Integrated Flood Risk Assessments ... 167

6.6.2 Use in Data-Scarce Coastal Floodplains ... 170

6.6.3 Use in Evolving Coastal Floodplains ... 171

6.7 Rapid Appraisal Tool: Approach and Model Limitations ... 173

6.7.1 Quasi-2D SPR Modelling Approach ... 173

6.7.2 Quasi-2D SPR Model Application ... 174

6.7.3 Bayesian Network Model Modelling Approach ... 175

6.7.4 Bayesian Network Model Application ... 176

7 Conclusions ... 179

7.1 Introduction ... 179

7.2 Achievement of Research Objectives ... 180

7.3 Directions for Further Research ... 184

7.3.1 Further Research: Quasi-2D SPR ... 185

7.3.2 Further Research: Bayesian Network Model ... 186

7.3.3 Further Research: Teignmouth and Portsmouth Coastal Floodplains ... 187

7.3.4 Further Research: Integrated Systems Analyses of Coastal Floodplains ... 188

References ... 191

Appendices ... 221

Appendix 1: Model-builder for Quasi-2D SPR 223
Appendix 2: Bayesian Network Node Equations for Teignmouth.....225
Appendix 3: Bayesian Network Model Equations and Inputs for Portsmouth 231
Appendix 4: Example Programme Code for Bayesian Networks in Netica 249
Appendix 5: Peer-reviewed Journal Publications 253

List of tables

Table 1: Chapters 3-6 and their corresponding Objectives (see Section 1.3)..... 7

Table 2: Quasi-2D SPR Application Sites (N Nested site; * Discussed in this thesis) 48

Table 3: Summary of Quasi-2D SPR Applications in Poland, France and England75

Table 4: Quasi-2D SPR Evaluation: Feedback from Site Applications (✓ Achieved; ○ Partially achieved; X Not achieved) 76

Table 5: Quasi-2D SPR Evaluation (based on Kelly et al. 2013) ('✓': easy; 'o' : possible but difficult; 'X': not possible) 86

Table 6: Conditional Probability Table for Node Seawall in Figure 21 91

Table 7: Comparison of flood probabilities between BN model and conventional model calculations 101

Table 8: Teignmouth Network Mode: Node Descriptions 114

Table 9: Teignmouth Network Model: Equations (EurOtop Manual, 2007) (also see Appendix 2) 116

Table 10: Input parameter values for overtopping validation calculations 119

Table 11: Teignmouth Network Model: Flood Extent Simulations 121

Table 12: Teignmouth Network Model: Uncertain Input Simulations ((B) – Baseline simulation) 124

Table 13: Portsmouth Model: Node Equations and Descriptions (also see Appendix 3) 143

Table 14: Comparisons with Portsmouth Network Model 144

Table 15: Network Model Evaluation: Comparison with EA IFMs and LISFLOOD Models 150

Table 16: SPR Network Models: Comparison with EA IFMs and LISFLOOD Models (✓ Possible; × Not Possible) 159

List of figures

Figure 1: Procedural flow-chart for a typical coastal flood risk study (adapted from Sayers et al. (2002b) 9
Figure 2: Common methods and models in flood risk studies 16
Figure 3: The DPSIR Framework for systems analyses 17
Figure 4: The SPRC conceptual model (adapted from FLOODsite Consortium, 2009b) 18
Figure 5: Nesting of SPRC model in the DPSIR framework (adapted from Evans et al., 2004) 19
Figure 6: Translation of SPR Conceptual Model to Risk Components 20
Figure 7: SPR Model Conceptualisation of Risk Assessment Process 21
Figure 8: Relationship of SPR model to flood risk propagation (In Equation: R is the flood risk, P_f is the probability of flood defence failure and E(D) is the expected damage) (reproduced from LWI Technical University, 2013) 22
Figure 9: Land-use Map for Quasi-2D SPR system diagram 50
Figure 10: Quasi-2D SPR System Diagram 51
Figure 11: Flowchart for Quasi-2D SPR Construction 52
Figure 12: Location, Land-use Map and Quasi-2D SPR for Hel Peninsula, Gdansk, Poland 55
Figure 13: Land-use Map for Gironde Estuary Quasi-2D SPR 58
Figure 14: Quasi-2D SPR for Gironde Estuary 59
Figure 15: Land-use Map for Medoc Quasi-2D SPR 61
Figure 16: Medoc Quasi-2D SPR 62
Figure 17: Location, Land-use Map and Quasi-2D SPR for the Teign Estuary, Devon, England 64
Figure 18: Land-use map for the Teignmouth Quasi-2D SPR 67
Figure 19: Quasi-2D SPR for Teignmouth, Devon, England 68
Figure 20: Bayesian network example of basic coastal floodplain 89
Figure 21: Description of example node in floodplain network 90
Figure 22: Network, nodes and CPTs of illustrative example floodplain 94
Figure 23: Quasi-2D SPR and Bayesian Network for illustrative example floodplain 97

Figure 24: Estimated flood probabilities of nodes in illustrative example floodplain network 101
Figure 25: Schematic showing differences in flood sources, pathways and receptors for Teignmouth and Portsmouth floodplains.......... 104
Figure 26: Map of Teignmouth indicating floodplain extent and areas of interest in Quasi-2D SPR 106
Figure 27: Quasi-2D SPR for Teignmouth (reproduced from Figure 19 in Chapter 3) 108
Figure 28: Teignmouth Bayesian Network... 111
Figure 29: Comparison of Teignmouth Network Model and EA Indicative Flood Maps (Environment Agency, 2013a) for a 1 in 1000 year ESWL (3.46 m) assuming no defences 118
Figure 30: Comparison of data and BN model results for mean overtopping rates over time at node ‘Seawall Rly2’ 120
Figure 31: Teignmouth Network Model Predictive Flood Extent Simulation .. 122
Figure 32: Open-coast flood pathways in Teignmouth network model 125
Figure 33: Flood probabilities for all open-coast flood pathways for Case 6 in Table 12 126
Figure 34: Node-state probabilities for Nodes Seawall 1972 and Seawall 1991127
Figure 35: Node-states for Teignmouth flood pathways along Seawall 1972 and Seawall 1991 128
Figure 36: Overtopping rate probabilities at node Seawall_72 for different Sediment Input cases, for a fixed ESWL of 3.28 m. 130
Figure 37: Standard deviation and run-time versus number of samples for node 'TeignFP_West' in Teignmouth network 132
Figure 38: Portsmouth, England: Location 135
Figure 39: Land-use Map for Portsmouth Quasi-2D SPR 137
Figure 40: Portsmouth Quasi-2D SPR (built using GIS Software) 138
Figure 41: Portsmouth Model: Bayesian Network 139
Figure 42: Portsmouth Model: Example Urban Area Node 142
Figure 43: Portsmouth Flood Extent Comparisons: Network Model and EA IFMs145
Figure 44: Portsmouth Flood Extent Comparisons: Network model and LISFLOOD Model (50 m) 147
Figure 45: Portsmouth Flood Extent Comparisons: Network Model and LISFLOOD Model (50 m) 148

Figure 46: Example Portsmouth flood pathway with probabilistic ESWL inputs (no SLR scenario) 153
Figure 47: Node-states versus node-state probabilities for probabilistic ESWL and SLR inputs for example flood pathway in Figure 46 (top – No SLR; bottom – normally distributed SLR with a mean of 0.6 m and standard deviation of 0.09) 154
Figure 48: The Rapid Appraisal Tool for Coastal Floodplains 160
Figure 49: Positioning of Rapid Appraisal Tool within Flood Risk Study Process163
Figure 50: Algorithm for Multiple Cycles of SPR Conceptual Model Analyses 165
Figure 51: Using the Rapid Appraisal Tool for Down-scaling Floodplain State Descriptions within the DPSIR Framework 172
Figure 52: Example model-builder for quasi-2D SPR 223

DECLARATION OF AUTHORSHIP

I, SIDDHARTH NARAYAN, declare that this thesis and the work presented in it are my own and have been generated by me as the result of my own original research.

A Conceptual Model and Rapid Appraisal Tool for Integrated Coastal Floodplain Assessments

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as detailed on the following page.

Signed: Siddharth Narayan

Date: January 16th 2014

Peer-Reviewed Journal Publications (see Appendix 5)

Narayan, S., Nicholls, R. J., Clarke, D., Hanson, S., Reeve, D., Horrillo-Caraballo, J., le Cozannet, G., Hissel, F., Kowalska, B., Parda, R., Willems, P., Ohle, N., Zanuttigh, B., Losada, I., Ge, J., Trifonova, E., Penning-Rowsell, E., and Vanderlinden, J. P.: The SPR systems model as a conceptual foundation for rapid integrated risk appraisals: Lessons from Europe, Coastal Engineering, http://dx.doi.org/10.1016/j.coastaleng.2013.10.021, 2013.

Narayan, S., Hanson, S., Nicholls, R. J., Clarke, D., Willems, P., Ntegeka, V., and Monbaliu, J.: A holistic model for coastal flooding using systems diagrams and the source - pathway - receptor (SPR) concept, Nat. Hazards Earth Syst. Sci, 12, 1431-1439, 2012.

Monbaliu, J., Chen, Z., Felts, D., Ge, J., Hissel, F., Kappenberg, J., Narayan, S., Nicholls, R.J., Ohle, N., Schuster, D., Sothmann, J., Willems, P.: Risk assessment of estuaries under climate change: Lessons from Western Europe, Coastal Engineering, http://dx.doi.org/10.1016/j.coastaleng.2014.01.001, 2014.

Conference Publications and Abstracts

Narayan, S., Kebede, A. S., Nicholls, R. J., Clarke, D., le Cozannet, G., and Hissel, F.: An investigation of scale issues using a conceptual systems model, FLOODrisk 2012, p38, Rotterdam, Netherlands, 2012.

Narayan, S., Nicholls, R. J., Trifonova, E., Filipova–Marinova, M., Kotsev, I., Vergiev, S., Hanson, S., and Clarke, D.: Coastal habitats within flood risk assessments: Role of the 2d spr approach, Coastal Engineering Proceedings, 1, management. p12, Santander, Spain, 2012.

Narayan, S., Nicholls, R., Clarke, D., and Hanson, S.: Investigating the source - pathway - receptor - consequence framework for coastal flood systems, ICE Coastal Management 2011, p22-31, Belfast, 2011.

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Abbreviations and Glossary

ABM: Agent Based Model; a modelling approach that simulates a system in terms of individual, interacting agents and their behaviour.

AEP: Annual Exceedance Probability; refers to the probability that a flood event of a given magnitude will occur (or be exceeded) in any year. The probability is expressed as a percentage.

ANN: Artificial Neural Network; a modelling approach that uses artificial 'neurons' for analysing large datasets, based on neurological principles.

BN: Bayesian Network; a graphical network of nodes and links that uses the rules of Bayesian probability theory to represent the dependencies between these nodes in terms of their factorised probability distributions. The term is also used to refer to the modelling approach that uses these networks to simulate the behaviour of a system.

CCM: Coupled Component Models; a numerical modelling approach that couples multiple models together to study a system.

CPT: Conditional Probability Table. A table that holds all possible values for each state of a node in a Bayesian Network mapped to the corresponding states of its parent nodes.

DAG: Directed Acyclic Graph. A graph of nodes connected by links, such that all links have a direction and there exists no link-path by which a node may be traced back to itself.

DPSIR: The Driver – Pressure – State – Impact – Response conceptual framework used to describe the components of a system.

ESWL: Extreme Still Water Level. Defined in this study as the sum of tide and storm surge, expressed as an absolute value (m).

IFM: Indicative Flood Map. The flood maps produced by the Environment Agency, UK, indicating areas at risk of flooding for specific flood events (generally a 1 in 1000 year and a 1 in 200 year ESWL)

JPM: Joint Probability Methods. JPMs refer to a class of methods for the analyses of the probability of the joint occurrence of multiple random variables.

PDF: Probability Density Function. The probability density function of a random variable is a function that describes the relative likelihood that this variable will take on a given value.

SD: System Dynamics; a numerical modelling approach used to simulate the dynamic changes to different parts/processes of a system.

SLR: Sea-level Rise, expressed as an absolute value (m). Means the same and is used interchangeably in this study with RLSR (Relative Sea-level Rise) which includes local geostatic or subsidence.

SPRC: The Source – Pathway – Receptor – Consequence conceptual model that describes the components of a pollution risk or flood risk assessment.

Component: A unique entity of a system. Used interchangeably with Element, when describing the coastal floodplain.

Coastal Floodplain: The region of the coastal zone that can potentially be flooded due to a defined coastal flood event.

Coastal Manager: An authority and/or expert with sufficient knowledge about coastal systems, coastal engineering and the principles of flood risk, responsible for flood and erosion risk management in a coastal floodplain.

Conceptual Framework: A conceptual description of the basic structure of a system – in this context the coastal floodplain, which allows further descriptions of the system, and operations on this description. Used interchangeably with '**Conceptual Model**'.

Down-scaling: The process of reducing the scale (increasing the fine-ness of representation) of a model, an analysis process, or its outcomes

Driver: An agent that causes/drives changes to the inputs at the boundaries of a system, e.g., global climate change is a driver that causes changes to sea-levels at the boundary of a coastal system.

Duration-dependent: Used to describe a process whose outcome depends on the total length of time within which the process occurs – the process itself may be dynamic or static.

Dynamic: Used to describe a time-varying process, or a numerical model that uses time-steps.

Element: A unique component of a system; in this work, a unique physical component of a coastal floodplain. An element in a floodplain system is equivalent to a node in a floodplain network (see **Node**).

Flood Risk: Defined as the product of the probability of a flood event and the negative consequences of that event to assets within the floodplain. In this work, Flood Risk is used interchangeably with Coastal Flood Risk since only coastal flood events are discussed here.

Integrated Assessment: In the context of this work, an integrated assessment refers to an assessment where knowledge and data from multiple fields and disciplines (e.g. artificial structures, coastal ecology, coastal morphological features, etc.) are integrated within the assessment.

Linear description: In this context, a one-dimensional description of the relationship between the elements of a system

Link: A description of a connection between two nodes of a network, or two elements of a system. The connection may be physical or otherwise, though in the context of this study, almost all links refer to a physical connection.

Network: A graphical representation of several components that are connected to one another through links.

Node: A component of a network, generally representing a variable or constant. A node in a floodplain network is equivalent to an element in a floodplain system.

Pathway: In this context, a route through which a flood wave may propagate from a source. (e.g. a Seawall over which overtopping occurs).

Pressure: A forcing acting on a particular part of a system that may be influenced by a set of Drivers, e.g., Sea-level-rise is a pressure on a coastal system, influenced by drivers e.g. climate change and subsidence.

Qualitative model: A model that does not provide any numerical or quantitative information in its description of the system

Quantitative model: A model that provides some sort of numerical information in its description of the system

Quasi-2D: In this context, a description of a system that preserves the topology and spatial relations of the components of a system (or network) though it may not be a fully 2D description.

Rapid Appraisal Tool: In this context, a tool and methodology by which conceptual and quantitative descriptions of a coastal floodplain system can be rapidly built.

Raster: A numerical modelling representation that divides the model domain into a grid of regular, usually rectangular or square units, or cells.

Receptor: in this context, an element of the system (or node of the network) that receives a flood wave, from one or more sources, through one or more pathways, with certain consequences.

Scaling: The process of choosing the scale of an analysis. (also see up-scaling and down-scaling)

Scoping Tool: A tool (or methodology) with which to assess the sensitivities and behaviour of a system to changing conditions (e.g. changes in input conditions or system state). Used interchangeably with **Rapid Appraisal Tool**.

Source: In this context, the source of flood water (e.g. an extreme water level at the shoreline). Used interchangeably with Flood Source.

Static: Used to describe a process that is not time-varying, or a numerical model that does not use time-steps.

State: The physical description of the components of the system or network, in this work described at snapshots in time. For instance, the state of a seawall may be described on the basis of the overtopping volumes at the seawall.

System: A collection of components that interact with one another as a coherent whole. The term is used inter-changeably with Network.

Systems Diagram: A graphical description of the components of a system, usually expressed as elements with connecting links.

Up-scaling: The opposite of down-scaling: the process of increasing the scale (reducing the fine-ness of representation) of a model, analysis process, or its outcomes.

1 Introduction

1.1 Coastal Flooding and Floodplain Systems

Coastal flood disasters are the costliest natural disasters of the last decade (Kron, 2013). Extreme events like Typhoon Haiyan in the Philippines (BBC, 2013), Cyclone Phailin in India (BBC, 2013), Hurricane Sandy (Schultz, 2013) in the US and Storm Xavier in Northern Europe (Climate Central, 2013), demonstrate that it is impossible to completely control or prevent damage due to such disasters. While the likelihood of coastal flood damage will increase in several places due to relative sea-level rise in the near and long-term future (e.g., IPCC, 2013, Brown et al., 2014) coastal zones are, and will remain, focal points for human settlement (McGranahan et al., 2007, Lichter et al., 2010). The drivers of coastal flood risk are multiple and wide-spread. Understanding and managing this flood risk is therefore a matter of urgent concern to local, and national, decision-makers and authorities (Hall et al., 2003a, Hall et al., 2006).

Even where there are excellent models and tools for event prediction and forecasting, damage during an extreme flood event still occurs to varying degrees (e.g., Kolen et al., 2010, Seed et al., 2008, European Commission, 2007). Forensic analyses of recent extreme flood events and local preparedness highlight multiple challenges to the management of coastal flood risk (e.g., Seed and Bea, 2006, Narayan et al., 2012a). A significant challenge to effective risk management lies in integrating the multiple aspects of the coastal floodplain that require management.

Coastal floodplains form the interface between human, physical and natural systems which are in turn influenced by multiple natural (Friess et al., 2012, Gibson et al., 2007) and human-induced pressures and drivers (Hallegatte et al., 2013, Nicholls and Klein, 2005). They sometimes span large areas crossing administrative and geo-political boundaries and are often managed by different authorities (de Moel et al., 2009, EXCIMAP, 2007). Integrated risk management studies of coastal floodplains therefore need to treat these floodplains as regions of interacting physical, socio-economic and ecological systems (Hanson et al., 2012, Mokrech et al., 2008, Safecoast, 2008). Further, studies that assess flood risk at national and continental scales need methods to integrate analysis and understanding of coastal floodplains across multiple spatial and temporal scales (Dawson et al., 2009, Hall et al., 2005a, Pitt, 2008a, Evans et al., 2004).

A typical flood risk study involves assessment of a) the sources of flooding; b) the potential pathways (or barriers) that influence the propagation of flood waters, and c) the receptors of inundation damage. Data and information on these aspects of flood risk are available in different forms and often held by different authorities: for instance in the UK data and statistical information on flood source water levels and wave heights may be held by regional monitoring programmes (Channel Coastal Observatory, 2013); data about structural coastal flood defences may be obtained from national databases (Environment Agency, 2013c); data and information about floodplain inundation may be obtained from historic observations (Ruocco et al., 2011) or numerical inundation models (Bates et al., 2005). In addition integrated flood risk assessments may include numerical models of other relevant floodplain elements such as coastal morphology and ecology. As a result many of the larger flood risk studies that assess coastal floodplains at national and continental scales involve several experts, use detailed numerical models and can run for several years (e.g., Safecoast, 2008, THESEUS Consortium, 2009). The outputs of these studies are tailored for use by coastal managers usually in the form of guidelines that provide information on the coastal floodplain (Safecoast, 2008) or tools that can be used by managers to obtain a basic understanding of their coastal floodplain (Mokrech et al., 2011).

Developing a basic understanding of a complex system such as the coastal floodplain requires as its starting point a comprehensive conceptual description (Robinson, 2007). At present the conceptual models of most flood risk studies are used to communicate the concept of flood risk and the process of flood risk assessment to the end-users (FLOODsite Consortium, 2007a). In these models the flood system is described in terms of 1) the flood sources; 2) the flood defences that prevent or reduce the ingress of flood water and; 3) the floodplain behind these defences comprising all features considered to be at risk from flooding (e.g., Oumeraci et al., 2012), FLOODSite Consortium, 2009a, Sayers et al. 2002b). This model facilitates consensus on the implemented process of flood risk assessment amongst experts and communicates the concept of flood risk effectively to end-users. However, the model does not fully describe the elements of the coastal floodplain that are assessed by subsequent numerical models. At present integrated flood risk studies do not build or use descriptive conceptual models of the coastal floodplain. Rather, there is a bias towards the direct use of detailed numerical models for the various aspects of the coastal floodplain system. These studies will benefit significantly from a conceptual model that can inform the use of subsequent numerical models.

1.2 Problem Statement

Managing and adapting coastal floodplains to extreme flood events is an increasingly relevant and immediate concern to coastal managers and decision-makers world-wide. A typical coastal floodplain comprises several interacting human and natural elements. These systems interact with internal and external drivers and pressures across multiple spatial scales, may extend across administrative and geo-political boundaries and are often managed by multiple authorities. Effective preparedness of a floodplain for extreme flood events therefore requires structured and integrated understanding of all its elements and their interactions. The knowledge, data and information required for this understanding are often spread across disparate sources. Coastal flood risk studies that assess floodplains across multiple scales, and consider the influence of diverse elements therefore need to use specific numerical models and analysis techniques for the different floodplain elements.

At present, the conceptual models of integrated flood risk studies focus on describing and communicating the process of flood risk assessment amongst the researchers and end-users. These models though effective in communicating the concept of flood risk do not fully describe the different elements of the coastal floodplain. There are currently no conceptual models for flood risk studies that facilitate comprehensive and integrated descriptions of the coastal floodplain at the start of the study. Given the complexity to which these studies analyse the floodplain system and the disparate nature of information and data on the various elements of the floodplain system a descriptive conceptual model will help inform, target and prioritise the use of further numerical models. Building a conceptual description of the floodplain will also facilitate the active participation of experts and end-users, ensuring a) that they benefit from the conceptual understanding of the floodplain gained through the process of conceptual model development, and b) that their expert knowledge on the coastal floodplain is captured and used in the later stages of the study.

One important issue increasingly recognised throughout the course of this work is scale. The multiple spatial scales across which natural and human coastal systems operate have been recognised and studied in the field of coastal geomorphology (e.g., Cowell et al., 2003, Stive et al., 2011). For coastal flood risk assessments the ‘Risk Assessment of Flood and Coastal Defences for Strategic Planning (RASP)' study applies a methodological conceptual framework (HR Wallingford and University of Bristol, 2004, Hall et al., 2003a). The RASP study introduces the notion of systems analyses at progressive scales using the Source – Pathway – Receptor – Consequence (SPRC) approach. This approach formalises the traditional description of the flood system in terms of flood sources, pathways and receptors as described in Section 1.1. A priority recommendation from the RASP study was the extension of the existing conceptual framework to a full system description of the coastal floodplain to include other floodplain elements such as coastal morphological elements and inland floodplain features that also act as flood pathways or barriers. Achieving this description at multiple scales requires a shift from an approach-based conceptual model to a descriptive conceptual model that can fully describe the elements of the coastal floodplain at multiple scales.

This thesis extends the RASP methodology to a scalable and progressively detailed description of the coastal floodplain as a system of inter-linked floodplain elements. This description has evolved in this work – starting from an existing linear non-spatial schematisation of the coastal floodplain (Evans et al., 2004) to a spatially descriptive systems diagram (Narayan et al., 2012a), and finally, an explicitly defined quasi-2D qualitative and quantitative model that is applied and tested across a range of coastal floodplains (Narayan et al., 2013).

Another aspect of scale recognised in the development of the conceptual model in this thesis is the issue of resolution when quantifying the role of individual floodplain elements as flood pathways. For instance an urban coastal floodplain may have relatively small, linear features such as coastal defences and roads that nevertheless considerably influence flood propagation and often need to be manually included within numerical inundation models (Battjes and Gerritsen, 2002). A conceptual model that can map and quantify the role of such features will provide useful information when constructing subsequent numerical models.

1.3 Research Aims and Objectives

The overall aim of this work is to develop a rapid, comprehensive conceptual model and appraisal tool to help structure systems understanding of the floodplain within flood risk studies and inform decision-making for strategic flood risk management.

This comprises the development of a scoping tool for large and complex floodplains to provide rapid, strategic assessments. The scoping tool will be designed to critically assemble knowledge of the floodplain. It will hence inform, target and prioritise subsequent more detailed numerical model applications.

This aim is achieved through the following objectives:

1. ***Develop a generic, scalable qualitative model*** built by a participative process for describing any coastal floodplain as a system of interacting human and natural elements.
2. ***Apply and test the qualitative model*** across a range of coastal floodplain systems and across multiple scales as a formalised and descriptive conceptual foundation for a quantitative assessment model.
3. ***Develop a quantitative model*** of key floodplain elements and their behaviour. This will provide rapid integrated assessments of floodplain response to changes in input conditions and states of floodplain elements.
4. Apply and test the ***quantitative model*** for rapid appraisals to two contrasting coastal floodplains. This will provide a quantitative description of the existing state of the floodplains and identify key flood pathways and flood probabilities.

5. Evaluate the combined use of the qualitative and quantitative models as ***a rapid appraisal tool for integrated assessments of coastal floodplains.*** This will provide a systems understanding of the floodplain and identify knowledge gaps. This information can then be used to target further data-gathering and/or numerical modelling exercises.

1.4 Thesis Structure

This thesis consists of 7 chapters. Chapters 3 to 1 describe the work done to achieve the research objectives defined in Section 1.3 (Table 1). Chapter 2 describes the process of a coastal flood risk assessment and discusses the role and use of conceptual models and numerical models within this process. This review identifies the need for a descriptive conceptual model for coastal floodplains that reflects the floodplain state descriptions used in numerical models. The first part of Chapter 3 describes the development of a new descriptive conceptual model – the quasi-2D SPR, in line with Objective 1 in Section 1.3. The second part of Chapter 3 applies the quasi-2D SPR model to 8 European coastal sites. It evaluates the advantages and limitations of the quasi-2D SPR as the foundation for a rapid quantitative assessment model. Chapter 4 discusses Objective 3 – the development of a quantitative model for assessing coastal floodplains as integrated systems using the descriptions provided by the quasi-2D SPR. Chapter 5 applies the quantitative model – a Bayesian network model – to two contrasting coastal floodplains and evaluates network model performance in both floodplains. The combined use of the qualitative and quantitative models as a rapid appraisal tool (Objective 5 in Section 1.3) is discussed in Chapter 6. Chapter 7 reviews the achievements of this thesis and provides directions and suggestions for further work.

Table 1: Chapters 3-6 and their corresponding Objectives (see Section 1.3)

Chapter Number	Chapter Description	Objectives
3	Qualitative Model: Selection of Modelling Approach, Development, Application and Evaluation	1 and 2
4	Quantitative Model: Selection of Modelling Approach and Model Development	3
5	Quantitative Model: Model Application and Evaluation	4
6	Rapid Appraisal Tool: Discussion and Evaluation of the combined use of the two models	5

2 Literature Review: Challenges to Effective Integrated Flood Risk Management

2.1 Introduction

This chapter reviews the process of risk assessment for coastal floodplains within flood risk studies. The aim of a coastal flood risk study is to analyse and investigate the nature of flood risk within a coastal floodplain. Coastal flood risk studies typically follow a five-step process as shown in Figure 1. The first step is defining the flood risk problem and the boundaries of the floodplain. This is followed by the development of a conceptual model that invariably describes the process of risk assessment. The next step is the collection of data for the numerical model inputs followed by application of these models to estimate flood propagation and flood risk within the floodplain. The results of these models are used to create flood risk maps and other outputs designed to communicate information regarding floodplain flood risk to the end-users. Often, the numerical models developed and applied within a flood risk study are also key outputs of the study.

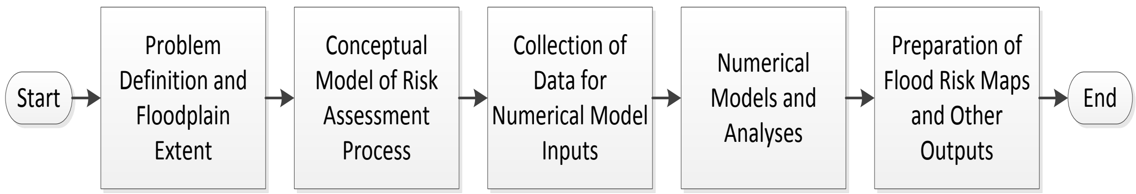

Figure 1: Procedural flow-chart for a typical coastal flood risk study (adapted from Sayers et al. (2002b)

The first section of this chapter, Section 2.2, provides a brief introduction to the concept of risk and the components of flood risk before discussing the steps of a typical flood risk study. Section 2.3 discusses the evolution, motivation and types of integrated risk-based approaches for mitigating flood damage in coastal floodplains due to extreme flood events. The following sections synthesise current numerical and conceptual treatment of coastal floodplains within a typical coastal flood risk study. Section 2.4 first describes the current conceptual models and frameworks used in flood risk studies and how these are used to conceptualise the subsequent numerical models and their inputs. Section 2.5 then describes these numerical models. Section 2.6 describes the outputs and intended uses from these numerical models. Section 2.7 then reviews some lessons and challenges for flood risk management highlighted by recent extreme flood events. Finally, Section 2.8 concludes by discussing the need for an integrated, descriptive conceptual model of the coastal floodplain system.

2.2 Estimation of Risk in Coastal Flood Risk Studies

The term “risk” is defined by the Oxford English Dictionary to mean “the exposure of an individual or asset of value to danger, harm, or loss” (Oxford University Press, 2012). The numerical estimation of risk facilitates a rational and transparent approach to decision-making in the face of uncertainty. Moreover it provides methodologies for weighing the desirability of different actions and informing future policies to help select the ‘most desirable’ actions. Engineering disciplines generally express risk as a function of the probability of a hazard (a damaging event) and its negative consequences (Cline, 2004).

$$Risk = P(h) \times C \tag{1}$$

In coastal flood risk studies a ‘hazard’ refers to a coastal flood event defined here as an event where the water levels and/or wave heights at the boundary of the floodplain exceeds the expected ‘normal’ water level. The negative consequences of a flood event can range from disruption of industrial and business services to destruction of life and property. In such cases the flood event is a hazard – and poses a flood risk – to the individuals and assets potentially harmed. Most estimation methods unpack Equation (1) into the following components (Gouldby and Samuels, 2005):

1. The *probability* of occurrence of a flood event (e.g., a storm event with a certain return period)
2. The *exposure* of assets to the flood event (e.g., the number or extent of assets exposed to flooding by a storm)
3. The *susceptibility* of an exposed asset to harm by a flood event (e.g., the structural damage to a building due to a given flood depth)

4. The *value* of a harmed asset (e.g., the economic value of the structural damage to a building)

Thus,

$$Flood\ Risk = f(probability, exposure, susceptibility, value) \tag{2}$$

The term P*(h)* in Equation (1) relates to the terms probability and exposure in Equation (2). The probability of a flood event at the floodplain boundary is a function of the input hydraulic conditions at the boundary of the floodplain. The exposure of the floodplain to this event is a function the state and performance of any intervening flood defences and the topography of the floodplain (Kron, 2005). The consequence of a flood event, as described in Equation (1) is a function of the latter two components of Equation (2) i.e., susceptibility and value. Susceptibility is generally estimated using observations and knowledge on how exposed assets respond to a particular flood event i.e., the structural response of an inundated hospital to a given depth of flooding or hydraulic loading (Pistrika and Jonkman, 2010). Susceptibility could also include a measure of the effect of inundation on services provided to the hospital such as electric power (Kazmierczak and Kenny, 2011). The term 'vulnerability', though not used in this definition, can be understood as a function of the susceptibility of an element and its value, taken together with the element's ability to resist/recover from flood damage (Gouldby and Samuels, 2005, Romieu et al., 2010).

The value of damage due to flooding is generally considered in terms of direct costs such as physical damage to assets and disruption of production processes, indirect costs such as induced damages to services or processes and intangible costs that refer to damages to goods and services that cannot be expressed in monetary terms, such as long-term health impacts, impacts to ecosystems, or impacts to cultural heritage (Markantonis et al., 2012). The components susceptibility and value are often expressed in flood loss models in terms of depth-damage (also called stage-damage) curves that relate a specific asset types to specific damage costs, for a given flood depth (Kreibich et al., 2005a, Penning-Rowsell et al., 2005). The benefits of risk reduction measures are then usually evaluated in terms of the avoided costs due to implementation of a measure, as a result of reducing the probability of inundation of the floodplain, or as a result of reducing the cost of damage due to flooding (e.g., Meyer et al., 2012, de Moel et al., 2013).

Equation (2) expresses the risk of flooding from a single flood event. However most flood risk assessments use a probability distribution of multiple flood events to estimate an average annual risk of flooding (e.g. Evans et al., 2006, Hall et al., 2008). This risk may be expressed directly in terms of an expected annual damage R, given by,

$$R = \int_0^{y_{max}} p(y).D(y)dy \qquad (3)$$

where, y_{max} is the greatest flood depth from all considered cases, p(y) is the Probability Density Function (PDF) for flood depth y and D(y) is the damage in that area for a flood depth of y m (Hall et al., 2005a). D(y) is generally expressed in the form of depth-damage curves that relate the depth of flooding to a level of damage for a certain structure or land-use classification (Penning-Rowsell et al., 2005). The flood depth y is a function of the hydraulic loads at the floodplain boundary and the characteristics of the floodplain defences and topography. The PDF of y is the probability distribution of flooding resulting from all flood events expected to occur. Assuming that the characteristics of the floodplain defences and topography are fully known the PDF of y relates to the probability distribution of a defined set of hydraulic loads at the floodplain boundary. Thus given a probability distribution of hydraulic loads at the boundary, information on the flood defences and topography and a depth-damage curve the average annual damage R can be calculated for any floodplain. However this equation assumes no spatial variation in the manner and extent of flood propagation within the floodplain.

A floodplain with multiple and differing hydraulic loads, flood propagation pathways and floodplain elements can show variations in the average annual flood damage depending on the location. To resolve this flood risk assessments treat the floodplain as consisting of multiple flood compartments with each compartment having a specific value of R (e.g. Lhomme et al., 2008, Sayers et al., 2005). The total average annual damage for the floodplain is therefore obtained by summing the R values for all its flood compartments. An important implication of this is the expression of a spatial distribution for risk within the floodplain. The recognition of the spatial distribution of flood risk becomes relevant when analysing the relative contribution to risk of different flood pathways.

In this manner Equation (3) provides a comprehensive method of integrating the four components of Equation (2) – probability, exposure, susceptibility and value over multiple flood events and for spatially distinct flood compartments for a given floodplain. Flood risk conceptual models and frameworks describe the risk assessment process in terms of the four components of Equation (2). This thesis focuses on the first two components of risk in Equation (2) i.e., the probability of the flood event and exposure of floodplain assets.

2.3 Evolution of Integrated Risk-based Approaches for Coastal Floodplains

The management and mitigation of damage due to flooding in coastal zones is increasingly using risk-based approaches in order to make rational and effective decisions that consider all relevant aspects of flood risk mitigation. A risk-based flood management policy implies the allocation of available resources for reduction of flood risk in the most cost-efficient manner (Sayers et al., 2002a). Many of these policies have been catalysed by natural disasters. The 1991 cyclone in Bangladesh was a catalyst for the construction of several cyclone shelters in vulnerable areas, resulting in a significant reduction of loss of life during subsequent cyclone seasons (Agrawala et al., 2003). In the UK, the floods of 1998 and 2001 gave impetus to the shift towards new risk-based policies for flood disaster management (Johnson et al., 2005). In their evolution from more deterministic approaches these policies have therefore often focused on the protection of human and artificial coastal assets. For instance flood management measures in Bangladesh focus on urban areas where the population is most vulnerable and the consequences of damage greatest (Samuels et al., 2006). Flood defences in the Netherlands have traditionally been designed on the basis of the ‘highest recorded flood levels’, with greater expenditure typically invested in the defence of more economically valuable areas (Battjes and Gerritsen, 2002).

The use of risk-based approaches has resulted in the increasing recognition of the role and value of natural coastal elements in flood risk reduction. For instance, the Mississippi floods of 1993 in the USA triggered a move towards more comprehensive floodplain management and planning at the state and local levels and a greater focus on natural resources (Johnson et al., 2005, Batker et al., 2010). Similarly the devastating summer floods of 2002 in central Europe were a major catalyst for the enforcement of the EU Floods Directive (2007/60/EC) that requires all member states to carry out an assessment and mapping of their risk from flooding (Klijn et al., 2008, Socher and Böhme-Korn, 2008). In addition to human assets the EU Floods Directive requires member states to list and map all natural coastal habitats that are at risk of flooding and assess the value of the ecosystem services they provide. This includes the mapping of knock-on effects such as pollution runoff due to flooding (The European Commission, 2007).

From a broader perspective risk-based approaches emphasise a more holistic understanding and management of the risk of flooding in terms of both the probability of an event as well as its consequences (e.g. Sayers et al., 2002c). As such, they provide a basis for decision-making in flood risk management that is based on rational and transparent cost-consequence analyses (e.g. Ten Brinke et al., 2008). In the past two decades, flood risk management approaches in many European countries have started looking further landward than their primary structural defence systems.

These approaches tend to consider solutions such as secondary defences, space allocation for flood water storage, adaptive building and pro-active spatial planning. Planning these solutions necessitates greater integration across different disciplines and greater involvement of a diverse range of stake-holders. Recognition of the need for integration of flood risk research and policies across disciplines and across administrative and political boundaries has resulted in a large number of regional and national scale flood risk studies in Europe and elsewhere (e.g., Ramsbottom et al., 2012, Oumeraci et al., 2012, CLIMSAVE Consortium, 2011, Environment Agency, 2013b).

Figure 2 illustrates through some examples of recent European flood risk studies the variety of methods and models for risk estimation conceptually mapped to the concepts of ‘probability’, ‘exposure’ and ‘susceptibility’ in Section 2.1. The nature of the models and methods used by these studies for flood risk estimation are strongly related to the scale of the overall study. Depending on its scope and available resources each study may use different data and methods for risk estimation. What is common across all these studies is the conceptualisation of the coastal floodplain in terms of the components of flood risk described in Section 2.1. The comprehensiveness and detail to which each component of risk is analysed is greatest for studies that are conducted at local-scales and have access to considerable data and computational resources. The diversity in the methods listed in Figure 2 is also true of the ‘value’ estimation step in these studies though this is not discussed here.

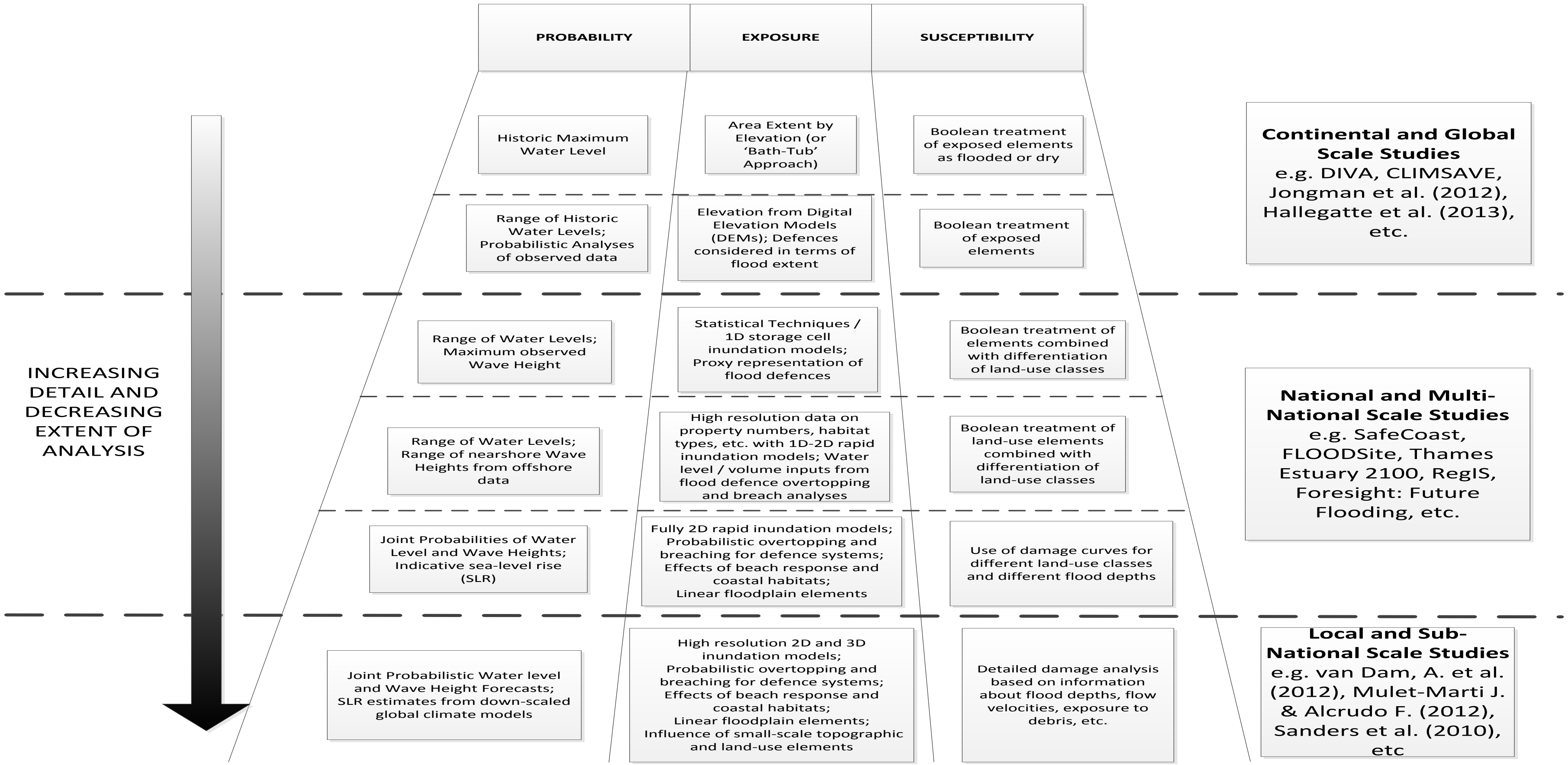

Figure 2: Common methods and models in flood risk studies (Sources: Evans et al., 2004; Klijn et al., 2008; Hervouet, 2000;Hinkel and Klein, 2009; Mokrech et al., 2008; Ramsbottom et al., 2012; Safecoast, 2008; Syme, 2001; The Environment Agency, 2012; van Dam et al., 2012; Mulet-Marti and Alcrudo, 2012; Jongman et al., 2012b; Hallegatte et al., 2013; Harrison et al., 2013; Sanders et al., 2010)

2.4 Conceptual Models and Frameworks in Flood Risk Studies

Most of the studies shown in Figure 2 are applied to risk assessments within coastal zones. The coastal zone itself is driven by external forces operating at a range of spatial and time-scales such as off-shore water levels and waves, climate change effects and human influences such as coastal zone management decisions and actions. The relationship of the coastal zone to these external pressures and drivers is generally described in these studies using larger-scale frameworks such as the suitably named Driver – Pressure – State – Impact – Response (DPSIR) framework (Figure 3) that allow conceptualisation of the dynamic relationships between the state of the coastal zone and the externally operating forces that drive this state (Kristensen, 2004).

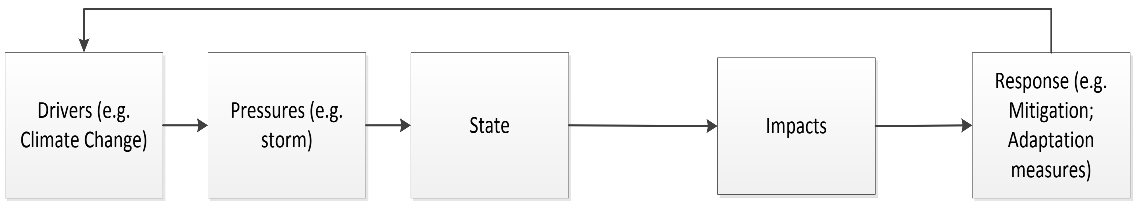

Figure 3: The DPSIR Framework for systems analyses

The specific aspect(s) of the coastal management problem being studied are generally described using separate more specific conceptual models that may or may not be nested within a larger conceptual framework and are also dependent on the scale of the analysis. For instance studies that analyse the cost-effectiveness of adaptation and mitigation measures at a global scale will use simple conceptual descriptions of the key components of their analyses to structure and communicate their methods (e.g., Hinkel et al., 2013, Jonkman et al., 2013). Similarly studies that primarily estimate the probability or risk of flooding for a given set of external forces may use a nested conceptual model to describe the state of the assessed floodplain.

With rapid developments in computational capabilities and data availability, new architectures and frameworks are emerging for enabling the coupling of several such numerical models (e.g., Harvey et al., 2012, Harvey et al., 2008). These architectures are however different to traditional conceptual models in that they do not, in themselves, describe the coastal system being assessed; rather they provide a means to organise and integrate the various models and analysis techniques within the study.

The communication of the concepts of flood risk and the flood risk assessment process still pose a challenge to the effectiveness of flood risk management (e.g., Sprague and Greiving, 2012, Terpstra, 2012). At present a common and effective conceptual model in coastal flood risk studies is the Source – Pathway – Receptor - Consequence (SPRC) model. The model visualises the process of flood risk propagation from a source of flood water, through a pathway – usually a structural coastal defence, to a receptor of flood damage, and further on, to the consequence, or value of this damage (Figure 4) (e.g., Burzel et al., 2012, FLOODSite Consortium, 2009a, North Carolina Division of Emergency Management, 2009, Bakewell and Luff, 2008). The model was first used in the environmental sciences to describe the movement of a pollutant from a source, through a conducting pathway to a potential receptor (Holdgate, 1979) and was first adapted for coastal flooding in the UK by the Foresight: Future Flooding study (Evans et al., 2004).

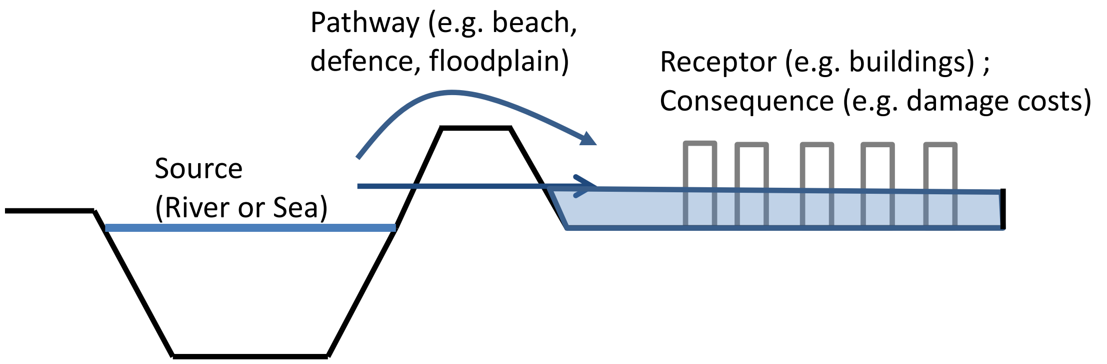

Figure 4: The SPRC conceptual model (adapted from FLOODsite Consortium, 2009b)

The SPRC model visualises the state of the floodplain in terms of flood risk propagation as a snapshot in time and is used by most of the flood risk studies mentioned in Figure 2, as a simple and effective way of communicating and achieving consensus on the flood risk assessment approach. In most of these applications the model is nested within a larger-scale framework such as the DPSIR (Figure 5).

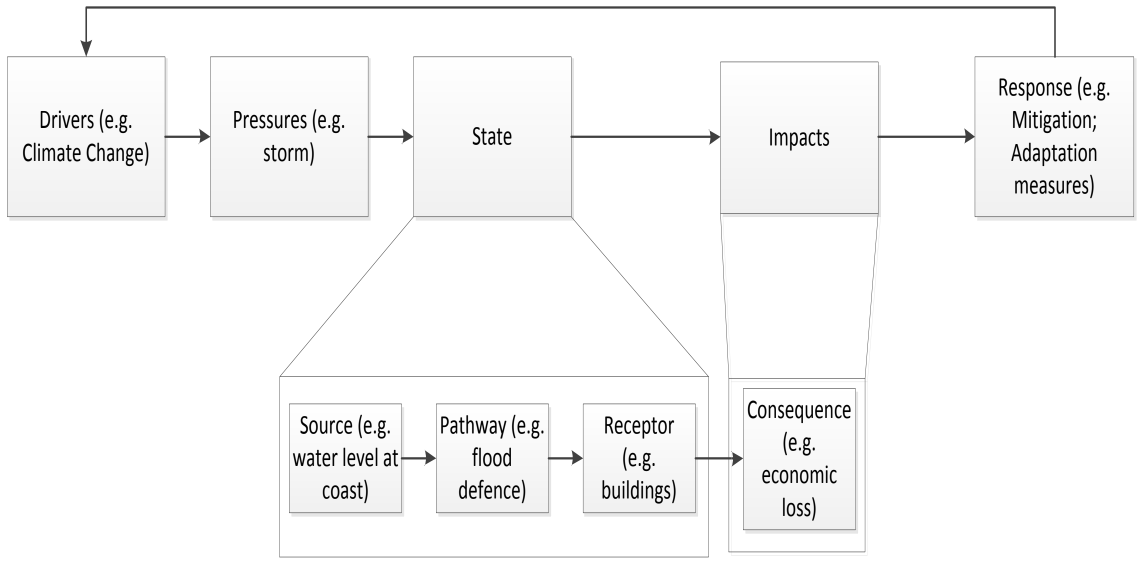

Figure 5: Nesting of SPRC model in the DPSIR framework (adapted from Evans et al., 2004)

Figure 5 shows the division between the 'State' of the floodplain in terms of Sources, Pathways and Receptors and the economic (or other) 'Impact' of this 'State' in terms of consequences. This work follows this division between the State and the Impacts and will henceforth discuss only the Source – Pathway – Receptor (SPR) model. This division also corresponds to the division between probability and consequence in the components of flood risk described in Section 2.2. The main reason for the effectiveness and popularity of the SPR model is the direct mapping of these terms to the components of the risk estimation process discussed in Section 2.12.2 (Figure 6).

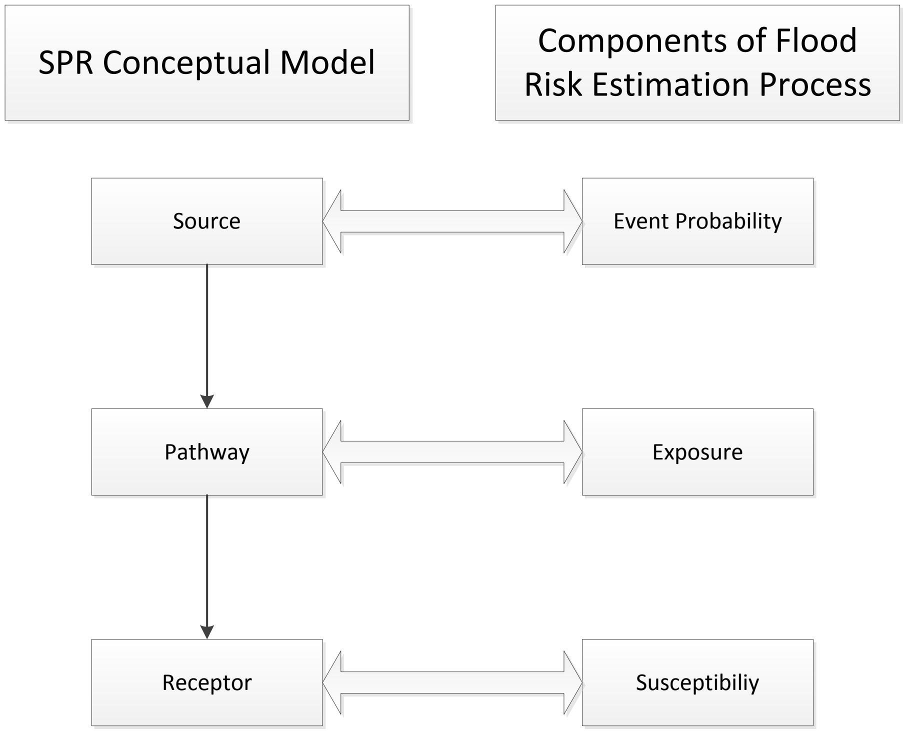

Figure 6: Translation of SPR Conceptual Model to Risk Components

The nesting of the SPR model within the DPSIR framework is illustrative of a systems approach to coastal flood risk assessments. The RASP project was one of the first flood risk studies to formally introduce an 'entire systems' approach to flood risk assessments. Flood risk assessments that use the RASP framework involve three levels of analysis with progressively increasing levels of detail – a High Level Methodology for national-scale floodplains that uses minimal data inputs and an in-built statistical inundation model; a nested Intermediate Level Methodology that provides the conceptual framework for more detailed off-line models of sources, pathways and receptors; and a high-resolution Detailed Level Methodology that provides the framework for highly detailed numerical analyses of flood risk propagation within local-scale floodplains. The RASP structural framework uses the SPR conceptual model to structure these models and analyses (HR Wallingford and University of Bristol, 2004).

The SPR model describes flood risk propagation across the floodplain as a linear process from Source to Receptor. In practice specialised and detailed numerical models are often used at each step of the risk assessment process to describe the influence of different floodplain elements. Figure 7 unpacks the flood risk assessment process as conceptualised by the SPR model by mapping it to the inputs and models of a ‘typical’ coastal flood risk assessment. A description of the flood risk propagation process in a recent coastal flood risk study (Figure 8) illustrates this relationship of the SPR model to the process of flood risk assessment (LWI Technical University, 2013).

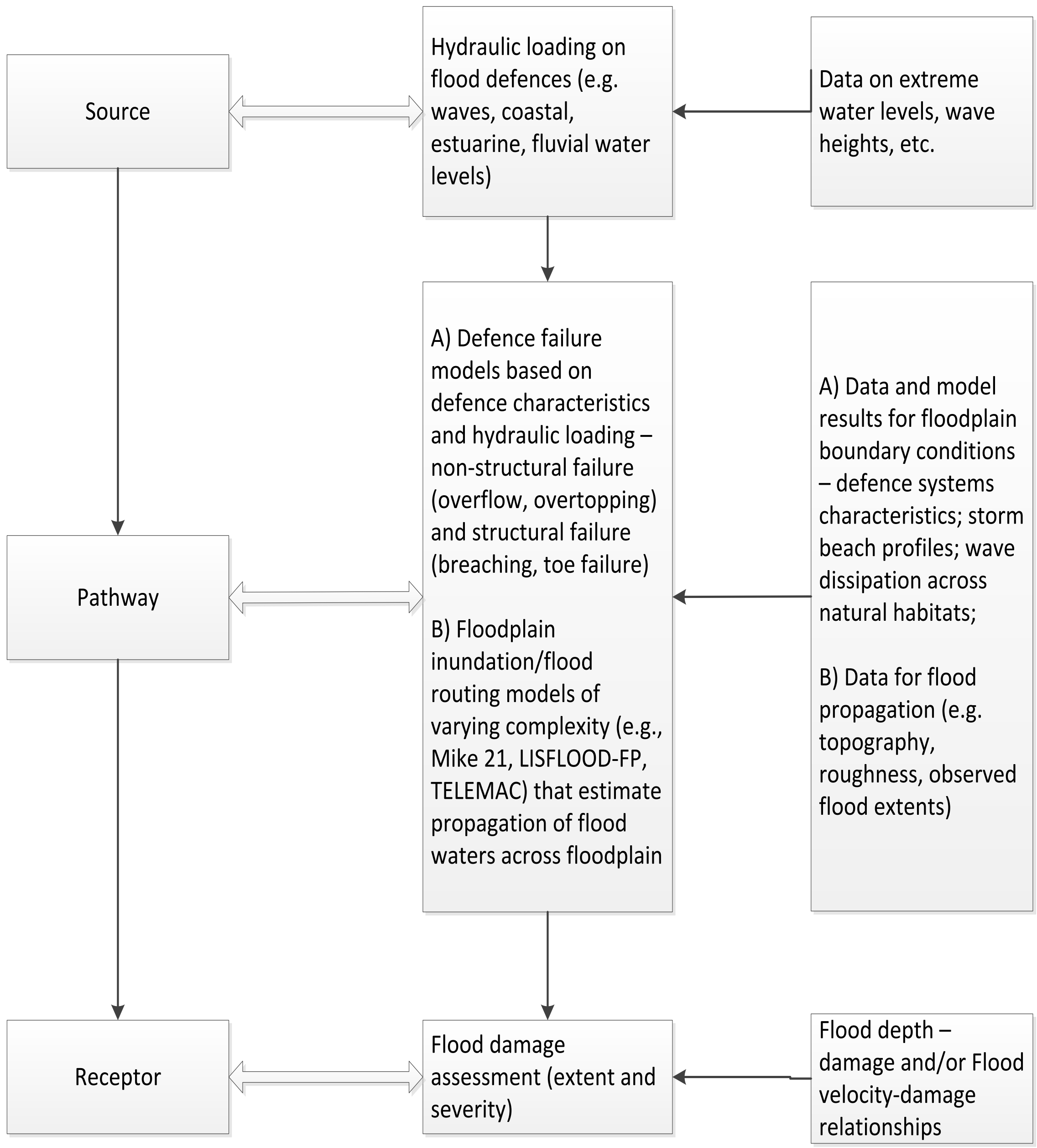

Figure 7: SPR Model Conceptualisation of Risk Assessment Process

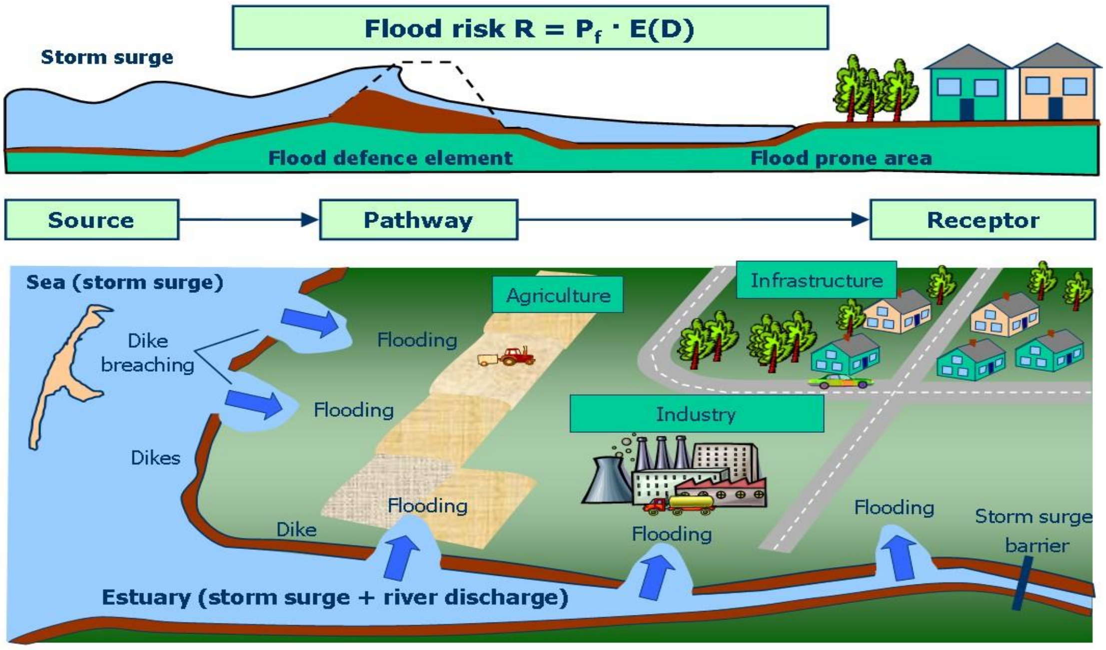

Figure 8: Relationship of SPR model to flood risk propagation (In Equation: R is the flood risk, P_f is the probability of flood defence failure and E(D) is the expected damage) (reproduced from LWI Technical University, 2013)

Figure 8 shows the flood propagation process to be influenced by the coastal morphological system, the flood defence system and the inland floodplain system. The SPR model description for this floodplain system will be the same as for any coastal floodplain. In contrast coastal morphological studies often use descriptive conceptual models of the state of the morphological system that vary according to the morphology being described (e.g., French et al., 2010, Carpenter et al., 2012, Rossington et al., 2011). This is achieved by the use of spatially descriptive conceptual models such as in the Coastal Geomorphology study which assesses the role of coastal morphological evolution on floodplain flood risk (Whitehouse et al., 2009).

Recognising the influence of coastal morphological evolution on inland flood risk the two aspects of coastal systems analyses are sometimes integrated. For instance the outputs from a coastal morphology study may form the inputs to subsequent flood risk assessments carried out within the RASP conceptual framework (HR Wallingford and University of Bristol, 2004). These inputs are generally incorporated within flood risk models as follows: coastal morphological processes such as beach erosion or accretion modify the sources of flooding – i.e. the input water levels and the pathways – i.e. structural behaviour which in turn influence flood risk within the inland floodplain. These and other descriptions of the various floodplain elements that influence flood risk are described in the following section.

2.5 Numerical Models and Methods in Flood Risk Studies

2.5.1 Coastal Hydraulic Parameters (Flood Source)

The range of numerical models and methods that exist for estimating flood risk in a given floodplain is illustrated in Figure 2 in Section 2.3. The frameworks with which these models are conceptually described are discussed in Section 2.4. Once the scope of the study and the extent of the floodplain are defined and the conceptual models describing the risk assessment process are built the next step in a flood risk study is the quantitative estimation of the different components of flood risk. To start with the probability of occurrence of a flood event is calculated (see Section 2.2).

Coastal flooding is an episodic phenomenon that occurs when coastal water levels at the boundary of a floodplain exceed the height of the adjacent land (e.g. McRobie et al., 2005). The flooding of the land – in this context referred to as the coastal floodplain, typically occurs through a combination of extreme water levels and waves (Bruun and Tawn, 1998). A coastal flood event is usually expressed in terms of the water levels and/or wave heights at the boundary, or shoreline, of the coastal floodplain. A quantitative assessment of these inputs is necessary to estimate the amount and location of flood water entering the floodplain. Depending on the type and level of detail of the flood risk study these assessments may vary between a simple approximation of a static extreme water level at the boundary of the floodplain relative to floodplain height (e.g. Poulter and Halpin, 2008), to detailed statistical analyses of the probability distributions of extreme water levels and waves at specific locations (e.g. Wahl et al., 2012, Haigh et al., 2010b).

Large-scale vulnerability and impact assessments that analyse floodplains of spatial extents greater than a few hundred kilometres use analysis techniques at the simpler end of this spectrum for rapid assessments of the effects of step-changes to the input values (e.g. Hallegatte et al., 2013, Bosello et al., 2012). Some large-scale studies may comprise several smaller-scale studies each of which focuses on a relatively smaller coastal floodplain (e.g. THESEUS

Consortium, 2009). Smaller-scale studies that analyse hydraulic loads on floodplains of a few kilometres typically focus on providing guidance to coastal engineers for local-scale risk mitigation and adaptation measures. Wave-heights and water levels – and the atmospheric conditions that drive them – inherently carry uncertainties making it necessary to use statistical and probabilistic analyses of available data to obtain estimates useful to coastal engineers and managers (e.g. Thornton and Guza, 1983). Engineering structures such as dykes, seawalls and breakwaters are often designed to withstand loads occurring from a combination of multiple parameters such as tides, surges and wave heights. For instance in designing a seawall the combined effect of sea level and waves is of interest in determining the overall loads on the seawall and the likelihood of damage to the structure (e.g. Goda, 2011). Since each of these parameters is itself expressed as a probabilistic distribution Joint Probability Methods (JPMs) of analysis are a common way of assessing the combined load contribution of multiple parameters (Hawkes, 2005, Purvis & Bates, 2008).

JPM refers to a class of methods by which the joint probability – the probability of two or more events occurring simultaneously – is assessed. For instance the likelihood of an extreme wave height occurring in combination with an extreme water level at a structure can be obtained using a joint probability analysis of wave height and sea level distributions for that location. Such an analysis would be applied by: a) obtaining the independent (marginal) probability distributions for each variable – i.e. wave height and water level; b) estimating the dependence (conditional relationship) between the two variables; and c) estimating the distribution of their joint probabilities of occurrence from their marginal probability distributions and conditional relationships. This distribution can then be used to estimate the probability within a given time-frame (e.g. return period) of a composite event – in this case an extreme wave height and extreme water level. In some cases the maximum value of the composite event of two variables may not occur at the maximum value of either of the two variables. In such instances JPMs are useful in assessing the location of the composite maxima within the distribution of variable values.

In addition to estimating the likelihood of composite events using dependence information JPMs can also be applied to observations to provide information on the dependence between the occurrences of variables and can help assess the relative importance of a particular variable to a combination. For instance, a joint probability analysis of a set of observations of extreme water levels, extreme wave heights, tides and rainfall at a certain location may indicate that the wave height does not influence the joint distribution of the other three variables. Most JPMS in coastal flood risk studies use known dependencies and observations of water levels and wave heights to obtain the probability distribution of a composite hydraulic load which will determine the design standards and specification of the flood defence structures. To do this, these studies require detailed information on the relevant hydraulic variables. Typically this information is obtained from historical data and numerical models. As a result insufficient information on variable values or their dependencies can have a significant influence on the computed joint probability distributions (Hawkes, 2005).

Apart from the inherent variations in these load values flood risk studies across all scales have to consider the effect of climate change drivers such as global sea level rise that could affect the behaviour of these parameters. At national to continental scales these may be expressed in terms of region-wise estimates of sea-level change to construct scenarios within which the sensitivity of the floodplain to step changes in the hydraulic inputs and other drivers can be assessed (Nicholls et al., 2008). Estimating the effects of these global drivers at local-scales however requires more effort in down-scaling predictions that are currently mostly at national to continental scales (e.g., Murphy et al., 2007, IPCC, 2013). Climate-change induced trends in their drivers may also affect the dependencies between variables such as water levels and wave heights resulting in modified joint probability distributions (Chiny & Stansby, 2012).

These hydraulic parameters, whether expressed as probability distributions of single variables such as extreme water level or as joint probability distributions of water levels, wave heights and tides are used to estimate the impact on adjacent floodplain elements such as the coastal flood defence structure – which forms the next step of the flood risk assessment.

2.5.2 Structural and other Flood Defences (Flood Pathway)

Once the probability of a flood event is determined the next step in the risk assessment process is estimating the 'exposure' of the floodplain to a flood event (see Section 2.2). The exposure of the floodplain is determined by two factors: a) the protection afforded to the floodplain by its flood defences which form the pathways through which the flood waters reach the inland floodplain; and b) the topography of the floodplain and the pathways of flood propagation. Determination of the latter quantity depends on estimating the occurrence and extent of failure of the flood defences. At present many flood risk studies assess a flood defence structure in terms of a probability of failure expressed as a function of the hydraulic loads on the structure and the resistance capacity of the structure. This represents the current best practice in an evolution from fully deterministic methods of structural analysis to limit-state and reliability-based approaches to fully probabilistic analysis.

Historically coastal flooding has been of interest in areas where the impacts to human assets are significant resulting in the construction of coastal flood defence structures (e.g. Charlier et al., 2005). Given the emphasis in such places on a 'defend at all cost' approach the design and analyses of these defence structures have traditionally followed a deterministic approach. In a deterministic approach such as the permissible stress design the load and structural resistance characteristics are assumed to be fully known and the structure is designed for a certain load severity while incorporating a 'factor of safety' to ensure the reliability of the design (e.g. Goda, 2010).

The increasing recognition that the failure of a structure is not always avoidable and at the same time may not occur at a single deterministic threshold resulted in the development of the limit-state approach. A limit-state approach uses the concept of a distribution of structural performance over a range of levels from functional performance (reliability) to structural failure – usually expressed as the serviceability limit state and the ultimate limit state. For instance a seawall may be designed to allow a certain level of overtopping without failing structurally. As long as overtopping remains within these limits the seawall is said to be within its serviceability limit. Further if the seawall were to breach it would have exceeded its ultimate limit state (e.g. Bakker and Vrijling, 1980).

The limit-state and reliability approach has since been extended to a fully probabilistic risk-based consideration of not just the integrity of the structure but also the distribution of hydraulic loads and the expression of all possible combinations of the two (e.g., Dawson et al., 2004, Hawkes, 2005, Buijs et al., 2005, Bachmann et al., 2013). An important extension from previous approaches is the recognition of a tolerable, or acceptable, level of risk to the floodplain that is incorporated within the design of the flood defences. Thus in a risk-based design of a flood defence structure the structure is designed to provide a certain average 'standard of protection' to the inland floodplain. By extension a risk-based design for an entire floodplain will include the contribution of all relevant floodplain elements to the overall risk (e.g. Sayers et al., 2002).

Coastal elements in the inter-tidal zone or seaward of the structural defences – i.e., elements such as coastal habitats, beaches or offshore barrier islands – are generally expressed as a modification of the hydraulic loading at the defences. Depending on the scale and level of complexity of the study the design of a flood defence could vary from a simple comparison of the heights of the flood defences and the outer water-levels (Jonkman et al., 2013) to an empirical model of seawall overtopping or breaching for specific load and resistance parameters (van Damme and Borthwick, 2012). In addition the performance of these structures may be modified by the presence of ecological and morphological elements. Many numerical models and analyses exist that provide estimates of the short-term and long-term behaviour of beaches, spits and coastal habitats (e.g., Hanley et al., 2013, Suzuki et al., 2012, Reeve et al., 2008, King and Lester, 1995). The outputs of these models can be used to modify the loads on the structural defences that are affected by them.

Though coastal morphology and ecology are widely researched fields in themselves, the influence of these elements on coastal flooding is recognised as being highly uncertain (Reeve et al., 2008). The extent of detail to which these elements are included in a risk assessment varies depending on a number of factors including the scale and scope of the study, the information present and the resources available (see Figure 2). For instance, most beach nourishment schemes are implemented as isolated projects with the objective of the scheme being a specified beach profile. Where such a scheme is implemented for flood protection the beach is usually translated into a crest-height as a proxy for a standard of protection (Hanson et al., 2002). Similarly, coastal habitats such as salt-marshes are generally incorporated into the engineering design of coastal structures as a roughness parameter that attenuates the incoming wave heights (e.g., Möller et al., 1999, Ba et al., 2001, Suzuki et al., 2012). Though the role of coastal morphology and habitats in coastal flood protection has long been recognised and utilised in several places (e.g. Bradbury and Kidd, 1998, Environment Agency, 2013d, Doody, 2012, Acreman and Holden, 2013) there are few flood risk studies that explicitly integrate analyses of the influence of these elements or provide guidance on their management (Hanley et al., 2013, Slobbe et al., 2013, Spalding et al., 2013).

Coastal elements landward of the flood defences such as storage areas or secondary urban defences may or may not be included in subsequent models of floodplain inundation as discussed in the following section. Each of these elements prevents or modifies the manner in which flood water enters the inland floodplain thereby affecting the extent and form of inundation within the floodplain. To be comprehensive coastal flood risk studies need integrated analyses of multiple pathways such as structural defences, coastal morphology and coastal habitats.

2.5.3 Floodplain Inundation (Flood Receptor)

The second component of 'exposure' of a floodplain asset (see Section 2.1) is its location within the floodplain relative to the propagation of flood water.

Having identified the amount, locations and manner in which flood water enters the floodplain, the next step in estimating exposure is calculating the extent of flooding within the floodplain. Floodplain inundation models use the flood sources and flood pathways described above as inputs and can vary in sophistication across a wide spectrum.

The variation in input requirements of an inundation model generally reflects its complexity which in turn depends on the floodplain extent and the data and modelling resources available to the study. For instance rapid scoping assessments of floodplains larger than several tens of km^2 may use basic inundation models that calculate flood extents based on floodplain elevation relative to the extreme water levels at the boundary. Such a 'bath-tub' model will only require water level values for the flood source inputs and the elevation of the floodplain as flood pathway inputs (e.g., Hinkel et al., 2013).

An improvement on this is the ‘storage-cell’ approach. Storage-cell models are 2D inundation models that use floodplain topography and the continuity equation to simulate the propagation of a finite amount of flood water within a floodplain. These models treat the floodplain as a series of discrete connected flood storage cells with the flow between cells being calculated explicitly using analytical formulae. Each downstream storage cell is flooded by the excess outflow from all adjacent cells that are situated at a higher elevation (e.g. Bates and De Roo, 2000, Hunter et al., 2006). As they rely on topographical divisions of the floodplain storage-cell approaches are popular in GIS-based flood inundation models. Storage-cell methods are superior to the bath-tub approach due to the use of height and connectivity as controls in flood propagation and have been shown to provide good estimates of flood extents (Hunter et al., 2007).

At the simpler level a storage-cell model may simply conserve volume or use an equation such as the Manning’s equation to distribute downstream flow proportional to the slope and heights of the receiving cells. A more sophisticated inundation model may involve spatially distributed 2D computations of the physical propagation of a flood wave through the floodplain (e.g., Bates et al., 2005, Hunter et al., 2007) that will require more detailed flood source inputs – a time-series of water-levels, or a time-varying flood volume due to combined water-level and wave overtopping action (e.g., Wadey et al., 2012); and pathway inputs – performance of the structural defences with regard to overtopping and failure (e.g., van Damme and Borthwick, 2012, Zanuttigh et al., 2013). The analyses of flood sources and pathways may also be combined to provide joint probability distributions of flood volumes entering a floodplain for a range of flood defence system states (e.g., Dawson et al., 2005).

Usually flood risk studies that use 2D inundation models are applied to coastal floodplains at sub-national to local scales and provide estimates of flood extents and flood depths at different locations within the floodplain. In these models the floodplain is usually described as a grid of cells each of which has a height and a roughness coefficient the latter generally serving as the calibration parameter for the model. The propagation of the flood wave is typically simulated using continuity and momentum conservation equations (e.g., Bates et al., 2010, Hunter et al., 2007). Nowadays highly sophisticated inundation models are also available (e.g., van Dam et al., 2012) that solve the shallow-water equations to provide detailed, 3D representations of flood wave propagation. Due to their relatively high resolution and accuracy these models provide practically useful predictions of detailed flow characteristics such as rise velocities, flow velocities, accompanying debris flow, flow around structures, etc. (e.g. Mignot et al., 2006). These models are increasingly being used in detailed studies of flood propagation at fine scales especially in urban environments. They provide information on flow characteristics that can be used for assessments of local-scale flood response strategies such as warning, evacuation and rescue (e.g. Sanders, 2010, Lämmel et al., 2010). However their use in coastal flood risk assessments is currently limited due to their high computational expense and the relatively larger uncertainties associated with the flood sources and pathways that provide the inputs to these inundation models (Pappenberger et al., 2006).

The final extents (and depths) of flooding within the floodplain are obtained by coupling the flood source, flood pathway and floodplain inundation models. This information can take the form of flood extents and flood depths in case of rapid 1D and 2D models (e.g., Jamieson et al., 2012), or flood durations and velocities in the case of more sophisticated models (e.g., van Dam et al., 2012).

Many flood risk studies estimate the first two components of flood risk – probability and exposure by coupling the analyses and models described in this section. This information is then used to determine the susceptibility to damage of the flooded assets, and the costs of this damage (e.g., Penning-Rowsell et al., 2005, Kreibich et al., 2005b, Jongman et al., 2012a).

2.5.4 Uncertainties in Model Simulations

A numerical model simulation of a real-world process or environment is never perfect but is always accompanied by uncertainties. The uncertainties in a model simulation can be roughly classified into three types – a) inherent or aleatory uncertainties; b) knowledge/data, or epistemic uncertainties; and c) model uncertainties:

Inherent Uncertainties: These are the uncertainties inherent in the processes and data simulated by the numerical model and are irreducible uncertainties, independent of the quality of the model or the data inputs (Merz and Thieken, 2009). In coastal flood risk assessments, inherent uncertainty is generally highest in the input parameters. For instance the expected ESWL in any given year rather than being a single value is generally expressed as an 'annual exceedance probability' distribution. Flood risk assessment studies often find it more useful to express flooding in terms of a cumulative annual probability of flooding under specified conditions rather than analysing specific events (e.g., Evans et al., 2004, Hinkel et al., 2013). Similarly wave heights in the near-shore and surf zone are highly variable and are usually expressed as energy-frequency spectral distributions from which a single design value wave-height may be extracted (Hasselmann et al., 1980, US Army Corps of Engineers, 2002). These inherent uncertainties arising as a result of the natural variability in the parameters and processes described are significant causes of uncertainty within coastal flood risk assessments (e.g., Sayers et al., 2002c, Domeneghetti et al., 2013).

Data/Knowledge uncertainties: The uncertainties arising out of natural variability of a parameter are often described in combination with the uncertainties that are a result of our incomplete knowledge and understanding about the processes that influence the values of these parameters. The latter are generally referred to as knowledge uncertainties or epistemic uncertainties. In coastal flood risk assessments, knowledge uncertainties may exist, for example, in our descriptions of local tide-surge interactions (Quinn et al., 2012), structural defence response to hydraulic loading (Buijs et al., 2005), or floodplain inundation (Pappenberger et al., 2005). A more fundamental example of knowledge uncertainty is the uncertainty in the accuracy of the basic structure of the model and its description of the real-world environment which it simulates (Kelly et al., 2013).

In coastal flood risk assessments the uncertainties in the structure of a floodplain description are a reflection of our current understanding and assumptions about the floodplain and the deviation of this description from what is observed. As such this uncertainty can be analysed in the conceptual model of the flood risk assessment through an iterative process of gaining understanding about the floodplain and refining the model's descriptions accordingly. The traditional conceptual models for coastal flood risk assessments describe the assessment approach rather than the assessed floodplain and therefore do not lend themselves to such a process of iterative refinement. Structural uncertainties in the numerical models used in these studies therefore cannot be directly analysed or reduced. More importantly, the communication of these uncertainties is important since they often include the assumptions made during the modelling process (Hunter and Lamb, 2012).

Model uncertainties: These are uncertainties that arise as a result of the inevitable incompleteness of a numerical model in describing real-world environments and processes. Model uncertainties are typically a function of the resolution of the model and the accuracy and detail with which the relevant processes are described, and in probabilistic models, errors introduced by the lack of an adequate number of samples. Model uncertainties therefore vary widely, depending on the sophistication of the implemented resolution and process descriptions (Apel et al., 2004). These in turn depend on the scales of implementation of the model, the complexity of the modelled environments and the data and computational resources available to enable a sufficiently accurate description.

2.6 Outputs and Utility of Flood Risk Studies

The key outputs of a flood risk study may take the form of flood risk maps (e.g., EXCIMAP, 2007, HR Wallingford and University of Bristol, 2004), models and modelling frameworks (e.g., Jonkman et al., 2008), or management and policy guidelines (e.g., Evans et al., 2004). Flood risk studies rely on the use of maps to understand, present and communicate their results (Merz et al., 2007). Flood risk mapping is an accepted tool in many countries to inform flood risk management. In the UK the Environment Agency produces Indicative Flood Maps describing areas at risk of flooding from certain flood events (Environment Agency, 2013a). In Europe the Floods Directive (Directive 2007/60/EC) requires member states to carry out a comprehensive flood risk mapping exercise by the end of 2013 (European Commission, 2007). In the USA, regular flood risk mapping exercises inform governmental insurance and flood risk management policies (Burby, 2001). In many countries flood risk and flood hazard mapping are receiving increasing attention as tools for effective, evidence-based flood risk management (e.g., Saxena et al., 2013, Apel et al., 2013).

Flood risk maps describe the spatial distribution of the risk of flooding to assets within a floodplain and are a final output of the flood risk assessment process. They are usually produced using multiple coupled or cascading numerical models (e.g., Rodriguez-Rincon et al., 2012, Czajkowski et al., 2013; also see Section 2.4).

Many recent large-scale flood risk studies also provide decision-support tools with interfaces that allow users to integrate information on multiple results from these studies. Some decision-support tools allow users to investigate the effects of different coastal adaptation and mitigation options in response to different hydraulic events at the boundaries of the coastal floodplain. These may either be based on pre-assessed and pre-provided libraries of simulations and design options (e.g., CLIMSAVE Consortium, 2011), or they may be simplified representations of underlying analyses that can be computed 'on-the-fly' (in real time) using inputs provided by the end-user (e.g., THESEUS Consortium, 2009).

The effectiveness of a flood risk study depends on the usefulness of its outputs to flood risk management. For instance, highly computationally sophisticated numerical models of floodplain inundation may be of limited use for risk management in floodplains where data on the flood sources, flood defences and floodplain receptors are relatively scarce or uncertain (Bates, 2012). Alfieri et al. (2013) describe the use of multiple, local datasets and models to address some of the challenges in consistent flood risk mapping across Europe. In relatively data-scarce floodplains inexpensive computational models such as those that allow rapid analyses of the relative importance of different sections of a flood defence system can still provide useful information for the prioritisation of defence maintenance activities to local coastal flood risk managers (Dawson and Hall, 2006). The end-users of these maps, frameworks and tools are usually coastal authorities and decision-makers at local or national levels who are generally not involved in the actual analysis process and may therefore require some amount of training in order to be able to use these outputs. A few studies (e.g., EurOtop Manual, 2007, FLOODSite Consortium, 2007b) tailor their outputs for coastal engineering experts and modellers who will use these outputs to design appropriate coastal risk mitigation measures and where relevant communicate these to the decision-makers.

The outputs of an effective flood risk study will reflect the needs of the stakeholders. To ensure effective integration of the multiple aspects of flood risk management within these outputs these studies need to involve the scientific experts, authorities and other stakeholders at the initial stages of the study (e.g., de Vries et al., 2011, Cassel and Hinsberger, 2013). At these stages there is limited scope for the use of detailed numerical models or floodplain maps and the conceptual model is generally used as a tool to develop consensus and a shared understanding of the floodplain. To date, flood risk studies that use the SPR model start off with a conceptually simplified, one-dimensional description of the coastal floodplain in terms of a source, pathway and receptor. As a result the conceptual models that inform the flood risk study do not provide a full description of the coastal floodplain.

2.7 Extreme Coastal Flood Events and Lessons for Flood Risk Management

Damage due to an extreme coastal flood event is in most cases impossible to avoid. However the lessons learnt from every such event can be and have been applied to improve strategic flood risk management in order to reduce the damage caused by the next event. Improved monitoring and data collection exercises have paralleled increasing computational capabilities in many floodplains (e.g., Gall et al., 2012, Bates et al., 2010, Harvey et al., 2009). However widespread damage still occurs repeatedly despite excellent forecasts and numerical models being available. Effective flood risk management requires effective tools to predict flood events and effective methods to understand and manage the risk from these events. Despite being predicted and accurately forecasted events such as Hurricane Sandy and Hurricane Katrina in the US, Storm Xynthia in France and the July 2007 floods in the UK caused considerable damage when they made landfall. These events have revealed challenges to the effective management of flood risk in these coastal floodplains that still need to be addressed in order to minimise further damage (e.g., Pitt, 2008b, Kolen et al., 2010). These challenges relate mainly to the diversity of these floodplains and the comprehensiveness with which they are understood and managed. The key challenges to effective flood risk management as revealed by forensic analyses of past coastal flood events, are discussed briefly here.

2.7.1 Weak Links and Critical Elements

Hurricane Katrina in 2005 in New Orleans, U.S.A. is one of the costliest coastal flood disasters so far. Though bigger than expected and designed for, the event provided several key lessons for flood risk management. Due to the size and complexity of the New Orleans coastal defence system as well as the relevant organisations there was a lack of overview on the state of flood defences prior to the event. This led to weaknesses and maintenance gaps in some dyke sections being overlooked that aggravated flooding in the region (Seed et al., 2008). Lack of overview on emergency response measures during the July 2007 floods in England and the state of flood defences during Storm Xynthia in France in 2010 led to aggravation of damage in both cases (Pitt, 2008b, Kolen et al., 2010). Power outages due to a storm surge above design levels in Hurricane Sandy in October-November 2012 left more than 900,000 people without power for weeks in New York (The Economist, 2012). In some cases the lessons learnt have also been from positive outcomes of effective local flood risk management. For instance during Hurricane Sandy areas of Long Beach Island, New Jersey that had an on-going dune nourishment program fared better than adjoining areas where there were gaps in the dune system due to a delay in construction of the dunes (NJ News, 2012). These examples highlight the necessity for being able to identify long before an event occurs the weak areas and critical elements of a floodplain and subsequently prioritising efforts towards better understanding and management of these elements. This can often become a challenge in large, densely urbanised floodplains or in floodplains where data availability is scarce.

2.7.2 Diversity in Floodplain Elements and Management

Coastal floodplains are zones of multiple human and natural systems with diverse elements that are inter-related and act upon one another over multiple spatial scales. These elements often extend across administrative boundaries and their management may involve experts from a variety of disciplines (de Moel et al., 2009). Providing a platform for experts and authorities from diverse fields to arrive at a shared and comprehensive understanding of their coastal floodplain is a difficult task. Informal knowledge held by local experts and stakeholders is often important for effective flood risk management and could form a vital part of numerical model simulations and flood risk assessments. However this knowledge may be qualitative or uncertain. The challenge here is to ensure the structured inclusion of such knowledge when attempting to understand and manage flood risk (Wadey et al., 2012). The development of a common understanding of the floodplain is further complicated by inter-dependencies between floodplain elements. Floodplain elements that are considered as defending an inland asset may themselves be of significant value if they are damaged in a flood event. For instance, natural coastal habitats such as mangroves and salt-marshes provide protection during flood events, but are often themselves affected by flood events (McIvor et al., 2012). In many countries natural coastal habitats are protected by law and offer other important services (Millenium Ecosystem Assessment 2005, The European Commission, 2007). Also a change in the state of such a habitat due to human activity (e.g., pollution) could affect the flood risk of the populated area inland during future extreme events. Recognising such dependencies between diverse floodplain elements and developing a shared understanding of their aggregated effect on the floodplain remain a significant challenge.

2.7.3 Developing a Quantitative Systems Understanding of Coastal Floodplains

The challenges to effective flood risk management described in Sections 2.7.1 and 2.7.2 illustrate an underlying necessity– that of developing an understanding of the coastal floodplain as a system of diverse but inter-related elements. While specific analysis techniques exist for specific elements, integrating them within a single framework remains a significant challenge in flood risk management. The variables describing these elements may be expressed probabilistically (EurOtop Manual, 2007, Dawson et al., 2009), may operate across different spatial scales (Merz et al., 2007, Whitehouse et al., 2009) and carry significant uncertainties (Harvey et al., 2012, Hall and

Solomatine, 2008). Full-scale integration of the numerical models for the entire coastal floodplain though possible is still difficult. Flood risk assessments therefore focus on a few key variables to simplify the problem most often the characteristics of flood sources and coastal defences. Quantitative probabilistic models of these key coastal descriptors such as water level return periods, coastal morphology and flood defences typically require decades of data (Hawkes, 2005, Catenacci and Giupponi, 2013). Models simulating extreme flood events face a further challenge given the scarcity of data and information on such events (Horritt, 2006). An alternative approach is needed to quantitatively describe the coastal floodplain as a system of inter-linked elements similar to the simplified conceptual model for flood defence prioritisation mentioned in Section 2.6.

2.8 Integrated Flood Risk Management: Challenges and Requirements

The management of coastal flood risk as described in Section 2.2 entails the estimation of several components and aspects of flood risk within the coastal floodplain. Some definitions of flood risk also recognise the importance of modelling the spatial distribution of flood risk. The need for rational management of flood risk in coastal floodplains and the recognition of the role of non-structural floodplain elements has resulted in a number of integrated coastal flood risk studies as discussed in Section 2.3. Each of these studies is a large and expensive undertaking typically involving several researchers working on multiple aspects of the problem and can take several months to complete. The numerical models of these studies discussed in Section 2.4 are often highly detailed and specialised requiring specific expertise and skills to build and run them. Specific coastal and inundation models can be built relatively quickly and easily for a local-scale coastal floodplain. However the integration of these models in a manner that is meaningful to coastal managers and decision-makers – the central motivation of most existing flood risk studies – is still a significant challenge.

Many flood risk studies use an approach-based conceptual framework such as the SPR model which provides a generic and simplified description of the coastal floodplain. The SPR's strength as a conceptual model lies in its simplicity and flexibility in describing the risk assessment process – from a source of flooding, through a pathway, to a receptor. This however means that current conceptual models based on this framework do not fully describe the coastal floodplain – rather they focus on describing the state of the coastal defence system as the pathway (or barrier) to the inundation of the landward floodplain. The outputs of these studies correspondingly provide information relevant to coastal managers, e.g., floodplain inundation maps and information on the relative importance of coastal defence sections. Integration of analyses of the different floodplain elements requires a comprehensive conceptual description of the coastal floodplain.

Recent extreme flood events reveal significant challenges to flood risk management while highlighting the need for an integrated approach to analysing coastal floodplains. These events illustrate the difficulties in managing complex urban floodplains as well as the necessity for understanding the key pathways of flooding from a whole-systems perspective. Flood risk studies that aim to integrate analyses of different floodplain elements therefore need to describe the role of all elements of the floodplain system, including those seaward and landward of the coastal defences. This requires the use of targeted numerical models for each of these elements. These models will significantly benefit from prior information on the elements of the floodplain that require detailed analyses. Additionally assessments of coastal floodplains across multiple scales and multiple disciplines need to build consensus amongst experts and stakeholders about what is known of the floodplain system and what is required of the flood risk study when defining the current state of the floodplain. These needs can be addressed by a simplified conceptual model that nevertheless provides a comprehensive integrated description of the coastal floodplain as a system of interacting elements.

3 The quasi-2D SPR Conceptual Model for Integrated Coastal Floodplain Assessments

3.1 Introduction

This chapter discusses Objectives 1 and 2 defined in Section 1.3 namely, the development and application of a qualitative conceptual model as the first stage and foundation of a comprehensive conceptual model that will provide a structured and integrated understanding of the coastal floodplain.

A structured and integrated understanding of the floodplain is essential for achieving effective long-term preparedness for future events. An increasing number of flood risk studies recognise this need and are expanding their scope to deal with diverse floodplain elements that often operate at multiple spatial scales. The focus of these studies is integration of the analysis of different elements in flood risk propagation. The research gap addressed in this thesis, as discussed in Chapter 1 and examined using the literature review in Chapter 2 can be summarised in three points:

1. Flood risk studies are increasingly using multiple numerical models for the integrated assessment of multiple elements within the coastal floodplain.
2. These numerical models will greatly benefit from rapid and inexpensive *a-priori* analysis of the coastal floodplain to identify the key areas where further detailed analysis is needed. Ideally this understanding will be achieved using a conceptual model at the start of the flood risk study to then inform subsequent use of numerical models.
3. Currently, conceptual models are used in flood risk studies to describe the process of risk assessment rather than the state of the coastal floodplain. A descriptive conceptual model is therefore needed that will provide an integrated systems understanding of the coastal floodplain at the start of the study.

The qualitative model is developed as a descriptive systems model for the coastal floodplain based on the objectives described in Section 3.1. Systems models are a popular and effective means of conveying relationships between elements and are used in various fields such as electricity and transportation infrastructure. A widely known systems map is the London Underground map that conveys functional topological relationships of the underground railway system in London. Such maps can be very useful in conveying complex information at the right level of abstraction (Kramer, 2007).

Descriptive conceptual system models have to date not been used to describe coastal floodplains within flood risk assessments. They are however a widely used tool in the field of coastal geomorphology. The ASMITA model for tidal basins (Rossington et al., 2011) is an example of a conceptual systems model that describes the aggregated-scale morpho-dynamic evolution of a tidal basin under hydrodynamic forcing. Rossington et al. (2011) discuss the successful use of this model for future predictions of the estuary under sea-level rise and anthropogenic forcing such as dredging activity. The Coastal Geomorphology study (Whitehouse et al., 2009) and the Coastal Systems Mapping study (French et al., 2010) use a systems model to describe and analyses coastal geomorphological systems consisting of several elements with complex interactions. Being scale-independent, the model allows the description of coastal elements that exist at different scales and also helps to formally describe current understanding of the coastal system. Another example of a descriptive conceptual systems model is the meso-scale SCAPE model (Walkden and Hall, 2005) – currently being used within a larger coastal geomorphology project (Nicholls et al., 2012) – that describes the coast as a broad system of coastal geology and hydrodynamic forcing, to simulate the episodic and long-term retreat of soft rock shorelines.

Generally conceptual models in flood risk assessments are applied to specific aspects of the flood system – such as the coastal defence system. Fault tree methods have been applied to failure analyses of coastal flood defences, varying from detailed studies of the failure modes of a singly dyke or dune (e.g., Apel et al., 2006) to larger studies of entire flood defence systems (Voortman, 2003). Floodplain inundation assessments are relatively simpler in terms of the analysis process since the entire floodplain is generally treated as a single entity within a numerical inundation model (see Section 2.5.3). These assessments therefore may not make use of a-priori conceptual models. The rational prioritisation of coastal defences based on their overall contribution to flood risk in the floodplain is a topic of increasing importance (e.g., Dawson et al., 2004, Hall et al., 2003b). Such analysis requires a more detailed treatment of the inland floodplain. Dawson and

Hall (2006) describe a methodology for assessing the 'importance' of a specific defence section in terms of contribution to flood risk using statistical analysis of defence section failure probability and the resultant consequences. Lhomme et al. (2008) similarly describe a pathway analysis technique by coupling a defence failure model and a numerical inundation model that keeps track of the flood propagation process to identify the defence section 'responsible' for flooding in a particular flood zone. Floodplain compartmentalisation also becomes an issue at larger extents due to differences in land regulations, changing land-use, and the use of urban flood storage and other flood reduction solutions (e.g., Alkema and Middelkoop, 2007, Koks et al., 2013). The RASP study, discussed in Section 2.4, uses the traditional SPR model to introduce the notion of a scaled, systems approach to flood risk assessments. The SPR model in RASP is however used as a framework to structure the process of risk assessment and is not intended to describe the coastal floodplain.

The qualitative model developed in this thesis provides a comprehensive systems description of any coastal floodplain for flood risk assessments by combining the Source – Pathway – Receptor concept as introduced by Evans et al. (2004) and RASP (HR Wallingford and University of Bristol, 2004, Sayers et al., 2002b) with a descriptive systems approach as used in coastal geomorphology (e.g., Whitehouse et al., 2009). To achieve full description of the floodplain, the SPR concept is extended in the new qualitative model to allow multiple flood pathways including other elements such as coastal morphology, coastal habitats or even man-made elements within the inland floodplain such as secondary coastal defences none of which are described by existing conceptual models of the coastal floodplain.

Some of these elements such as coastal habitats or beaches may be considered as flood pathways as well as receptors of flood damage. The qualitative model modifies the notion of 'Pathways' and 'Receptors' such that each floodplain element is described as a pathway and/or a receptor depending on the context of the analysis and the element's corresponding functionality. Flood propagation from the source to the floodplain elements is described by a systems approach using the topology of, and physical links between, these elements. The qualitative model thus provides an explicitly spatial description of the floodplain where topological information about individual floodplain elements is preserved. Since this process results in a 'quasi-2D' conceptual description of the coastal floodplain, the qualitative model is henceforth also referred to as the Quasi-2D SPR (also see Narayan et al., 2013).

3.2 Quasi – 2D SPR: Objectives

Based on the requirements for integrated flood risk assessments identified in Chapter 2, the following objectives for the Quasi-2D SPR are listed:

4. ***Rapid description of large, complex, floodplains***: Ensure that the conceptual framework and model can be rapidly built to describe large, coastal floodplains consisting of widely distributed elements.

5. ***Capture local knowledge***: Develop a qualitative model capable of capturing relevant local knowledge across floodplain elements in a formalised and structured manner.

6. ***Participatory Construction Methodology***: Develop a methodology in which the qualitative model is built by experts and stakeholders from diverse disciplines across the assessed floodplain in a participatory process.

7. ***Consistent and universal methodology***: Ensure that the model-building methodology is consistent and universally applicable.

The Quasi-2D SPR model has been developed and applied to 8 coastal floodplains in this thesis. Section 3.3 describes the selection of a participatory process for model construction based on good practices in existing participatory approaches. Section 3.4 describes the development of a common construction methodology for all the Quasi-2D SPRs. Section 3.5 discusses in detail the construction and application of the model to 3 sites. Section 3.6 evaluates model application across all sites.

3.3 Quasi – 2D SPR: Selection of Participatory Process

The Quasi-2D SPR is the conceptual model of the EU FP7 THESEUS project (www.theseusproject.eu) which is developing innovative solutions for consistent and integrated flood risk management of Europe's varied coastal zones. Set within a larger, DPSIR-based conceptual framework the model describes the state of the coastal floodplain in each of the project's case-study sites and is set within a larger DPSIR-based framework (Narayan et al., 2013). The quasi-2D SPR is an inter-disciplinary conceptual model whose purpose is to comprehensively map a coastal floodplain in terms of all its relevant source, pathway and receptor elements. An objective of the quasi-2D SPR model is to build a common understanding of the coastal floodplain through a participative process of construction.

Inter-disciplinary studies often use participatory methods to develop a common shared conceptual model that informs the rest of the study (e.g. Kenyon, 2007). Since their inception in the 1960s and 70s within system dynamics and environmental decision – making they have been used across a wide range of disciplines including hazard and vulnerability assessments, rural appraisals, health care systems etc. (van Aalst et al., 2008, Gawler, 1998, Tran et al., 2009, Chambers, 1994, Vennix and Gubbels, 1992). Due to their highly variable and subjective nature no universal framework exists for these approaches. In the context of this thesis these participatory approaches can be classified into two categories – knowledge-elicitation and formalisation and data and information – gathering.

Knowledge-elicitation exercises use tools that facilitate the extraction and formalisation of knowledge from a group of experts. These include approaches such as the Delphi Method, questionnaires, flow or network diagrams or knowledge maps that emphasise the extracting, collecting and formalising of informal expert knowledge from experts in the relevant disciplines (Elmer et al., 2010, Shaw and Woodward, 1990, Vennix et al., 1992).

Data and information-gathering exercises are used in multi-disciplinary exercises such as natural resource mapping, environmental assessments and floodplain management (Duvail et al., 2006, Bousset et al., 2005, Simonovic and Akter, 2006). Depending on their purpose these may include top-down rapid appraisal techniques such as transect walks or more bottom-up, community-based assessment techniques such as interviews and focus groups (van Aalst et al., 2008, IFRC, 2007).

Disaster and vulnerability assessments that involve experts and stakeholders from different disciplines use tools that combine knowledge-elicitation and information-gathering. Examples of these include consensus-building processes of data-gathering, sharing and mapping using meetings, workshops or online collaboration (Taha et al., 2010, Chiwaka and Yates, 2005). Similar to vulnerability and disaster assessments flood risk assessments also often use a mix of information-gathering and knowledge-elicitation approaches such as meetings, focus groups or workshops (Pelling, 2007, Castelletti and Soncini-Sessa, 2007, Sultana et al., 2008, Priest et al., 2012).

The quasi-2D SPR model is built by experts as well as other stakeholders from a range of disciplines and backgrounds. It gathers information about floodplain elements as well as relevant knowledge on flood propagation across these elements. Based on existing participatory approaches the process used for quasi-2D SPR construction is a combination of knowledge-elicitation and information gathering similar to other flood risk, disaster and vulnerability assessments.

3.4 Quasi – 2D SPR: Construction Methodology

The implementation of the participatory approach in quasi-2D SPR construction is determined by three aspects – purpose, participants and process (IFRC, 2007, Taha et al., 2010). The construction methodology of the quasi-2D SPR model is examined in terms of these three aspects.

Purpose: The purpose of the quasi-2D SPR model decides the type of participatory approach to be used. The quasi-2D SPR is a conceptual model for flood risk assessments. The main objectives of the model are to describe the coastal floodplain at each site through the capture of local knowledge and the development of a shared understanding. The approach used for the quasi-2D SPR builds on a commonly used approach in flood risk assessments and participatory plans for consensus-building – the focus group, or interactive discussion approach (Kenyon, 2007, Castelletti and Soncini-Sessa, 2007, Holman et al., 2008, de Vries et al., 2011).

A focus group is an organised, interactive discussion ideally among a small group of stakeholders with knowledge or experience on a shared topic (Steyaert and Lisoir, 2005). Focus groups are primarily used for initial concept exploration to generate creative ideas, engage the stakeholders and also obtain qualitative information pertaining to the study objectives. They are especially useful in generating information on complex topics and subjects, and provide a relatively efficient and inexpensive method for information gathering. Furthermore different sites can adopt a common methodology to their site depending on their specific aims, challenges and resources (Krueger, 2009, Steyaert and Lisoir, 2005, Pedregosa and Perera, n.d.).

As such, this technique offers a combination of participative mapping and knowledge-elicitation that can be readily applied for Quasi-2D SPR model development at each study-site. The use of focus groups allows easy representation of complex floodplain maps and a formal method for gathering qualitative information and developing a shared description of the floodplain elements. The focus group method does not by itself require the development of consensus among the participants. Since consensus is a required outcome from the quasi-2D SPR model this method is extended here using an iterative process of analysis and feedback used in other consensus-building methods (Taha et al., 2010, Chiwaka and Yates, 2005, Bousset et al., 2005).

Participants: In a participative process the selection of participants is as inclusive as possible within the scope and framework of the study and should ideally include the agents as well as the targets of the study. The participants should be willing to donate their time and efforts to the process and be motivated by the study. Finally the inclusion of participants is determined by criteria specific to the study – in this case, these include the availability of the relevant experts and stake-holders on flood risk at each case-study site (University of Kansas, 2013, Steyaert and Lisoir, 2005, Taha et al., 2010).

In this thesis the quasi-2D SPR model has been applied in 8 coastal floodplains across Europe including four nested sites. Except for one site all the floodplains are part of the EU FP7 THESEUS project. The diversity and complexity of these sites make them ideal for testing the model development process. The model development process was adopted in each site according to the local knowledge, expertise and resources available. Each site had a local team of experts and stakeholders covering decision makers and local residents/businesses as well as scientists from engineering, ecology, economics and the social sciences.

Process: The participatory process involves a) determining the questions posed to the participants; b) the methods by which these questions are answered; and c) specifying the desired outcomes of the process (IFRC, 2007, Chiwaka and Yates, 2005). The questions posed to the participants in this context are based on the objectives of the quasi-2D SPR summarised in Section 3.2. These objectives are achieved by a mapping exercise within the focus group, with the desired outcomes being a floodplain map and a systems diagram. A four - step algorithm for model construction was developed for all site teams to ensure consistency in model development. This is described below with the help of a fictitious, representative coastal floodplain.

Step 1 – Floodplain Extent: The landward boundaries of the coastal floodplain system are first decided using a planar water level model for the most extreme water level being considered. This is done under the assumption of a worst-case scenario where complete failure (or absence) of defences is assumed. This assumption will indicate the full extent of the natural floodplain system and ensure that all system elements are included in subsequent analyses. The seaward boundary of the floodplain system is placed at the lowest tidal level (Mean Low Water Neap) to ensure inclusion of all inter-tidal floodplain elements seaward of the shoreline.

Step 2 – Mapping Floodplain Elements: Once the natural system extent is defined all floodplain elements, including flood defences and seaward coastal elements, are mapped as unique entities classified based on land-use (Figure 9). Linear elements such as roads, railway lines and coastal defence structures are mapped as distinct elements. Using a flexible land-use classification scheme this map provides a platform for future integration of any analysis with the socio-economic aspects of a flood event such as economic consequences or land-use planning scenarios. For instance critical elements such as water treatment plants or flood pumps may be mapped as distinct elements. Where relevant (such as in floodplains with highly varied topography), contour lines corresponding to lower-order events can be used to limit the size of each element. That is, no floodplain element will cross a contour line corresponding to a selected flood event. This step is a vector mapping process analogous to the creation of a topography and land-use database in a grid-based inundation model.

Step 3 – Mapping Floodplain Links: Once the elements are mapped the physical links between these are defined. The quasi-2D SPR emphasises the relative role of a floodplain element as a receptor in its own right and a pathway to linked downstream elements. A link is identified between any two elements if they share a geographical boundary. Links between engineered flood defences and the rest of the system are also identified on the same basis. Flood compartments created by these defences can therefore be studied as part of the bigger natural floodplain system, rather than as isolated sub-systems.

Step 4 –Map to SPR System Diagram: The elements and links are then schematised to obtain a systems diagram (Figure 10). The system diagram which in most cases is built manually fully preserves the links (and therefore the topological relationships) between floodplain elements though it allows some flexibility in terms of actual spatial representation. The move from a geographical map to a systems diagram allows easy analyses of the relationships between elements regardless of their location or size. Once the system diagram is built for the coastal floodplain it is extended to include all the sources of flooding that are identified at and if necessary within the floodplain boundaries.

The construction methodology forms the basis of the participatory process of model development. The participatory process may be one of consultation – i.e. obtaining options, partnership – i.e. in-depth engagement, or deliberation – i.e., co-decision. In the case of the quasi-2D SPR the process is one of in-depth engagement by the participants in mapping the coastal floodplain and identifying the sources, pathways and receptors of flooding. In each site the process involves a team of participants and a facilitator (Pedregosa and Perera, n.d., Steyaert and Lisoir, 2005, Taha et al., 2010, University of Kansas, 2013).

Table 2 lists the 8 sites and 4 nested sites for which the model was constructed and the teams that constructed the models. In all twelve sites facilitation of the focus group was carried out as part of this thesis. In seven sites the model construction process was led primarily by each site-team, with external facilitation. In the other five sites, the model construction process was led by the facilitator with inputs and feedback from the site-teams.

Table 2: Quasi-2D SPR Application Sites (N Nested site; * Discussed in this thesis)

No.	Location	Coastal Classification and Approximate Extent	Construction (Participants Involved)
1*	Teign Estuary, England, South Devon, English Channel	Estuary and Open Coast, (12-14 km²)	By site team (local hydraulic and coastal engineers, ecologists, land-use planners, stakeholders)
2 (N)*	Teignmouth, England, South Devon, English Channel	City with estuarine and open coast, (1-2 km²)	By facilitator (local hydraulic and coastal engineers)
3*	Gironde Estuary, France, Atlantic Coast	Estuarine coast and Atlantic Ocean coast (250 km²)	By facilitator (local hydraulic and coastal engineers)
4 (N)*	Medoc Region, France, Gironde Estuary	Estuarine coast and Atlantic Ocean coast (85 km²)	By site team (local hydraulic and coastal engineers and land-use planners)
5	Scheldt Estuary, Netherlands-Belgium, North Sea	Estuarine coast and Riverine bank, Scheldt Estuary (150 km²)	By facilitator (local hydraulic engineers)
6 (N)	Dendermonde, Belgium, Scheldt Estuary	Estuarine and riverine bank, (4-6 km²)	By facilitator (local hydraulic engineers and land-use planners)
7	Elbe Estuary, Germany, North Sea	Estuarine and riverine banks (200 km²)	By site team (local hydraulic engineers and land-use planners)
8 (N)	HafenCity, Germany, Elbe Estuary	Estuarine and riverine banks, (8 – 10 km²)	By facilitator (local hydraulic engineers and land-use planners)
9*	Hel Peninsula, Poland, Bay of Puck, Baltic Sea	Spit and Open Coast (10–12 km²)	By site team (local coastal engineers, authorities, land-use planners, ecologists)
10	Varna, Bulgaria, Black Sea	Open Coast (35 – 40 km²)	By site team (local coastal engineers, authorities, land-use planners, ecologists)
11	Cesenatico, Italy, Mediterranean Sea	Open Coast (9 – 11 km²)	By site team (local coastal engineers, land-use planners, ecologists)
12*	Portsmouth, England, the Solent, English Channel	Open Coast (8 – 10 km²)	By facilitator (local flood risk experts)

The process, shown in Figure 11 is iterated until consensus is reached among team members that the model captures all relevant understanding concerning the coastal floodplain. For instance links may be added or removed or floodplain elements may be modified if these are too large, cross a contour line or require more detailed land-use classification. All team members work together either by face to face or online collaboration to create their version of the system functionality and identify linkages that will permit ingress and movement of floodwater. The iterative process is complete when the final map that is used to create the quasi-2D SPR system diagrams is satisfactory to all team members in terms of floodplain extent, element description and level of detail.

Following this methodology in some sites a larger model was first constructed that immediately identified an area of the floodplain requiring attention, resulting in a nested model. Three case-studies including two nested sites from Table 2 are further described in Section 3.5. These are: 1) the Hel Peninsula (spit and open coast) model; 2a) the Gironde Estuary (open coast/estuary) model; 2b) the Medoc region model nested within the Gironde Estuary; 3a) the Teign Estuary (open coast/estuary) model; and 3b) the Teignmouth city model nested within the Teign Estuary. These case-studies illustrate the development of the SPR system maps across a range of coastline types, flood risk challenges and management policies. A discussion of the cross-scale application of the model can also be found in (Narayan et al., 2012b). The Teignmouth quasi-2D SPR described in this Chapter is subsequently used as the foundation for the Teignmouth quantitative model in Section 5.2. The Portsmouth quasi-2D SPR constructed to inform the Portsmouth quantitative model is described in Section 5.3. Table 4 at the end of this section describes the lessons learnt from quasi-2D SPR model development and application and evaluates its performance in terms of its objectives and the participatory approach in all the sites.

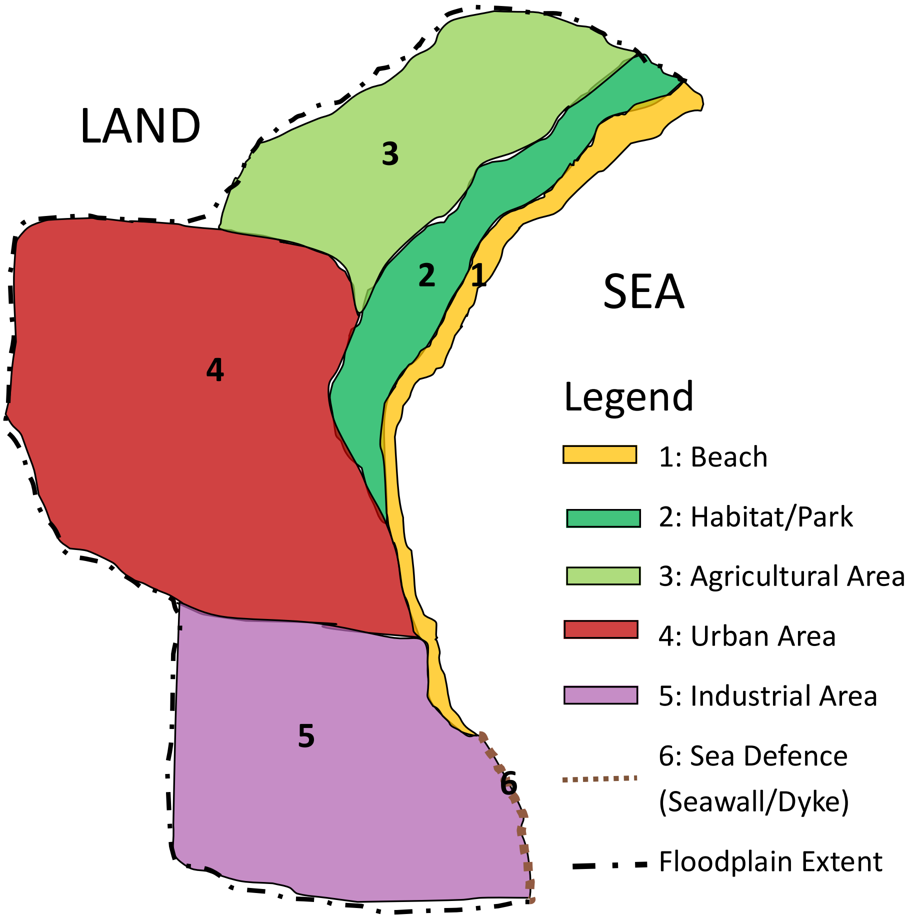

Figure 9: Land-use Map for Quasi-2D SPR system diagram

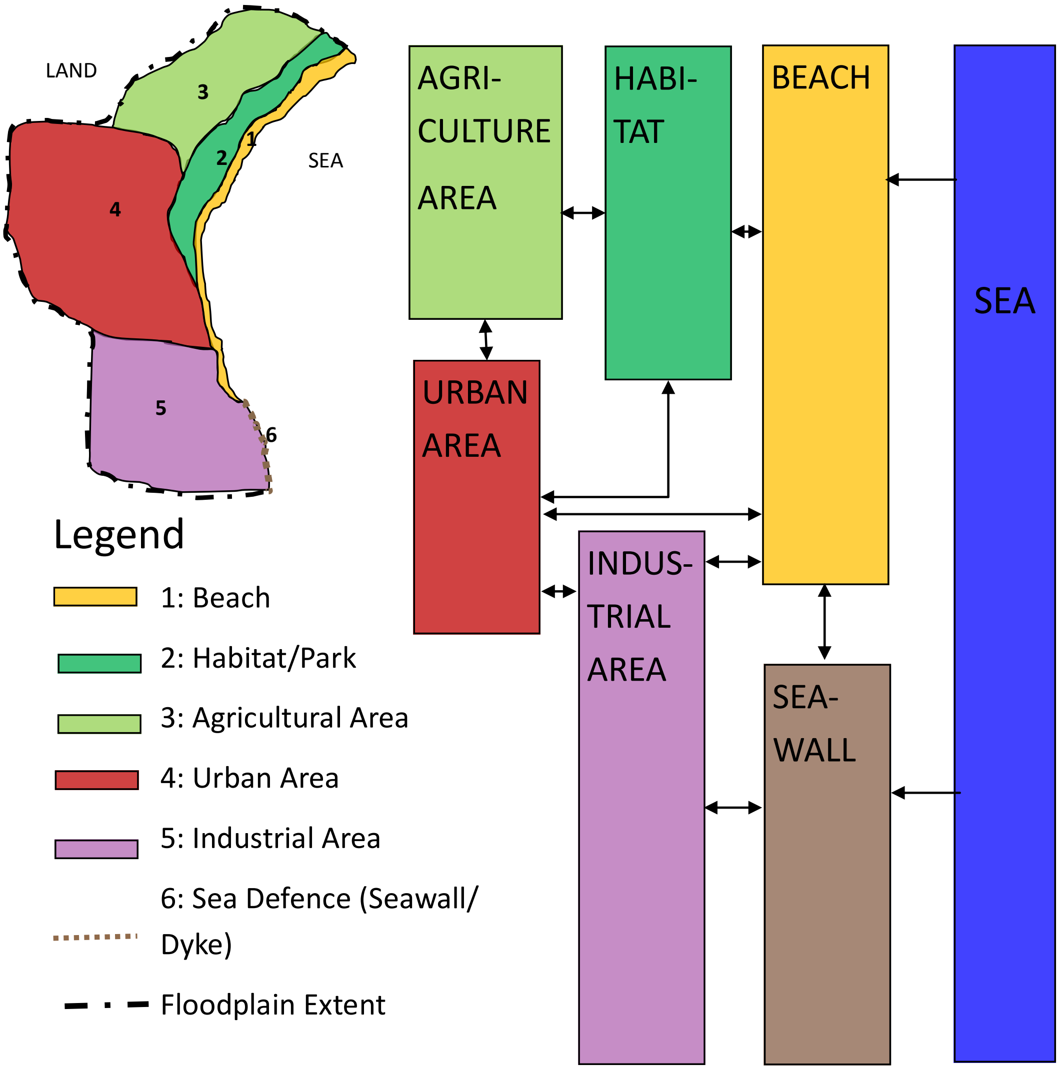

Figure 10: Quasi-2D SPR System Diagram

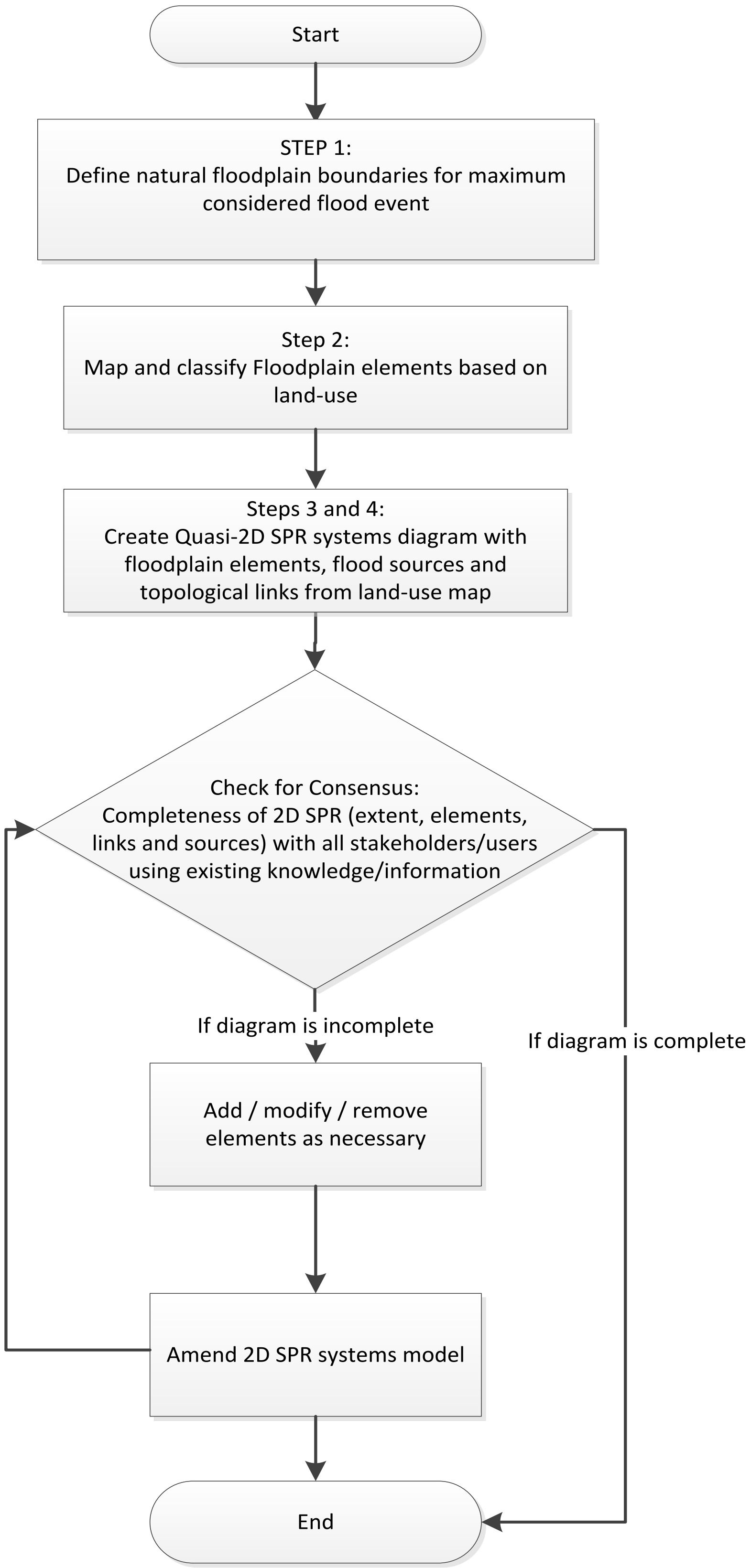

Figure 11: Flowchart for Quasi-2D SPR Construction

3.5 Quasi – 2D SPR: Case-Studies

3.5.1 Hel Peninsula, Gdansk, Poland

The Hel Peninsula is a 35 km peninsula located in northern Poland between the open Baltic coast and Puck Bay (see Figure 12). The peninsula is a long and narrow natural formation and as a result it is highly exposed to coastal erosion and flooding by breaching. Due to its geography and shape the peninsula is vulnerable to breaching by waves and inundation due to storm surges and rising sea-levels. Most of the peninsula is low elevation except for a high dune-belt along the open coast whose highest point is 15 metres above sea-level. An extreme 100 year return period water level for the region accounting for sea-level rise is estimated to be around 1.4 m at present and predicted up to 2.78 m by AD 2100. The region has a resident population of around 18000 and receives more than 100000 tourists at a time during summer for its wide sandy beaches and world-renowned kite-surfing and wind-surfing sites. The peninsula has a number of camping sites and four fishing ports. A road and railway track providing essential transport especially during the tourist season run through the length of the peninsula. Though the entire region is vulnerable to flooding this case-study focuses on the north-eastern tip as this is the most vulnerable to flooding as well as the most important in terms of potential consequences. The northern coastline of the peninsula is maintained by annual sand nourishment of around 400 thousand m^3 (THESEUS Consortium, 2012).

The quasi-2D SPR is applied to the north-eastern segment of the Hel Peninsula. The floodplain extent this case was defined as the 100 year flood extent based on observed flood events and sea-level rise predictions. Examination of past events and the concentration of key elements near the base resulted in the SPR diagram for the site being limited to a 10 km stretch at the landward end of the peninsula. Data for constructing the model used available information on past flood events obtained from the Maritime Office – the government authority in charge of management of the Peninsula, and from land-use charts prepared by the local community. The SPR system diagram is built to reflect the dominantly bi-directional nature of flooding in the region – one flood source from the open coast to the north, and the other from the Puck Bay to the south. Model construction and problem-framing were a multi-disciplinary approach necessitating the involvement of sociologists, economists, hydraulic engineers, coastal geomorphologists, local authorities, local businesses and residents. The involvement of professional maritime stakeholders and the local community in building the systems model helped in mapping different floodplain elements from a range of perspectives. Model construction also let the stakeholders identify particular floodplain elements, interactions and flood routes between these elements (see de Vries et al., 2011)

The Hel Peninsula is currently maintained by a range of hard coastal defence structures as well as beach nourishment programs. The root of the peninsula consists of a heat and power generating factory. This critical infrastructure is protected by a seawall and a gabion revetment built into an artificial dune. There are several other commercial and urban areas in the region. The beach along the open coast is nourished in some parts and has a continuous groyne system along its length. The Puck Bay side of the peninsula consists of natural green areas, camping sites on beaches and revetment flood defences. Three different types of green areas can be distinguished in the region from the system diagram – forests that protect the dunes, natural green areas and insulation green areas. The insulation green areas protect the road and railway lines which run along the centre of the peninsula. With regard to flooding from Puck Bay the system diagram shows that the road and railway elements could themselves function as highly effective flood barriers.

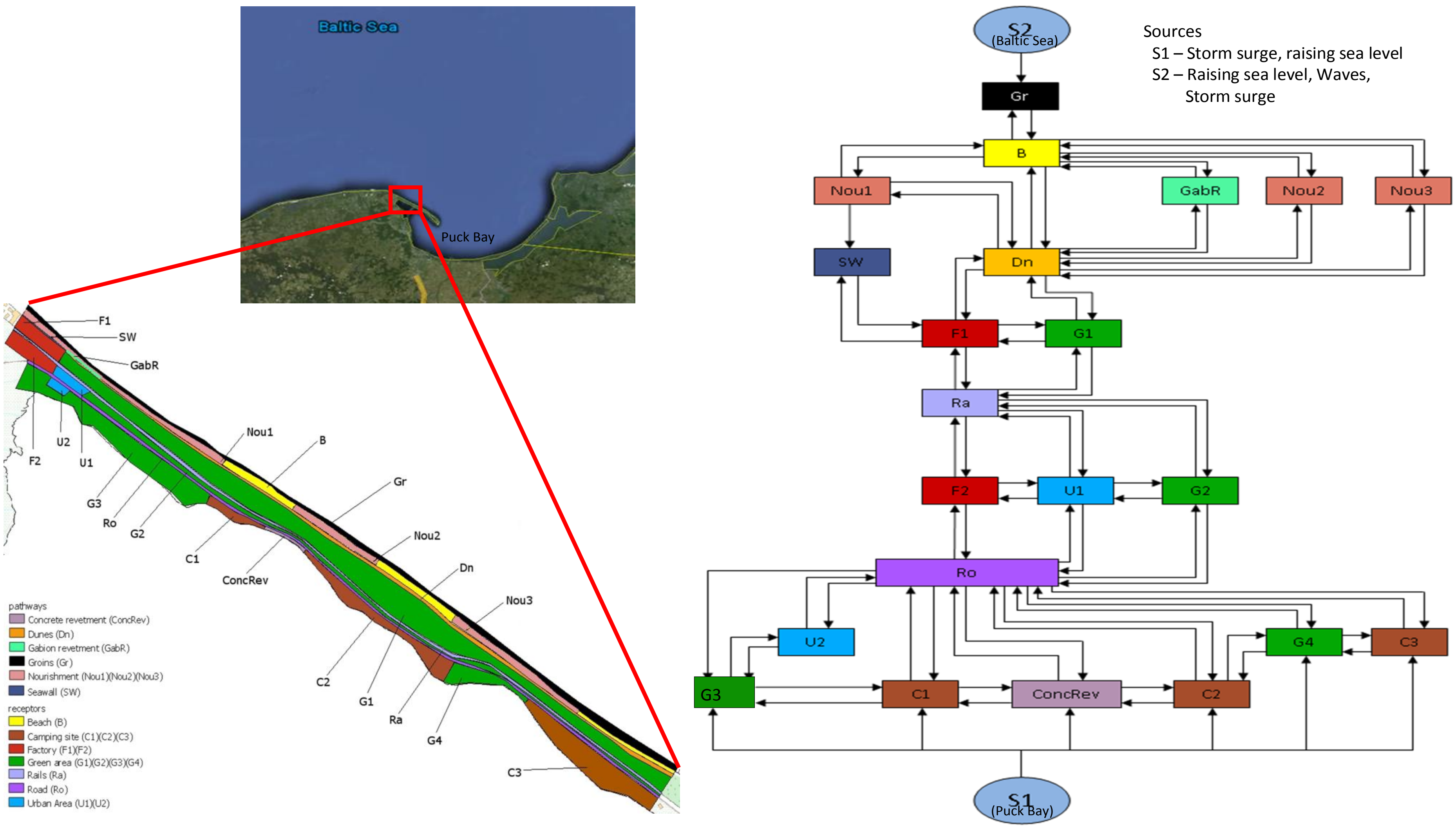

Figure 12: Location, Land-use Map and Quasi-2D SPR for Hel Peninsula, Gdansk, Poland

3.5.2 Medoc Region, Gironde Estuary, France

The Gironde is the largest estuary in Europe with a high tide water surface area of 645 km^2. The estuary is created by the confluence of the Garonne and Dordogne rivers which merge near Ambès. The length of the estuary from there to the mouth is 75 km. The estuary is tide-dominated with mean tidal amplitude varying from 3.2 m at the mouth to 4.2 m at Bordeaux. The risk of flooding has always been a major concern in the region. Historical records show frequent annual flooding from AD 1212 to AD 1770 when flood defences were built after a significant flood at Bordeaux. However more damage occurred again in the years 1835, 1855 and 1856. The biggest flood events of the last half century have been river flooding combined with high tidal amplitude in December 1981, the storms Lothar and Martin in 1999, and more recently, storm Xynthia in 2010. The largest part of the estuarine floodplain consists of agricultural fields of which several are high value wine crops representing 80% of the vineyard region of Bordeaux. Industrial assets notably include a nuclear plant at Le Blayais on the northern shore of the estuary which was partly flooded during the 1999 storms. The floodplain additionally consists of urban areas including Bordeaux, forests and wetlands some of which are listed under the framework of the European Directive Natura 2000 (THESEUS Consortium, 2012).

The team in the Gironde case study consisted mainly of flood defence managers and scientists. Since the Gironde is a large estuary with very different stakeholders and configurations, building a full SPR model at high resolution is a difficult task. Thus two models are constructed one at an estuary-wide level which aimed to identify those flood-prone areas that require detailed investigation, and a smaller model studying the identified region in greater detail for both flooding and erosion.

The first is a larger model for the region between the estuary and the Atlantic Ocean, from the estuary mouth up to the city of Bordeaux. The maximum flood extent is assumed as the present 100 year flood event. This is based on a planar water level model using the maximum value of tidal amplification along the length of the estuary. The inland extent of the floodplain for this water level varies between 3 and 5 km along the length of the estuary. Figure 13 shows a map of the region with floodplain elements classified based on their predominant land-use. Homogenous dyke sections – i.e., sections with one owner and uniform crest height are also mapped. The land-use map is used to build the large-scale SPR model for the left bank of the estuary shown in Figure 14 (also see Narayan et al., 2012b).

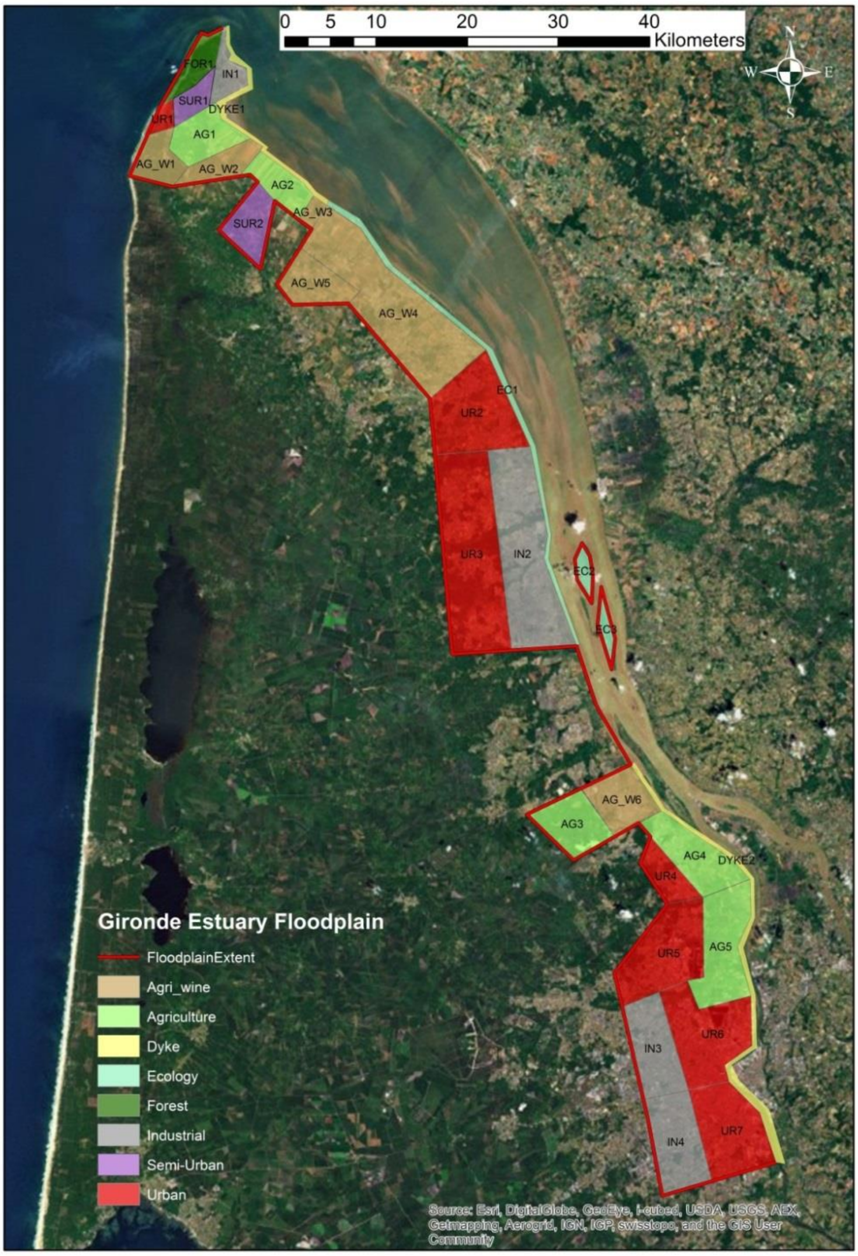

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Figure 13: Land-use Map for Gironde Estuary Quasi-2D SPR

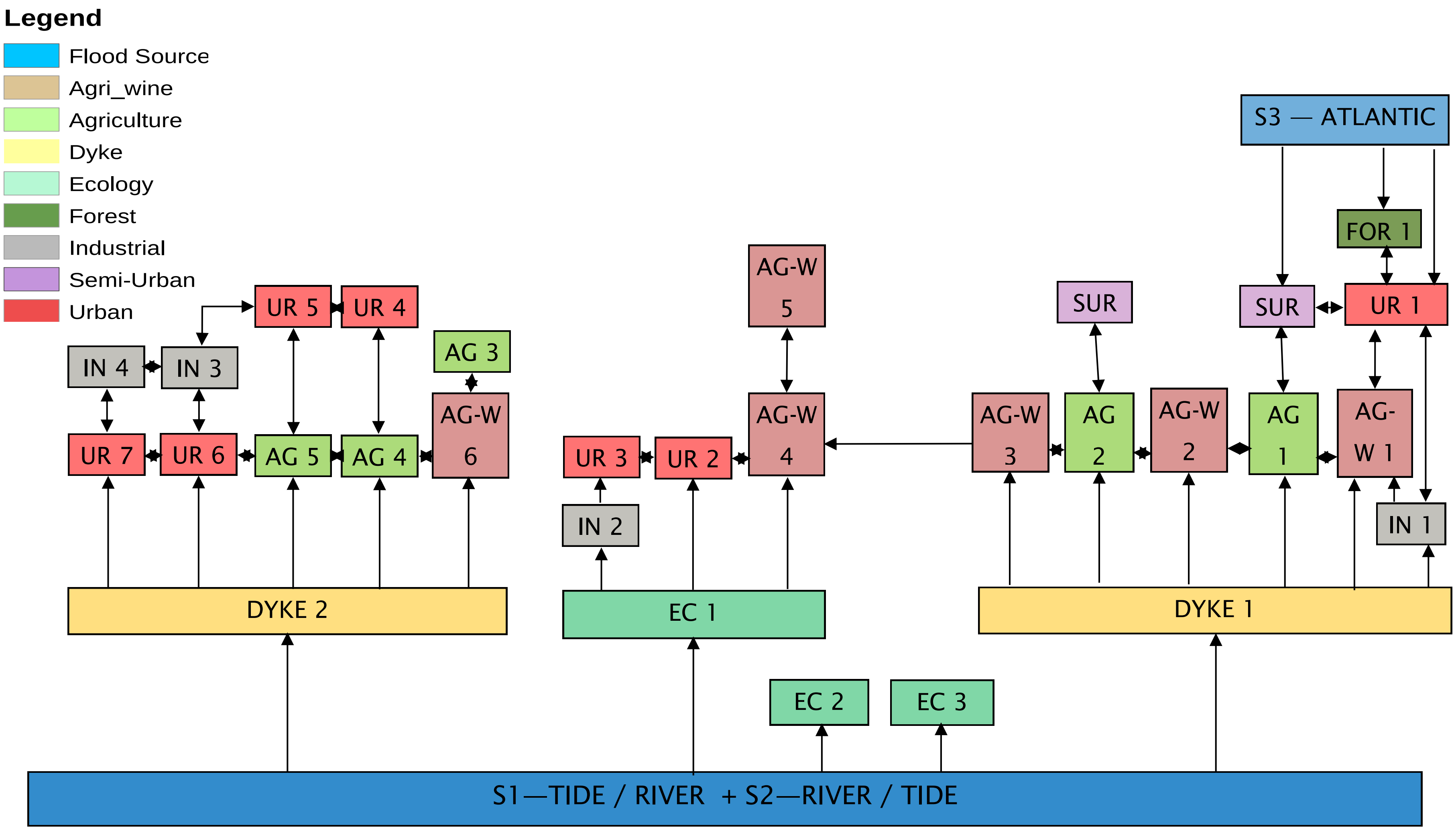


Figure 14: Quasi-2D SPR for Gironde Estuary

From this diagram historical data and maps from the Aquitaine Coastal Observatory identified the most likely location of a breach during a storm in 2100 that would result in flooding from the Atlantic Ocean (Aubié and Tastet, 2000). A nested quasi-2D SPR is subsequently constructed for the Medoc region. The main purpose of the nested model is to identify specific local-scale flood pathways and flood zones, both current and anticipated, based on existing knowledge of flood pathways, and erosion and breach scenarios.

Current knowledge indicates that the Atlantic coast in this region is subject to long-term coastal erosion due to the effects of a northward alongshore current from Pointe de la Négade (south of Soulac) to the Pointe de la Grave (Aubié and Tastet, 2000). Accelerated erosion of the coastal dune in this area could result in the opening of a new pathway from the Atlantic Ocean to the floodplain in the future if no preventive measures are taken. Such a scenario would be consistent with the Holocene history of shoreline retreat in this area (Lesueur et al., 2002). The breach is considered possible as a consequence of sea level rise and continued shoreline erosion along with an extreme event and corresponds to a management scenario where nothing is done to prevent on-going erosion.

A major difference in the nested quasi-2D SPR developed here to the larger Gironde estuary model is the basis for defining and classifying the receptors. Rather than using a generic land-use classification scheme the team used the French planning regulations for risk prevention (PPRI) which define three zones:

1. Zones where building is forbidden
2. Zones where building is allowed provided some conditions are met, mainly to raise the standard of protection of existing buildings and ensure that new buildings will withstand the more common flood events.
3. Zones where building is allowed without restriction.

In the PPRI a significant portion of the floodplain is classified as zone 1 which means only small parts of the floodplain can be built upon. There is little information present at this scale about the coastal defences and an inventory of existing defence types and their characteristics is currently on-going in the region. Since the detailed quasi-2D SPR describes a specific breach as definitely occurring, it does not map any existing defences. As seen in the larger Gironde quasi-2D SPR, flooding itself may be caused by tidal water levels, waves, upstream river discharge or a conjunction of these. The southern floodplain boundary is decided based on the expected maximum extent of flooding due to the breach at South Le-Royannais. Figure 15 shows a map for the Medoc region classified based on the PPRI land-use regulations. Figure 16 shows the Quasi-2D SPR for the Medoc region.

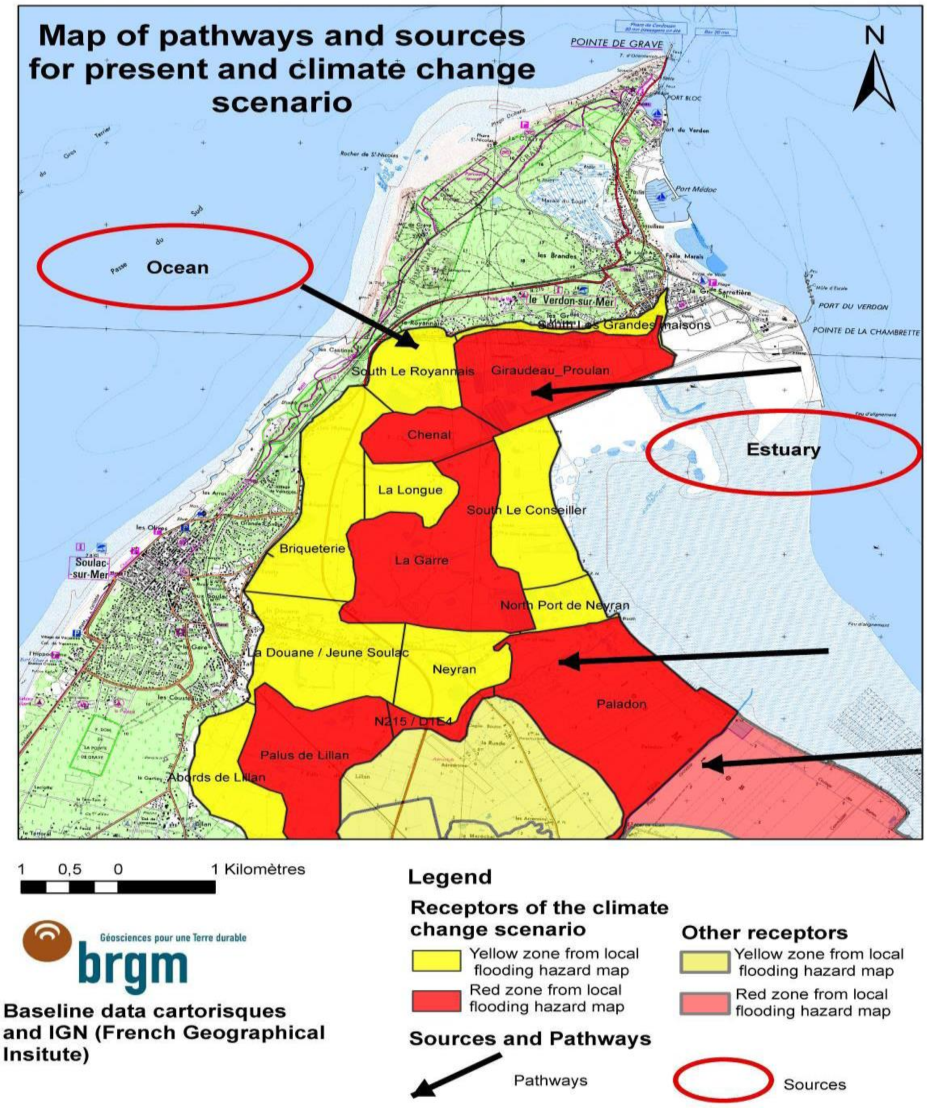


Figure 15: Land-use Map for Medoc Quasi-2D SPR

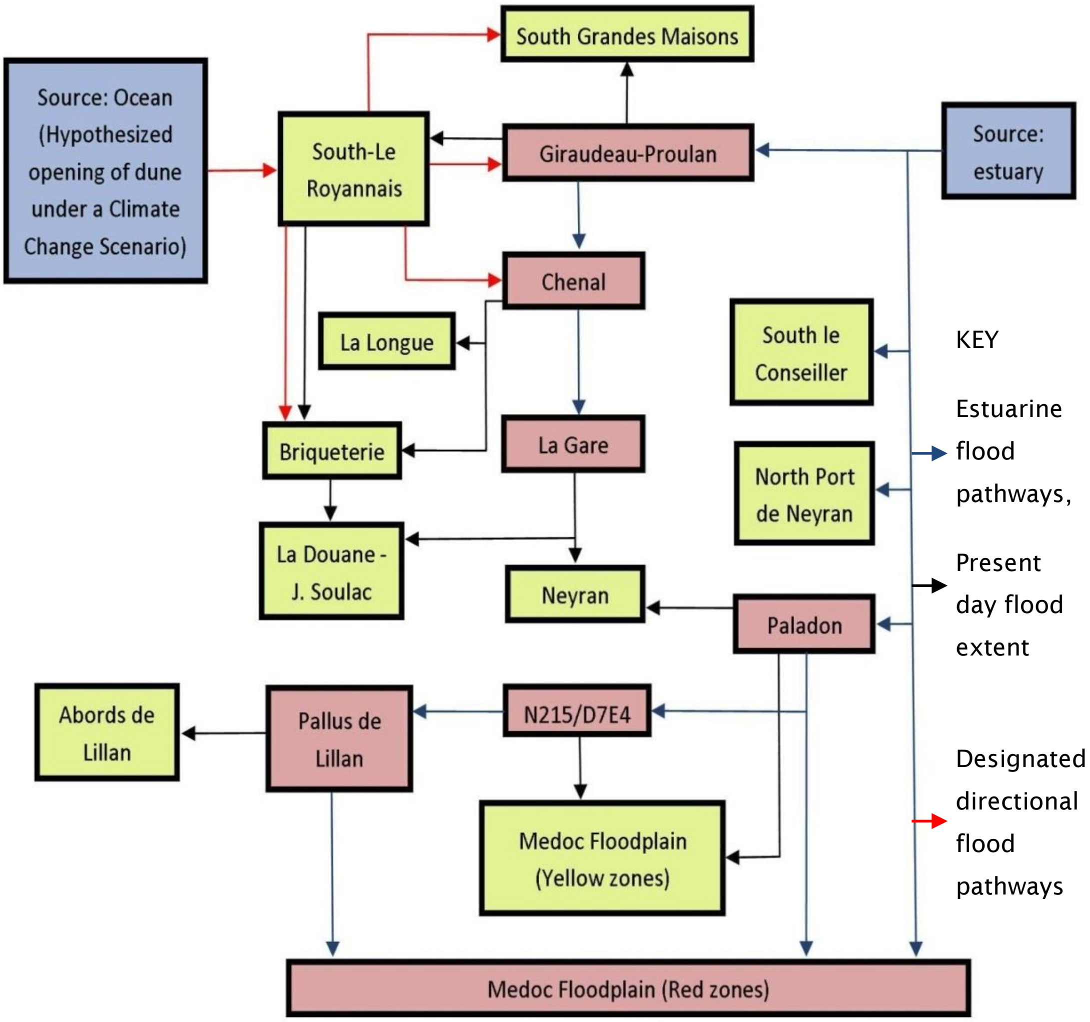


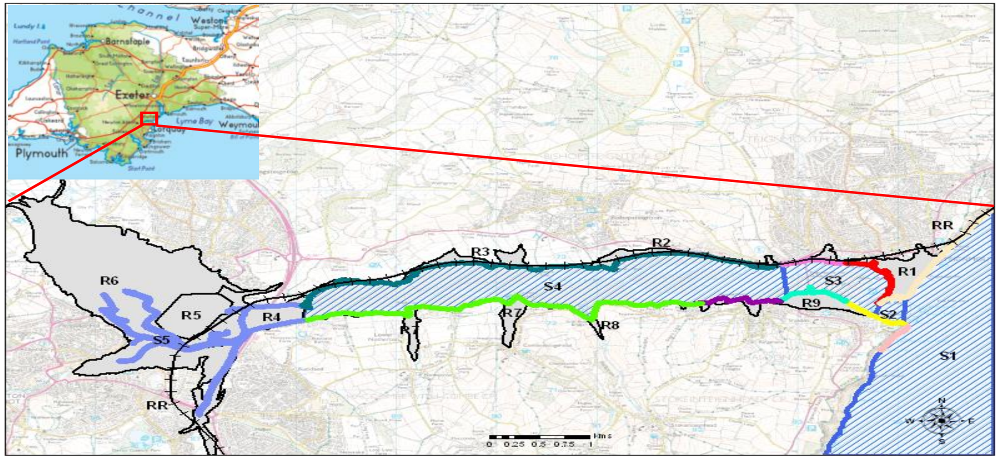
Figure 16: Medoc Quasi-2D SPR

The Medoc quasi-2D SPR contains more detailed and specific information compared to the larger Gironde system diagram. The larger model is rapidly built and gives an overview of the entire estuarine floodplain highlighting the sensitivity of the Medoc region to bi-directional flooding using existing information. This informs the downscaling process and the decision to focus on the administrative region of Medoc for the nested quasi-2D SPR. Information is easier to obtain for the Medoc model as it is lesser in extent and more homogenous in terms of data availability. This model gives detailed information on potential new flood pathways that will result from a breach on the Atlantic Ocean coast.

3.5.3 Teign Estuary, South Devon, UK

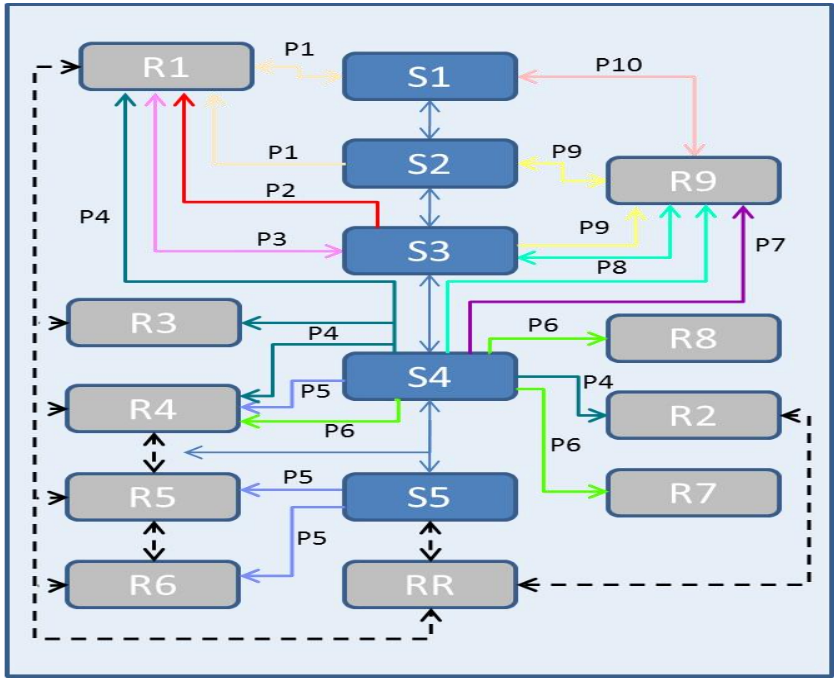
The Teign estuary is located in southwest England formed by the River Teign which is 50 km in length. The estuary is defined by steeply rising hills, resulting in several urban flood compartments including the historic port city of Teignmouth and a range of important and sensitive habitats. A key artificial coastal element is the railway line running along the site from Teignmouth at the mouth of the estuary to Newton Abbot upstream. Coastal defence lines that protect this critical transport link have had an impact on coastal processes in the region (Halcrow Group, 2011).

Flood source characterisation for the site is based on a detailed assessment of wave and water-level conditions on the open coast and within the estuary. The flood sources are represented to a higher detail than in the Hel and Gironde sites and are distinguished by the relative contributions of waves and tides and the changing nature of sources from the estuary mouth to the upstream artificial tidal limit at the city of Newton Abbot. The maximum water levels at the mouth of the Teign estuary vary between 2.6 m for a 1 in 2 year return period and 3.44 m for a 1 in 1000 year return period. The estuarine floodplain is defined on the basis of the current 100 year flood applied along with the predicted relative sea-level rise for the year 2100 (McMillan et al., 2011). The quasi-2D SPR for the 6 km long Teign estuary is shown in Figure 17.



Receptor Elements
RR - railway line
R1 - Teignmouth
R2/R3 - agricultural lowlands
R4 - marsh
R5 - race course
R6 - Newton Abbot - industrial parks and domestic
R7/R8 - agricultural lowlands
R9 - Shaldon (domestic)

Pathway Elements
P1 - beach backed by concrete seawall
P2 - walls (vertical)
P3 - port quayside
P4 - embankment with stone revetment
P5 - unprotected riverbank
P6 - earth/clay embankment with assorted toe armour
P7 - vertical blockwork wall and wave wall
P8 - new flood defence scheme, (blockwork)
P9 - cliff fronted with toe protection
P10 - cliff



Sources
S1 - open sea (waves + tides)
S2 - estuary mouth/channel (waves + strong tidal flow)
S3 - estuary entrance (tides + diffracted waves)
S4 - central estuary (tides + local waves)
S5 - river (some tidal effect, no waves)

Figure 17: Location, Land-use Map and Quasi-2D SPR for the Teign Estuary, Devon, England

In the Teign quasi-2D SPR floodplain elements are classified based on their location within flood compartments. The elements are further distinguished as floodplain elements that function primarily as receptors and those that are primarily flood pathways. For instance pathway elements mainly include sea defences, dunes and embankments. Receptor elements include urban floodplains and the railway line. Seven of the nine Teign estuary flood compartments flood from a single direction. Though most of these are in isolated flood compartments, elements R4, R5 and R6 are connected to one another. Also these elements which include the urban area of Newton Abbott, are exposed to a confluence of river (S5) and tidal (S4) (also see Reeve et al., 2012).

The Teign quasi-2D SPR identifies two estuarine flood compartments – the city of Teignmouth on the eastern bank (R1) and the town of Shaldon (R2) on the western bank that are exposed to multiple flood sources: estuarine water levels and coastal surge and waves. The city of Teignmouth is of significant economic importance to the region and has had a history of flooding in the past. To analyse the likelihood and pathways of flooding in more detail, a nested quasi-2D SPR is constructed for Teignmouth. The quasi-2D SPR for the Teignmouth floodplain is built combining information from a Digital Elevation model for the area (www.channelcoast.org), land-use information from Ordnance Survey maps, and details about the coastal floodplain. The floodplain is bounded by the 5 m contour line to ensure that all elements lower than a 1 in 1000 year flood water level are included.

Floodplain elements are mapped and classified using a scheme that combines information on land-use types and topological relationship to the coastal and estuarine flood sources (Figure 18). Links are drawn between adjacent elements that share a boundary. The coastal elements represented in the quasi-2D SPR (Figure 19) are the beaches along the inner estuary and the open coast, the harbour and other estuarine infrastructure, and multiple seawall sections along the open coast distinguished in terms of their crest height and/or type of construction. The railway line is the only floodplain element that links the Teignmouth floodplain to flood compartments of the larger Teign estuary. The railway line traverses a significant length of the floodplain and is therefore difficult to represent as a single element. For ease of representation it is split into three linked elements. Inland floodplain elements outside the central urban areas, such as residences and coastal roads are classified as near-coastal elements in the quasi-2D SPR.

The quasi-2D SPR has two urban floodplains – the central urban floodplain, 'TeignmouthFP' and the western urban floodplain north of the railway line, 'TeignmouthFP_West'. A key advantage of the flexibility of the SPR approach is the inclusion of non-local elements that have a direct influence on the coastal floodplain. For instance the width of the beaches along the open coast is influenced by erosion occurring updrift along the coast from cliffs that are not included in the model extent (Halcrow Group, 2011). Though they do not lie within the considered floodplain they are included as a 'Sediment Input' element in the quasi-2D SPR.

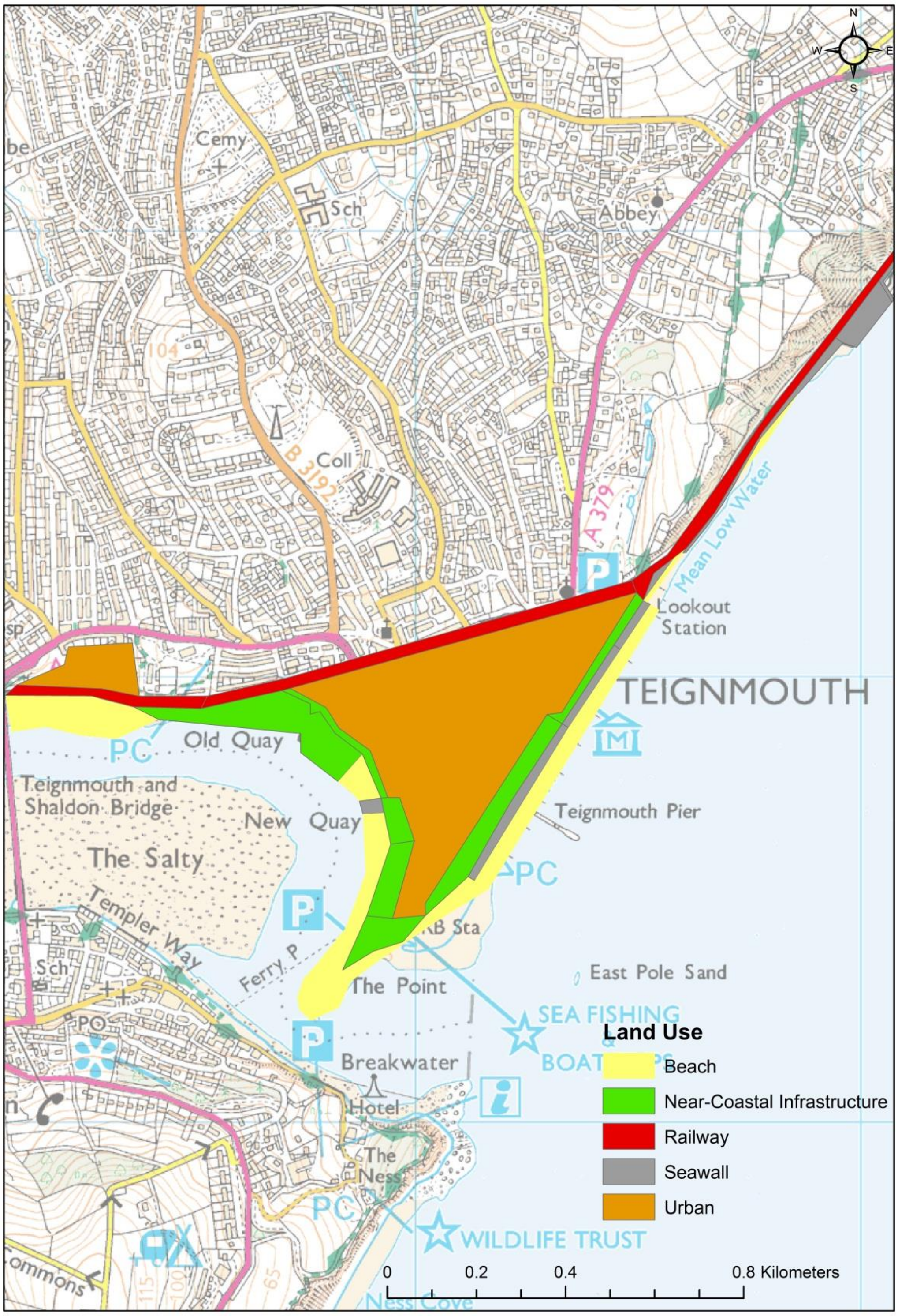


Figure 18: Land-use map for the Teignmouth Quasi-2D SPR

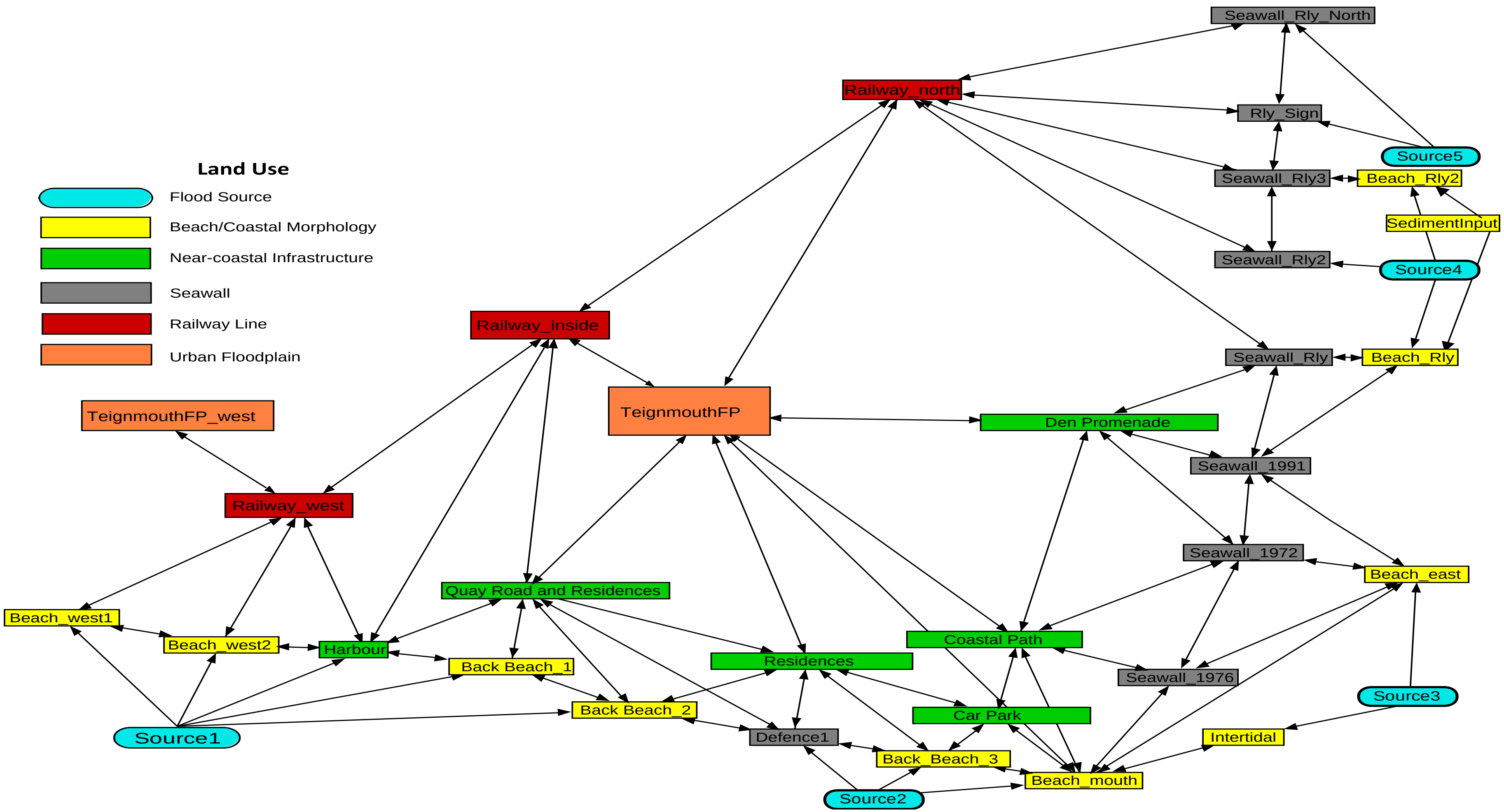


Figure 19: Quasi-2D SPR for Teignmouth, Devon, England

Quasi – 2D SPR: Evaluation

The quasi-2D SPR applications have provided insights into the key characteristics of coastal floodplains that an integrated flood risk assessment should consider. For the qualitative model to be practically useful however, evaluations of at all study sites are necessary. In this section the lessons learnt from model application about the characteristics of each floodplain, as well as the difficulties in quasi-2D SPR model application, its advantages and limitations are discussed in terms of the model objectives listed in Section 3.2. These are summarised in Table 3 at the end of the section. Feedback from all seven sites on model performance with regard to the objectives in Section 3.2 is summarised in Table 4.

3.5.4 Description of Complex Coastal Floodplains

The Hel Peninsula SPR was found to be useful in providing a clear picture of the floodplain to local decision-makers and a clear method for information mapping. The model highlights the exposure of all floodplain elements to flooding from two distinct sources, and the vulnerability of all floodplain elements due to the narrow, elongated shape of the peninsula. Due to its relatively high resolution, the model also allows classification and identification of direct and indirect influences between particular floodplain elements. A limitation of this application is the arbitrary floodplain extent for which the model is constructed. The fact that only one SPR is built for the Hel Peninsula means that assumptions regarding the floodplain extent are not made explicit. This could be improved by building nested SPRs which include the entire natural floodplain like in the Gironde case.

The Gironde quasi-2D SPR model covers a much larger, naturally limited estuarine floodplain and focuses on a low-resolution description of the floodplain, to identify sensitive regions of the floodplain. Similar to the Hel Peninsula, the estuarine floodplain in the Gironde SPR can be flooded from two directions. However, current knowledge on erosion processes in the region indicates that flooding from the Atlantic Ocean is limited to a single location. This information in turn informs the construction of the nested Medoc model. The nested model has a resolution similar to the Hel Peninsula SPR. However the floodplain description is very different reflecting differences in the way the floodplain is managed and analysed at this scale. The larger Gironde model maps the generic, dominant land-use of the areas that are at risk of flooding due to the failure of a coastal dyke section; the Medoc model maps the floodplain in terms of flood regulation zones and describes potential flood pathways in the event of a certain breach. The breach scenario in the Medoc model is representative of an overall ‘do – nothing’ scenario where no beach protection or nourishment is carried out along the Atlantic open coast. Though this is an unlikely scenario at present it serves to highlight the vulnerability of the region to a coastal dune breach.

The Teign SPR, unlike the Gironde and Hel diagrams, consists of a number of localised and isolated floodplain elements between which no pathways exist. Here again, two regions of the Teign Estuary floodplain are identified that are exposed to flood sources from two directions. Shaldon and Teignmouth at the mouth of the estuary are exposed to estuarine water levels as well as open coast waves and storm surges. Unlike the Gironde, however, the compartmental nature of the floodplain elements means that Shaldon and Teignmouth do not act as pathways to other regions. The quasi-2D SPR also identifies upstream elements including the urban area of Newton Abbott that are exposed to a combination of river and flood sources. One of the challenges in building the Teign estuary SPR, associated with the topography of the site, was in defining the floodplain elements. This was due to the difficulty in obtaining land levels in the 0-5m range, corresponding to the extreme water levels of the flood events considered. The model-building process was found to be a useful method of identifying knowledge gaps such as the difficulty in obtaining land level data. Gaps in data on land-levels in the 0-5 m range, and on flood defence pathway elements were identified and efforts made to collect additional information. Like in the Gironde study a nested quasi-2D SPR model is built for Teignmouth city that describes its floodplain in more detail than the coarser Teign estuary model. The Teignmouth model focuses on capturing flood pathways into the floodplain from multiple sources– the estuary to the south and the open coast to the east. The influence of cliff erosion occurring outside the model boundary is also indicated in the system diagram as an input to the floodplain system.

In all three sites, the quasi-2D SPR emphasises the duality of an element’s status – i.e., flood pathway and flood receptor. For instance, flood protection in the Hel Peninsula is a combination of engineered defences and beach nourishment programs. In this context, the beaches are flood pathways to the rest of the system. However, the beaches are also of high importance to tourism, and therefore also qualify in their own right as receptors of flood damage. For each of the three case-studies, the quasi-2D SPR site provides a unique description of the floodplain. Table 3 which summarises feedback from SPR applications in the eight THESEUS sites shows that the model achieves a satisfactory description for all sites.

3.5.5 Participatory Construction Methodology

Quasi-2D SPR development is a participatory process that builds on existing participatory approaches for knowledge-elicitation and information gathering. The reason for a participatory methodology is to ensure a shared ownership of the floodplain across stakeholders from multiple disciplines by engaging them in model construction. The same process is followed in all sites though the manner and extent of stakeholder inclusion varies for each site. Of the case-studies discussed in this thesis the Hel Peninsula shows the widest inclusion of stakeholders followed by the Gironde and the Teign. The Hel Peninsula model construction process necessitated cooperation and exchange of information between multiple authorities responsible for coastal management. The suggested methodology and outcomes provided a framework for mapping the coastal floodplain and developing a shared understanding of the different sources, pathways and receptors. The Gironde case-study demonstrated different forms of stakeholder inclusion at different scales. The larger, estuary-scale model primarily involved regional flood risk experts, geologists and engineers whereas the smaller-scale Medoc model also involved land-use planning expertise. The Teign estuary and Teignmouth models were the least inclusive amongst the three and primarily involved flood risk experts, ecologists and coastal engineers.

The construction methodology does not define a specific tool or time-frame for the mapping exercises, which may vary from site to site. For all the THESEUS sites the information gathering and mapping process was facilitated using the common construction methodology developed in this thesis. For all sites communication within site-team members took place at regular meetings while facilitation and feedback during the iterative process were through online collaboration. The quasi-2D SPR for each site was constructed on average within a week. While single focus group or workshop sessions are often the norm in such exercises the geographic spread of the sites and the range of stakeholders make this impractical. An advantage of the extended time-frame iterative feedback process over an extended time-frame also allowed for better formation and clarification of pertinent information.

A potential limitation of model construction methodology is that it does not define the number and type of stakeholders to be included. This is due to the potential variation at each site, in the nature of the floodplain and the range and extent of stake-holder involvement in the flood risk study for which the quasi-2D SPR forms the common conceptual model. Table 4 highlights the strong relationship between the effectiveness of the participatory methodology and knowledge-capture. For instance, in four of the seven THESEUS sites, a fully inclusive participatory methodology was not possible due to time constraints and the SPRs were built solely by hydraulic engineers using existing data on flood inundation extents, sources and pathways. This resulted in floodplain descriptions that were hydraulically complete, but lacking in terms of an integrated, multi-disciplinary approach and therefore represent partially complete knowledge-capture.

3.5.6 Model Limitations

A chief limitation of the quasi-2D SPR and approach is the subjectivity involved in the assumptions and model construction. Site applications summarised in Table 4 show difficult and/or inconsistent application of the SPR model for the Teign, Scheldt and Elbe estuarine sites. For the Teign estuary this is a reflection of the highly compartmental nature of the floodplain and the lack of information on elevations between 0-5 m. The other two sites – the Scheldt and Elbe estuaries, are characterised by a large quantity of existing information on inundation and flood risk. Achieving a clear and concise conceptual description of these floodplains is therefore in some respects more difficult since this requires concise distillation of the questions being asked and the required level of detail and classification methodology required to answer these questions. For instance, the SPR model for the Medoc region could either focus on the causes of the breach along the Atlantic Ocean, or on its effects on the regulatory flood pathways, or other questions that might be posed.

Most of the effort and time in model-building is associated with the collection of data for the land-use maps and organising stakeholder participation for the iterative process of model construction. The average construction time of the quasi-2D SPRs across the eight sites was under one week. While the model can be built by an individual with minimal available data on elevations and land-use this is not ideal and is generally reflected in an incomplete floodplain description. However, the approach allows users to rapidly recognise key challenges in characterising their sites such as data availability or system size and complexity, before application of detailed numerical models. In fact the conceptual description of these challenges is an essential step to inform the inputs to and choice of further models that assess flood inundation (e.g. Jamieson et al., 2012) and flood damages (e.g. Burzel et al., 2012).

The qualitative SPR does not provide any information regarding the mapped floodplain elements, apart from their topology and the links considered. Also while it does not provide a dynamic description of the floodplain, the model can be easily built to describe multiple snapshots representing changes to floodplain state over time if so desired.

The model does however provide a platform for collecting, integrating and organising existing knowledge about the floodplain. As such, it shows promise as the foundation for the next stages of this work: a quantitative conceptual model of the coastal floodplain. Quantification of the information mapped by qualitative model will allow the users to assess the state of the coastal floodplain for different input conditions and make informed decisions regarding the management of specific floodplain elements. Also, quantification of the collected knowledge about the floodplain system is required for integrating this within larger flood risk studies. The quantitative conceptual model is developed on the foundation provided by the qualitative model described in this chapter.

3.5.7 Scale Issues in the Quasi-2D SPRs

A useful feature of the quasi-2D SPRs that emerges from the model construction process is the scalability of the model – both in terms of its extent as well as the flexibility in choosing the size of individual floodplain elements. All three SPR models highlight a common feature of their floodplain systems:

areas of the system exposed to flooding from two directions. In the Hel SPR this covers the entire peninsula, whereas in the Gironde and Teign floodplains these are limited to regions at the mouth of the estuary – Medoc in the Gironde, and Teignmouth and Shaldon in the Teign. The Gironde qualitative model illustrates a structured downscaling approach using which model can 'zoom in' to the Medoc region once this is identified as a region of interest. The downscaling approach also illustrates the difference in the issues investigated at each scale due to new/additional information or changing priorities. The Teignmouth quasi-2D SPR which is used as the foundation for the Teignmouth quantitative model described in Chapter 5 also focuses on the issue of multiple sources in multiple directions, and additionally indicates the influence of an external input to the system – upstream cliff erosion.

Table 3: Summary of Quasi-2D SPR Applications in Poland, France and England

Site	Floodplain Characteristics	SPR MODEL		
		Difficulties in Application	**Model Advantages**	**Model Limitations**
Hel Peninsula, Poland	Flooding from two directions; Extent limited to northern end; Combination of engineering and beach nourishment for flood protection; Key land-uses are industry and tourism	Information on floodplain is distributed across multiple authorities and stake-holders	Model Application facilitated dialogue Prioritised data gathering Useful for identifying potential risk reduction measures	Subjective model-building process Limited extent No quantification
Gironde estuary, France	Possibility of future flooding from Atlantic Ocean Two models constructed at two scales	Large extent of study site Information on potential flood routes needed for small-scale model	Easy and structured approach to down-scaling Smaller model can assist local planning by using regulation-based classification scheme	Model assumptions are need to be communicated clearly No quantification
Teign estuary, England	Multiple isolated flood compartments Multiple flood sources near the mouth Widely varying size and characteristics of floodplain elements	Data availability for 0 – 5m contour; Large extent of study site	Easy inclusion of railway line element Identification of data-gaps Structured down-scaling	Large model uses very coarse resolution No quantification

Table 4: Quasi-2D SPR Evaluation: Feedback from Site Applications (✓ Achieved; ○ Partially achieved; X Not achieved)

Case-study Site	Stakeholders/ Disciplines Involved in SPR Application	Feedback: Did the SPR achieve its objectives?			
		Participatory Methodology	Capture local knowledge	Rapid description of large, complex coastal floodplains	Consistent and universal application
Medoc Region, France	Geologists, geomorphologists; results from a modelling studies and official coastal risk prevention plans were used.	✓	✓	✓	✓
Teign Estuary, England	Environment Agency, Teignbridge District Council, Local business owners, Port & Harbour interests	✓	✓	✓	X
Dendermonde, Belgium	Hydraulic engineers	○	○	✓	X
HafenCity, Germany	Hydraulic engineers	○	○	✓	X
Cesenatico, Italy	Hydraulic engineers	○	○	✓	✓
Hel Peninsula, Poland	Maritime Office in Gdynia, Local Authority, Wladyslawowo, IBW PAN, IMGW PIB including economics and social sciences	✓	✓	✓	✓
Varna, Bulgaria	Hydraulic engineers, geomorphologists and ecologists	✓	✓	✓	✓

4 Development of a Quantitative Model for Rapid Integrated Floodplain Assessments

4.1 Introduction

The quantitative model forms the second stage of the conceptual model, and is developed on the foundation of the quasi-2D SPR. This chapter describes the considerations for the selection of a suitable modelling approach and development of a quantitative model, in line with Objective 3 defined in Section 1.3.

The considerations for selecting a quantitative modelling approach are closely linked to the motivations for development of the quasi-2D SPR. The quasi-2D SPR is developed to address the key challenges to the integrated assessments of coastal floodplains. These are recalled below:

1. Coastal floodplains can often be large in extent and diverse in the type of elements they contain, making it difficult to understand possible inter-relationships between these elements.

2. Though coastal flood risk studies often use multiple numerical models for specific aspects of the coastal floodplain, the complexity of these models mean that a full-scale integration is difficult to structure and execute.

3. Most flood risk studies are themselves large and expensive to execute. There is to date no easy or inexpensive method by which the information gathered in these studies can be integrated to provide a basic, comprehensive understanding of the floodplain system.

4. Flood risk studies often span multiple scales in the floodplains they assess and the processes they analyse. Integrating information across these studies and scales in a meaningful way is a significant challenge.

Construction of the quasi-2D SPR is a participative process that encourages experts in multiple disciplines to develop a shared and common understanding of the coastal floodplain and the key issues that need investigation. The model integrates knowledge pertinent to the floodplain and provides a comprehensive description of all recognised pathways of flood propagation. Quantification of this information is necessary for assessing the response of the coastal floodplain to changes in input conditions and/or individual elements, and identifying critical areas of the floodplain.

4.2 Quantitative Model: Aims and Objectives

The aim of the quantitative model is to provide rapid assessments of flood propagation for the entire coastal floodplain, for a range of inputs and through multiple pathways. The model is intended as a scoping tool that helps bound the problem and allows quick analysis before moving on to more computationally expensive approaches if and where these are appropriate and desired.

The quantitative model will achieve its aim by:

1. Estimating the likelihood of flooding across the coastal floodplain in response to a range of inputs
2. Quantitatively describing the states of floodplain elements to indicate their role as receptors and/or as pathways of flood propagation to downstream elements
3. Identifying new/critical flood pathways that emerge in response to changing inputs and quantifying the influence of the floodplain elements along these pathways.

4.3 Quantitative Model: Considerations

The quantitative model is developed to include two key issues: i) the propagation of flood water from flood sources through multiple pathways across the floodplain depending on the input conditions (e.g. water levels and wave heights); and ii) the influence of changes to floodplain elements such as a change in the height of a seawall or the erosion of a beach, on flood propagation.

In most flood risk studies the input conditions and sometimes the floodplain elements are described probabilistically (see Chapter 2). The model is therefore designed for probabilistic assessments of flood propagation. The importance of qualitative, 'expert' knowledge on certain aspects of the floodplain has been recognised in literature and in the quasi-2D SPR models. The quantitative model should have a methodology by which to incorporate such information where it is relevant. As a scoping tool the model should be inexpensive to build and easy to operate. At the same time it needs to combine descriptions of multiple floodplain elements and processes. In order to achieve this the model will require simplification of the processes that still allows a sound overview of the system to be obtained. It is reiterated that the quantitative conceptual model is not meant as a substitute for existing numerical tools but rather for providing initial information on the floodplain to better direct the use of more detailed models. Based on these considerations the following requirements for the quantitative model are identified:

1. The model should provide a ***comprehensive overview*** of the floodplain that furthers the understanding developed from quasi-2D SPR applications.

2. It should facilitate a ***computationally inexpensive probabilistic approach*** for quantifying and assessing flood probabilities across the floodplain.

3. It should be able to incorporate ***quantitative as well as qualitative data***, and where necessary, work with incomplete or uncertain data and inputs.

4. To support decision-making the approach should be able to ***clearly communicate assumptions and uncertainties*** associated with the modelling process.

5. The quantitative model should ***make use of the quasi-2D SPR system diagrams***. The quasi-2D SPR results in a comprehensive mapping of floodplain understanding through an iterative and participatory process. The constructed quasi-2D SPRs can vary greatly in scale and extent. The quantitative model should, as far as possible, be built using the quasi-2D SPR system diagrams to reflect the scale, extent and purpose of the flood risk study and preserve the mapped understanding of the floodplain.

Several modelling approaches exist that are capable of systematically integrating different types and forms of knowledge, data and information and are suitable for systems analyses (Kelly et al., 2013). The most common approaches are Component Models (CCMs), System Dynamics (SDs), Bayesian Networks (BNs), Coupled, Agent – Based Models (ABMs) and Artificial Neural Networks (ANNs). The next section is a brief review of these techniques that is used to identify the most appropriate modelling approach for the quantitative model, based on its aims, objectives and requirements.

4.4 Network and Systems Models: A mini-review

4.4.1 Introduction

This section describes the selection of a suitable modelling approach for the quantitative systems model. The modelling approach should facilitate the quantification of flood probabilities and flood pathways across floodplains consisting of different elements for which limited and varying quality of information may be available.

Network and systems analyses embody a wide and well-studied range of techniques and approaches applied in social networks (Burt et al., 2013), stakeholder interaction and policy (Lienert et al., 2013), infrastructure networks (Burgholzer et al., 2013) and artificial intelligence (Fung and Chang, 2013), etc. All these approaches emphasise the representation, description and analysis of networks – i.e. systems consisting of multiple, linked elements. The floodplains described by the Quasi-2D SPRs are characterised by complex networks and varying, sparse and uncertain data. Kelly et al. (2013) describe a decision-tree to differentiate between some relevant approaches including Coupled Component Models (CCMs), System Dynamics (SDs), Bayesian Networks (BNs) and Agent – Based Models (ABMs). Another class of models relevant to the coastal floodplain networks described in this thesis is that of Graph-theoretic Models (GMs). A brief introduction to and review of these five approaches is presented here. Based on the five considerations listed in Section 4.3 the most suitable approach is chosen to construct the quantitative systems model.

4.4.2 Coupled Component Models

Coupled Component Models (CCMs) refer to a class of methods that combine multiple models from different sectors or disciplines to provide a single outcome. CCMs are popular in fields that involve modelling of disparate processes that feed into one another such as global-scale climate change models (e.g., Drobinski et al. 2012) local scale physical systems models (e.g. Ashton et al. 2013), or coastal flood risk assessments. Most large-scale flood risk studies use the CCM approach (see Chapter 2). A CCM flood risk assessment will include the following components at varying degrees of complexity: a) offshore wave and water level models; b) coastal and near-shore morphological models; c) structural models for coastal flood defences; and d) flood inundation models (e.g. Dietrich et al., 2012).

The CCM approach is a powerful and flexible way of dealing with disparate systems and numerical models that feed into one another. The nature of model coupling within these frameworks may either be ‘loose’ where inputs from one model are manually obtained and entered as outputs to the next, or ‘strong’, where the communication between models is also automated (Kelly et al., 2013). Depending on the nature of the models and the coupling, the approach can become computationally expensive and require training in the requisite software skills for model development and linking. The results and information obtained from models within the CCM approach however can be used to inform simpler integrated flood risk appraisal tools. The conceptualisation and placement of all the component models within a single framework is a significant challenge. Harvey et al. (2012) describe a conceptual modelling framework REFRAME that is being built to structure and facilitate CCM approaches in flood risk studies. These models are intended as frameworks within which to place numerical models and do not provide any independent descriptions of the assessed floodplain.

4.4.3 System Dynamics

System Dynamics (SD) is a form of modelling that uses state variables and causal feedback loops to explore the behaviour of a system over time. An SD study starts with a diagram and a set of assumptions that are used to describe the situation. The assumptions are formulated as ordinary differential equations and used to model the evolution of the system state over time (Lane, 2008). These are represented in an SD model in terms of stocks characterising the state of the system variables; flows characterising the inflow and outflow of quantities to these variables; and loops characterising the positive or negative feedbacks that determine flow-rates to the variables.

SD's are a powerful way of structuring system knowledge and are popular in modelling environmental systems that consist of dynamic inter-relationships and feedback loops (e.g. Guo et al. 2001). They are typically used to model systems consisting of processes that interact over multiple scales (e.g. Meadows et al., 1972). They have been applied to the coastal zone to model the effect of policies and management options in coastal zone systems (e.g. Chang et al. (2008). SD studies typically have limited spatial representation in their conceptual model of the system though they can be used to model the processes that drive spatial activities such as flood evacuation response (Simonovic and Ahmad, 2005) and coastal processes (Nicholls et al., 2012). A potential weakness of this approach is the relative difficulty in including qualitative data and knowledge (McLucas, 2003, Luna-Reyes and Andersen, 2003). Though well suited for developing understanding of the dynamics of systems, SDs are generally deterministic in nature and are not easily linked to probability analysis techniques (Mohaghegh, 2010). They require an explicit treatment of uncertainties which may be a disadvantage in situations where this is a concern.

4.4.4 Graph-theoretic Models (GMs)

Graph theory refers to a field of modelling approaches for a variety of applications mainly concerned with the efficiency of flow or routing in networks or circuits. Graph-theoretic concepts are popular in network analyses and are so-called since they make use of information contained in the structure of a network's graph to measure its efficiency and other performance parameters. A graph is defined as a set of nodes or vertices and edges such that each edge connects a pair of nodes (Barnes and Harary, 1983). Graph-theoretic models emphasise the analysis of the structural properties of a graph such as its diameter, average path length or the degree of clustering of its components.

Graph-theoretic models are widely used in disciplines related to networks such as computer systems, electrical networks, ecology, banking, etc. (Phillips and Swiler, 1998) study the vulnerability of computer systems to internal and external attacks. Graph-theoretic studies generally use metrics of the graph to measure the efficiency of the network. In their study on the resilience of electrical networks to external perturbations (Holmgren, 2006) use graph properties such as the average path length and the degree of connectivity to quantify the effects of removing sub-stations. The study finds this approach to be useful in capturing the effects of large changes in network topology. (Boss et al., 2004) use a graph-theoretic network model of the Australian inter-banking network to gain an idea of its resilience to random shocks such as the defaulting (removal) of a specific bank (node). (Urban and Keitt, 2001) quantify the effect on the Mexican Spotted Owl of changes in landscape connectivity. They use a graph-theoretic model to relate information from vector-based land-use polygons defining known habitat patches and raster-based grids describing land-use changes. They find that even a simple graph construct can provide important insights into the relative importance of individual landscape patches to connectivity within the overall landscape. Graph-theoretic models such as this one are useful when dealing with patchy or incomplete data for a network. While they are well-suited for analysing the structural vulnerability of networks they are generally used in situations where node descriptions are uniform and limited in detail (Beineke and Wilson, 2013).

4.4.5 Bayesian Networks

Bayesian Networks (BNs) refer to a probabilistic systems modelling approach that uses a network diagram describing the system, and the principles of Bayesian probability theory to model the propagation of defined probabilities across the system (Pearl, 1982). Bayesian networks can be considered an extension of the graph-theoretic concept using the principles of Bayesian probability theory and conditional dependencies (Pearl, 2000). Bayesian Networks are widely used for developing understanding of complex systems where the use of qualitative and/or uncertain data and knowledge is necessary (Spiegelhalter et al., 1993). They are flexible in the nature and type of constituent system components and are a powerful method for handling qualitative data inputs. Unlike SDs the network diagram of a BN model does not permit the representation of feedback loops. BNs have been widely used in the analyses of systems where information is poor, unstructured and mainly empirical. First developed for artificial intelligence applications as a computationally feasible alternative to conventional joint probabilistic analyses they have since been adopted in diverse fields like environmental management and assessments (Varis, 1995, Wooldridge and Done, 2004), medical diagnostics (Oniśko et al., 2001), water resource management (Castelletti and Soncini-Sessa, 2007) and catchment assessments (Ticehurst et al., 2007).

BNs have recently become popular in coastal zone applications. Plant and Holland (2011b), (2011a) apply a BN model to a localised description of wave-breaking in the surf-zone. In their study quantifying dune erosion response to extreme storm events in the Netherlands den Heijer et al. (2012) demonstrate the usefulness of the BN approach in generating rapid assessments of system sensitivities to uncertainties. Schultz (2012) use a BN model to assess the impacts of sea-level rise and storm surges on the performance of infrastructure networks at commercial ports. The network consists of a spatial description of the port infrastructure and the model provides a qualitative assessment of operational infrastructure facilities in a port during a storm event. They conclude that the approach is useful in developing system understanding and provides insights into knowledge-gaps at this scale of analysis. Catenacci and Giupponi (2013) uses a BN model at a more abstract level and with a limited number of nodes to assess the effectiveness of sea-level rise adaptation strategies for a coastal lagoon system in Italy that uses a consultation process with experts to formulate the model structure. Karunarathna and Reeve (2008) use a Boolean network approach to predict long-term estuarine change and assess the relative influence of multiple drivers. Their study illustrates the usefulness of simplistic relationships in the form of system and network diagrams to draw out relationships between variables in a complex system.

4.4.6 Agent-Based Models

Agent-Based Models (ABMs) are computational methods for simulating interactions between autonomous decision-making entities within a system, most often consisting of humans. In an ABM each agent has a defined objective and accordingly makes a decision informed by a set of rules and an assessment of the situation. The purpose of an ABM is to assess the ‘emergent’ effect of the decisions and actions of all agents on the system as a whole. ABMs are tailored for situations where decision-making by individual agents influences the aggregated system with regard to a particular outcome (Bonabeau, 2002). They are generally not used to model the state of the system: rather, they model the dynamic response of individual system agents and identify emergent behaviour patterns.

They are popular for policy and institutional analysis and for simulating socio-economic or socio-ecological processes with an aim to understand emergent behaviour as a result of dynamic interactions. Recently ABMs have been used in flood risk management studies. An example application is the study of human evacuation response during a flood incident (Dawson et al., 2011). A longer term ABM study that focuses on flood insurance uses a combination of spatial and non-spatial agents to assess the aggregated financial performance of two flood insurance policy options (Brouwers and Boman, 2011). The complexity of interactions between agents often requires the use of detailed information to parameterise the model, which may result in a limitation of the spatial scale of the application. It is generally not easy to address uncertainties in ABM simulations and outputs. While they are very well-suited to modelling real-world processes, model results, especially when these are emergent or unexpected, are more difficult to communicate.

4.5 Selection of Modelling Approach

The five approaches are compared in terms of the requirements of the quantitative model listed in Section 4.3. From the discussion and comparison an approach is selected for implementing the quantitative model (Table 5).

Comprehensive overview of system interactions. All the approaches provide an overview of the system. However BNs and SDs are better than the other three in this regard due to their explicit use of system diagrams and maps that are drawn through an active process of user and stakeholder participation. Amongst the two approaches BNs are more suited for a spatially distributed representation of the physical system whereas SDs are generally used to map non-spatial systems in terms of stocks and flows.

Table 5: Quasi-2D SPR Evaluation (based on Kelly et al. 2013) ('✓': easy; 'o' : possible but difficult; 'X': not possible)

Approach	**Quasi-2D SPR Requirements**				
	Comprehensive overview	**Computationally inexpensive probabilistic approach**	**Qualitative and quantitative data**	**Clearly communicate assumptions and uncertainties**	**Use of quasi-2D SPR system diagrams**
CCM	o	x	x	o	o
SD	✓	x	o	o	o
GM	✓	o	o	o	o
BN	✓	✓	✓	✓	✓
ABM	✓	x	✓	o	x

Computationally inexpensive probabilistic approach. Of the five approaches BNs being tailored specifically for probabilistic analyses are the best suited for developing an aggregated understanding of the probabilistic behaviour of the system. SDs can be used within probabilistic frameworks though this is not as easy in BNs. Graph-theoretic models can also be used within a probabilistic framework, but are computationally expensive and offer limited detail in node descriptions. In contrast, BNs are easier to build, run faster and are more suited for describing nodes with incomplete or uncertain data.

Handle qualitative and quantitative data. BNs are the most suited among the five approaches for handling qualitative data since they are not constrained by the use of formal equations and can therefore incorporate expert judgements and qualitative inputs as part of the system knowledge. Qualitative data inputs are also possible in ABMs, and though more difficult, in SDs. Graph-theoretic models offer limited qualitative data handling capabilities to the extent that they often use Boolean representations of network nodes.

Clearly communicate assumptions and uncertainties. All five approaches can treat uncertainty though in different ways and to different degrees. CCMs are essentially not a probabilistic approach though separate treatment of uncertainties in the inputs and the models is possible. This often involves repeated model simulations for multiple scenarios and is there dependent on available computational power. The treatment of uncertainties within SDs also needs to be done separately. Similar to SDs graph-theoretic models can incorporate uncertainty assessments in the form of statistical significance tests of network parameters for multiple simulations. By contrast BNs include uncertainty analyses automatically during the modelling process. None of the five approaches however are capable of treating uncertainties in the structure of the model.

Use of quasi-2D SPR system diagrams: Using a system diagram is one way of ensuring that key assumptions about the structure are communicated effectively to the users. Of the five approaches SDs and BNs are the best in terms of transparency of these assumptions. The communication of structural and modelling assumptions is a challenge with CCMs though this can be achieved with an externally constructed conceptual model describing various model couplings. Graph-theoretic models can make use of a system diagram though the analyses performed on these diagrams are essentially structural and independent of its spatial configuration.

The quasi-2D SPR system diagrams can therefore be used with three of the five approaches – CCMs, SDs and BNs. Though possible in CCMs this is difficult as it will require a separately constructed model that is constantly updated and coupled to the rest of the study to ensure its usefulness. The use of the system diagrams is easier in SDs since these already use spatial system diagrams in the modelling process. However the SPR system diagrams describe the floodplain in terms of a directed flow whereas SDs are generally used to study non-spatial processes with multiple feedback loops. BNs use a spatial network diagram very similar to the SPR system diagrams and are the most suitable of the three approaches to direct implementation of these diagrams.

The comparison shows that Bayesian Networks are best suited to make direct use of the quasi-2D SPR system diagrams. BNs and SDs are the most suitable models in terms of the other four requirements of the quantitative model. However probabilistic analysis is not easily possible in SDs. BNs also outperform SDs in terms of inclusion of qualitative data and the communication of assumptions and uncertainties. Though BNs cannot model feedback processes these are not considered relevant for the flood propagation analyses conducted here since this process is usually considered a linear flow from sources through flood pathways to receptors. Graph-theoretic models in general are comparable to Bayesian network approaches for networks where individual node-details are less significant than the structural properties of the network's graph. As a probabilistic extension of graph theory BNs offer greater flexibility in the description of individual nodes handling of qualitative and incomplete data and probability and uncertainty analyses at a node and a network level. On this basis a Bayesian Network approach is chosen to build the quantitative conceptual model for rapid integrated coastal floodplain assessments.

4.6 Quantitative Model: Description

The Bayesian network model used in this work is the commercially available Netica software (Norsys Software Corp, 2010). BN models use rules that have their basis in Bayes' theorem which describes the conditioning of the probability of occurrence one variable on the occurrence or observation of another. Bayes' theorem for two random variables A and B is given by:

$$P(B|A) = \frac{P(A|B) \times P(B)}{P(A)} \quad (4)$$

where P(A) is the probability density function (PDF) of A, P(B) the PDF of B, P(A|B) is the probability of A given B and P(B|A) is the probability of B given A. The theorem states that P(B|A) - the probability of B given that A has occurred, can be estimated as the product of the probability of A given that B occurs, P(A|B) and the unconditional probability of B, P(B). The denominator P(A) in this formula serves as a normalising constant.

The strength of this theorem within a causal reasoning model with multiple variables arises from the fact that the conditional probability P(A|B) is locally determined and usually independent of other propositions within the knowledge base. These conditional independences assumptions are derived in a Bayesian network model from the structure of the network graph (Pearl, 2000).

A Bayesian network graph consists of nodes connected to one another by directed links. The direction of a link indicates the direction of influence between the linked nodes. Figure 20 shows a Bayesian network graph of a basic coastal flood system consisting of a sea-level flood source, a floodplain and two intervening coastal elements – a beach and a seawall. The network describes the direction and pathways of flooding from the source to the floodplain.

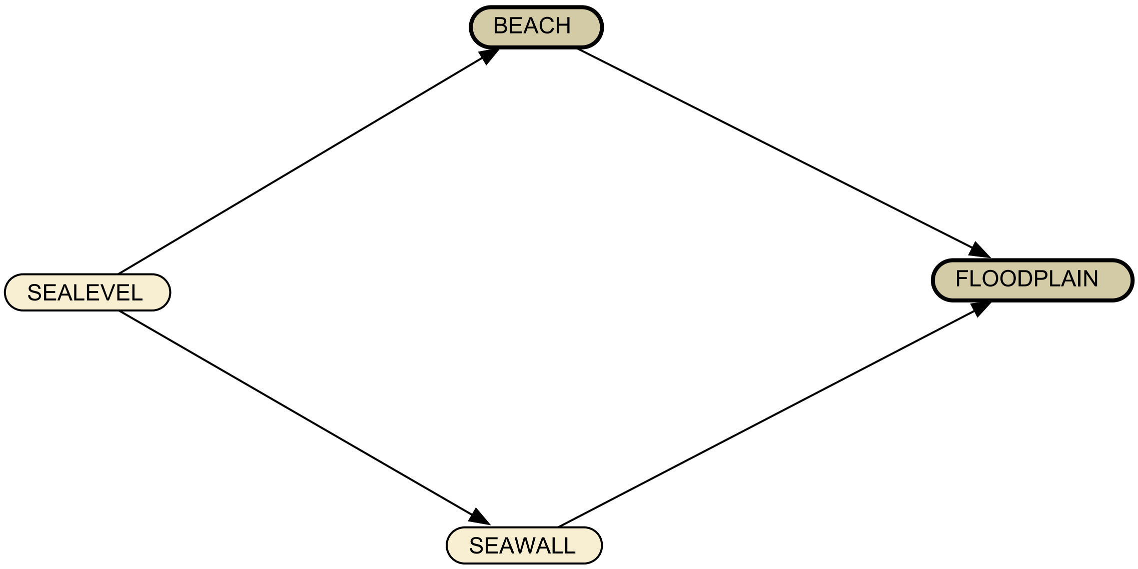


Figure 20: Bayesian network example of basic coastal floodplain

Each node in this network is described by its 'state.' For instance, the floodplain has two states – flooded or dry. The beach is also assumed to exhibit two states – flooded or dry. A seawall can exist in multiple states with regard to flooding. Here it has four states – overflow, overtopping, dry and breach. These node-states are expressed in terms of relative probabilities. The sea-level is the input node in this network and is also described by four states – high, medium, low and baseline with an associated probability distribution. The seawall has a probability distribution associated with its four states – overflow, overtopping, dry and breach (Figure 21). The floodplain and beach each have a probability distribution associated with their two states flooded and dry.

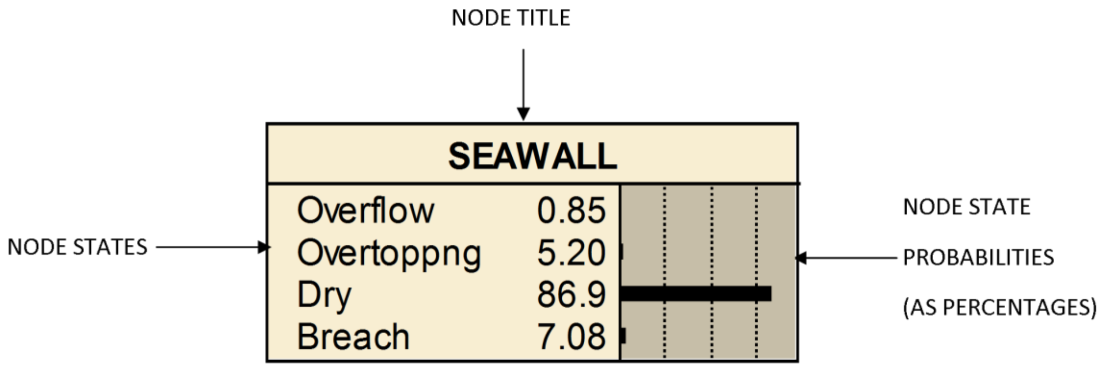


Figure 21: Description of example node in floodplain network

In this example the node-state probability distribution of the sea-level node is used to calculate the node-state probabilities at each network node. To do this the Bayesian network model requires two pieces of information – the conditional independence assumptions of the network and the relationships between node-states for every pair of linked nodes.

The conditional independence assumptions are derived from the structure of the network graph. This can be stated mathematically as follows (Pearl, 2000):

Let V be a finite set of variables and X, Y, and Z be any three subsets of variables in V. For any configuration x, of the variables in X, and for any configurations y and z of the variables in Y and Z satisfying P(Y=y, Z=z) > 0, the sets X and Y are said to be conditionally independent given Z if,

$$P(X = x|Y = y, Z = z) = P(X = x|Z = z) \quad (5)$$

For instance, in the network in Figure 20 the probabilities of the floodplain states are conditional only on the states of its ‘parent’ nodes, beach and seawall. In other words, the floodplain is independent of the sea-level, given that the states of beach and seawall are known. Further, the beach is dependent only on its parent node, sea-level. The seawall is also conditional only on the sea-level. Hence, the beach and seawall are independent of each other given that the sea-level is known. These conditional independence assumptions form the basis for the factorisation of the conditional probability distributions within the Bayesian network. The conditional probability distributions for each node are tabulated in a Conditional Probability Table (CPT).

A node's CPT also describes the relationship between a node and its parent(s) (Table 6). The CPT does this in two ways – a) its structure describes every possible combination of parent node-states that influence its probability distribution; b) the CPT also holds the probability values that each node-state takes for every possible combination of parent node-states. These values may either be entered directly into the CPT of each node or specified in the form of logical, deterministic or probabilistic equations.

Table 6: Conditional Probability Table for Node Seawall in Figure 21

SEALEVEL (Input)	Overflow	Overtopping	Dry	Breach
High	0.34	0.33	0	0.33
Medium	0	0.25	0.25	0.5
Low	0	0.25	0.5	0.25
Baseline	0	0	1	0

The Bayesian network uses the probabilistic node-state relationships described by the node CPTs and the conditional independence assumptions described by the network graph to calculate the forward propagation of probabilities. In the network in Figure 20 the node-state probabilities of beach and seawall are calculated using the probabilities of the sea-level node-states and the CPTs of the beach and seawall. In turn these probabilities and the CPT of the floodplain are used to calculate the state probabilities of the floodplain.

The process of estimating node-state probabilities for the network in Figure 20 is illustrated here with an example. The entire network with the estimated node-state probabilities and CPTs is shown in Figure 22. In this example, the states of each node are the same as described above. The CPTs specify the relationships between the node-pairs. Here, these relationships are entered directly into the CPT based on assumptions about the flood system:

1. The floodplain is assumed as lying below the level of the beach and seawall. Thus it stays dry if and only if both the beach and seawall are dry and is flooded otherwise.

2. Similarly the beach is assumed to have a crest-height corresponding to a medium sea-level and is accordingly defined as being dry if and only if the sea-level is less than medium and flooded otherwise.

3. The seawall has a more complex definition since it can exhibit multiple states with a different probability distribution for each state of its parent sea-level (Table 6).

4. The sea-level is the input node in this network and has no parent nodes. The probability distribution of its states is directly defined as an exponential distribution increasing from High to Baseline as P(High) = 0.025, P(Medium) = 0.075, P(Low) = 0.1 and P(Baseline) = 0.8 with High being the maximum absolute sea-level state and Baseline being the minimum.

Using these input values, conditional probabilities and node relationships, the probability of flooding at the floodplain is calculated as follows:

$$P(Floodplain = Flooded) = 1 - P(Floodplain = Dry) \quad (6)$$

From Equation 5 the floodplain is dependent only on the beach and seawall. Eight parent state combinations – 2 beach states and 4 seawall states influence the floodplain. As per the node definitions, the floodplain is dry if and only if both the beach and seawall are dry. Thus

$$P(Floodplain = Dry) = P(Beach = Dry) \cap P(Seawall = Dry) \quad (7)$$

The beach and seawall are both conditional on the states of their common parent sea-level. For any sea-level state k,

$$P(Beach = Dry)_k = P(Beach = Dry|Sealevel_k) * P(Sealevel_k) \quad (8)$$

and,

$$P(Seawall = Dry)_k = P(Seawall = Dry|Sealevel_k) * P(Sealevel_k) \quad (9)$$

Summing over all sea-level states and assuming the upper bound of the intersection,

$$P(Beach = Dry) \cap P(Seawall = Dry) =$$
$$\sum_{k=1}^{4} MINIMUM[P(Beach = Dry)_k, P(Seawall = Dry)_k] \quad (10)$$

Substituting for $P(Beach = Dry)_k$ and $P(Seawall = Dry)_k$ from (8) and (9),

$P(Beach = Dry) \cap P(Seawall = Dry) = MIN(0 * 0.025, 0 * 0.025) + MIN(0 * 0.075, 0.25 * 0.075) + MIN(1 * 0.1, 0.5 * 0.1) + MIN(1 * 0.8, 1 * 0.8)$

$= 0 + 0 + 0.05 + 0.8 = 0.85$

Thus from (7),

$P(Floodplain = Dry) = 0.85$

and from (6),

$P(Floodplain = Flooded) = 1 - 0.85 = 0.15$

In this manner the probability propagation calculations are broken down into one-to-one relationships between every linked node pair. The Netica software uses such conditional independence assumptions to factorise the joint probability distribution of any Bayesian network into multiple connected subsets of variables with locally calculable PDFs known as cliques. Since these cliques are connected to one another in specific ways, locally calculated probabilities need to be passed between the cliques in a manner consistent with their relative positions within the network. The process of structuring this communication between network cliques is known as compilation and involves a series of transformations. In large and complex networks the compilation process becomes an NP-hard problem of optimisation (Spiegelhalter et al., 1993).

A useful optimisation technique for network compilation is the generation of tree-structured graphs known as junction trees (Pearl, 2000). In Netica compilation is done prior to calculating node probabilities using an in-built optimisation algorithm based on the concept of message passing in junction trees. This involves three steps: a) decomposing the Bayesian network into multiple connected cliques; b) establishing communication – i.e. message passing – links between the cliques, and c) ordering these links so that the direction and pathways of probability propagation within the network are preserved. Once a network has been compiled its structure is stored in the model. Multiple probability propagation calculations on the same network can then be performed rapidly and with greatly reduced computational effort (Norsys Software Corp, 2010, Spiegelhalter et al., 1993).

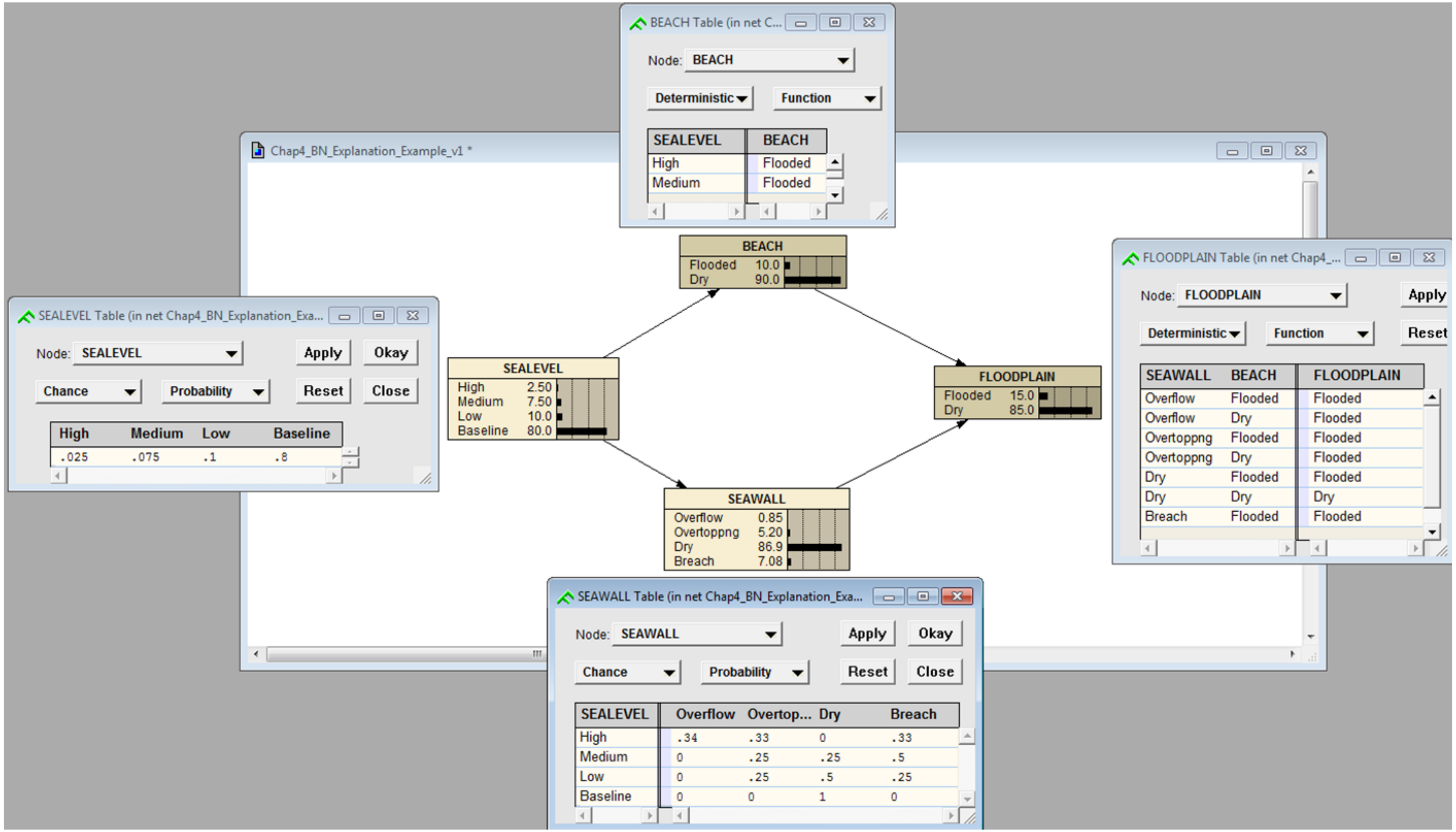


Figure 22: Network, nodes and CPTs of illustrative example floodplain

4.7 Bayesian Network Model: Construction

The BN model is built analogous to a conventional floodplain inundation model. A floodplain inundation model uses a grid-cell description of the floodplain. It starts by assuming a completely dry floodplain and re-evaluates the state of each grid-cell as either 'dry' or 'wet' based on a set of rules and inputs. The BN model similarly starts with an initial description of each floodplain element as a variable with pre-defined 'states' and re-evaluates these 'states' based on a set of rules and inputs. The structure, components and construction of the Bayesian Network (BN) model are illustrated in Figure 23 and briefly described below:

Step 1: Construction of Floodplain Network. The spatial structure of the floodplain is described by a network consisting of nodes and links (Figure 23). When derived from a quasi-2D SPR, each node of the network corresponds to an element of the quasi-2D SPR system diagram and the links to, and from, that node are derived from the arrows of the system diagram.

Step 2: Description of Floodplain Connectivity (Links). The network diagram is completed by removing any unwanted links, taking care to ensure that no 'loops' exist in the final network diagram (see Section 4.4.4). The SPR system diagram has two-directional links between every element pair. This redundancy is provided to facilitate case-specific descriptions of the links in the network model. In the network each link represents a directed flow from an upstream 'parent' node on a downstream 'child' node. This flow may describe an influence, or a flood flow (see Section 4.3). For a typical floodplain, the links will describe the propagation of flooding from an upstream parent node to a downstream child node.

Step 3: Description of Floodplain Nodes. Once the network is constructed the influence of each node on flood propagation is described using information gathered during quasi-2D SPR construction or from other sources. Each network node is a variable that has different 'states' or values depending on its specific role in flood propagation. For instance a flood source node will have states corresponding to water level values while a seawall node will have states corresponding to heights or overtopping volumes. This specification of states for each node is analogous to the description of properties such as geometry, height or roughness for each cell in a conventional inundation model.

Step 4: Description of Flood Propagation (Node Relationships). After having described each node, its relationship to its parents is specified. This relationship is defined by logical or empirical equations that are used to calculate the probabilities of the node-states. The equations can either describe flood propagation or some other process e.g. the influence of a fronting beach on overtopping rate.

Step 5: Entering Input Values. The final step before running the model is to specify its input values. The model inputs are the nodes that hold information necessary for modelling flood propagation i.e. the hydraulic inputs and known properties of floodplain elements (e.g. water level, beach slope, seawall height). Depending on the node these may be probabilistic or deterministic inputs. Inputs which are unlikely to change across multiple simulations e.g. element heights may be specified as constants (Figure 23).

Once the network model is built from the quasi-2D SPR using steps 1-5 it can be run to simulate the propagation of flooding across the floodplain. The first time the network is constructed it is compiled (see Section 4.6). Thereafter network probabilities are computed every time the model is run for a specified number of samples at each node by the procedure described in Section 4.6.

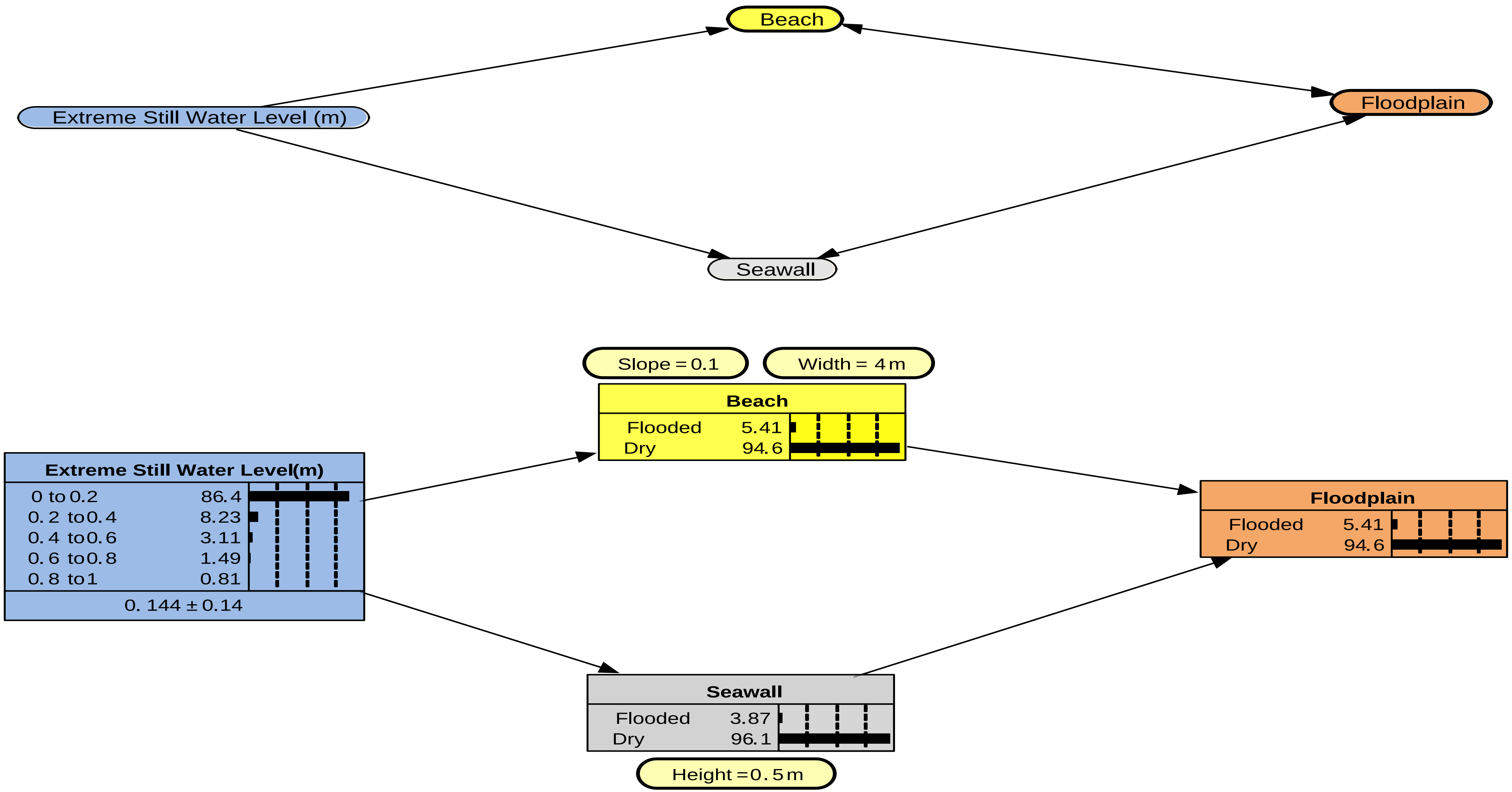


Figure 23: Quasi-2D SPR and Bayesian Network for illustrative example floodplain

4.8 Quantitative Model: Illustrative Example

The process of a node-state calculation on a compiled network is illustrated with an example (Figure 24). In this example the input sea-level node described as an Extreme Still Water Level (ESWL) causes the flooding of the Floodplain node via the Beach and Seawall nodes. The steps in calculating the flood probabilities at each node are described and compared with the procedure followed in a conventional model (e.g. EA, 2004). The network is shown in Figure 24 along with node probabilities from the BN model and conventional model calculations (Table 7).

Let the input node Extreme Still Water Level (ESWL) be w, event (Beach=Flooded) be D_1, event (Seawall=Flooded) be D_2 and event (Floodplain=Flooded) be F. Events (Beach=Dry), (Seawall=Dry) and Floodplain=Dry) are represented as $\overline{D_1}$, $\overline{D_2}$ and $\bar{F}$.

The ESWL is specified as an extreme value Weibull distribution with shape parameter $a = 0.5$ and scale parameter $b = 0.055$,

$$p(w) = Weibull(w, a, b) \qquad (11)$$

The Beach, Seawall and Floodplain nodes are Boolean nodes that can be flooded or dry. The probability of flooding of each of these nodes is conditional on the probability of its input node. The Beach node uses constants slope and width to estimate its crest height. The probability of the beach being flooded is determined by the probability that its height is less than the input ESWL and is given by

$$P(D_1|w) = \begin{cases} 1, w > 0.4 \\ 0, otherwise \end{cases} \qquad (12)$$

Similarly, the seawall is flooded when its height is less than the ESWL,

$$P(D_2|w) = \begin{cases} 1, w > 0.5 \\ 0, otherwise \end{cases} \qquad (13)$$

The floodplain node is assumed to lie below the beach and seawall nodes in this example and is flooded if at least one of the beach and seawall nodes is flooded. Thus event F can occur in one of three ways - $D_1 \cap D_2$, $\overline{D_1} \cap D_2$ or $D_1 \cap \overline{D_2}$. Therefore $P(F)$ is given by,

$$P(F) = P(D_1 \cap D_2) + P(D_1 \cap \overline{D_2}) + P(\overline{D_1} \cap D_2) \tag{14}$$

Grouping the first two terms on the R.H.S we have

$$P(F) = P(D_1) + P(\overline{D_1} \cap D_2) \tag{15}$$

Since the seawall is higher than the beach in this example $P(\overline{D_1} \cap D_2)$ is zero. The calculation of $P(F)$ is now compared for the BN model and a conventional model like the RASP study. In the BN model the ESWL node is discretised into 5 states from 0 to 1. Thus,

$$P(D_1) = \sum_{j=0}^{5} p(w_j).P(D_1|w_j) \tag{16}$$

and,

$$P(D_2) = \sum_{j=0}^{5} p(w_j).P(D_2|w_j) \tag{17}$$

From Equations 15, 16 and 17 and since $P(\overline{D_1} \cap D_2)$ is zero,

$$P(F) = P(D_1) = \sum_{j=0}^{5} p(w_j).P(D_1|w_j) \tag{18}$$

Solving Equation 18 using these values we have,

$P(F) = 0.054$.

In comparison, in a conventional model the unconditional probability

$$P(D_1) = \int_0^x p(w).P(D_1|w).dw \tag{19}$$

and,

$$P(D_2) = \int_0^x p(w).P(D_2|w).dw \tag{20}$$

From Equations 12, 13 and 15 and since $P(\overline{D_1} \cap D_2)$ is zero we have,

$$P(F) = P(D_1) = \int_0^x p(w).P(D_1|w).dw \tag{21}$$

Solving Equation 21 we get,

$P(F) = 0.061$.

The difference in $P(F)$ between the two methods and its implications are discussed further in Section 4.9.

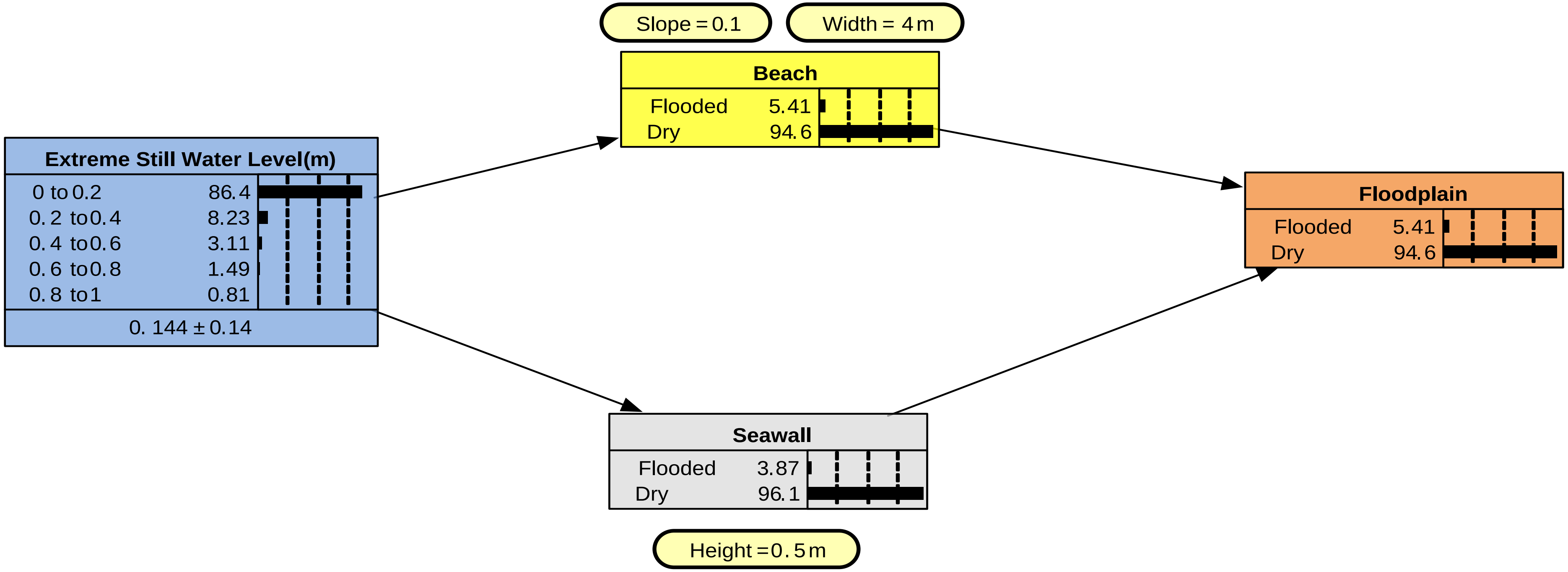


Figure 24: Estimated flood probabilities of nodes in illustrative example floodplain network

Table 7: Comparison of flood probabilities between BN model and conventional model calculations

Model / Node	Extreme Still Water Level (m)	Beach: P(D_1)	Seawall: P(D_2)	Floodplain: P(F)
BN Model	0.114 +- 0.14	0.054	0.038	0.054
Conventional Model	0.110 +- 0.12	0.061	0.051	0.061

4.9 A Bayesian Network Model for Rapid Integrated Floodplain Assessments

In this chapter a new quantitative model has been developed for the rapid assessment of coastal floodplains based on a Bayesian network approach. The key pre-requisites of the quantitative model are that it reflect and use the systems perspective and knowledge gained through quasi-2D SPR application and enhance this systems understanding by providing a quantification of the behaviour of multiple floodplain elements as flood sources, pathways and receptors. The Bayesian network approach is chosen as the most suitable approach among the available approaches since it allows flexible computationally inexpensive probabilistic quantifications of the floodplain as a network. Importantly the quantitative model developed here makes direct use of the quasi-2D SPR system diagram to build the network structure. The construction and use of the BN model are illustrated using a simple example floodplain with four nodes (Section 4.7). The BN model illustrates the relative importance of the beach and seawall elements to the flooding of the inland floodplain. While the quasi-2D SPR for this model describes all possible flood pathways the quantitative description of each elements role in flood propagation allows the user to assess the relative importance of each pathway. This becomes especially useful when applied to a real floodplain consisting of several nodes and links.

The BN model's quantification method is compared with a conventional risk-based analysis framework. In this example, the BN model values for ESWL (mean) and $P(F)$ differ from the conventional model by 3.5% and 11.5% respectively. This difference is due to the discretisation required in the BN model of its node descriptions. The extreme value distribution of the ESWL in the example is discretised into five class intervals of 0.2 m width each. By contrast, in the conventional analysis the ESWL is treated as a continuous probability density function. Though more accurate than a BN model the conventional method becomes exponentially more expensive for an actual floodplain where the number of nodes and links are often higher by an order of magnitude. In Chapter 5 the Bayesian network model is applied to two actual coastal floodplains of more than a 100 nodes and validated by comparison with conventional numerical inundation models.

5 Application of a Bayesian Network Model for Rapid Integrated Floodplain Assessments

5.1 Introduction

This chapter discusses the application of a quantitative rapid assessment model for coastal floodplains, as per Objective 4 in Section 1.3. In Chapter 4 a Bayesian Network approach has been chosen as the most suitable for building the quantitative model. The model has been developed based on the objectives as discussed in Sections 4.2 and 4.3. In this chapter the Bayesian network model is built and applied to assess flood extents and flood pathways in two contrasting floodplains. A brief summary is given here of the basic differences between the two floodplains that are reflected in their network models. The floodplains and model applications are described in detail in Sections 5.2 and 5.3.

The case-studies chosen for Bayesian network model application are the coastal floodplains of Teignmouth in south-west England and Portsmouth in south-east England. The floodplains are of comparable though different sizes, Teignmouth with an extent of 1-2 km^2 and Portsmouth with an extent of 8 – 10 km^2. The two sites are significantly different in terms of the types of flood sources, the nature of the coastline and coastal defences, the characteristics of the inland floodplain as well as the type and quality of data available for flood propagation modelling (Figure 25). For instance flooding in the Teignmouth coastal floodplain which is described in detail in the following section is driven by a combination of estuarine water-levels and open coast wave overtopping and inundation events. In contrast flooding in the Portsmouth floodplain is caused by open coast overtopping and inundation events throughout its coastline.

Flood defences for the Teignmouth floodplain vary along the coastline with some scattered defences along the estuarine coast and artificial seawalls and nourished beaches along the open coast. In contrast the Portsmouth floodplain is heavily defended throughout by artificial seawalls built to withstand flood events of varying degrees of severity.

In terms of the inland floodplain Teignmouth is relatively small in extent (1-2 km^2) and consists of two low-lying semi-urban flood compartments connected by a railway line. The Portsmouth floodplain is larger with an extent of 8-10 km^2. Most of the Portsmouth floodplain is highly urbanised with a complex geography consisting of multiple isolated flood compartments.

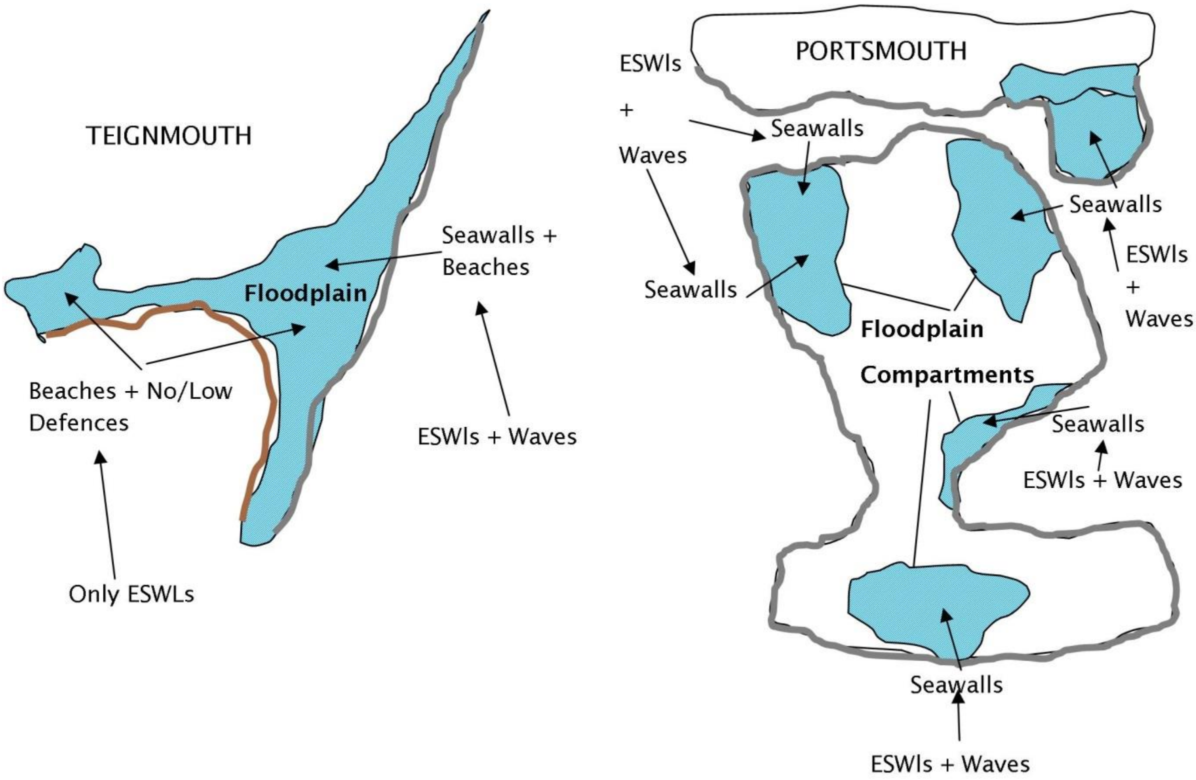


Figure 25: Schematic showing differences in flood sources, pathways and receptors for Teignmouth and Portsmouth floodplains

The Bayesian network models for both sites are derived from their quasi-2D SPR diagrams that describe the relevant floodplain characteristics. In addition to floodplain characteristics data availability and quality are key issues in determining the network model structure, model resolution and the flood propagation processes. The Portsmouth floodplain is a well-studied region with multiple case-studies that investigate the properties of the flood sources, seawalls and inland floodplain compartments along with historic flood inundation data with a view to characterising flood extents and flood risk. The Teignmouth floodplain is relatively scarcely studied with less data on flood defences and floodplain heights available for use in the network model.

The network model for each site is built and applied to reflect these differences in floodplain properties and data. For instance the Teignmouth network model has access to minimal data on the estuarine and coastal flood defences. The lack of detailed data on flood defences is reflected in the mixed use of a bath-tub and a storage-cell approach for different parts of the floodplain and coarse resolution descriptions of the floodplain elements. The Portsmouth application uses readily available information on coastal seawalls from a previous case-study for a detailed representation of seawall overtopping volumes which in turn allow the use of a storage-cell based approach throughout the floodplain. The Portsmouth application also makes use of a high resolution digital elevation model to accurately describe the heights of inland floodplain elements.

As a result, the final structure of the network model is different for each site. However, the methodology of model construction and the description of specific processes such as run-up and overtopping are kept consistent across both applications. Section 5.2 describes the Bayesian network model application to Teignmouth, and Section 5.3, the application to Portsmouth.

5.2 Case-Study: Teignmouth, England

5.2.1 Site Description and Quasi-2D SPR

The Bayesian Network model built and described in Chapter 4 is applied to the coastal floodplain of Teignmouth city in south-west England (Figure 26). The quasi-2D SPR for the Teign estuary (see Figure 17 in Chapter 3) pinpointed Teignmouth as an area of interest due to its exposure to estuarine and coastal flood sources from multiple directions. Based on this a nested quasi-2D SPR was built for Teignmouth that describes the possible flood pathways form these sources and is shown in Figure 27 (see Section 3.5.3). The inland floodplain boundaries for the quantitative model for Teignmouth is the same as that of the quasi-2D SPR – the maximum floodplain extent for the current 1 in 1000 year return period extreme still water level which is 3.46 mOD (Halcrow Group, 2011). The construction of the Teignmouth quasi-2D SPR helped to gather and structure information about the Teignmouth coastal floodplain salient to the analysis of flood propagation. The quantitative network model for Teignmouth is based on the following floodplain characteristics identified from quasi-2D SPR construction:

Floodplain Description: Teignmouth, situated at the mouth of the Teign estuary, is one of Devon's oldest seaside resorts. The floodplain comprises two zones: the stretch of open coast from Sprey Point to The Point – a spit marking the southern boundary of the city at the mouth of the estuary; and the south-western shoreline of Teignmouth city along the inner bank of the estuary from the Point up to the Teignmouth and Shaldon Bridge (Figure 26). The railway line runs along the open coast from Holcombe to north Teignmouth and through the city to its south-western boundary. The floodplain is almost entirely south of the railway line except for the West Teignmouth flood compartment consisting of residences and a hospital, which lies north of the line.

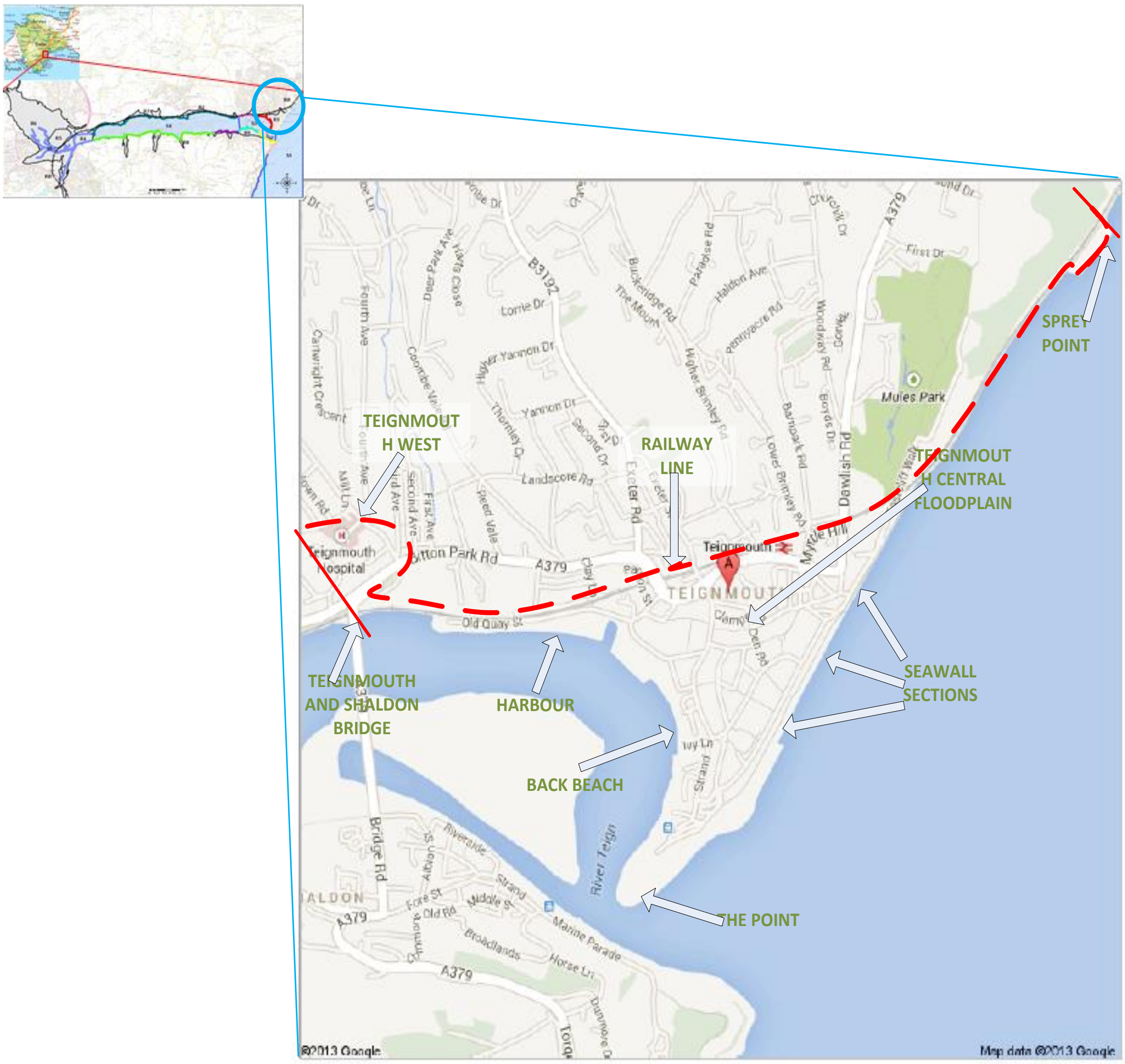


Figure 26: Map of Teignmouth indicating floodplain extent and areas of interest in Quasi-2D SPR

Vulnerability to Flooding: West Teignmouth is sheltered by Teignmouth Harbour, though still exposed to flooding by extreme still water-levels within the estuary (Environment Agency, 2012). The low-lying town centre, the seafronts on the

English Channel coast and areas behind Back Beach and Teignmouth Harbour all lie within the 1 in 1000 year floodplain extent. The section of railway line between Holcombe and north Teignmouth and the central urban floodplain have both been flooded from the sea several times in the past.

Flood defences on the estuarine coast at Back Beach are vulnerable to overtopping at low-order events. Increased risk of tidal flooding from the estuary has resulted in the commissioning of a new 4 million pound flood defence scheme for the Back Beach area of Teignmouth (Royal Haskoning, 2011). Undermining and overtopping of the seawall on the English Channel coast in 1969 and again in 1975 led to the construction of 145 metres of seawall and beach groynes to maintain beach levels in front of the existing seawall. A further 500 metres of seawall was rebuilt in 1976/77. In the storms of December 1989, the 1976/77 walls performed well, while the 1972/73 sections were significantly overtopped along with the short length of sea front at Den Promenade, resulting in serious flooding of the town centre. In 1991 a new seawall was built along the sea front to the height of the 1976/77 sections, consisting of a front wall with a wave return profile and a rear wall with a raised footpath on the landward side. The heights of the seawall sections presently vary from 4.9 to 6.9 m above MSL with a berm height of around +2.00 m above MSL (Royal Haskoning, 2011).

Coastal Management Issues: Due to the importance of the railway line as a vital transport link the current shoreline management policy for the open coast between Holcombe and The Point is to 'Hold the Line' – i.e., actively maintain and upgrade the sea-defences along the coast to mitigate flooding of the railway line. The 'Hold the Line' policy also applies for the estuarine coast of Teignmouth city. The Point itself is to be allowed to undergo monitored natural evolution (Halcrow Group, 2011). There are morphological interactions between floodplain elements along the open coast, and areas outside the system boundaries that could affect local flooding. The continued protection of the cliffs to the north of the floodplain will result in sediment starvation at the down-drift beaches which in turn will result in a lowering of the standard of protection for the seawalls at Teignmouth due to coastal squeeze. Active beach recharge will be necessary in such a case to maintain the required standard of protection for the seawalls. The beaches within the floodplain also show a historical cycle of rotation that may be affected by management of the estuary's tidal regime (Halcrow Group, 2011).

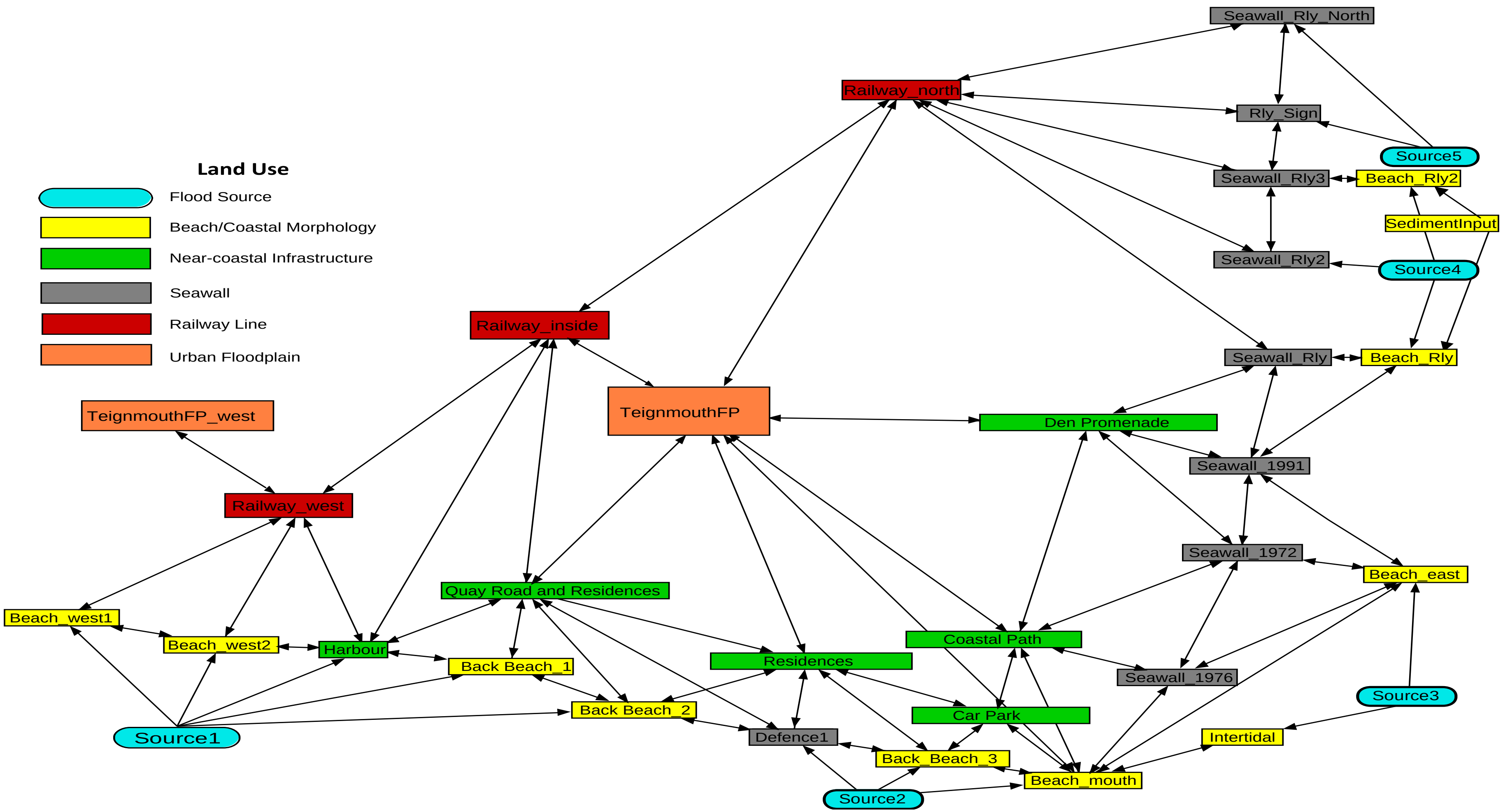


Figure 27: Quasi-2D SPR for Teignmouth (reproduced from Figure 19 in Chapter 3)

5.2.2 Stage II: Bayesian Network Model

The Bayesian Network model for Teignmouth is built using the structure and procedure described in Chapter 4. The two issues considered by the Teignmouth model are flood propagation and the influence of changes to inputs and/or floodplain elements on flood propagation. A unique feature of the Teignmouth floodplain described by the quasi-2D SPR is the difference in flood sources – still water levels on the estuarine coast and a combination of still water levels and wave heights on the open coast. The quantitative model is built specifically to represent these differences.

The model is directly derived from the quasi-2D SPR for Teignmouth. Each node of the network represents a particular property of its corresponding floodplain element in the SPR system diagram. Inundation models typically require the specification of multiple parameters for each feature – e.g., height, geometry and roughness. Similarly the SPR floodplain elements are described in terms of multiple parameters in the network model. Some parameters such as element height and geometry or steady-state wave heights and time periods, that remain constant during the study, are specified as 'constant' nodes that do not form part of the network but can be used in the equations of the network nodes. Thus the number of nodes in the quantitative model is more than the number of floodplain elements in the quasi-2D SPR diagram. The main considerations for deriving the network model from the quasi-2D SPR are detailed below.

Step 1: Construction of Floodplain Network. Most elements of the quasi-2D SPR are maintained without modification in the network model. An exception is the central urban element which is represented in the conceptual model as a single element covering a relatively large area of the floodplain. This element can be flooded either via the railway line to the north or via the near-coastal elements to the south. These routes are dissimilar since the railway lines are exposed to the open coast while the near-coastal elements are exposed to both estuarine and open coast flood sources. To capture any differences in flood propagation between these pathways the central urban floodplain is split into two nodes – a northern node linked to the railway lines and a southern node linked to the near-coastal nodes (Figure 27).

Step 2: Description of Floodplain Connectivity. The link directions of the nodes in the network are in the direction of flood propagation, i.e. from the flood source, inland. The coastal elements are all linked to a local flood source each of which is driven by an English Channel source. On the open coast flooding at a seawall section is assumed to be independent of the flooding at adjacent seawall sections and the links between the seawalls are removed. Similarly links between beaches on the estuarine coast are removed. Some of the connections between the near-coastal elements may permit cross-flow of flood waters. The links between these nodes are therefore maintained. Where additional network nodes are used to describe node properties such as heights these are directly linked to their associated node. Figure 28 shows the network of the quantitative model for Teignmouth.

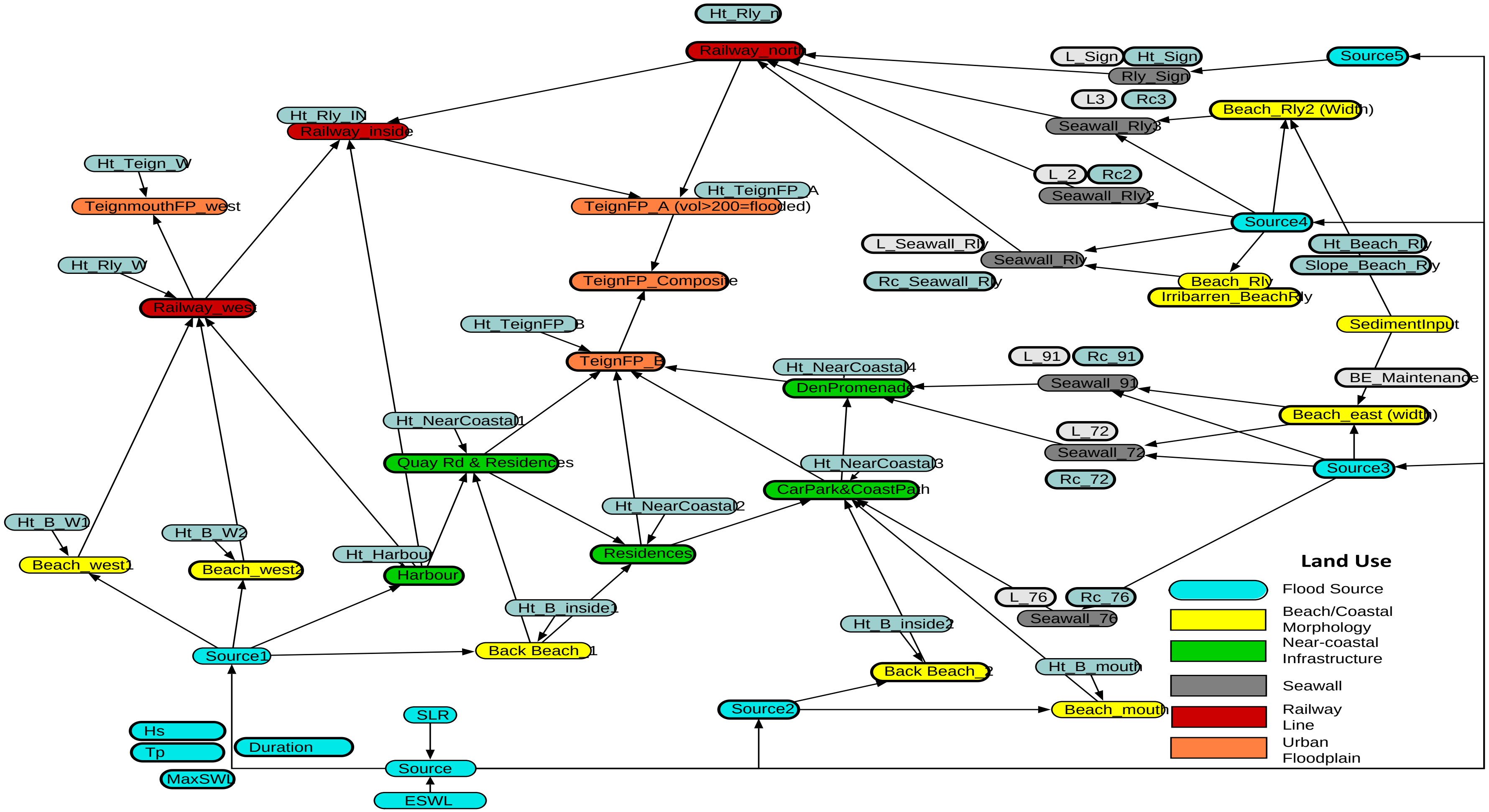


Figure 28: Teignmouth Bayesian Network

Step 3: Description of Floodplain Nodes. Model nodes are divided into two types - a) Nodes exposed to the estuarine water levels are described in terms of heights and flood states ('dry' or 'flooded') and b) nodes linked to the open coast flood sources are described using empirical formulations of overtopping rates estimated from the open coast water levels and wave heights. Table 8 lists the floodplain element nodes, their types and descriptions. The central urban floodplain is represented as a composite of two nodes, both described as 'dry' or 'flooded' – the northern floodplain linked to the railway lines and the southern floodplain linked to the near-coastal elements. The northern and central railway line nodes are exposed to the open coast and are described in terms of flood volumes calculated from the overtopping flows at the linked seawalls. The western railway line is exposed to the estuarine water levels and is described as Boolean 'dry' or 'flooded'. All near-coastal and urban elements are also described as 'dry' or 'flooded'. All the nodes with more than two states are described as continuous values that are discretised into class intervals. The required range and number of class intervals for each node are determined by trial and error refining the node description until the desired level of accuracy is reached (see Section 5.4 for a discussion on node classes).

Step 4: Description of Flood Propagation. The equations for nodes linked to the estuarine sources – i.e. the estuarine beaches, harbour, the western railway section and the near-coastal elements are logical descriptions of their flood states based on the water levels, the height of the concerned node and the heights and flood states of its upstream 'parent' nodes. The equations, input parameters and assumptions for all nodes are summarised in Table 9.

The nodes linked to the open coast flood sources are empirical descriptions of overtopping rates in case of seawalls and width or run-up values in case of beaches. Overtopping rates at the seawalls are calculated using the EurOTOP formulae for overtopping at a vertical sea-wall (EurOtop Manual, 2007). Run-up values are calculated using the input wave climate and a beach slope and if the run-up value is greater than the crest height of the beach it causes overtopping at the downstream seawall. Railway_North is described as a pathway node that, if it is of a sufficiently low height to be flooded, transfers all the flood volume received from the upstream seawalls to the downstream railway section (see Table 9). This node, Railway_Inside in turn influences the flood state of the northern half of the central urban floodplain and the western railway section.

The urban floodplains are evaluated as dry or flooded, similar to the estuarine nodes. The central urban floodplain is described as a composite of two floodplains – one to the north linked to the railway line and one to the south linked to the near-coastal elements (see Figure 28).

Table 8: Teignmouth Network Mode: Node Descriptions

Nodes	Node Type and Range	Node Class Intervals	Node Description
Flood Sources (Sources1-5)	Water Level 0 to 4.75 (m)	Continuous, 10 bins: 0-2.5 and 0.25 m intervals thereon	These are input nodes. Node range specified based on the maximum cumulative value of the highest return period ESWL and SLR.
Beach_Rly	Run-up Height 0 to 13 (m)	Continuous, 7 bins: 0 to 1, and 2 m intervals thereon	Nodes describe run-up heights. This height is compared to the height of the beach crest and if greater, results in overtopping at downstream seawall
Beach_east and Beach_Rly2	Beach width 20 to 0 (m)	Continuous, 4 bins: 5 m intervals	Beach width is assigned based on input values for Sediment Input node. This translates to a crest height, influencing water depth at downstream seawalls
Seawalls (Seawalls 76, 72, 91, Rly, Rly2, Rly3 and Rly_Sign)	Overtopping rate -10 to 110 (l/s/m)	Continuous, 12 bins: intervals of 10	Node states indicate probabilities of different overtopping rates capped at a maximum of 100 l/s/m. Tolerable limit is 50 l/s/m. The state -10 to 0 indicates complete inundation. Seawall height may be set to zero to indicate breach.
Railways – (North and Inside)	Volume from seawalls -100 to 5000 (l)	10 bins: 2 of interval 100, 8 of interval 500	Input flood volumes from linked seawalls calculated using storm duration. Node state -100 to 0 indicates complete inundation.
All Estuarine Beaches from Beach_west1 to Beach Mouth, Harbour, Railway_west, Near-coastal nodes, urban FPs	Probability of flooding 0 to 1 (dimensionless)	Discrete, 2 values: 0,1	Probability of flooding estimated based on a topography-controlled approach based on estuarine ESWLs and heights of linked upstream elements

Step 5: Entering Input Node-State Values. The hydraulic inputs at the boundary of the floodplain are the Extreme Still Water Levels (ESWLs), wave heights, wave periods and storm duration. The ESWLs for all five sources – estuarine and open coast – are the same and are driven by a single ESWL in the English Channel. The ESWL for Teignmouth is calculated as the sum of a surge, tide and sea-level rise (see Table 9). The wave climate is assumed to be steady-state and is defined as 'constants' that are not part of the network (i.e. no physical links to network nodes) and are used only in the equations of the beach and seawall elements. The storm duration is used to calculate the volume of overtopped flow from the seawalls to downstream elements.

The input node 'Sediment Input' affects the width of two of the three open-coast beaches. This node represents an additional model functionality introduced to assess the influence of an external driver of coastal processes on the Teignmouth floodplain. Existing shoreline management policies indicate an active programme of beach nourishment in this area. The node 'Sediment Input' represents the absence or presence of this beach nourishment. Since no data was available on actual beach widths, it is assumed that the 'natural' beach width in the area is 2.5 m, in the absence of active nourishment sediment input. When sediment input is present, this is assumed to add an additional 10 m to the beach width. Based on a user-specified slope and assuming a triangular profile this width is translated to a crest height at the toe of the downstream seawalls influencing the water depth and hence the overtopping rates.

Inputs such as node heights and geometries are also defined either as constants or as physically linked network nodes. Once all nodes and equations are described and the values of the flood sources and all other inputs are specified, the network model is run to estimate the probability of the flood (or other indicator) states of the floodplain nodes. Model validation is described in Section 5.2.3. Section 5.2.4 describes some predictive model simulations, findings and discusses related model issues.

Table 9: Teignmouth Network Model: Equations (EurOtop Manual, 2007) (also see Appendix 2)

Nodes	Node Type and Units	Associated Inputs and Parameters	General Form of Node Equation	Assumptions/Considerations
Flood Sources (Sources1-5)	Water Level (m)	Hs, Tp, Duration, ESWL (= surge + tide), SLR)	$\text{Flood Source} = \text{ESWL} + \text{SLR}$ (22) where $\text{ESWL} = \text{Storm surge} + \text{Tide}$ (23)	ESWL, SLR, Hs and Tp values are user-specified (default Hs = 2 m, Tp = 8s corresponding to a 1 in 50 year return period)
Beach_Rly	Run-up (m)	Height, slope, Irribarren number	$\text{Run-up}\left(\text{m}\right) = \text{Irribarren number} * \text{Hs}$ (24), where $\text{Irribarren number} = \text{Beach\_slope} / \left(2*\pi*\text{Hs} / \left(\text{g*Tp}\right)^2\right)$ (25)	If run-up > input beach crest height, overtopping occurs at linked seawall
Beach_east and Beach_Rly2	Beach width (m)	Sediment Input, slope	If (Sediment Input == present) Then Beach width = 12.5 m Else Beach width = 2.5 m	Initial width is 2.5 m Sediment input adds 10 m width Beach profile is triangular
Seawalls (Seawalls 76, 72, 91, Rly, Rly2, Rly3 and Rly_Sign)	Overtopping rate (l/s/m)	Water Level (h), Hs, Tp, Crest Height (H), impulsive/non-impulsive (h_*), Beach width, run-up (if applicable)	Overtopping Rate for a vertical seawall $q = 0.00028*((h_* *(H/Hs))^{-3.1} * h_*^2 * \text{sqrt}\left(gh^2\right)$ (26) (Beach run-up switches overtopping on at seawall if this is greater than the beach crest height) (Beach width modifies water-depth at toe as h = Source water level– Beach width*Beach slope)	Depth at toe, h, is equal to flood source water level; Wave conditions are impulsive (h_* <0.2 holds true for all simulated cases)
Railways (North and Inside)	Volume from seawall (litres)	Node Height, Duration, Length of Linked Seawall, L	$\text{Flood Volume} = q * \text{Duration} * L$ (27)	Node acts as a channel and does not store any flood water
All Estuarine Beaches from Beach_west1 to Beach Mouth, Harbour, Railway_west, Near-coastal nodes, urban FPs	Probability of Flooding	Node Height, Heights and flood states of upstream nodes, i=1 to n, Node heights obtained from 10 m resolution DEM	$P\left(Node = \text{flooded}\right) = \sum_{i=1}^{n} P\left(E_i = \text{Flooded AND Height<= Height}\left(E_i\right)\right)$ (28)	Extreme case of all upstream elements flooded also considered by comparing element height with max ESWL

5.2.3 Teignmouth Model: Initial Runs and Validation

The Bayesian Network model for Teignmouth is built, compiled and run for a current 1 in 1000 year ESWL of 3.46 m and assuming no structural defences along the open coast. This is done by setting the heights of all seawall nodes to zero. Since the harbour is a receptor by itself and not just a flood defence, it is included in the simulation. The simulation randomly samples 500 values at each node to calculate its node-state probabilities from its equation (see Section 5.2.6 for discussion on optimum number of samples). The entire simulation takes less than a minute on a standard PC for a total of 200,000 conditional probabilities across 50 network nodes. The network model results for flood extents are input into GIS software to produce maps of flood extents.

Figure 29 compares the output flood extents of the model with available indicative flood maps for the region (Environment Agency, 2013a) which indicate the maximum floodplain extent in the absence of structural sea defences. In Figure 29 an area is considered flooded if its node has a non-zero probability of flooding. There is a 93% agreement between the two maps in terms of flooded area and a very good spatial agreement of flood extents except for the harbour area and a strip of land north of the railway line. This difference is most likely due to differences in the elevation data used by the two models – the network model identifies these areas as not being flooded since they are above the ESWL of 3.46 m. Overall, the network model flood extent is higher by 0.014 sq. km. This is attributed to a) the mapping by the SPR model of inter-tidal beach elements; and b) the low resolution of some floodplain elements in the SPR model resulting in a larger area characterised as flooded.

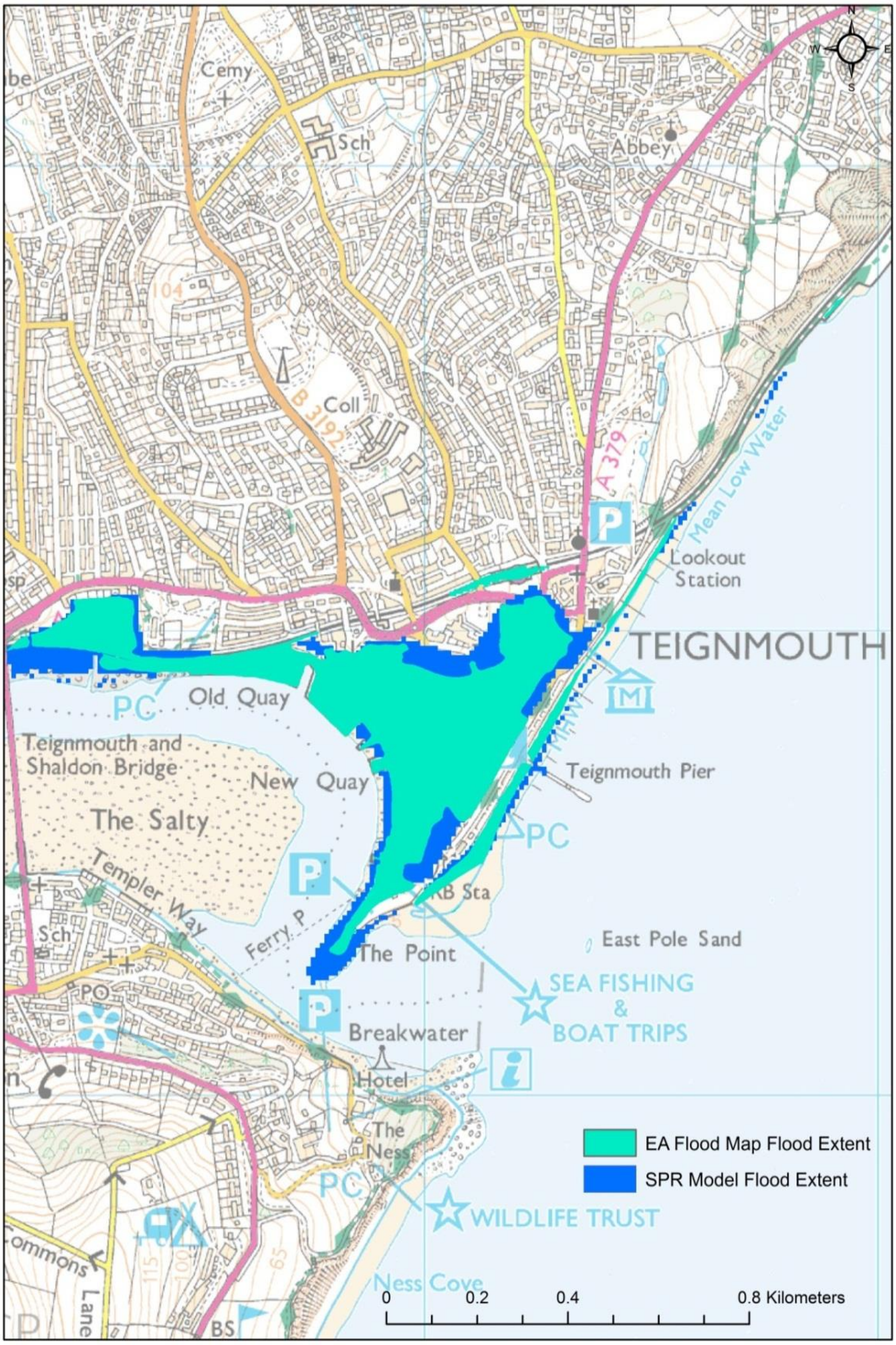


Figure 29: Comparison of Teignmouth Network Model and EA Indicative Flood Maps (Environment Agency, 2013a) for a 1 in 1000 year ESWL (3.46 m) assuming no defences

The network model is validated for overtopping rates along the open coast. The validation is done using overtopping estimates by Mouchel Parkman (2008). Overtopping rates at the node "Seawall Rly2" in the network model (Figure 27) are compared with the corresponding seawall section "208m39c" in Mouchel Parkman (2008). For the purpose of this validation the network model uses the same structural parameters – i.e. seawall configuration (vertical wall) and crest height, and hydraulic loading parameters - i.e. extreme water levels, sea-level rise and wave heights as used in Mouchel Parkman (2008) (Table 10). Network model overtopping rates are compared with the data for a 1 in 100 year water level at three time-slices 2020s, 2050s and 2080s.

Table 10: Input parameter values for overtopping validation calculations

Time-slice	ESWL (m)	SLR (m since 2006 AD)	Hs (m)	Tp (s)
2020s	3.18	0.18	4.1	8.5
2050s	3.36	0.33	4.1	8.5
2080s	3.51	0.48	4.1	8.5

Network model overtopping rates compare well with the data. Figure 30 shows very good agreement between network model overtopping rates and those of Mouchel Parkman (2008) for the 2020s and 2050s time-slices. The network model under-predicts overtopping rates by 20 l/s/m by for the 2080s time-slice. This under-prediction is due to the discretisation of water levels in the ESWL node which lumps together water levels for the 2050s and 2080s into a single class interval of 3.5 to 3.75 m.

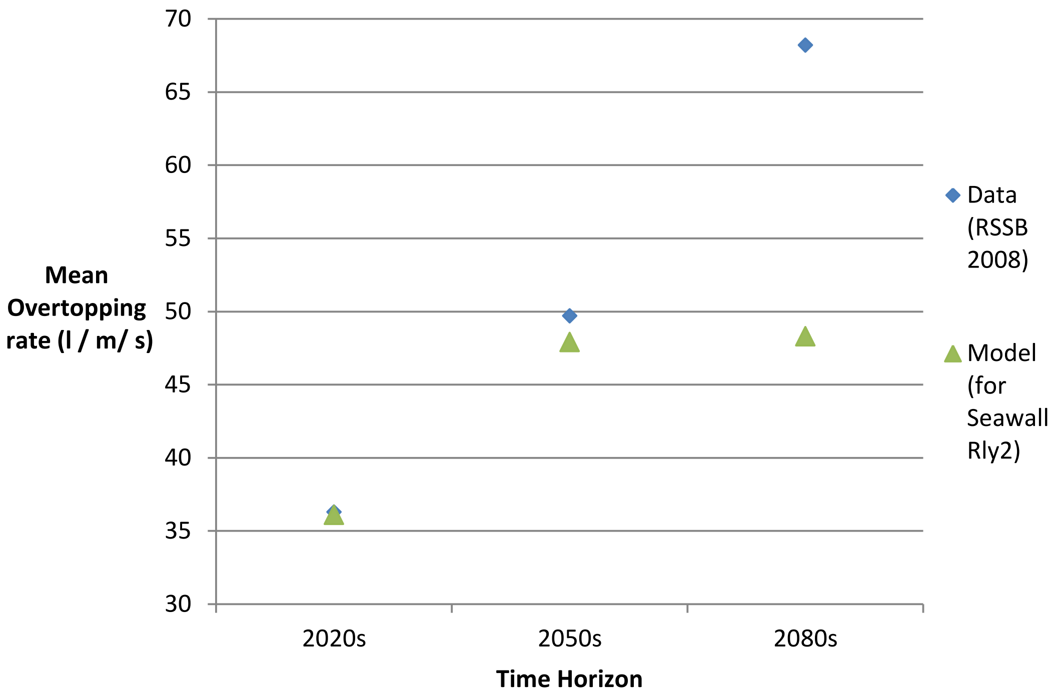


Figure 30: Comparison of data and BN model results for mean overtopping rates over time at node 'Seawall Rly2'

5.2.4 Teignmouth Model: Analyses of Flood Extents

The Bayesian Network model is used to predict flood extents for flood events of different return periods under current conditions. To do this the seawall nodes are all set to their present heights. The model is then run for multiple flood water levels corresponding to 1 in 10, 1 in 50, 1in 200 and 1 in 1000 year return period Extreme Still Water Levels (ESWLs) (McMillan et al., 2009) (see Table 11). Since these are current ESWLs, no sea-level rise is included. Based on existing shoreline management practices, it is assumed that sediment input is available to maintain the width of the open coast beaches at a constant 12.5 m (Table 8). The wave height and period are maintained constant for all simulations at 50 year return period values of 2 m and 8 s, respectively.

Table 11: Teignmouth Network Model: Flood Extent Simulations

Simulation No.	Return Period (years)	Extreme Still Water Level (m)
1	10	2.97
2	50	3.13
3	200	3.28
4	1000	3.46

Figure 31 below shows a map of the varying flood extents for the different return periods. Since all defences are included in these simulations, the map shows flooding of the inter-tidal beaches, the seawalls and the floodplain nodes. Most of the floodplain lies below the 1 in 10 year flood level of 2.97 m and is therefore flooded from the estuary for a 1 in 10 year flood event. Flooding from the open coast starts occurring for the 1 in 200 year event of 3.28 m. However an increase from 3.28 m to a 1 in 1000 year level of 3.46 m does not cause any increase in flood extent resulting in identical flood extents for both scenarios.

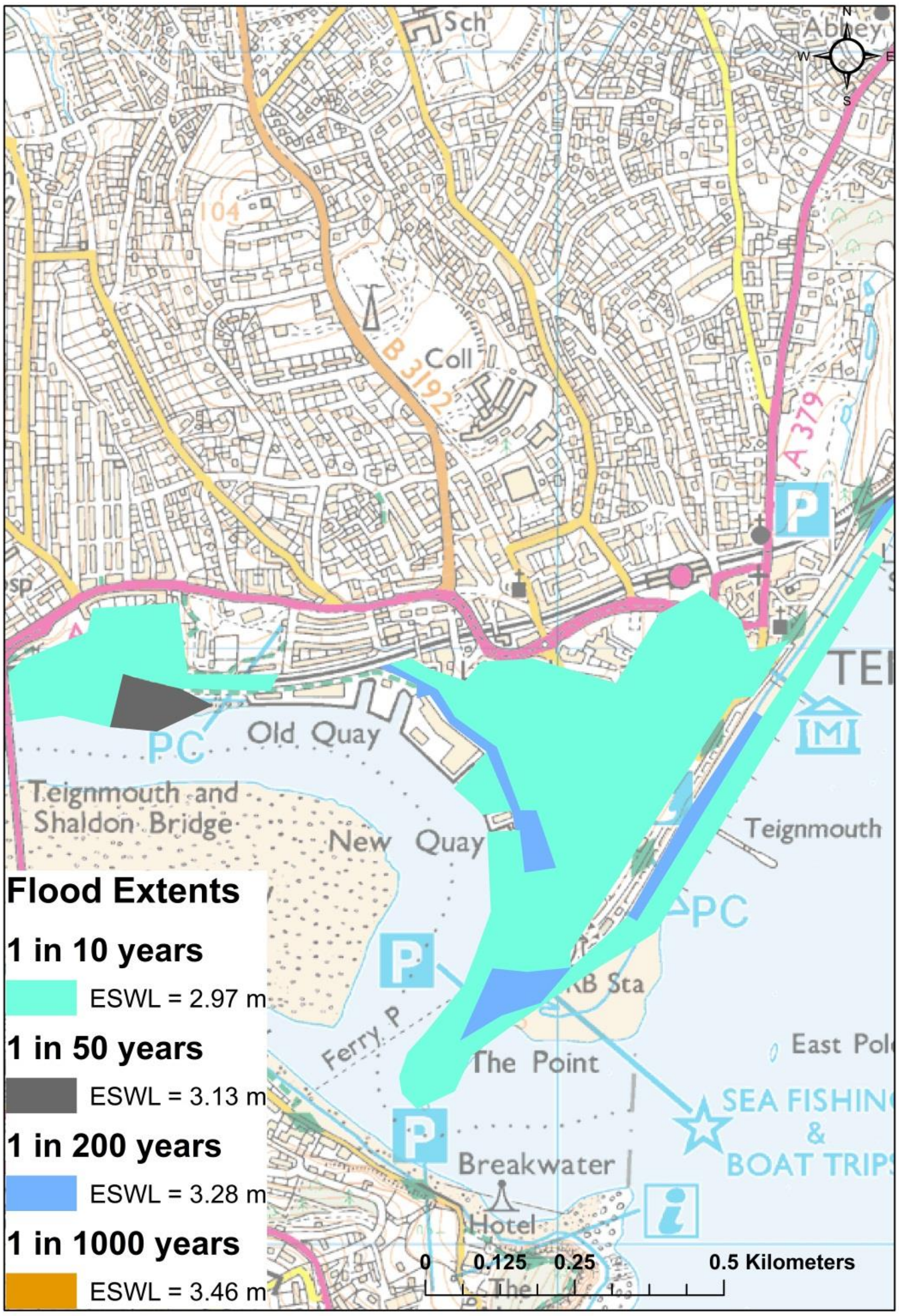


Figure 31: Teignmouth Network Model Predictive Flood Extent Simulation

Along the estuarine coast almost all nodes are low-lying and flooded by a 1 in 10 year event. This includes the western urban floodplain which gets flooded via the western-most beach and the low-lying section of railway line. The Quay Road and Car Park which lie on higher ground are only flooded by the 1 in 200 year event. The harbour area remains dry for all simulated flood events, including the 1 in 1000 year event. The flood pathways to all the estuarine near-coastal nodes are via the back-beach for the low-order events. Flooding via the estuarine Back Beach area is a recognised problem in Teignmouth. Until recently, local defences were put up by individual owners in the area though these are not included in this model. Currently a larger more organised coastal defence scheme has been commissioned and construction is on-going (Environment Agency, 2012). The central urban floodplain is low-lying and floods early (for a 1 in 10 year event) via the estuarine flood sources through the near-coastal elements to the south. In contrast, there are no flood pathways to the town-centre via the open coast.

By contrast the central urban floodplain is relatively well-defended against flooding from the open coast. Most of the open-coast seawalls do not flood for events less than a 1 in 200 year ESWL. Where flooding of the open coast seawalls does occur the railway line to the north and the coastal path to the south immediately behind these walls are high-elevation linear features and act as barriers to flooding even where the seawalls in front experience some overtopping. Two seawall sections that do not have any beaches in front of them are overtopped by events greater than a 1 in 200 year ESWL. However, seawall sections of a comparable crest height – i.e. the 1972 and 1991 seawalls, that have a fronting beach, do not flood for the simulated events (see Section 5.2.1).

During previous flood events significant overtopping has been known to occur along the 1972 seawall flooding Den Promenade and the downstream town-centre (see Section 5.2.1). This flood pathway does not exist for the current situation due to the presence of a beach that is being maintained in front as an additional defence measure. In the absence of this beach the seawall will be vulnerable to overtopping by a 1 in 200 year event, as shown by the failure of an adjacent seawall section of comparable crest height. Rising sea-levels means the maintenance of these beaches will become increasingly critical and expensive. To investigate the sensitivity of the floodplain to this and other possible pathways the network model is run for six cases of combined sea-level rise and sediment input scenarios. These are run over a baseline event of 1 in 200 years which is shown by model simulations to be the threshold at which flooding along the coastal seawall sections starts to occur.

5.2.5 Teignmouth Model: Floodplain Response to Uncertain Inputs

The Teignmouth Bayesian Network model is run for six cases that are a combination of three sea-level rise and two sediment input scenarios (Table 12). Central estimate sea-level rise values are provided for three time-slices AD 2010 (current), 2050 and 2100 (UK Climate Projections, 2009). The sea-level rise values affect all flood sources in the same way, as described in Table 9.

Sediment input in the model affects two beaches along the open coast and can be one of three options – 'present', where it is certain that the beach widths are maintained at 12.5 m; 'absent', where it is certain the beach widths are not maintained, and are assumed as a constant 2.5 m; and 'uncertain', where the management regime is unknown or uncertain, there is an equal probability of the sediment input being present or absent and consequently an equal probability of the beach width being 2.5 m or 12.5 m. The sediment input cases simulated here are 'present' and 'uncertain'.

In all these simulations it is assumed that the new flood defence scheme along the Back Beach area will stop flooding of the central urban floodplain via this route for the cases simulated here. This is implemented in the model (and in the quasi-2D SPR) by introducing a new defence node between the estuarine flood sources and the near-coastal nodes (not shown here). All other descriptions and equations remain the same as in previous simulations.

Table 12: Teignmouth Network Model: Uncertain Input Simulations ((B) – Baseline simulation)

No.	Time-Horizon (year)	SLR (m)	ESWL (m)	Sediment Input
1 (B)	2010	0	3.28	Present
2	2010	0	3.28	Uncertain
3	2050	0.15	3.43	Present
4	2050	0.15	3.43	Uncertain
5	2100	0.5	3.78	Present
6	2100	0.5	3.78	Uncertain

With all other inputs remaining the same, the model is re-run for each case, for 500 samples at each node. As a result of the estuarine flood defence the central floodplain is only sensitive to the open-coast pathways shown in Figure 32.

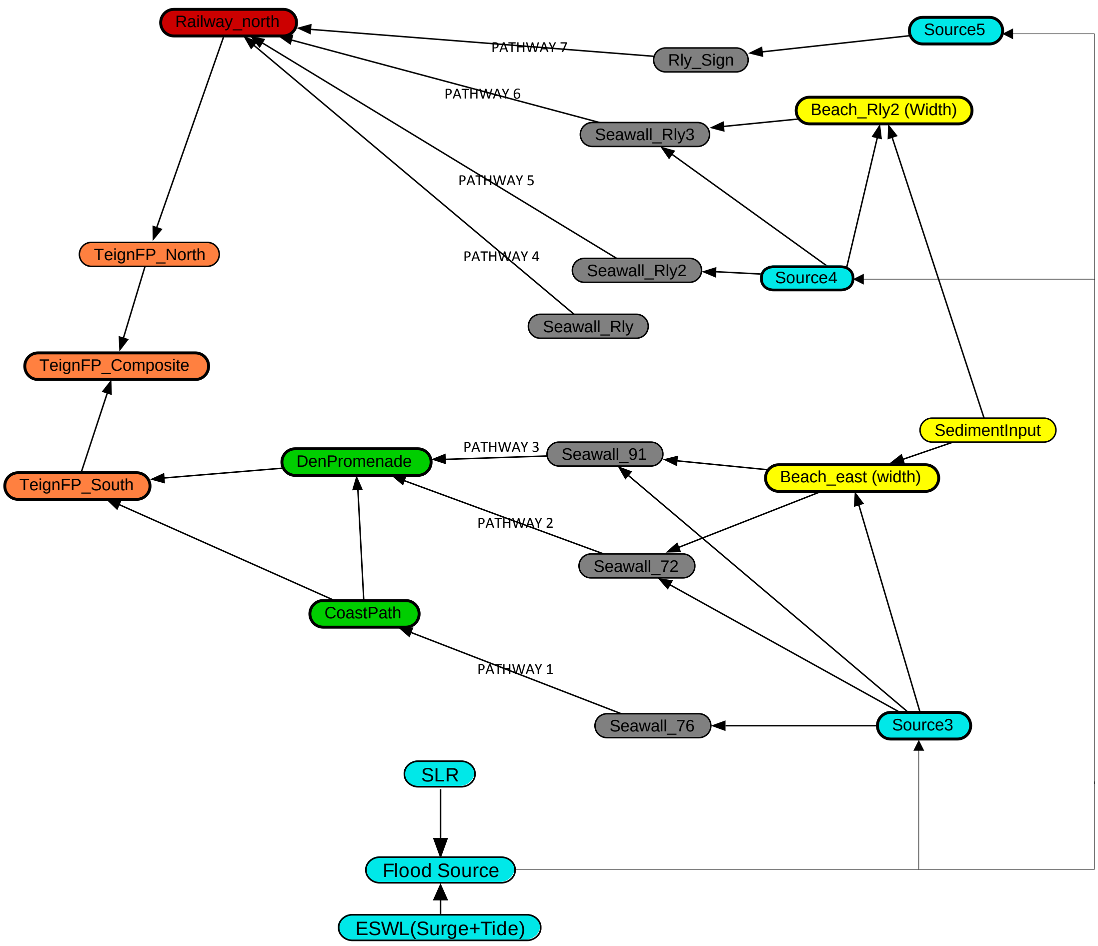


Figure 32: Open-coast flood pathways in Teignmouth network model

The flood probabilities of the nodes along all the open-coast pathways from the flood defences to the central urban floodplain are plotted for a sample case (Case 6 in Table 12) in Figure 33, to assess the relative importance of these pathways to flooding within the central urban floodplain.

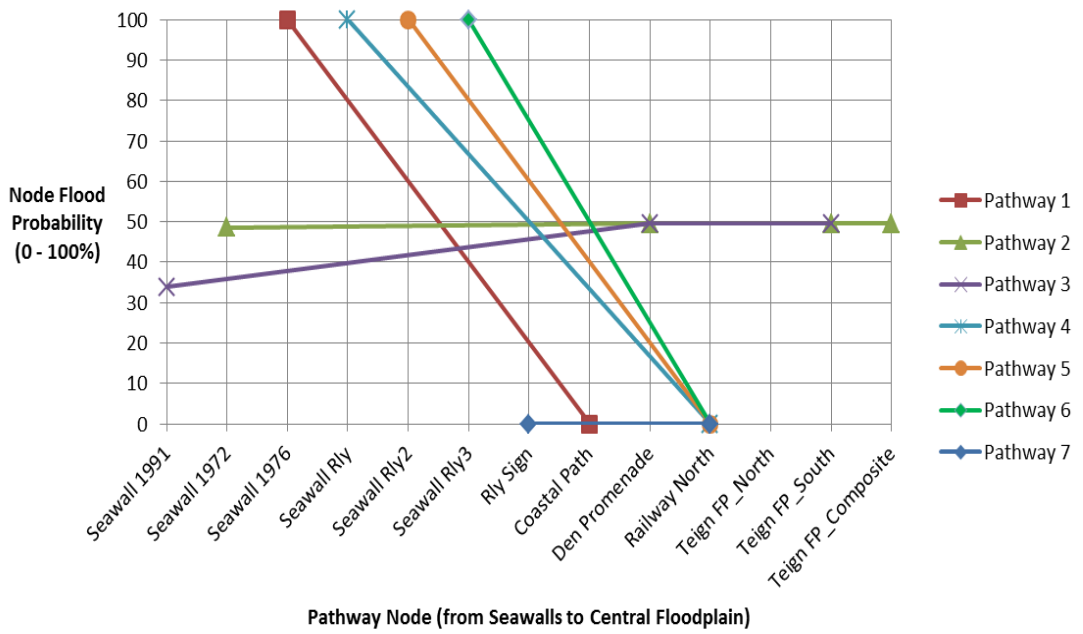


Figure 33: Flood probabilities for all open-coast flood pathways for Case 6 in Table 12

Figure 33 shows that the only pathways that cause flooding of the central urban floodplain are Pathways 2 and 3 along the 1972 and 1991 seawall sections. All other flood pathways show overtopping at the seawalls but do not go beyond into the floodplain due to the high-elevation linear features – namely the railway line and coastal path that act as flood barriers. The only seawall section that is not flooded for this case is the Rly_Sign which has a very high crest height.

Though the 1991 and 1972 seawalls perform better than the other seawall sections in terms of overtopping extents, the failure of these seawalls is relatively more important since they form the only pathways through which flooding of the inland floodplain occurs. Unlike the areas behind the other seawalls, the Den Promenade node adjacent to these two seawalls is a low-lying area and does not act as a flood barrier. For both Pathway 2 and Pathway 3 the central urban floodplain is flooded via the Den Promenade node.

The flooding at these seawalls is in turn driven by the presence or absence of the upstream beach. The beach that lies upstream of these two seawalls is an effective flood defence for all sea-level rise scenarios when external sediment input is present. However when this input is uncertain or absent, flooding along these pathways occurs. When the beach input is uncertain this uncertainty drives the uncertainties in the flood states of all downstream nodes along these two pathways. The flood probability for all the nodes along Pathways 2 and 3 (for the seawalls this is the probability of overtopping > 50 l/s/m) is plotted in Figure 34 against sea-level rise for the three 'uncertain' sediment input cases (see Table 12).

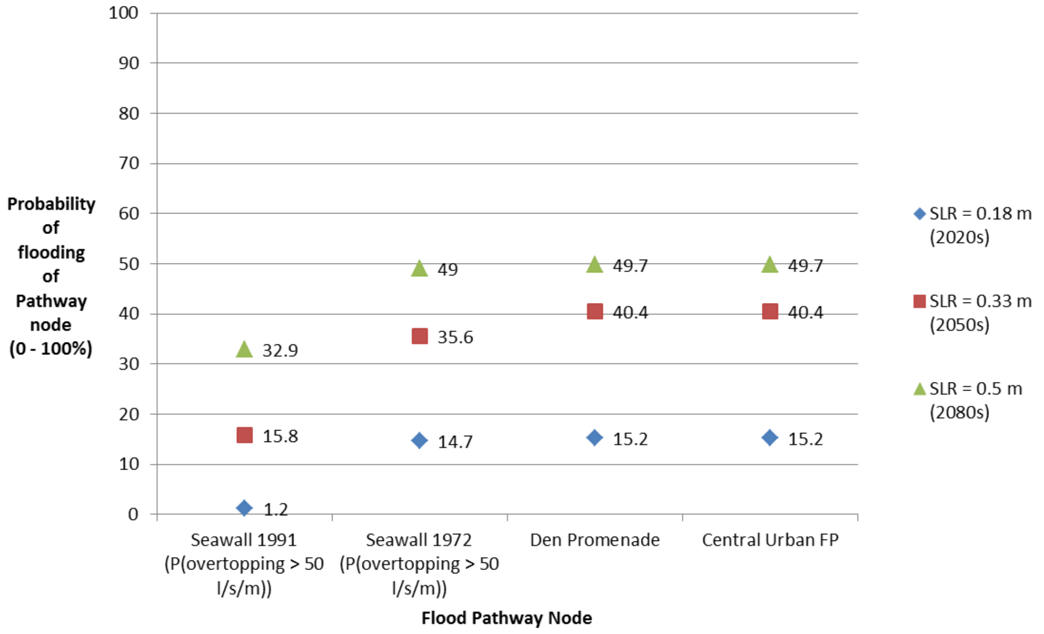


Figure 34: Node-state probabilities for Nodes Seawall 1972 and Seawall 1991

The 1972 seawall under-performs the 1991 seawall in all three cases and is the main driver of flooding at Den Promenade and the urban floodplain though both show a large spread in the probabilities of their overtopping rates. This is seen in Figure 35 which shows a 'screen capture' of the two flood pathways as simulated in the network model for Case 6 with an uncertain sediment input and SLR of 0.5 m. The effect of this and other uncertainties on model performance is discussed in Section 5.2.6.

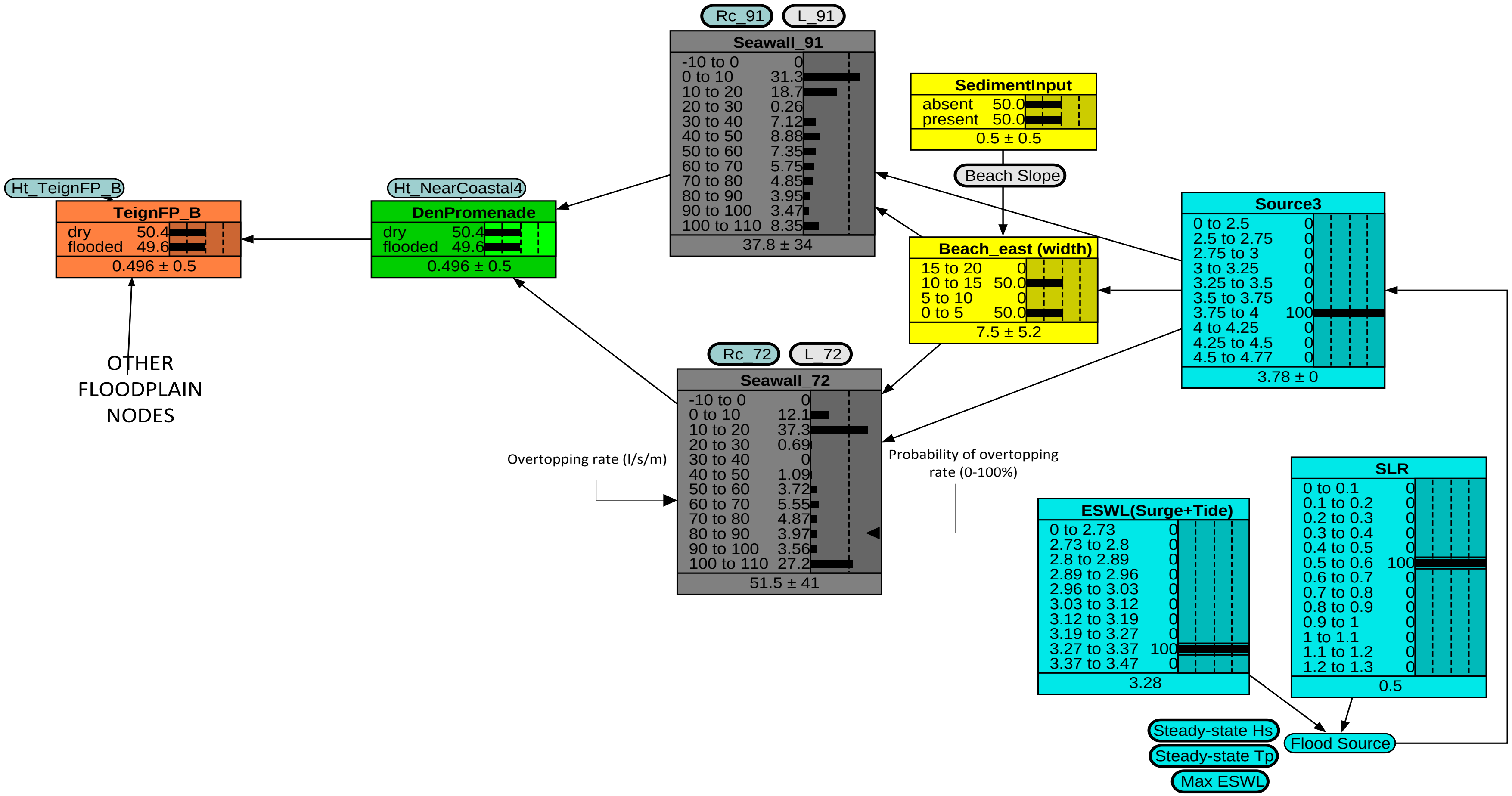


Figure 35: Node-states for Teignmouth flood pathways along Seawall 1972 and Seawall 1991

5.2.6 Teignmouth Model: Uncertainty in Model Simulations

The Bayesian Network model is a useful tool for predicting flood extents as well as identifying flood pathways to specific nodes. Another advantage of this approach is the easy analysis of most of the uncertainties that accompany any numerical model simulation. The treatment and description of uncertainties in the Bayesian network model are discussed here in terms of the three types of uncertainties described in Section 2.5.4.

Inherent Uncertainties: These are the uncertainties inherent in the processes and data simulated by the numerical model independent of the quality of the model or the data inputs. In coastal flood risk assessments inherent uncertainty is generally highest in the input parameters. For instance, the expected ESWL in any given year rather than being a single value is generally expressed as an 'annual exceedance probability' distribution. Flood risk assessment studies often find it more useful to express flooding in terms of a cumulative annual probability of flooding under specified conditions, rather than analysing specific events (e.g. Evans et al., 2004, Sayers et al., 2002c). The Bayesian network approach lets the user describe floodplain nodes either as unique values or as probability distributions. The Teignmouth application investigates the response of the floodplain to specific flood events for which it uses unique values of ESWLs. The influence of inherent uncertainties on floodplain flood risk is investigated in the next case-study in Section 5.3.

Data/Knowledge uncertainties: These are the uncertainties arising as a result of our incomplete knowledge and understanding about the processes that influence the values of these parameters.

A fundamental example of knowledge uncertainty is the uncertainty in the underlying structure of the numerical model. The Bayesian network approach followed in this thesis offers a significant advantage as a conceptual model, since it provides an explicit description of the assessed floodplain which allows immediate and direct assessment of any errors or uncertainties in the floodplain descriptions used within subsequent numerical models. Though the Bayesian network model cannot by itself assess structural uncertainty, it derives directly from a quasi-2D SPR which is designed in an iterative process to develop a robust and comprehensive understanding of the floodplain.

Floodplain descriptions in the quasi-2D SPR and Bayesian network models can be readily and easily modified during the course of the flood risk study to reflect any new knowledge obtained about the floodplain.

Another more direct example of knowledge uncertainty in the Teignmouth model is the uncertainty in our understanding of the role of a particular floodplain node on flood propagation. The external sediment input in the Teignmouth model is simply defined as 'absent', 'present' or 'uncertain' though this definition has a quantitative effect on the flooding at the downstream seawalls and floodplain nodes. Here 'uncertain' means sediment input is uniformly distributed (with a 0.5 probability) across its two states 'absent' and 'present.' The effect of the uncertainty in sediment input is shown in Figure 36 which plots the probability of flooding of the 1972 Seawall for three sediment input conditions – 'present', 'uncertain' and 'absent' for an extreme still water level of 3.78 m (corresponding to Case 6 in Table 12).

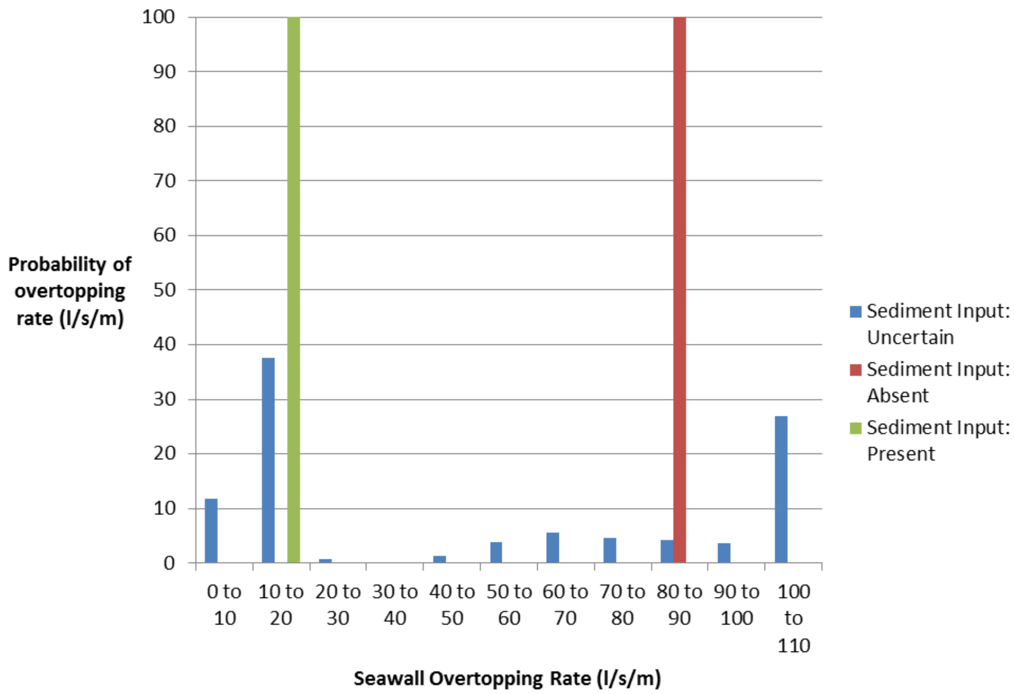


Figure 36: Overtopping rate probabilities at node Seawall_72 for different Sediment Input cases, for a fixed ESWL of 3.28 m.

The beach width is dependent on whether sediment input is 'absent', 'present' or 'uncertain.' When the beach height (calculated as beach width X beach slope) is higher than the wave height the beach is used in the seawall overtopping calculations to modify the overtopping rate (see Table 9).

When sediment input is uncertain the beach width values have a uniform probability distribution across the intervals 0 – 5 m and 10 – 15 m with a lower bound value of 0 and an upper bound value of 15. This range of values results in a wide probability distribution of overtopping rates at the seawall from 0 – 10 l/s/m to 100 – 110 l/s/m. Due to the definition of the beach node and the discretisation of its class intervals the absolute sediment inputs ‘absent’ and ‘present’ result in a minimum width of 2.5 m or a maximum width of 12.5 m. When used in the seawall overtopping calculations these result in overtopping rates of 10 to 20 and 80 to 90 l/s/m respectively.

Since the upper and lower bounds for the ‘uncertain’ case lie outside the absolute values the overtopping rate at the seawall for the ‘uncertain’ case is not bounded by the absolute cases though its mean value lies mid-way between that of the two absolute cases.

Model uncertainties: These uncertainties are a function of the resolution of the model and the accuracy and detail with which the relevant processes are described. Additionally in probabilistic models errors are introduced by the lack of an adequate number of samples.

In the Teignmouth model the floodplain nodes are described as continuous values that are discretised into class intervals (see Table 8) analogous to the grid-size of a conventional numerical inundation model. Model precision is therefore limited by the width of the coarsest class interval. A node, k that has m parents with n class intervals each will have n^m conditional probabilities in its CPT. Increasing the number of class intervals for any of its parents causes a multiplicative increase in the number of conditional probabilities at node k and a corresponding increase in computational time. Choosing an appropriate class interval therefore represents a choice between model precision and computational time. The number of node-states also depends on the information available when describing a node and the detail to which the node is described (also see (Plant and Stockdon, 2012) for their discussion on class intervals). For instance the seawall nodes where overtopping is described using an empirical relationship are continuous value nodes discretised as five overtopping extent classes. The Boolean nodes whose description is a relatively simple ‘dry’ or ‘flooded’, have only two states and qualitative inputs i.e., beach width and sediment input, on which less information is available, are also described using fewer states.

Uncertainties in the Teignmouth network model are expressed at each node in terms of a standard deviation over a mean value. In addition to inherent uncertainties in the input data and the node relationships this also includes uncertainties due to sampling errors. These are directly related to the number of samples used for each simulation: a greater number of sampled values reduces the model uncertainty but also increases run-time. Figure 37 shows the uncertainty and run-times for an increasing number of samples for an example node in the Teignmouth network. Based on this analysis 500 values were sampled at each node during model simulations.

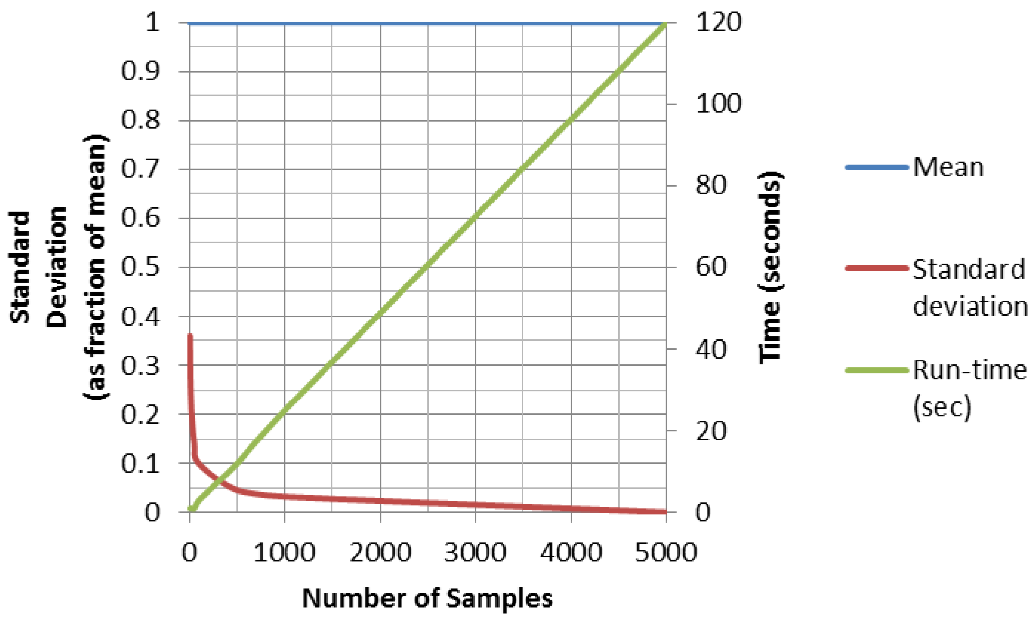


Figure 37: Standard deviation and run-time versus number of samples for node 'TeignFP_West' in Teignmouth network

5.2.7 Teignmouth Model: Lessons Learnt

The Bayesian Network model has been built and successfully applied to the Teignmouth coastal floodplain. The quasi-2D SPR and network model were both constructed within a week and network model run-time is less than a minute on a standard PC. Network model flood extents compare well with the EA Indicative Flood Maps. Useful initial insights into floodplain system behaviour are gained from relatively simple and quick network model simulations. The Bayesian network approach is also an effective means of describing the modelling uncertainties that influence flood risk mapping.

The Teignmouth floodplain has two distinct flood sources – estuarine and open coast, and is exposed to flooding for low-magnitude events. The manner of this flooding varies – driven by water levels along the Back Beach, and by water levels and waves along the open coast. The flexible mapping approach for the quasi-2D SPR and network model allows the representation of linear coastal elements such as beaches and seawalls. The network model describes these different flood pathways and identifies the sensitivity of the floodplain to flooding from lower-magnitude events via the estuarine flood pathways.

The city is well-defended along the open coastline up to a 1 in 200 year water level. Beyond this magnitude, the lower seawall sections along the coast show considerable overtopping though in most places the railway lines and areas behind them are high enough to act as flood barriers.

The quasi-2D SPR and Bayesian network map beaches in front of the 1991 and 1972 seawalls, whose width is dependent on the availability of external sediment input. Pathway analysis of the open-coast nodes for uncertain sediment input identifies these seawalls as important potential flood pathways into the central floodplain. In the mid- to long-term future, uncertain sediment input and sea-level rise may cause significant overtopping at these seawalls causing the creation of new flood pathways into the central floodplain via the linked inland node.

The relatively coarse resolution for the floodplain behind the seawalls in the two models (> 50 m on average) means that other potentially critical floodplain features such as roads and linear features that could influence flood propagation are not described. The issue of linear features in the floodplain is recognised as important, especially for urban floodplains (e.g. Fewtrell et al., 2008) and is discussed in the following case-study.

Another limitation in this case-study is the lack of data and information for more refined floodplain state descriptions and better validation of the network model. To address these issues, the following case-study is applied to an urban floodplain where better data and numerical model simulations are available for comparison.

5.3 Case-Study: Portsmouth, England

5.3.1 Site Description

The Bayesian network model has been demonstrated as a useful scoping tool in Teignmouth for identifying critical flood pathways and is now applied to the contrasting urban coastal floodplain of Portsmouth in southern England. The Portsmouth model focuses on two issues identified from application in Teignmouth – model resolution and probabilistic descriptions of input flood water levels. The model is built at a higher resolution than for Teignmouth, to test its limits with regard to its usefulness, accuracy and run-time as a flood prediction and scoping tool for a highly urban defended coastal floodplain. Additionally the model is used to understand the response of the Portsmouth floodplain to uncertain water level inputs.

The city of Portsmouth on the south coast of England (Figure 38) is the UK's only island city, and the only city in England with a higher population density than London. It comprises two regions – Portsea Island and a portion of the mainland to the north of the island. The city has approximately 45 km of coastline, of which 32 km are on Portsea Island. Though most of the coastline is defended, 25% of these may be below a 1 in 200 year extreme water level. Several properties behind these defences are in low-lying areas, exposed to a 1 in 200 year coastal flood. As a result coastal flood risk in Portsmouth is the highest in the Solent and believed to be the third highest in the UK, after London and Hull (Atkins, 2007, Wadey et al., 2012).

The Portsmouth floodplain and its quasi-2D SPR and network model are different from Teignmouth. The Teignmouth floodplain is a small region with a highly varying coastline and coastal flood pathways with the inland floodplain contained within one or two flood compartments. In contrast Portsmouth is densely urbanised with a complex geography consisting of multiple flood compartments and is almost entirely protected by artificial flood defences. The Portsmouth floodplain is however relatively well-studied, with more data and information available about floodplain characteristics, relative to Teignmouth. For example Wadey (2013) conducted an extensive case-study of the Portsmouth floodplain, which is used to inform the construction of the Portsmouth network model in this thesis.

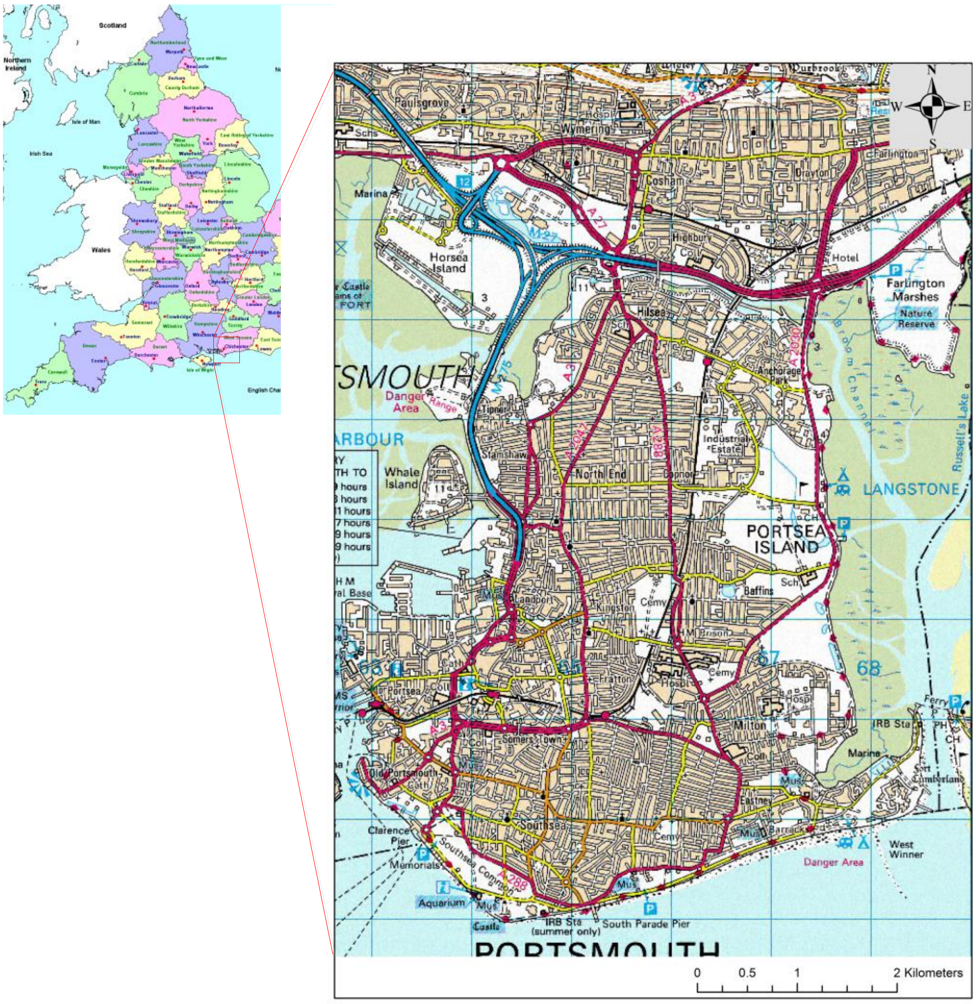


Figure 38: Portsmouth, England: Location

5.3.2 Stage 1: Quasi-2D SPR

As the first step to building the network model for Portsmouth, a quasi-2D SPR is constructed for the floodplain. The Portsmouth floodplain is heavily urbanised characterised by low-lying flood compartments and several urban features that influence the propagation of flood risk within these floodplains. Wadey (2013) in a detailed case-study of Portsmouth describe unique features of the Portsmouth floodplain – identified from site visits and an extensive data collection exercise, which could influence flood propagation (also see Ruocco et al., 2011). The quasi-2D SPR for Portsmouth uses this information to map these floodplain features so they can be modelled in the Bayesian network model to capture their influence on flood propagation. These features (Figure 39) include:

1. The frequently flooded Farlington Marshes to the north-east, and the open channel and road linking the marshes to the semi-urban area across the A27.

2. The underpasses under the A27 in the north-west of Portsea Island that could possibly lead to flooding of northern areas of Portsea Island.

3. The low-crested defences, including the coastal Eastern Road along the east coast and low-lying areas along the eastern waterfront to the north-east of the island.

4. The relatively high-crested and well-defended areas along the west coast, in the region of the Ferry Port and Naval Base, and along the south coast in the region of Gunwharf Quays and Southsea.

5. The ‘incidental’ flood defences provided by the old city walls at Hilsea, to the north of the island.

Figure 39 shows the land-use map for Portsmouth with all floodplain elements below the 1 in 1000 year ESWL (3.28 m). This map is used to build the quasi-2D SPR system diagram (Figure 40). Implemented at a higher resolution and for a slightly larger extent than Teignmouth the Portsmouth SPR system diagram has a total of 100 floodplain elements and 153 links, and is built using GIS software (see Appendix 1 for model-building process).

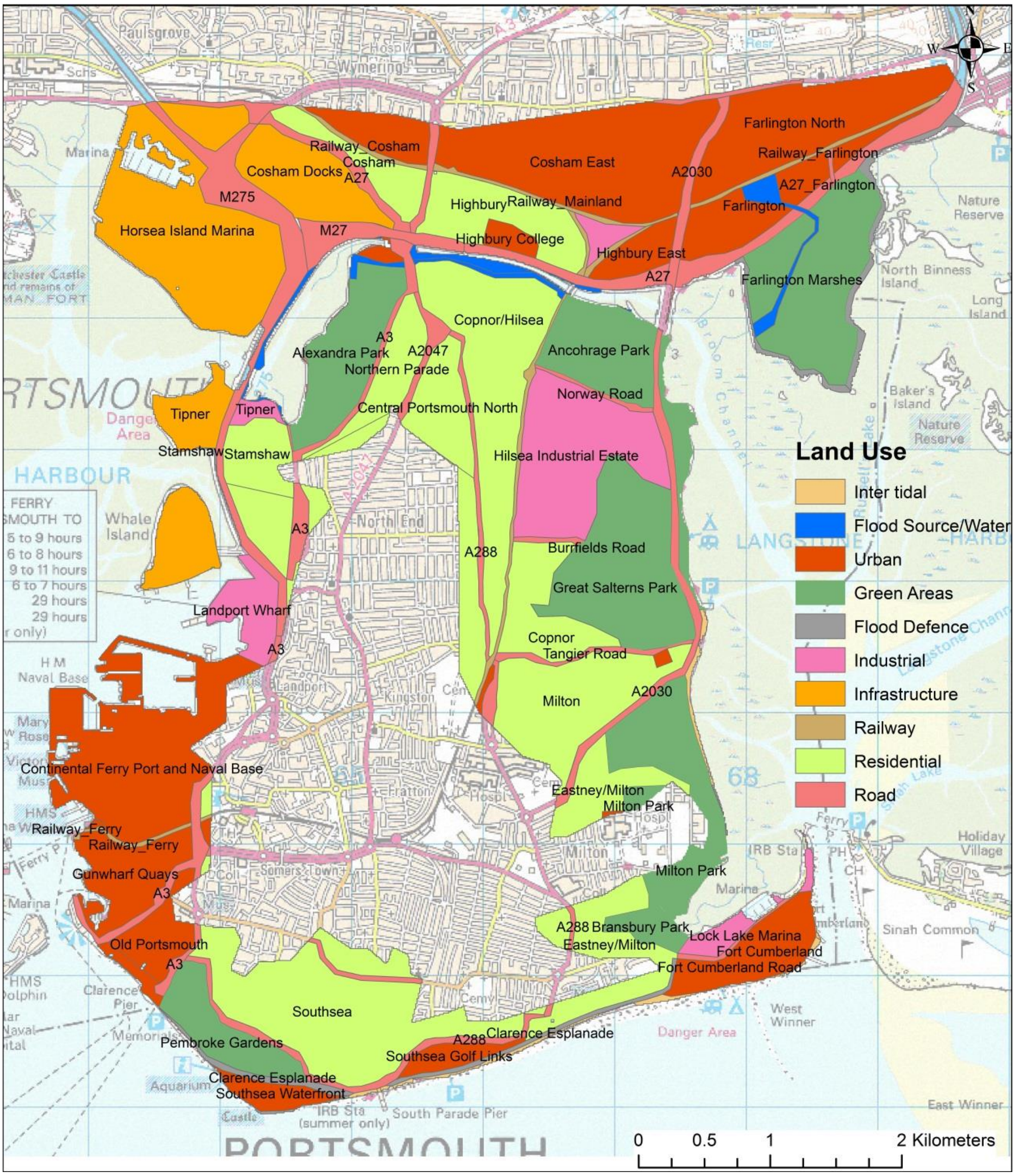


Figure 39: Land-use Map for Portsmouth Quasi-2D SPR

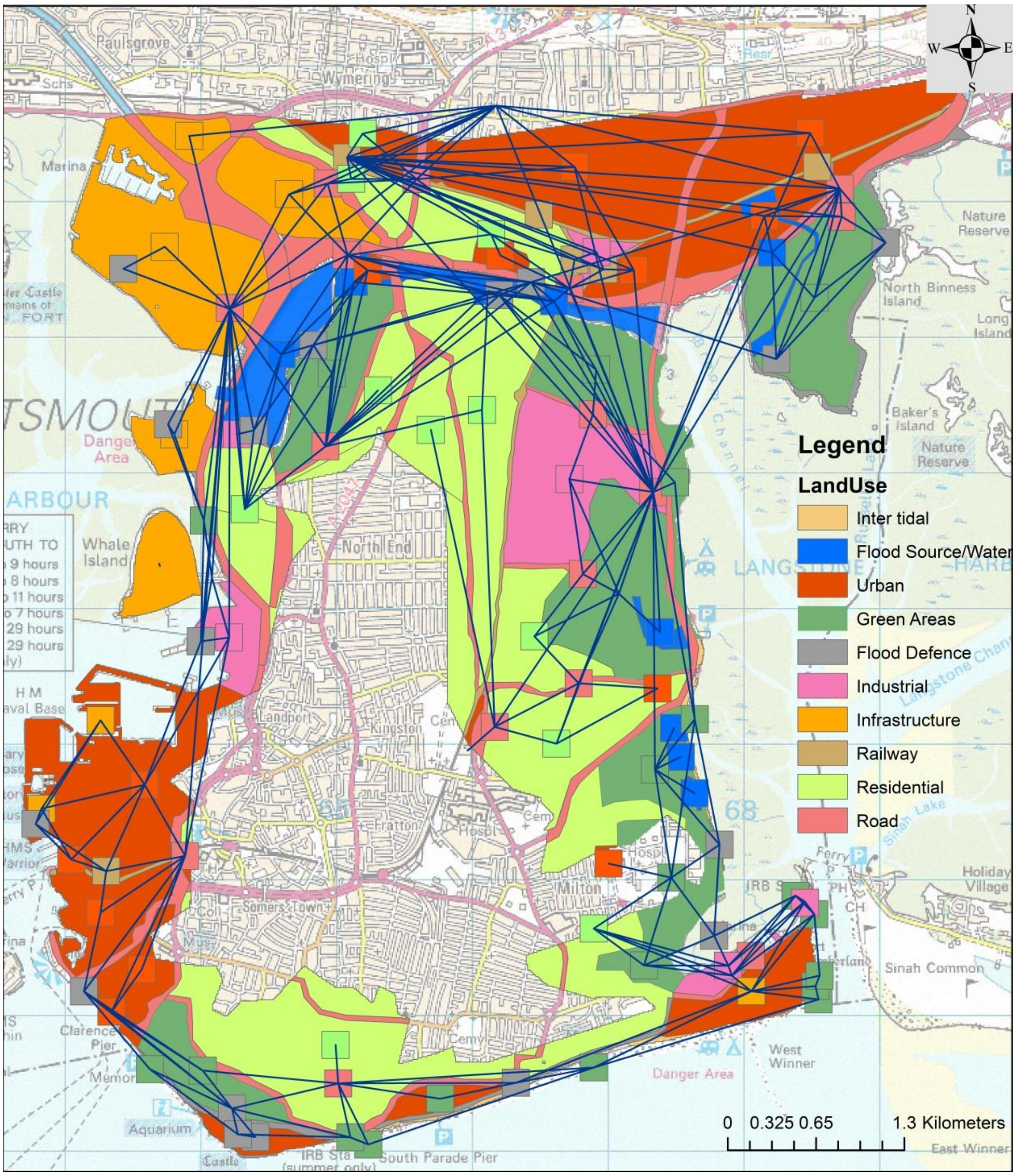


Figure 40: Portsmouth Quasi-2D SPR (built using GIS Software)

5.3.3 Stage II: Bayesian Network Model

The quasi-2D SPR system diagram combines information from the Portsmouth case-study of Wadey (2013) with height information from a 10 m DEM, averaged for each SPR element. The quasi-2D SPR system diagram is in turn used to create the network for the quantitative model. The Portsmouth network model is constructed in the same manner as the Teignmouth model (see Section 5.2.2).

Step 1: Construction of Floodplain Network. The Portsmouth model network, like the Teignmouth network, is constructed from its quasi-2D SPR. Each floodplain element in the quasi-2D SPR is a node in the network model, and the links between nodes are derived from the quasi-2D SPR. Due to its relatively higher resolution, the Portsmouth network has more flood source, sea defence and urban nodes than the Teignmouth network. All local flood sources are driven by a single flood source in the Solent. A snapshot of the network (without node titles or displays) is shown in Figure 41.

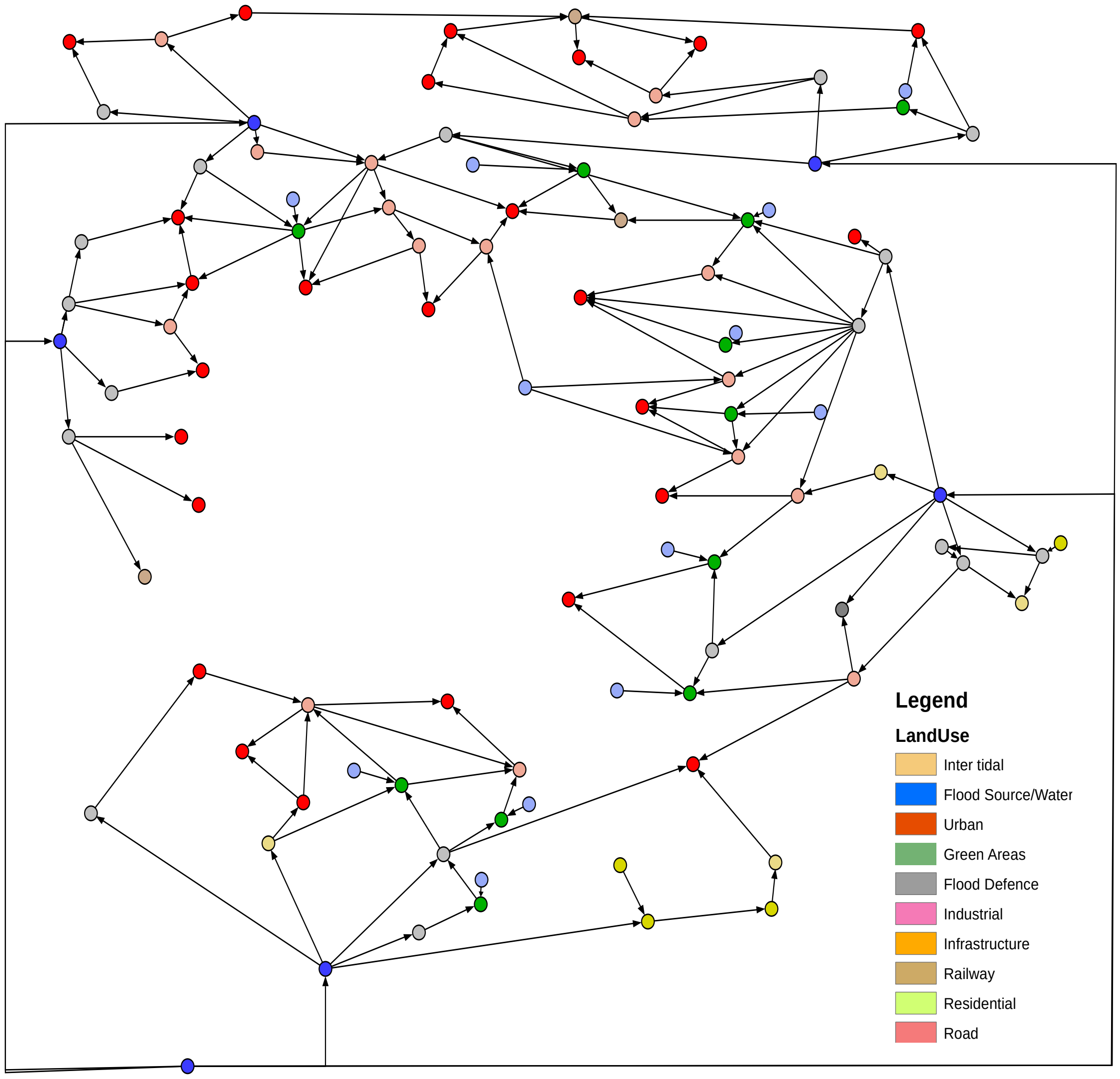


Figure 41: Portsmouth Model: Bayesian Network

Step 2: Description of Floodplain Connectivity. The links in the Portsmouth network are described similar to those in the Teignmouth model: all links representing the propagation of flooding from a source, through a pathway element to a receptor element are maintained, while links between independently flooded elements such as seawall sections are removed.

Step 3: Description of Floodplain Nodes. Like in the Teignmouth model each node in the Portsmouth network represents a specific property of the corresponding element in its quasi-2D SPR. The land-use classification of the floodplain nodes is different for Teignmouth and Portsmouth – for instance the Portsmouth quasi-2D SPR includes urban parks and linear features such as roads and railways. Table 13 describes the nodes and equations for the Portsmouth network. Unlike Teignmouth which is driven by estuarine water-levels and open-coast overtopping flooding in Portsmouth occurs almost entirely by overtopping and inundation of its seawalls. This uniformity in flooding mechanism allows uniformity in the description of all inland floodplain nodes as individual flood storage cells.

The higher resolution of the Portsmouth model and the extensive information available on the floodplain network allow more detailed descriptions of the nodes compared to Teignmouth. Floodplain network includes nodes describing all major linear features such as roads and railways and incidental flood defences such as the Hilsea Line Walls in north Portsea described in Wadey (2013). As seen from the Teignmouth model simulations linear features in floodplains have a considerable influence on flood propagation and may act as barriers or channels depending on their orientation with respect to the flow. The underpass under the A27 in north Portsea is also included in the network described as a Boolean ‘open’ or ‘close’ node. Similar to the Teignmouth model the range and number of class intervals are determined by trial and error refining the node-description until the desired accuracy of representation is reached (see Section 5.4).

Step 4: Description of Flood Propagation. Like for the Teignmouth model node relationships are specified using equations (Table 13): a) the beaches are described in terms of run-up values which determine if overtopping occurs at the seawalls; b) the seawalls are described in terms of the EurOToP overtopping formulae; c) the floodplain nodes are all described in terms of flood extents based on the storage-cell method.

Similar to the Teignmouth model the Portsmouth model uses the basic controls of height and connectivity to determine flood propagation pathways. Thus any node can only be flooded by an upstream node that is higher or at the same elevation and is itself flooded. One addition in the Portsmouth model is the uniform use of the storage-cell method to calculate flood propagation within the Portsmouth model. The storage cell method is based on the continuity equation and states that for a node i,

$$Vout_i = Vin_i - Vstorage_i \tag{29}$$

where, $Vout_i$ is the outflow from node i, Vin_i is its inflow and $Vstorage_i$ its defined storage volume. This model makes the following assumptions:

1. Every node is assumed to have a single, uniform elevation specified by its associated constant 'height.'
2. Every node is assumed to have a fixed area and tolerable flood depth and hence a fixed flood storage volume.
3. Every node is assumed to flood up till its storage capacity before any excess outflow occurs.
4. Excess outflow from every flooded node is assumed to be equally distributed amongst all connected downstream nodes.
5. Nodes such as roads and railways that are defined as having no storage capacity act as flood barriers and transfer all received flood volume amongst their downstream nodes.

Thus given a node i with n connected downstream nodes the inflow to any downstream node j is given by,

$$Vin_j = Vout_i/n \tag{30}$$

The high resolution of the Portsmouth model allows the estimation of the fraction of area flooded for all inland floodplain nodes. For any node j, assuming a uniform tolerable flood depth d, the fraction of area flooded, f is given by,

$$f_j = (Vin_j - Vout_j)/(A * d) \tag{31}$$

where Vin_j is the inflow flood volume, $Vout_j$ the outflow, and A is the total area of the node. The default tolerable flood depth for a node is set as 0.5 m, as the depth of water above which damage to structures and cars is significant (e.g. HR Wallingford et al., 2006). Figure 42 describes a node that is flooded up to the critical depth for two-thirds of its area, with a 100% probability.

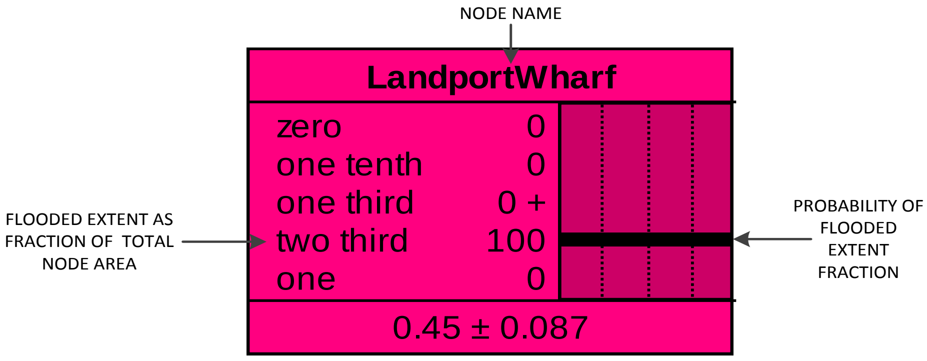


Figure 42: Portsmouth Model: Example Urban Area Node

Another addition to the Portsmouth model is the use of probabilistic rather than deterministic equations for estimating overtopping volumes at the seawalls. This is made possible by the relatively higher resolution and data availability for the flood defences in the Portsmouth model.

Step 5: Entering Input Values. The hydraulic inputs for the Portsmouth model are described similar to Teignmouth – Extreme Still Water Levels, steady-state wave climate, sea-level rise and storm duration. Portsmouth being a well-defended floodplain it is assumed that the beaches will be managed constantly independent of external sediment inputs. This additional functionality is therefore not included in the Portsmouth quasi-2D SPR or its network model. An additional detail in the Portsmouth model is the use of annual exceedance distributions for the input ESWLs. This is discussed further in the simulations in Section 5.3.4. Additional parameters such as node heights and other relevant constants are defined as 'constant' nodes. Once all input node values are entered and the network is compiled, the model is run for multiple scenarios of input conditions.

Table 13: Portsmouth Model: Node Equations and Descriptions (also see Appendix 3)

Nodes and Constants	Units and Range	Node Class Intervals	Node Equations and Description	Assumptions and Comments
Flood Sources: ESWLs (1-5), Constants: Hs, Tp, SLR, Duration	Water Level 0 to 4.75 (m)	Continuous, 10 bins: 0-2.5 and 0.25 m intervals thereon	Flood Source water level = ESWL+SLR. Default ESWL is a Weibull distribution based on (McMillan et al., 2011)	Hs, Tp, SLR and Duration are deterministic values (dafault Hs = 2.5 m, Tp = 8s corresponding to 1 in 50 year event).
Beaches: Run-up, Constants: Height, Slope, irribarren number	Run-up Height 0 to 8 (m)	Continuous, 8 bins: 1 m intervals	Run-up (m) = Irribarren number* Hs, see Eq (24)	If run-up>beach crest, flooding occurs at linked node.
Seawalls Constants: Crest Height, H, Length, L	Flood Volume 0 – 50,000 (m^3)	Continuous, 6 bins: 0-500, 500 – 10,000 and 10,000 m^3 intervals thereon	Overtopping Rate (when H > ESWL), see Eq (25) $\text{Overtopping volume} = \text{Normal Dist}\left(q,\ q*0.8\right) * \text{Length} * \text{Duration} \quad (32)$	When H = ESWL, the Eurotop formula for 'overtopping at zero freeboard' is used. When H < ESWL, the weir equation for inundation is used (EurOtop Manual, 2007). Breach is indicated by setting seawall height to 0.
Green Areas: Urban Parks and Marshes, Storage Volume, Constants: Storage Depth, Number of Links	Flood Volume -50,000 to 100000 (m^3)	Continuous, 12 bins: -50,000 to 0, 1 0 to 100, and 10 bins at 10,000 m^3 thereon	Output Flood Volume = (Total Input Flood Volume – Storage) / Number of Downstream Links where Storage = Park Area * Storage Depth	Default storage for Parks is 0. Negative volume implies Storage > input flood volume
Linear Features: Roads, Railway Lines, Walls, Constants: Height, Number of Links	Flood Volume 0 – 50,000 (m^3)	Continuous, 5 bins: 10,000 m^3 intervals	As Channel: Output Flood Volume = Input Flood Volume / Number of Links As Barrier: IF (Height > Upstream node Height) Then Acts as Channel, Else Dry.	Features act as channels when along the flow direction and as barriers if higher than and perpendicular to flow
Urban, Industrial, Critical and Infrastructure Areas, Constants: Height, Number of Links, Critical Flood Depth	Fraction of Area Flooded 0 – 1 (dimensionless)	Continuous, 5 bins: 0 – 0.1, 0.1 – 0.32, 0.33-0.65 0.66 – 1	% of Area Flooded > Minimum Flood Depth = Input Flood Volume / (Total Area * Minimum Flood Depth)	Default minimum flood depth is 0.5 m. Total area is the area of the SPR element.

5.3.4 Portsmouth Model: Evaluation and Analyses of Flood Extents

The Portsmouth SPR network model is analysed here specifically in terms of its performance in predicting flood extents. Due to actual flood data being unavailable for validating this study the model is compared against other model simulations. The network model is run for three input scenarios of varying degrees of severity – a) a hypothetical extreme 1 in 1000 year ESWL with no defences; b) a present-day 1 in 200 year ESWL along with extreme sea-level rise and high waves; and c) a present-day 1 in 200 year ESWL with no sea-level rise and no waves. Each of these runs is compared with results from previous flood maps and numerical models (Table 14). As for Teignmouth the network model results from the simulations are input into GIS to produce maps of flood extents. The results of all the three simulations are described here in terms of the key differences and similarities between the compared models. A more detailed summary of the differences in flood extents and the reasons for these is provided in Table 15 at the end of this section.

Table 14: Comparisons with Portsmouth Network Model

No.	Model	Input Scenario
1	EA Indicative Flood Map	ESWL of 3.28 m (1 in 1000 year ESWL), no waves, no structural defences
2	50 m resolution LISFLOOD model	ESWL of 3.72 m (1 in 200 year ESWL + 0.6 m SLR), 3 m wave height and structural defences included
3	10 m resolution LISFLOOD model	ESWL of 3.12 m (1 in 200 year ESWL), no waves and structural defences included

For the first comparison the network model is run for a 1 in 1000 year ESWL assuming no defences and compared against the EA Indicative Flood Map for the same conditions. The model is run for 500 samples and takes 4 minutes to run on a standard PC. Figure 43 shows the network model results for maximum flood extents along with the EA Indicative Flood Maps. The network model indicates all nodes that exhibit flooding above the minimum depth. The two maps show a 95% agreement in terms of total extent. In the areas where there is a difference in flood extents – Eastney-Milton in the south-east and Highbury in the north, this is a result of the difference between the storage-cell flood propagation method of the network model and the bath-tub method used in the EA IFM. This difference becomes apparent in these cases due to the influence of linear features: i.e. roads that act as flood channels in the case of Eastney-Milton transporting flood water from the source to these areas and a railway line that acts as a flood barrier in the case of Highbury in the mainland preventing ingress of flood water from the southern flood source. The Horsea Marina is not shown as flooded in the network model since this is already classified as a water-body. The network model picks up some additional flooding along the continental ferry port on the west coast. This area is represented with a single elevation value in the network model. The difference in flood extents may therefore be due to elevation differences within this area that are not captured in the network model.

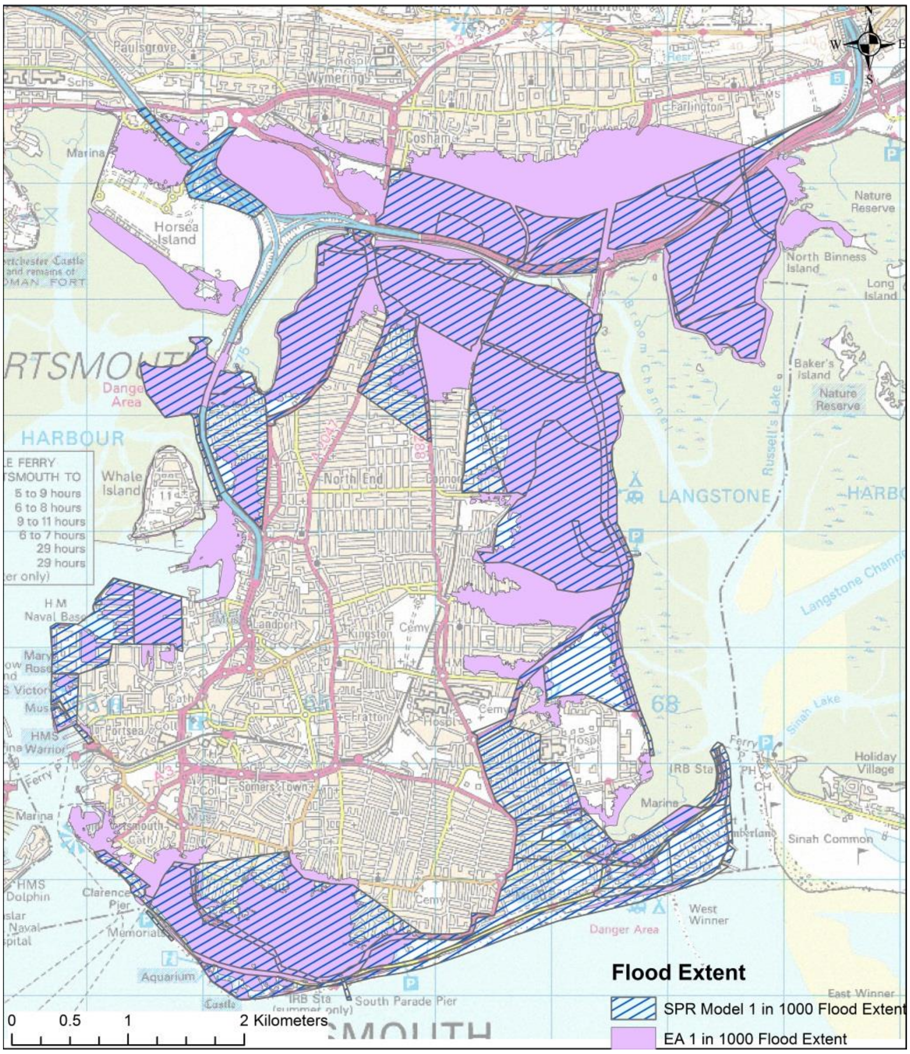


Figure 43: Portsmouth Flood Extent Comparisons: Network Model and EA IFMs

The network model is now compared with a 2D numerical model simulation Wadey (2013) who use a rapid 2D inundation model, LISFLOOD (Bates and De Roo, 2000) to approximate the dynamic 2D propagation of a flood wave in the floodplain. This comparison is carried out for the current state of the Portsmouth floodplain with the sea defences included for an extreme event corresponding to a present-day 1 in 200 year ESWL with 0.6 m sea-level rise and high waves.

The 2D inundation model henceforth referred to as the LISFLOOD model, uses a dynamic storage cell approach on a raster grid. Inundation at the shoreline (or seaward model boundary) provides the inputs to the LISFLOOD model which is then used to simulate the dynamic propagation of a given volume of water across the floodplain using continuity and momentum conservation equations. The volume of water entering the floodplain is limited by the duration of the event. Within the floodplain, variation in land-use is described using a Manning's roughness coefficient which serves as the calibration parameter for the model (see Bates and De Roo, 2000 and Bates et al., 2010) for detailed descriptions of the LISFLOOD numerical models and Wadey (2013) for a description of their use in Portsmouth). In comparison the network model described here uses a static flood spreading algorithm based on the law of conservation of volume (see Table 13). The total volume of water entering the floodplain is limited by the duration of the event and the floodplain itself is described as nodes of varying land-use each with a defined area, height and maximum and minimum flood depth. The network model is first compared with a 50 m resolution LISFLOOD model simulation. Figure 44 compares the flood extents from the two models.

The network model shows good overall agreement with the LISFLOOD model, predicting a total flood extent of 9 km^2 against a prediction of 9.58 km^2 by the LISFLOOD model. The network model does not show the spatial distribution of flood extents within individual nodes though it indicates the percentage of node area flooded. Network model flood extents agree with the LISFLOOD model in most areas – Farlington Marshes, the northern and eastern shorelines of Portsea Island and parts of Southsea. Additionally the network model also identifies the seawalls and roads that act as the flood pathways to these parts of the floodplain.

The main differences in flood extent are see in the north of the mainland and the Eastney/Milton area in the south-east. The difference in flood extents in these areas is again due to the influence of linear features acting as flood barriers or flood channels to these places – these are picked up in the network model but not in the 50 m resolution LISFLOOD model. Coastal areas in the south such as the Southsea Beach are picked up as flooded in the network model since it describes these inter-tidal areas as distinct nodes.

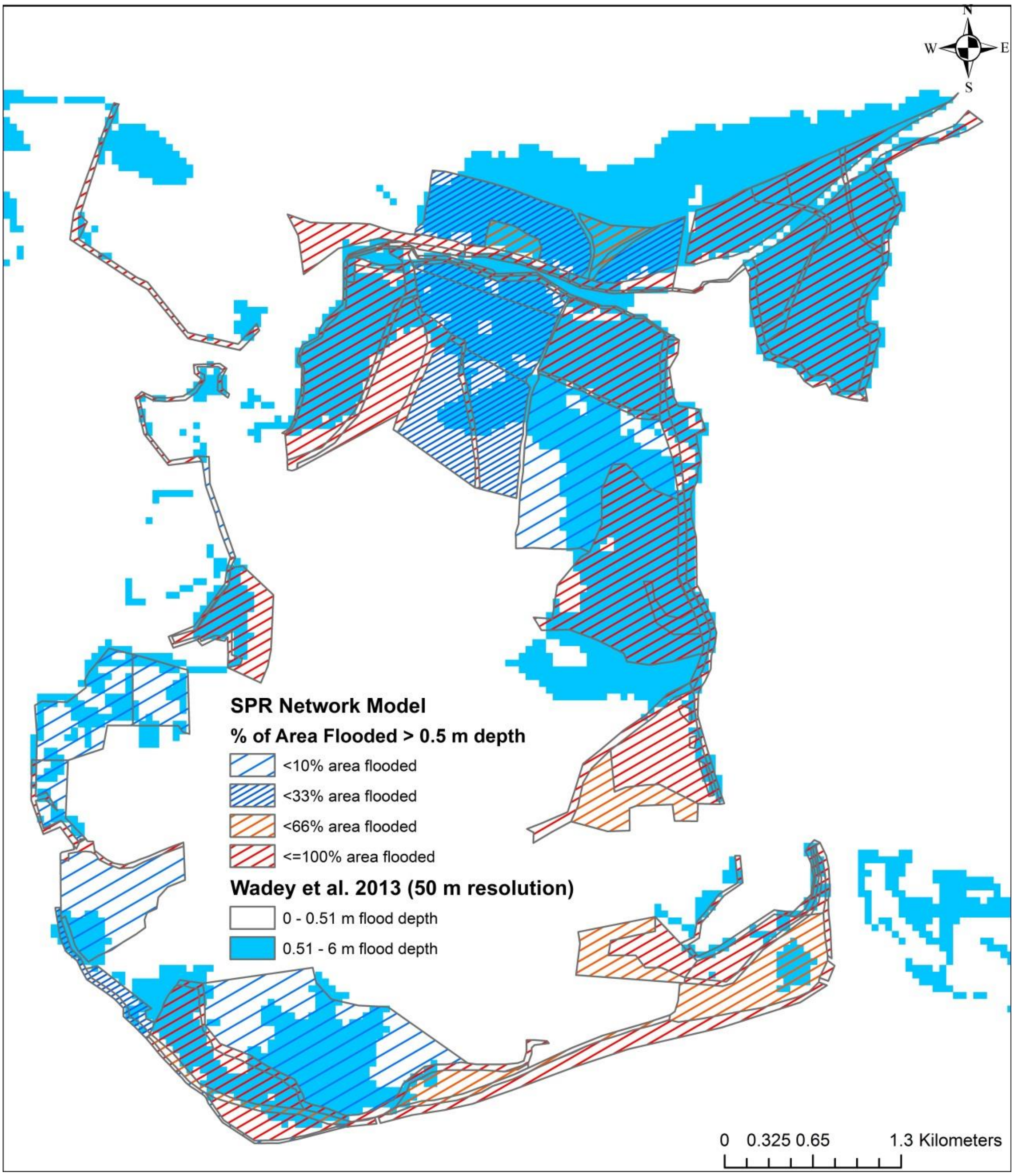


Figure 44: Portsmouth Flood Extent Comparisons: Network model and LISFLOOD Model (50 m)

Linear features within the floodplain are seen to have a considerable influence on flood extents in Portsmouth. Wadey (2013) use a higher resolution (10 m) model for Portsmouth to better capture these linear features. In Figure 45 results of the Bayesian network model are compared with those of a 10 m resolution LISFLOOD model for the existing state of the Portsmouth floodplain including sea defences driven by a low order event corresponding to a present-day 1 in 200 year ESWL of 3.12 m with no waves.

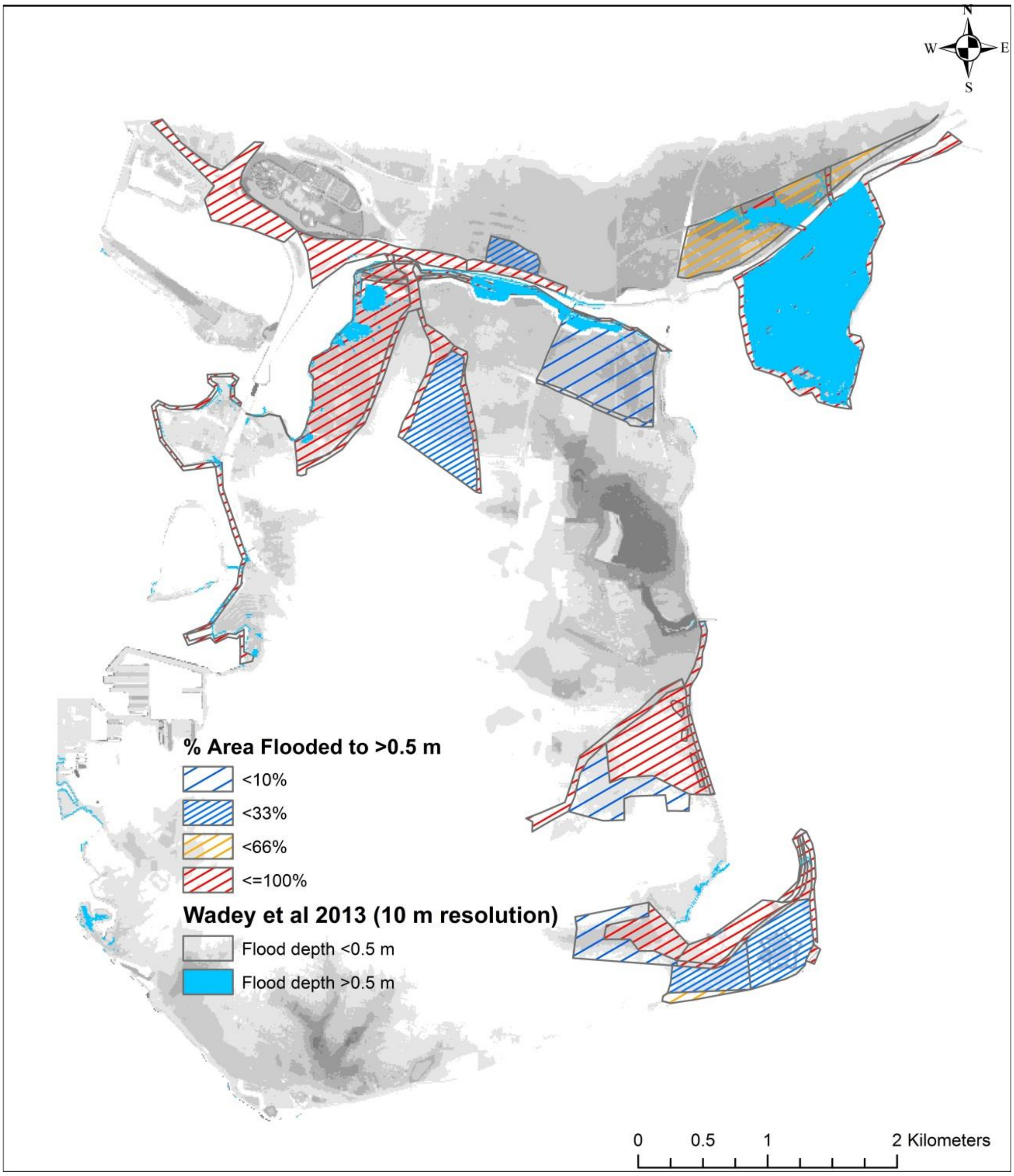


Figure 45: Portsmouth Flood Extent Comparisons: Network Model and LISFLOOD Model (50 m)

Spatially the network model compares well in some areas such as the Farlington marshes, the northern coastline of Portsea Island and parts of the western coast near Tipner and Stamshaw. In these areas the network model also identifies the pathways of flooding to these nodes. It also captures the flood protection offered by the mainland railway line and the old city walls at Hilsea Lines (see Section 5.3.1). There are a few areas in Eastney and the Continental Ferry Port where the 10 m LISFLOOD model picks up flooding that is not shown in the network model. However in general the network model over-predicts flood extents in comparison to the LISFLOOD model (5 km^2 for the SPR model versus 1.4 km^2 for the LISFLOOD model). This is mostly due to over-prediction of flood extents in and around the roads within the network model. The flooding of the roads is due to the comparatively coarse resolution of the seawall heights and water levels: a long section of seawall with a single crest height and a higher water level along the entire seawall length results in flooding of adjacent roads which in turn transport this flood volume further inland. Another effect of the low resolution of seawall heights and water levels is the over-prediction of flood extents in the parks directly behind the seawalls in north Portsea.

In summary network model simulations for the higher order flood events compare well with the EA Indicative flood maps and the 50 m LISFLOOD model. Additionally the model can identify the flood defence and linear features that form the flood pathways to the inland floodplain nodes. For the low order flood event the comparatively low resolution of the network model in terms of water levels and seawall heights results in an over-prediction of flood extents. As a result model flood extents do not compare as well with the 10 m LISFLOOD model. This is attributed mostly to the over-prediction of overtopping volumes at the seawalls which cause flooding at the adjoining roads that is then transported to the inland floodplain nodes. Table 15 summarises these comparisons of the Portsmouth network model with the models discussed here.

Table 15: Network Model Evaluation: Comparison with EA IFMs and LISFLOOD Models

No.	Compared Model	Model Type	Evaluation of Model Comparison		Differences in Flood Extents	Network Model Reasons for Flood Extent Differences
			Flood Extent Agreement	Spatial Agreement		
1	EA Indicative Flood Map (refer Figure 43)	Planar Water Level Model	95%, SPR model ~ EA map	Good	Eastney-Milton region in Portsea flooded in network model, not flooded in EA IFM; Regions north of mainland railway line not flooded in network model, flooded in EA IFM; Horsea Island Marina shown as flooded in EA IFM, not flooded in network model	Fort Cumberland road and Tangier road linking East Portsmouth flood sources to Eastney-Milton act as flood channels; Railway line remains dry and acts as flood barrier; Horsea Island Marina is not flooded since this is already classified as a water-body
2	50 m LISFLOOD model (refer Figure 44)	Rapid 2D Inundation Model	94%, SPR model > 2D model	Good	Eastney-Milton flooded in network model, not in LISFLOOD model; Southsea beaches flooded in network model, not in LISFLOOD model; Parts of West Portsea not flooded in network model, flooded in LISFLOOD model	Fort Cumberland and Tangier roads act as flood channels; Inter-tidal elements mapped explicitly in network model; Comparatively low resolution of seawall heights and water levels in network model results in differences in overtopping
3	10 m LISFLOOD model (refer Figure 45)	Rapid 2D Inundation Model	27%, SPR model >> 2D model	Poor	Most areas flooded in network model, not in LISFLOOD model (e.g. Eastney, north-central Portsea, Highbury college); Flood extents higher for parks in north Portsea	Low resolution of seawall heights and water levels causes over-prediction of overtopping, with roads acting as channels to inland nodes (e.g. Fort Cumberland Road, A2047(north), A27(mainland)

5.3.5 Portsmouth Model: Floodplain Response to Uncertain Inputs

All the comparisons discussed so far use deterministic water level inputs at the boundary of the floodplain. Flood probabilities are however often expressed in terms of an 'Annual Exceedance Probability' that is the probability of a flood event of given magnitude occurring, or being exceeded, in any year (Gouldby and Samuels, 2005). Analyses of the input loads and structural defence behaviour often use joint probability methods to describe the variations in these parameters (e.g. (Hawkes, 2005, Purvis et al., 2008, Chini and Stansby, 2012). Conventional numerical inundation models are usually deterministic and use multiple Monte-Carlo simulations to capture the uncertainties in model simulations (e.g. Pappenberger et al., 2006, Brown et al., 2007, Fewtrell et al., 2011, Hall et al., 2005b).

The Bayesian network approach is a computationally efficient way of studying the behaviour of floodplain nodes for multiple probabilistic inputs. The Portsmouth model factorises the probability distributions of overtopping at the seawalls by assuming a conditional dependency of this quantity on the input water levels which can themselves be expressed as probability distributions.

An example flood pathway analysis is conducted here to investigate the issues of uncertain inputs and floodplain node behaviour. The flood pathway comprises a flood source, the 'Horsea Lake Seawall', 'Alexandra Park' and an urban node 'Northern Parade' located along the north-west coastline of Portsea Island (see Figure 39). To analyse floodplain response to uncertain inputs two simulations are run – one for a current scenario with no sea-level rise and another for a scenario with an extreme sea-level rise of 0.6 m (corresponding to a five-hundred year time horizon by current estimates – see (Haigh et al., 2010a) but modelled here as a possible extreme scenario). Both scenarios use a steady-state wave height of 2.5 m corresponding to the current 1 in 50 year return period wave height.

The only difference in inputs between the two simulations is the extreme still water levels. The first simulation uses ESWLs expressed as an exponential distribution of existing annual exceedance probabilities of occurrence, with no SLR. These levels vary from a water level of 2.56 m with an AEP of 100% up to a maximum of 3.7 m with an AEP of 0.01% (McMillan et al., 2011). The second simulation uses as its input a joint distribution of the exponential ESWLs and a normally distributed SLR with a mean value of 0.6 m and a standard deviation of 0.09.

These probabilities influence the overtopping volumes at the seawall. The overtopping volume is calculated using the EurOToP equations for overtopping rates (see Equation 25) and a given duration. This is expressed as a function of overtopping rate normally distributed around a mean value to account for uncertainties in the empirical parameters (see Equation 25 and EurOtop Manual, 2007).

The probability distribution of overtopping volumes at the seawall is consequently reflected in the flood states of the floodplain nodes ‘Alexandra Park’, and ‘Northern Parade’. The final flooded extent at ‘Northern Parade’ is the result of the probability distributions of the upstream nodes and is calculated using the methodology outlined in Section 4.8. Figure 46 shows the state of the example flood pathway for the no-SLR scenario. Figure 47 plots the flood state probabilities of the nodes in this flood pathway for both simulations.

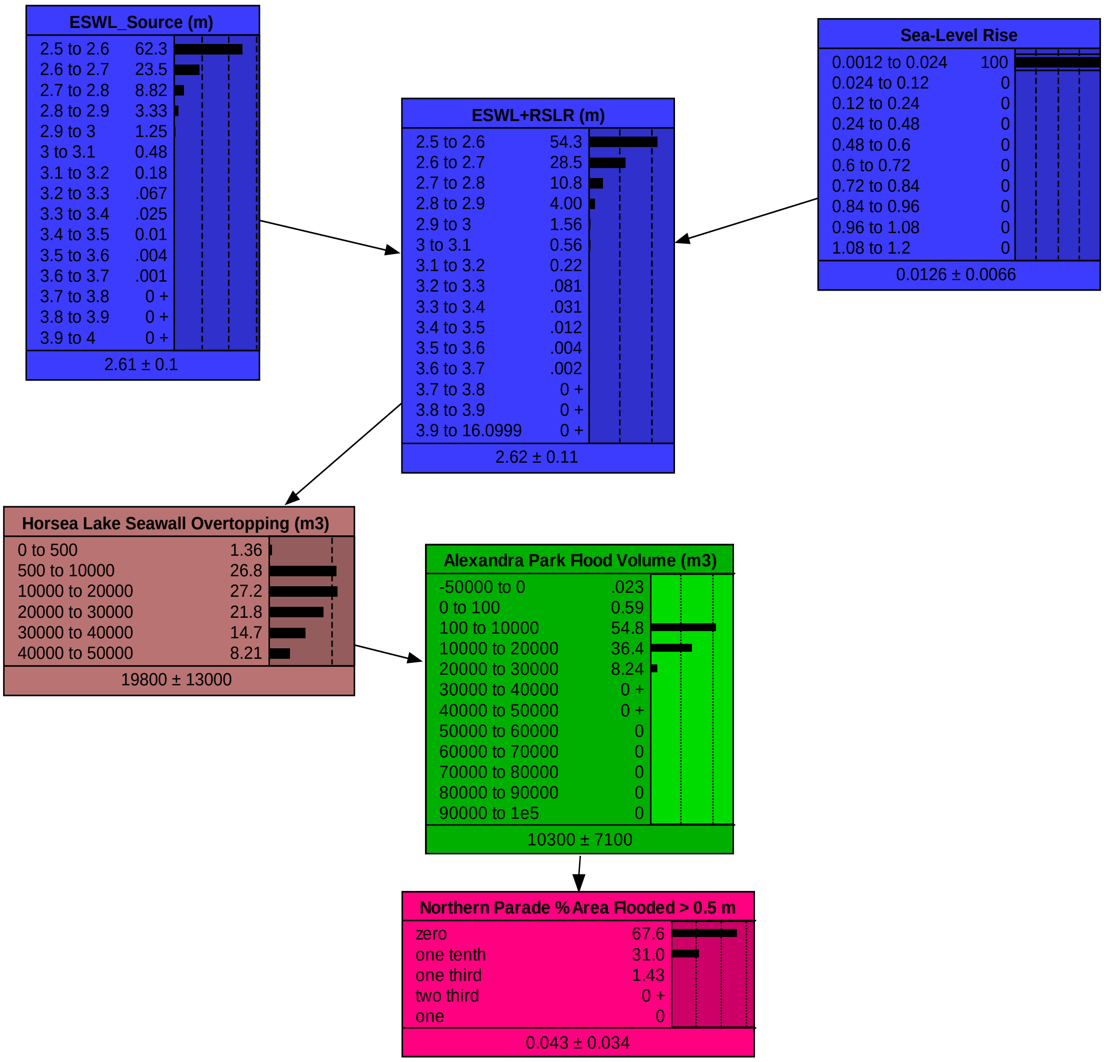


Figure 46: Example Portsmouth flood pathway with probabilistic ESWL inputs (no SLR scenario)

The node flood states for the no-SLR scenario in Figure 47 (top) describe an exponential ESWL with a mean of 2.6 m and a sea-level rise fixed at 0 m. The SLR scenario shown in Figure 47 (bottom) describes an exponential ESWL and a normally distributed SLR, resulting in in a joint normal distribution of the two values. The higher ESWL values for the SLR scenario cause a shift in the state probabilities of all downstream nodes towards the higher flood states – maximum flooding for the seawall, increased flooding in the park and greater flood extents at the urban node.

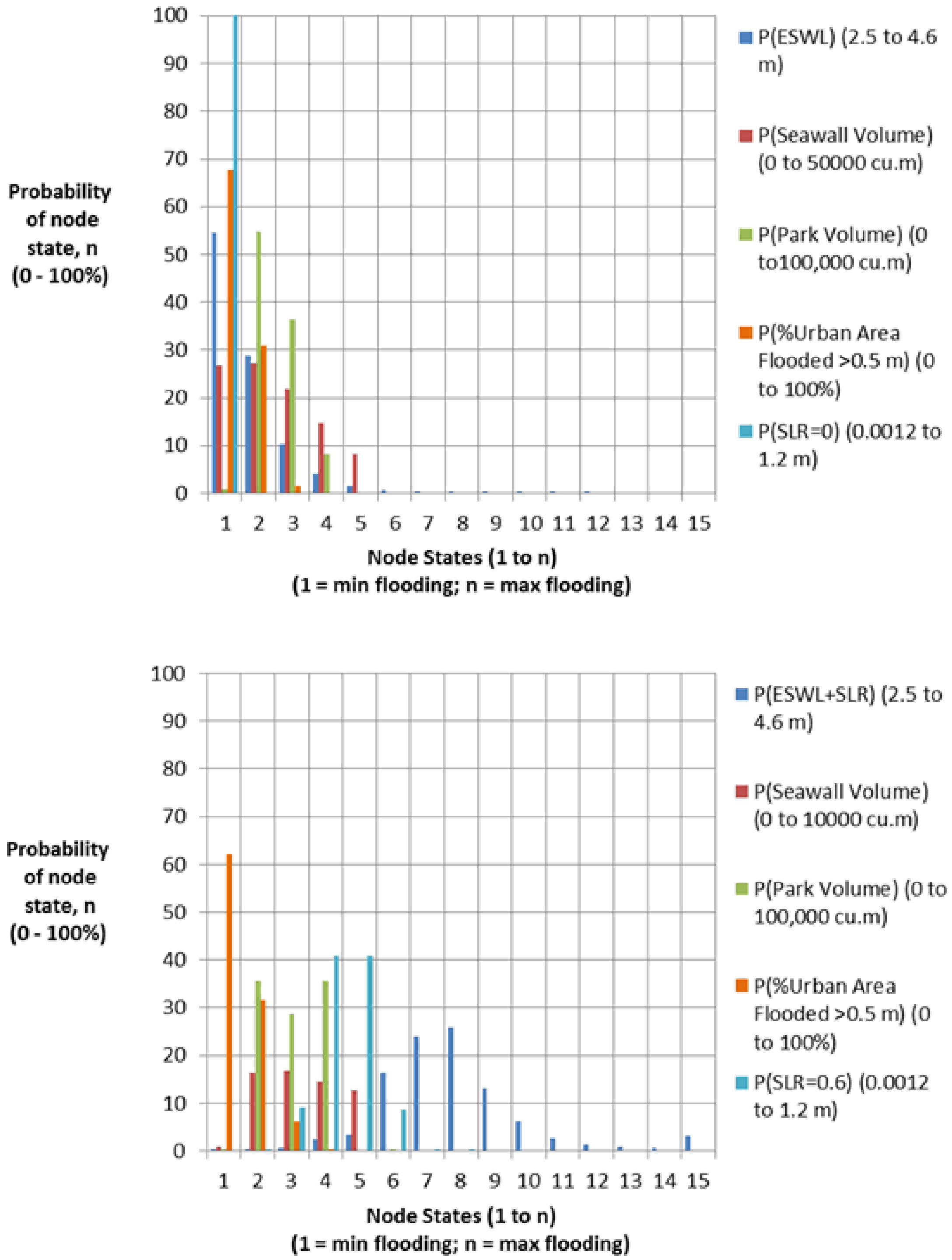


Figure 47: Node-states versus node-state probabilities for probabilistic ESWL and SLR inputs for example flood pathway in Figure 46 (top – No SLR; bottom – normally distributed SLR with a mean of 0.6 m and standard deviation of 0.09)

In addition to the increased flooding, the spread of values for the SLR scenario is also greater resulting in greater uncertainty in the flood state probabilities of the downstream nodes. The largest uncertainty is in the flood source node, which drives the uncertainties in the downstream nodes. Among the pathway nodes, the largest uncertainties are observed at the seawall. This is due to the propagation of uncertainties from the water level inputs as well as the inherent uncertainties in its overtopping formulations. These results are found to be true for the seawall and water level input nodes for similar flood pathways across the Portsmouth floodplain.

The flood pathway shown in Figure 47 is an isolated flood route when the underpass under the adjacent A27 is closed, as assumed in these simulations. In case of flooding of the A27 this can contribute to flooding at the park and urban nodes. Analyses of specific flood pathways should therefore be conducted keeping in mind any connections to the rest of the network model.

5.3.6 Portsmouth Model: Lessons Learnt and Model Uncertainties

The SPR network model has been built and applied to the Portsmouth floodplain and its performance with regard to flood extent predictions is evaluated by comparing it with available flood maps and 2D numerical models at different resolutions. The quasi-2D SPR and network model can be built from scratch in a week, and model simulations take under 5 minutes on a standard PC for 500 samples at each node. Network model simulations agree well in terms of flood extents with the EA Indicative Flood Maps and a 50 m resolution 2D LISFLOOD model. The simulations identify the flood propagation influence of linear features that are often too small to be captured in coarse-resolution models (Fewtrell et al., 2008) and therefore need to be manually digitised and included (Jonkman et al., 2008). In comparison with a 10 m resolution 2D LISFLOOD model the network model does not perform as well. Some influences of linear features are captured well by the network model though it continues to over-estimate flooding for much of the floodplain. This is due mainly to the relatively coarse resolution of the seawalls in the network model, and the uncertainties in the overtopping volume calculations. The network model illustrates the highly complex nature of the urban floodplain compartments in Portsmouth and the importance of linear features within the floodplain such as roads, railway lines and city walls as flood barriers in some instances and flood channels in others.

The network model facilitates quick analyses of inherent uncertainties associated with water level distributions and data and knowledge uncertainties associated with seawall overtopping volumes and flood propagation (see Section 5.2.62.5.4 for discussion on model uncertainties). The model is used to assess floodplain sensitivity to inherent uncertainties in the flood sources, expressed as probability distributions of the ESWL and SLR values. These are found to be the main drivers of uncertainty within the rest of the floodplain.

Among the flood pathway nodes the largest uncertainties are observed at the seawalls and are a combination of the inherent uncertainties at the sources and the knowledge uncertainties in the estimation of overtopping volumes. Joint probability methods in coastal flood risk assessments often treat knowledge uncertainties in structural defence behaviour with the use of fragility curves that relate the probability of failure of a structure to the incident loading (Buijs et al., 2005). The Bayesian network approach described here offers an equivalent way to model the probabilistic distribution of overtopping failure versus hydraulic loading at a particular seawall. The Bayesian network approach also makes it possible to independently specify the hydraulic loads and analyse the overtopping volume for each seawall section. Like in the Teignmouth application, model uncertainties for the Portsmouth model are reduced by using an adequate number of samples at each node (500 samples per node).

5.4 Bayesian Network Model: Discussions

5.4.1 Network Model Application

The Teignmouth and Portsmouth SPR network models have demonstrated their usefulness as a rapid and flexible scoping tool for local-scale floodplains. The Teignmouth application of the network model is characterised by relatively less quality and amount of data and correspondingly simplistic flood propagation representations, to provide an overview of the key coastal pathways, and the areas where which further data-gathering and research is needed. The Portsmouth application uses detailed information on the flood defences and floodplain from an existing case-study to provide a relatively higher resolution network description of the coastal floodplain, identifying key linear features within the urban floodplain that influence flood propagation. An analysis of uncertainties in the Portsmouth model identifies the flood sources and seawalls as the major drivers of uncertainty in flood propagation across the system. One shortcoming of the application described here is that defence health is not included as a parameter determining structural behaviour. (e.g., Wadey et al., 2012, Buijs et al., 2005). The use of a defence health parameter will make the analysis of structural response more complete in these models. Another limitation of the network models is that they do not consider seawall failure by breaching in detail. Rather seawall breaching is indicated in absolute terms with a seawall height of ‘0’ representing a breach. Since the network models are intended only as a rapid scoping tool, this simplistic representation of a breach is considered sufficient for the purposes of this study.

5.4.2 Network Model Construction

Joint probability analyses and extreme value analyses of hydraulic input parameters in flood risk assessments may involve the consideration of ‘outliers’ or unexpected extreme values (e.g. Wahl et al., 2011). The Bayesian network approach on the other hand assumes that the value-boundaries of the analysis are known in advance. This means that some trial and error is necessary in model construction when defining the upper bounds of node state values for example the overtopping rates at the Teignmouth seawalls (see Table 8) which are capped at 110 l/s/m. Within these boundaries the model follows the rules of conventional probability analysis for the factorisation of the joint probability distributions. This approach of analysing the floodplain as operating within pre-defined boundaries is considered appropriate for the intended use of the conceptual model as a scoping tool to identify weak links and critical areas for further analyses. The network models do not substitute for conventional numerical inundation models – rather they are meant to inform these in their floodplain descriptions. Table 16 compares the SPR network models alongside the models they have been compared to in this chapter.

5.4.3 Modelling Approach

Bayesian networks generally use extensive datasets to build the probability tables of the network nodes and study their behaviour, in networks where the relationships between these nodes are not clear (Kelly et al., 2013). In the models in this thesis the equations that specify flood propagation relationships between the nodes use known empirical formulae and logical rule-bases as a substitute for actual data on flood volumes. This is especially useful in the analysis of floodplain inundation where data on flood propagation is usually hard to come by but the key variables and parameters that drive the inundation process have been extensively studied. Data availability issues are often related to the scale of the application, with less data usually associated with larger floodplain extents (e.g. Sayers et al., 2002b). However this may not always be the case. In this respect the floodplains described here present an interesting contrast: though both sites are local-scale floodplains of extents under 10 km^2 the larger Portsmouth floodplain has more and better data sources for its structural defences and floodplain elements than Teignmouth. The network model structure and process descriptions are different for the two sites due to differences in data availability and floodplain characteristics. However the methodology for model construction and application is generic and can be used in any coastal floodplain to build and apply a Bayesian network model.

5.4.4 Use of Quasi-2D SPR System Diagrams

The network models are derived from the quasi-2D SPR system diagrams. These diagrams are constructed by an iterative process of data and information gathering amongst experts and offer a systematic way to refine our understanding and description of the floodplain and reduce errors and uncertainties in the assumptions about the floodplain in subsequent numerical models. The quasi-2D SPRs are scalable models that allow recognition and mapping of influences that may lie outside the defined boundary of the system through the use of nested models. These models can themselves be nested within larger-scale conceptual frameworks of the coastal system. A disadvantage in this respect of the Bayesian network model applications is that these are restricted in this thesis to local-scale floodplains. The issue of scale in using the two models is discussed further in Chapter 1.

Table 16: SPR Network Models: Comparison with EA IFMs and LISFLOOD Models (✓ Possible; × Not Possible)

Model	**Resolution (m)**	**Extent (km^2)**	**Run-time (minutes on a standard 2.5 GHz PC)**	**Build-time**	**Flood Prediction**		**Pathway Analysis**	**Influence of Linear Floodplain Features**
					Flood Extents	**Flood Depths**		
EA Indicative Flood Map	N.A.	N.A.	N.A.	N.A.	✓	×	×	×
SPR Network Model for Teignmouth	50 – 200	1 - 2	<1 (500 samples per node)	2-3 days	✓	×	✓	×
SPR Network Model for Portsmouth	10 - 200	8 – 10	4 (500 samples per node)	<1 week	✓	×	✓	✓
LISFLOOD Model (coarse-scale)	50	8 – 10	<1	2 weeks	✓	✓	×	×
LISFLOOD Model (fine-scale)	10	8 – 10	58	3 weeks	✓	✓	×	✓

6 Discussion

6.1 Introduction

This thesis has so far applied and developed a qualitative model for systems descriptions of coastal floodplains and a Bayesian network model for quantitative appraisals of coastal floodplain states. This chapter discusses the combined use of the qualitative quasi-2D SPR and quantitative Bayesian network models as a rapid appraisal tool for integrated assessments of coastal floodplains as per Objective 5 in Section 1.3. The rapid appraisal tool here refers to the combined use of the quasi-2D SPR and the quantitative Bayesian network model for rapid integrated assessments of any coastal floodplain (Figure 48).

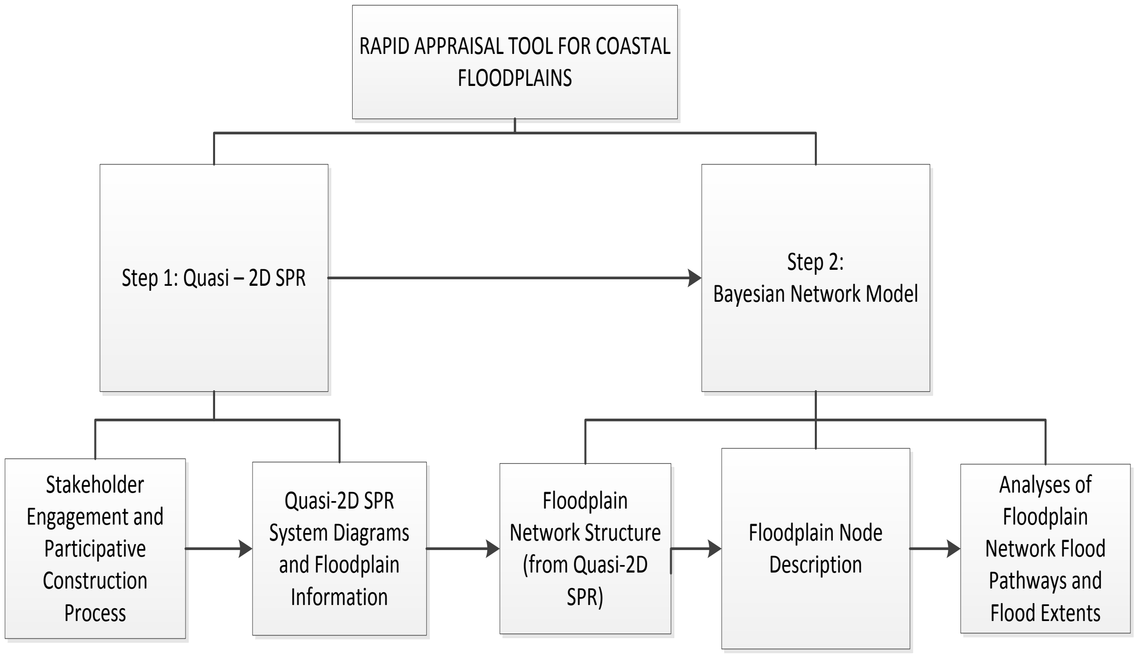


Figure 48: The Rapid Appraisal Tool for Coastal Floodplains

The conceptual foundation of the rapid appraisal tool is the quasi-2D SPR described in Chapter 3. Using a participatory process of stakeholder engagement and system diagram construction it provides a framework for integrating and structuring existing knowledge about the state of a coastal floodplain. These inform the construction and application of the Bayesian network model. The Bayesian network model developed and applied in Chapters 4 and 5 uses the floodplain descriptions from the quasi-2D SPR system diagrams and the information on the floodplain gathered in the process of SPR model construction to quantitatively assess flood propagation extents and pathways. Both models can be constructed from scratch for a coastal floodplain within a week and tested quantitative model run-times are of the order of a few minutes on a standard PC. The rapid appraisal tool is intended to fit into and inform the existing flood risk assessment and decision-making process. This discussion examines how this aim may be achieved by answering the following questions:

- ***Where***, and in which context, would these models be used as a rapid appraisal tool?
- ***When***, or at which stage of the flood risk assessment process, would this tool be used?
- ***How*** would this tool be constructed and executed?
- ***What*** are the expected outcomes of this tool?
- ***Why*** is this tool necessary, and how would it be useful to subsequent stages of a flood risk assessment?

6.2 *Where?* A Rapid Appraisal Tool for Integrated Flood Risk Studies

This section answers the first question raised in Section 6.1, i.e., in which context would a rapid appraisal tool be used. The rapid appraisal tool discussed here has been developed in two parts – the qualitative quasi-2D SPR and the quantitative Bayesian network model. The two models together are designed for use as a tool to inform and structure coastal flood risk studies. Coastal flood risk studies are increasingly treating coastal floodplains as networks of integrated, inter-connected elements.

The complexity and variety of numerical models used in these studies have necessitated the development of frameworks specifically for structuring the manner in which these models are coupled and integrated (e.g., Villatoro et al., 2014, Harvey et al., 2012). The application of these frameworks in different coastal floodplains shows that the choice and application of these models is site-specific and issue-specific and requires considerable prior understanding of the coastal floodplain system (Villatoro et al., 2014). The issues of selecting a suitable scale, level of analysis and ensuring consistency at the start of a flood risk study have been recognised as significant challenges to integrated flood risk management (e.g., Merz et al., 2007, Fekete et al., 2009, Fekete, 2012, Alfieri et al., 2013). These challenges become even more relevant with the adoption of non-traditional approaches to flood risk management such as spatial adaptation and land-use planning measures (e.g., Koks et al., 2013). In this context a robust conceptual model and tool that provide comprehensive systems understanding of the floodplain prior to application of detailed numerical models is needed.

6.3 *When?* Positioning the Rapid Appraisal Tool within a Flood Risk Study

This section answers question 2 in Section 6.1, namely, when the rapid appraisal tool would be used within a flood risk study. A typical flood risk study follows five steps as described in Figure 1 in Section 2.1. Chapter 2 uses the Source – Pathway – Receptor (SPR) model to describe the process of a typical flood risk assessment. Depending on its objectives and scope a variety of numerical models and methods can be employed at each stage of such an assessment. These choices of models and methods are informed by conceptual models and frameworks at the start of the study. Conceptual models are a means of answering a range of possible questions and issues posed by stakeholders including development of knowledge on flood risk, an overview of the relationship of flood risk management to other aspects of the region and an overview of available strategic options to address the identified issues (FLOODsite Consortium, 2007a). Conceptual models like the SPR are usually the first step of the flood risk assessment and are used to structure, inform and direct the rest of the study (e.g., Zanuttigh, 2011). The rapid appraisal tool is designed for the same purposes and as such will be applied at the start of the flood risk study to address the challenges discussed in Section 6.2 (Figure 49).

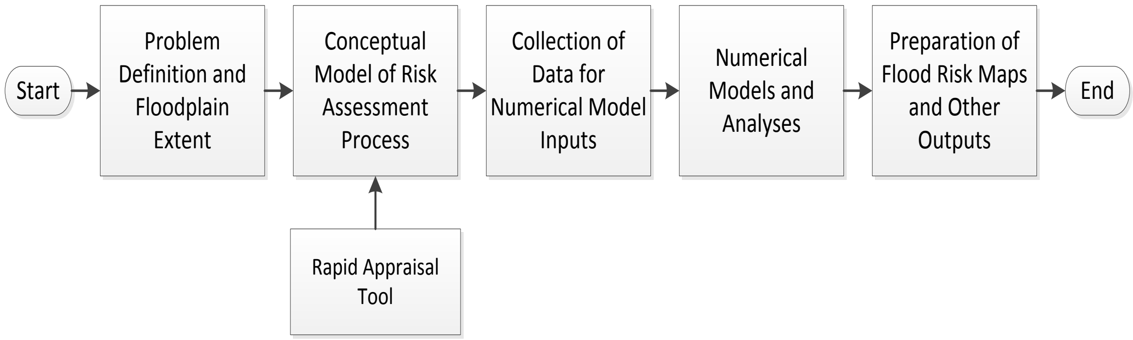


Figure 49: Positioning of Rapid Appraisal Tool within Flood Risk Study Process

The rapid appraisal tool is specifically intended for use in studies that assess flood propagation and risk for a coastal floodplain. Hitherto, conceptual models for flood risk studies as illustrated by the 1D SPR have been limited to describing the overall risk assessment approach of the study. These models do not fully describe the coastal floodplain that is being assessed – rather this description is achieved by the multiple numerical models employed in later stages of the study (e.g., de Vries et al., 2011, Oumeraci et al., 2012, Harrison et al., 2013). The tool developed here is unique in that it can offer a basic, rapid and comprehensive quantitative description of the coastal floodplain before the application of more detailed numerical models.

6.4 *How?* Applying the Rapid Appraisal Tool within a Flood Risk Study

This section answers question 3 in Section 6.1 namely, how the rapid appraisal tool would be applied within a flood risk study. The tool is built in two stages – the qualitative systems diagrams of the quasi-2D SPR, and the quantitative flood propagation descriptions of the Bayesian Network model. The quasi-2D SPR is built using a participative process of stakeholder engagement that collects, integrates and maps information about the state of the assessed coastal floodplain. Model construction takes about a week on average and results in a systems diagram of the floodplain classified using a land-use scheme that reflects the purpose of the study (for example see the Medoc case-study in Section 3.5.2). The quasi-2D SPR is flexible with regard to data requirements and can be built simply with a land-use map and low-resolution (>10 m) digital elevation data or even contour line maps. At this stage the tool can be used to identify areas of the floodplain that may require nested analysis. Nested quasi-2D SPRs and Bayesian network models can then be constructed to address specific issues at these sites.

The Bayesian network model can be built from the quasi-2D SPR in a few days and takes a few minutes to run on a standard PC. The model is equally flexible in terms of data requirements and can take a combination of quantitative and qualitative data inputs. Using data such as a 50 m resolution Digital Elevation Model, a land-use map, regional water level and wave climate data and information on the key parameters of coastal defence structures the quantitative model can be used to rapidly estimate flood extents and floodplain sensitivity to critical coastal and urban flood pathways.

Figure 50 shows an algorithm for application of the rapid appraisal tool to be applied at the conceptual stage of the flood risk study as discussed in Section 6.3. The process starts by constructing a large-scale quasi-2D SPR which informs the rest of the process including any down-scaling. The quantitative models are used to identify hot-spots and knowledge gaps at different scales. This knowledge in turn will inform the selection and use of more detailed numerical models in the latter stages of the flood risk study. In case a quantification of the quasi-2D SPR is not possible at a certain scale the analysis is down-scaled and a nested quasi-2D SPR and a network model are constructed. The network model being flexible in terms of data inputs quantification of the floodplain description should be possible to varying extents. In the rare case that no information is available for quantification such as in a floodplain where no data is currently available the information provided by the quasi-2D SPR is directly used to inform the next stages of the flood risk study. The tool describes the state of the coastal floodplain and as such may be nested within a larger framework such as the DPSIR framework as discussed in Section 2.4.

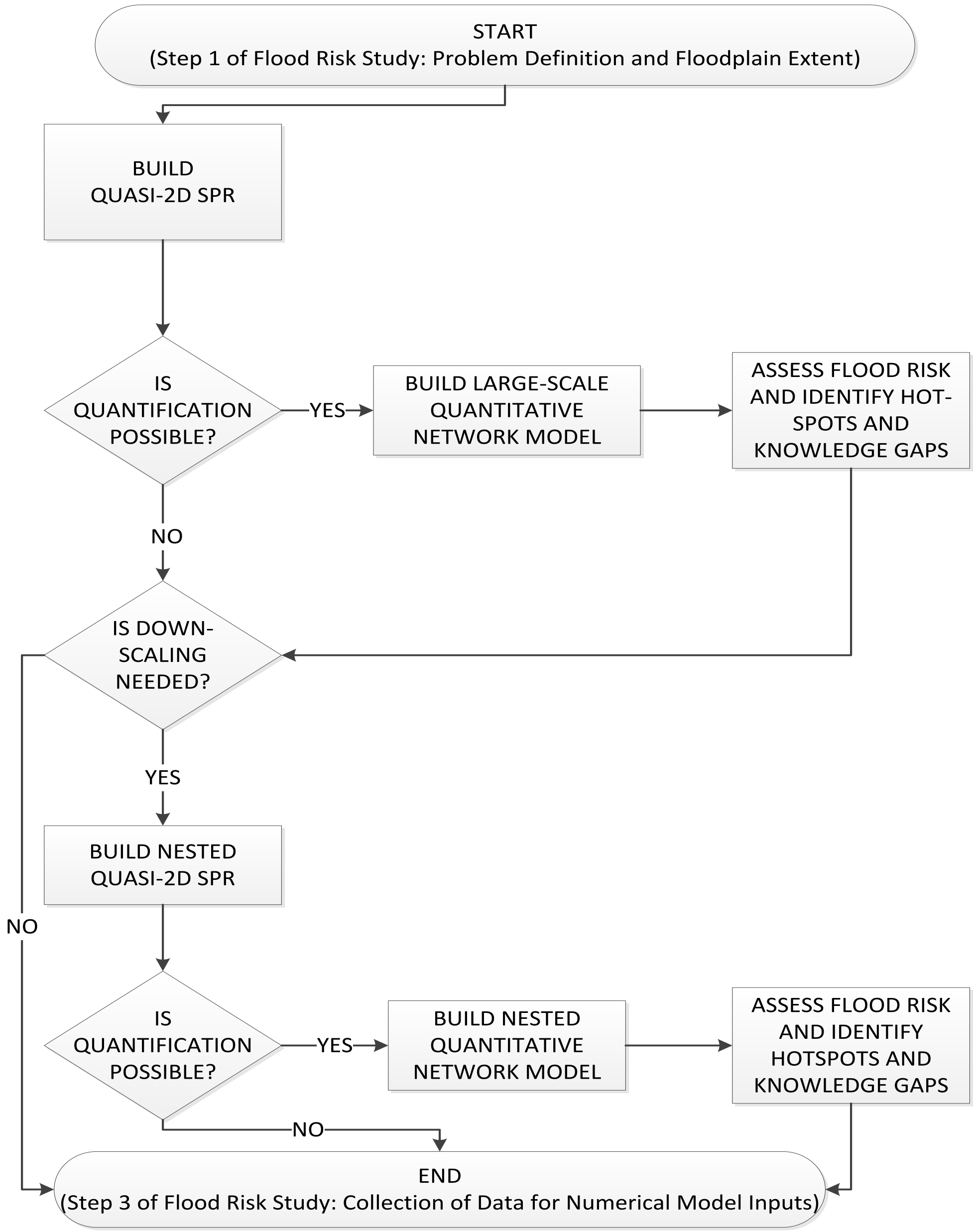


Figure 50: Algorithm for Multiple Cycles of SPR Conceptual Model Analyses

6.5 *What?* Outcomes of the Rapid Appraisal Tool

This section describes the outcomes of the rapid appraisal tool and the additional knowledge it will provide to the flood risk assessment process, in relation to question 4 in Section 6.1. Both stages of the tool provide outputs that can be used within the rest of the flood risk study. The advantages and outcomes of the quasi-2D SPR and the Bayesian network models have been discussed in detail in Section 0 and Section 5.4 respectively.

The overall outcome from using the rapid appraisal tool is an integrated and shared systems understanding of the assessed coastal floodplain that describes the physical floodplain characteristics and how these relate to the flood risk issues being investigated. There is increasing focus nowadays on stakeholder engagement (Priest et al., 2012) and participative approaches (Fuchs et al., 2013) within flood risk management studies. The quasi-2D SPR is a descriptive conceptual model of the coastal floodplain that encourages a participative mapping approach while providing an integrated systems understanding of the floodplain. This mapping exercise helps tailor the floodplain description to the issue being addressed and provides a strong foundation for the Bayesian network model which provides a quantitative understanding of the current state of the floodplain and its sensitivity and response to changes in the input conditions.

The key outcomes from the quasi-2D SPR are the comprehensive systems diagram of the coastal floodplain, the structuring of the scaling process of the analyses and the shared understanding of the system across multiple disciplines gained through the process of model construction. Quasi-2D SPR construction also allows the collection and integration of data on individual floodplain elements from disparate sources that can often be a challenge when assessing flood risk in previously unstudied floodplains (e.g., Danhelka et al., (2012); also see the Hel Peninsula case-study in Section 3.5.1). For instance the quasi-2D SPR for Portsmouth uses information from an extensive case-study by Wadey (2013) to describe the floodplain system. The system description and information gathered from the quasi-2D SPR form the foundation for the quantitative network model.

The second stage of the rapid appraisal tool – the network model, uses the quasi-2D SPR flood network and quantifies the influence of each pathway on flood propagation within the floodplain system. The Bayesian network model's key outputs are rapid initial estimates of flood extents across different flood events, quantification of the sensitivity of existing flood pathways into the inland floodplain, identification of new flood pathways that could emerge as a result of changing input conditions and in cases where sufficient data is available a quantification of the sensitivity of these flood pathways to uncertainties in the flood source inputs and flood pathway characterisations. The Bayesian network model application to Teignmouth showed flood extent predictions comparable to the EA IFMs and additionally facilitated analyses of key existing and emergent flood pathways (see Section 5.2). Application at a higher resolution to Portsmouth resulted in flood extents comparable to a 50 m resolution 2D inundation model (see Section 5.3).

The Porstmouth network model (see Section 5.3) makes effective use of information in the quasi-2D SPR on the role of linear features that influence flood propagation. The numerical models within a flood risk study may take a range of inputs depending on the characteristics of the floodplain, the study and the model itself (see Section 2.4). Often these inputs are decided by information about floodplain elements that may not be easily included within detailed numerical models (e.g., Ordnance Survey, 2013, Pitt, 2008c). For instance linear features such as the old city walls in Hilsea, in the Portsmouth model (see Section 5.3.1) are often difficult to capture within low-resolution digital elevation models and need to be explicitly digitised. In the rapid appraisal tool these features are mapped in the quasi-2D SPR and quantified in the network model. Thus the tool offers a way to structure the inclusion and integration of these inputs such that floodplain elements that may be critical to flood propagation are not omitted.

6.6 *Why?* Utility of the Rapid Appraisal Tool

6.6.1 Use in Multiple-Scale Integrated Flood Risk Assessments

This section discusses why the rapid appraisal tool would be useful in a flood risk study and how such a study could apply the rapid appraisal tool to maximum effect in relation to question 5 in Section 6.1. A key challenge in structuring a flood risk study is the issue of scale. The chief utility of the rapid appraisal tool as identified from this work is in providing consistency and structure to coastal floodplain assessments at multiple scales. The concept of a scaled approach to flood risk assessments was first introduced by the RASP framework (see Section 2.4) almost a decade ago. Since then a number of coastal flood risk studies have focused on multiple-scale integrated assessments spanning large extents. These may be large and expensive undertakings involving experts and using models that span multiple disciplines (see Chapter 2 for a detailed review of the scale and extents of current flood risk studies). Until now conceptual models and frameworks for flood risk assessments such as the SPR model used in the RASP framework emphasise description of the risk assessment process and simplify description of the coastal floodplain. Models like the SPR are powerful and effective ways of describing and achieving consensus about the process of flood risk assessment. However the lack of a descriptive conceptual model can have disadvantages in assessments that span multiple scales. One likely effect of down-scaling an assessment is a change in the way the coastal floodplain is described. This is illustrated by the fundamentally different descriptions of the quasi-2D SPR system diagrams for the Gironde estuary and the nested Medoc region (see Section 3.5.2). In comparison a traditional SPR conceptual model would look the same at both scales despite any differences in subsequent numerical models, since the process of risk assessment remains the same at both scales.

The quasi-2D SPR is the first stage of the rapid appraisal tool. It combines the SPR concept of the risk assessment process with a descriptive systems approach to provide a conceptual foundation that can be used in the initial stages to captures differences in floodplain descriptions at different scales. The second stage of the rapid appraisal tool – the Bayesian network model allows rapid, quantitative appraisal of the floodplain system to provide initial insights into critical areas and knowledge gaps. The Bayesian network model also demonstrates the capability to capture and highlight the influence of features that may be missed within coarse-resolution 2D numerical models. Results from the Bayesian network model can be used to inform further down-scaling or up-scaling of numerical models. The rapid appraisal tool itself is tailored to describe the state of the coastal floodplain, and as such will be used within and alongside larger, comprehensive conceptual frameworks.

Flood risk studies often use a holistic conceptual framework like the DPSIR (e.g., Newton and Weichselgartner, 2013, Sayers et al., 2013, de Vries et al., 2011, Catenacci and Giupponi, 2013), to describe the various components analysed. Generally different techniques are employed for scaling analysis of each component within this framework. For instance the drivers and pressures of local-scale flood risk assessments when these consider the effects of climate change and sea-level rise are often derived by down-scaling larger (i.e. regional and global) climate-change models (e.g., Barsugli et al., 2013, Brands et al., 2012). On the other hand national and global impact and damage assessments may rely on aggregation of local-scale data on structural damage and societal vulnerability estimates or synthetic damage functions and approximations derived from local-scale analyses (e.g., André et al., 2013, Cammerer et al., 2013, Jongman et al., 2012a).

Hallegatte et al. (2011) stress the importance of climate change impact assessments at city scales and describe a conceptual framework for estimating the monetary value of these impacts to urban areas. These assessments can then be aggregated to provide global measures of the impacts of climate change (e.g., Hallegatte et al., 2013). Similarly global estimates of the effect of climate adaptation and mitigation measures may be based on an aggregation of local-scale effects (e.g., CLIMSAVE Consortium, 2011, Hinkel et al., 2013). These local-scale assessments of impacts and mitigation measures require local-scale assessments of coastal floodplain states. Multiple-scale assessments of coastal floodplains can therefore be conceptualised within the DPSIR framework as being composed of parallel scales of analysis, with the outcomes from one scale driving the assessments at the other. At both scales physical drivers and pressures affect the state of the floodplain, with certain impacts and consequences which are used to provide a measure of the flood risk to the floodplain. This cross-scale relationship is shown in Figure 51. Different methods are used for the description of the drivers, pressure, impacts and responses at these scales. However there are to date no conceptual models for describing the state of the floodplain at multiple scales. The rapid appraisal tool in this thesis offers the first descriptive conceptual model for comprehensive integrated systems descriptions of the states of a coastal floodplain at multiple scales.

The quasi-2D SPRs provide qualitative system descriptions that can be used to identify locations that require down-scaling. The Bayesian network models provide quantitative descriptions of the coastal floodplain, as a system of multiple flood pathways whose state is affected by external forcing. The outputs from the network model can be used to inform further detailed numerical models that describe the state of the coastal floodplain or if applied within a larger scoping study they can be used directly in flood risk costs and impact analyses.

When applied as a scoping tool to inform numerical floodplain state models the rapid appraisal tool will be used in conjunction with existing methodological frameworks for numerical analyses. The RASP methodological framework and the frameworks introduced by Villatoro et al. (2013), Harvey et al. (2009) and Harvey et al. (2012) describe increasingly sophisticated means of structuring numerical models used to analyse the pressures, states and impacts of floodplain flood risk. The integrated, quantitative floodplain descriptions by the rapid appraisal tool will inform the numerical models and methods applied within such frameworks.

6.6.2 Use in Data-Scarce Coastal Floodplains

The discussion of the application and utility of the rapid appraisal tool has so far focused on coastal floodplains in areas where data and resources are available for the use of further sophisticated numerical models. In such situations the rapid appraisal tool is a useful scoping tool at the start of a detailed, integrated flood risk assessment. In many floodplains however data-scarcity is a challenge when assessing flood risk. The lack of data may be due to a combination of several reasons and is particularly the case in floodplains that have not been assessed previously to great detail (e.g. the Teignmouth floodplain – see Section 5.2), or where natural floodplain extents are large (e.g. the Gironde estuary – see Section 3.5.2) or where flood risk management is the responsibility of multiple authorities (e.g. the Hel Peninsula – see Section 3.5.1).

In such situations especially where the inclusion of stakeholders in flood risk and coastal zone management is necessary (e.g. The Hindu, 2013) a participatory process of mapping the coastal floodplain and describing the relationships between different floodplain elements will be a useful tool. While the use of a simplified tool will not provide much information on flood risk propagation the construction of the tool and the qualitative and quantitative knowledge gained in the process are useful ways to identify the goals and focus the aims of further flood risk and coastal zone assessments (Bart et al., 2012). The rapid appraisal tool's systems diagrams and network model allow easy description and communication of basic information about the coastal floodplain that can be built with available data, as a first-step assessment. Data and knowledge gaps identified by the quasi-2D SPR, and research needs identified by the Bayesian network model can be used to target further stake-holder engagement and data-gathering exercises.

6.6.3 Use in Evolving Coastal Floodplains

Coastal floodplains are dynamic systems with constantly evolving flood sources, flood pathways and floodplain receptors (e.g. (Kron, 2013). It is recognised in coastal flood risk studies that the nature of flood sources to a coastal floodplain are constantly changing and will continue to do so (e.g., Chini and Stansby, 2012, Haigh et al., 2010a). The need for upgrading flood defences to keep pace with sea-level rise and the conflicting need for prioritisation of the maintenance of these defences are also recognised in flood risk assessments (e.g., Jonkman et al., 2013, Dawson and Hall, 2006). Floodplain evolution in terms of land-use and population is often a major driver of flood risk (e.g., Evans et al., 2004, Koks et al., 2013).Many flood risk studies use scenario-based analysis techniques to assess the sensitivity of the coastal floodplain to multiple combinations of such changes (e.g., Oumeraci et al., 2012, Mokrech et al., 2012, Nicholls et al., 2008). The numerical models in these studies therefore need to evolve and change to reflect the changes in the floodplain that are being described. By contrast once they are applied at the start of the study the conceptual models in these studies do not change their description of the coastal floodplain. The systems diagram of the floodplain in the quasi-2D SPR and the quantitative descriptions in the Bayesian network model can be modified in a matter of minutes. The Bayesian network model can just as easily be updated to include new data or knowledge about specific floodplain elements. Therefore in addition to the initial floodplain state description at the start of a study the rapid appraisal tool can be used throughout the study to describe the coastal floodplain as a continually evolving system thereby accurately reflecting any observed changes in floodplain state or any new knowledge gained about floodplain elements during the research process.

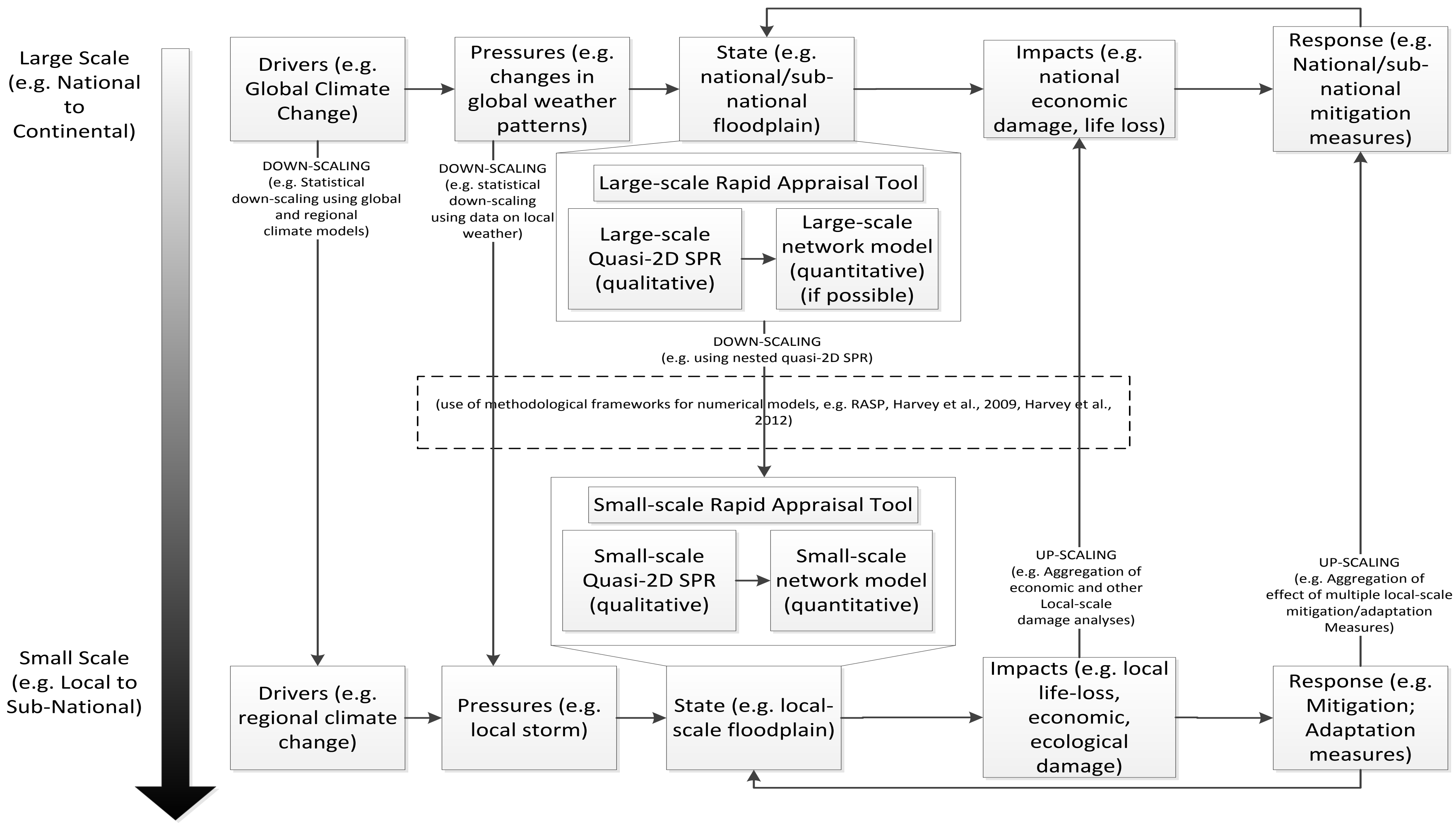


Figure 51: Using the Rapid Appraisal Tool for Down-scaling Floodplain State Descriptions within the DPSIR Framework

6.7 Rapid Appraisal Tool: Approach and Model Limitations

6.7.1 Quasi-2D SPR Modelling Approach

The quasi-2D SPR model has been developed as an integrative and descriptive model of the coastal floodplain that describes topological relationships between elements that may belong to different disciplines and operate at different scales. Based on scalable frameworks for flood risk estimation such as RASP and systems models of coastal processes such as the Coastal Geomorphology study the quasi-2D SPR builds systems diagrams for the entire coastal floodplain. Quasi-2D SPR construction is a participative process and is intended to include all stakeholders in the floodplain. The methodology for construction has been kept simple to allow flexibility in describing each floodplain as per the requirements of its study.

The resultant floodplain description is a subjective one that reflects a) the understanding of the stakeholders – of the floodplain, and of the issues being investigated; and b) the willingness, effort and time invested by the stakeholders in model construction. Participative qualitative models where stakeholder consensus is required are generally achieved using formal processes of stakeholder engagement and workshops (e.g., Cassel and Hinsberger, 2013, Haase, 2013, Foster et al., 2013). Quasi-2D SPR construction in this work was conducted through less formal methods of stakeholder engagement. In some cases the lack of time led to a construction process that was not fully inclusive resulting in a potentially incomplete description of the coastal floodplain. Being a spatially explicit description any omissions are more apparent than in a non-descriptive conceptual model. However a formalised methodology for ensuring a participative construction process for the quasi-2D SPR is highlighted as a necessary addition to this work.

Some of the quasi-2D SPRs in this work were automated in a GIS platform and made use of height information from local digital elevation models. Even when it was built manually the quasi-2D SPR often served as a framework for collecting and organising data on the floodplain. A formal organisation of a database management system in conjunction with the quasi-2D SPR systems diagrams (for example an automated database for adding specific, qualitative and/or quantitative information about each floodplain element) and a full automation of the construction process on a GIS software would greatly add to the utility of the model especially when mapping outcomes from the next stage of the work – the quantitative model onto existing flood risk maps.

6.7.2 Quasi-2D SPR Model Application

All the quasi-2D SPR model applications used a pre-defined maximum flood event to determine the maximum natural extent of the floodplain. This was done to ensure that administrative or other non-natural arbitrary boundaries did not delimit the floodplain. One limitation of the models described here was that this approach was not followed for all quasi-2D SPRs – for example the Hel Peninsula SPR used an arbitrary limitation of the floodplain based on a-priori assessments of the relative economic importance of different parts of the floodplain. However all other study sites used the full methodology to identify nested sites and down-scale the quasi-2D SPR models.

Another limitation of the models in this work is the resolution and detail to which heights of floodplain elements within the defined boundaries have been described. Given the diverse floodplains to which the model was applied the methodology purposefully did not specify a particular model resolution to allow site-specific descriptions of any non-local scale elements and also to allow for differences in the quantity and quality of available data. One disadvantage of this is that the built models may not provide a sufficiently adequate description of the floodplain for subsequent numerical analyses. The adequacy of floodplain description depends among other things on the resolution of floodplain elements and the land-use classification process. Future models could make more structured use contour lines corresponding to specific flood water levels to better describe floodplain elements in regard to flood propagation.

The outcome of the quasi-2D SPR is a spatially descriptive systems diagram that shows links between any two physically connected floodplain elements. A limitation of this to be addressed in further improvements to the model is that information on height and other differences that may decide the direction of a flood propagation link or an element influence link cannot be adequately represented. The flexibility in model construction meant that some system diagrams were modified to indicate these directions such as the Medoc SPR (see Section 3.5.2). However a more descriptive approach to the links between floodplain elements would mean that the quasi-2D SPR model can convey more information in itself.

As such basic system-wide knowledge about the mapped system can be extracted from the quasi-2D SPR diagrams – for instance the location of floodplain elements towards a particular flood source or the clustering of elements of a particular land-use type close to a flood source. However the model by itself does not provide any new quantitative information or description about the system. This was the chief motivation for the development of the quantitative, Bayesian network model.

6.7.3 Bayesian Network Model Modelling Approach

The quantification of the quasi-2D SPR is achieved using a Bayesian Network approach to develop a model for rapid scoping analyses of floodplain elements and flood propagation. Of the different systems modelling approaches available the Bayesian Network approach is chosen for its ability to use the quasi-2D SPR system diagrams for the description of the network, and qualitative and quantitative data inputs to provide rapid, probabilistic, spatial descriptions of flood pathways across the floodplain.

A limitation of the Bayesian network approach in regard to flood propagation assessments is that it requires a-priori definition of the sample space of values for all nodes. The factorisation of joint probabilities and the a-priori definition of value ranges mean that unlike a conventional joint probability analysis the Bayesian network model cannot model values that lie outside the defined/expected range. This means that there is some trial and error involved in defining the value range of the nodes to define the boundaries of the analysis. This is especially important in defining hydraulic inputs and uncertainties in structural defence behaviour due to changes that are driven by larger-scale processes. This limitation was addressed in the models described here by ensuring that the state descriptions of the floodplain nodes especially the input water levels and the seawall overtopping rates included all expected values.

Flood inundation studies are characterised by a wide variation in the probabilistic distributions and uncertainties in specific node properties – i.e., descriptions of the input water levels and the overtopping rates can be highly uncertain while the propagation of flood volumes within the inland floodplain is for the most part a deterministic process subject to fewer uncertainties. The influence of uncertainties in the flood source and pathway descriptions has been investigated in the Portsmouth case-study. A full and rigorous assessment of the effects of these uncertainties is however still necessary to understand their effects on model results.

6.7.4 Bayesian Network Model Application

The Bayesian network models have been applied to two local-scale floodplains in each case deriving information about the floodplain from the quasi-2D SPRs. A limitation of the model applications described in this thesis is that there has been no large-scale application of the quantitative model. For the Teignmouth application the network model was based on the Teignmouth quasi-2D SPR, which in turn was a nested SPR constructed from the Teign Estuary model. A useful extension to this work would be the quantification of the Teign Estuary Quasi-2D SPR. The key challenge in quantification at this scale is the availability of data. A Bayesian network model would therefore have to provide simplified quantitative descriptions of flood risk. For instance the model could focus on a simple quantification of the estimated impacts (i.e. costs) of flooding to each floodplain compartment and/or the costs of a disruption to the railway line to the region. Qualitative and semi-quantitative studies at larger scales have been shown before to be useful in identifying areas of the floodplain and issues that require attention and further analysis (e.g. Evans et al., 2004).

The structure of the Bayesian network model and the equations describing node relations are different for the two applications described in this thesis. These differences are due to the differences in floodplain characteristics and in the type and quality of available data at each site. Like for the quasi-2D SPR the choice of network and node description is left to the builder/user of the model to allow for flexibility in tailoring floodplain descriptions to the issues that are being analysed. Thus the Teignmouth model focuses on capturing the differences between water-level driven estuarine flooding, and overtopping driven coastal flooding; and the Portsmouth model focuses on a high-resolution description of the effect of the seawalls and linear urban features on flood propagation in the inland floodplain. The Portsmouth model uses higher resolutions in network and node descriptions to compare the limits of network model usefulness in terms of construction effort versus detail and accuracy of the results. The differences between the two models however make it difficult to compare model performance and results across the case-studies. The Bayesian network models described here are the first use of this approach to estimating flood extents and flood pathways. To provide in-depth understanding of the capabilities and limits of this approach in estimating flood extents and flood pathways further work on model behaviour for different resolutions is necessary.

Another limitation of the models described here is that they are not dynamic. Both Bayesian network models described in this thesis describe the floodplain as a snapshot in time. Dynamic coastal processes that may influence flooding such as coastal erosion are also currently represented as duration-dependent events. An extension to a dynamic model would allow more sophisticated assessments of floodplain response to dynamic coastal processes such as erosion. Additionally in the case of the Portsmouth model flood propagation within the floodplain is modelled using a static flood spreading algorithm with the input volume limited by the duration of the input flood event. Most 2D inundation models use a dynamic representation of the flood propagation process for more accurate and physically realistic predictions of flood characteristics. While dynamic Bayesian network models can be constructed for the networks described here this is a relatively roundabout process and basically involves the construction of multiple network models, each representing a snapshot of the floodplain at a particular time-step. For the network models' purpose as a rapid scoping tool, the existing capability in predicting approximate flood extents based on a finite volume is considered sufficient.

A related limitation of these model applications is that they only estimate flood extents as opposed to the flood depth duration and velocity estimates that may be provided by more sophisticated 2D numerical inundation models. The Portsmouth model described in Section 5.3 describes flood extents for a specified minimum flood depth at each node. Since they are intended only as a scoping tool to inform further numerical models the current capability of estimating flood extents for a minimum flood depth specified for each node is considered sufficient.

The sensitivity of model applications to the internal algorithms of the NETICA software needs to be investigated in detail. The NETICA modelling tool used for the applications in this thesis uses an algorithm to compile the Bayesian network. This involves the creation of a network structure based on a specific ordering of the network nodes. The NETICA model locates and uses a node-ordering that is computationally most efficient for the described network. The ordering of the nodes is meant primarily to increase the efficiency of the compilation process and does not affect node-state probabilities (Norsys Software Corp, 2010). The models described here have a compilation time of less than a minute. However a detailed sensitivity testing of model efficiency to this variable will be useful when using the model for batched analyses of multiple floodplain state scenarios or when applying the model at higher resolutions.

7 Conclusions

7.1 Introduction

This thesis has developed and applied a rapid appraisal tool for integrated assessments of coastal floodplains to inform flood risk studies. This research has been driven by the need for a tool that can be quickly built and applied at the start of a study to describe the coastal floodplain and identify the key hotspots and areas where further analyses is most needed. Due to rapidly increasing computational resources and better data availability in many countries where such studies are implemented there is currently a bias towards the immediate application of sophisticated and detailed numerical models (e.g. Bates, 2012, Harvey et al., 2012). By contrast there are few simple conceptual models and tools by which an initial systems understanding of the coastal floodplain can be gained prior to the use of more detailed numerical models. The main reason for this lack is that current conceptual models for coastal floodplains favour descriptions of the process of risk assessment and do not fully describe the coastal floodplain (see Chapter 2).

This research aims to bridge this gap by developing a rapid appraisal tool to conceptually describe the coastal floodplain as an integrated system of multiple, interacting elements. This tool comprises two parts – a qualitative quasi-2D SPR that generates a systems description of the coastal floodplain, and a quantitative Bayesian network model (see Chapter 1). The qualitative description is built through a participatory process involving stakeholders across multiple disciplines. The network model uses this system description to quantify the role of individual floodplain elements on flood propagation and thus identifies key flood pathways and flood probabilities. The combined use of these two models provides a rapid, strategic overview of the coastal floodplain as a system of interacting elements.

The rapid appraisal tool is unique in the following respects:

1. It is to date the only conceptual tool in coastal flood risk assessments that comprehensively describes the coastal floodplain in terms of all its elements, including the flood sources, inter-tidal floodplain elements, flood defences and inland floodplain elements.

2. The tool can integrate description of a variety of floodplain element types and associated processes, such as hydraulic boundary conditions, coastal morphology, structural defences and linear urban features.

3. The tool can provide descriptions of coastal floodplain states that are flexible in terms of data inputs and reflect the extent and availability of existing data and knowledge about the floodplain.

4. Quantitative descriptions of the floodplain are achieved based on a conceptual foundation that is built through a participative process of consensus-building among the experts and stakeholders involved in the flood risk study.

5. The conceptual foundation – the quasi-2D SPR is demonstrated as a scalable conceptual model that can be used to structure down-scaling processes when analysing large coastal floodplains.

6. The Bayesian network model is demonstrated as being able to quantify floodplain elements of varying resolution, enabling it to easily capture the influence of linear floodplain features that often need to be included manually within numerical model databases.

The following section discusses the achievements of the objectives of this thesis as stated in Section 1.3. Section 7.3 concludes by discussing some avenues for further research that have been highlighted in the process of this thesis.

7.2 Achievement of Research Objectives

The research aim of this thesis was to develop a rapid, comprehensive conceptual model and appraisal tool to help structure systems understanding of the floodplain within flood risk studies and inform decision-making for strategic flood risk management. Specifically, this comprised the development of a rapid scoping tool that provided a systems understanding and overview of the coastal floodplain to then inform and target further detailed numerical models. The objectives by which this aim was realised are listed in order along with a discussion of whether and to what extent each of these has been achieved in this research.

Objective 1: Develop a generic, scalable qualitative model built by a participative process for describing any coastal floodplain as a system of interacting human and natural elements.

This objective is achieved in the first part of Chapter 3 through the development of the quasi-2D SPR conceptual model. The quasi-2D SPR combines the popular Source – Pathway – Receptor (SPR) approach for describing the process of a risk assessment (Evans et al., 2004) with a descriptive systems diagrams approach. Applied at the initial stages of the flood risk study the quasi-2D SPR is intended to provide a comprehensive and integrated description of the coastal floodplain as a system of interacting elements each of which may influence flood propagation within the system. Quasi-2D SPR model development is structured to encourage and facilitate stakeholder engagement across diverse disciplines in an iterative, participative process of floodplain description using land-use maps and system diagrams.

Objective 2: Apply and test the qualitative model across a range of coastal floodplain systems and across multiple scales as a formalised and descriptive conceptual foundation for a quantitative assessment model.

The application of the quasi-2D SPR to 8 diverse European coastal floodplains is described in the second part of Chapter 3. In almost all sites model construction involved multiple participants and where possible these included experts and stakeholders from various fields and disciplines. The model can be built in a few days and provide a comprehensive systems description of any coastal floodplain.

These applications also demonstrated the scalability and flexibility of the model. In more than half the applications a large-scale quasi-2D SPR was constructed and used to very quickly identify locations in the floodplain that required more detailed descriptions and warranted a nested quasi-2D SPR model. Descriptions of a floodplain may change significantly when down-scaling an analysis. The quasi-2D SPR methodology and model were effective in capturing differences in floodplain descriptions at multiple scales. Feedback from site applications suggests that the model construction process is very useful in encouraging different local authorities and experts to talk to each other and exchange information and knowledge on the coastal floodplain. An advantage from this process was the integration and structuring of formal and informal knowledge about the coastal floodplain that was hitherto spread amongst disparate sources.

By collecting existing knowledge about the floodplain, achieving a shared consensus amongst stakeholders on current understanding of the floodplain and developing a systems diagram describing all floodplain elements, the quasi-2D SPR provides a robust foundation for further quantitative assessments of the floodplain system.

Objective 3: Develop a quantitative model of key floodplain elements and their behaviour. This will provide rapid integrated assessments of floodplain response to changes in input conditions and states of floodplain elements.

This objective is described in Chapter 4. The systems description in the quasi-2D SPR models is purely qualitative and needs to be quantified in order to be able to assess the role of different floodplain elements in flood risk propagation. Quantitative model approach and development are driven by a number of considerations. Given that a flood risk study by definition is a probabilistic assessment of flooding and given the uncertainties that often drive the sources, pathways and receptors of flood risk assessments the quantification of the floodplain descriptions would ideally be probabilistic. The model should also utilise the integrated systems descriptions and the formal and informal knowledge gathered by the quasi-2D SPR. At the same time the quantitative model to be useful as a conceptual model should be simple to build and to apply and computationally inexpensive. Based on a review of available modelling approaches for systems that fit these considerations a Bayesian network approach is chosen to develop the quantitative model.

The Bayesian network approach is chosen since it a) is a computationally inexpensive method of probabilistic analyses of systems; b) it can integrate multiple process-descriptions both formal and informal to provide an integrated, systems description of the coastal floodplain; and c) it can make direct use of the quasi-2D SPR system diagram as the structure of the floodplain network. Using this approach a construction methodology is developed by which a Bayesian network model can be constructed from an existing quasi-2D SPR.

Objective 4: Apply and test the quantitative model for rapid appraisals to two contrasting coastal floodplains. This will provide a quantitative description of the existing state of the floodplains and identify key flood pathways and flood probabilities.

The application and evaluation of the Bayesian network model are described in Chapter 5. The Bayesian network model is applied to two contrasting floodplains – a) Teignmouth which is a semi-urban floodplain with a coastline characterised by different types of flood sources and a single flood compartment; and b) Portsmouth which is a densely urbanised floodplain characterised by a single type of flood source, with several isolated flood compartments. In both applications the network model provides quantitative descriptions of floodplain system behaviour, existing and emergent flood pathways and flood propagation information that are used to produce maps of flood extents.

The Bayesian network model can be built for any coastal floodplain in under a week and takes a few minutes to run on a standard PC. Once the network model is compiled for a certain floodplain state description changes to individual network nodes are reflected almost instantaneously across the rest of the floodplain system making it possible to rapidly analyse scenarios of multiple floodplain system states (see Section 4.6 for description of model compiling).

Objective 5: Evaluate the combined use of the qualitative and quantitative models as a rapid appraisal tool for integrated assessments of coastal floodplains. This will provide a systems understanding of the floodplain and identify knowledge gaps. This information can then be used to target further data-gathering and/or numerical modelling exercises.

The use of the quasi-2D SPR and the Bayesian network model as a rapid appraisal tool is discussed in Chapter 1. Used together the two models offer a quick and efficient tool that can be readily applied to describe any coastal floodplain as an integrated system of multiple elements and as such is a useful starting point for flood risk assessments in coastal floodplains that have not been previously studied. The quasi-2D SPR system diagram is the first component of this tool and as such, can be applied independent of the Bayesian network model. However the quasi-2D SPR does not offer any quantitative information on the floodplain. The Bayesian network model offers a way to quantify the information about the floodplain gathered in the quasi-2D SPR. The Bayesian network model requires some form of network description of the floodplain state and is therefore always preceded by a quasi-2D SPR system diagram in this thesis. The network model is flexible in the description of the floodplain elements and the type of data inputs, which can be a mix of qualitative expert opinions and judgements or quantitative data on element characteristics.

In floodplains where previous assessments have been carried out and extensive data and computational resources are available the rapid appraisal tool can be applied at the start of a new flood risk study to target the use of detailed numerical models at multiple scales ensure that known critical floodplain elements are not missed during numerical model-building and communicate any underlying assumptions about floodplain state descriptions in these numerical models to stakeholders and end-users. A distinct advantage of the rapid appraisal tool is that the state description of the floodplain within the quasi-2D SPR and network models can be quickly modified (within minutes) to reflect changes to the floodplain state or any new knowledge about specific floodplain elements. Thus in addition to providing an initial description of floodplain system state the rapid appraisal tool can be used throughout the flood risk study for a continuously evolving description of the coastal floodplain that reflects the changing state of the floodplain and our existing knowledge about the floodplain.

7.3 Directions for Further Research

This section discusses some of the key areas for further research identified from the development and application of the quasi-2D SPR and Bayesian network models. This is done in four sections. Section 7.3.1 discusses further research on the participative and integrative aspects of flood risk and floodplain mapping pertaining to the use of the quasi-2D SPR. Section 7.3.2 discusses extending the work done on the Bayesian network model to a full risk assessment and decision-analysis tool utilising the capabilities of this approach. Section 7.3.3 discusses further improvements and work pertaining to the specific case-studies of Teignmouth and Portsmouth, and finally, Section 7.3.4 discusses further work to be done on the broader perspective of integrated coastal floodplain systems analyses, such as the extension to a vulnerability analysis.

7.3.1 Further Research: Quasi-2D SPR

Participative flood risk mapping and the inclusion of stakeholders in flood risk assessments are recognised as important aspects of an integrated flood risk assessment (e.g., Cassel and Hinsberger, 2013, Bianchizza et al., 2012, Priest et al., 2012). Local knowledge if collected at the start of a flood risk study can also prove useful in later stages of analysis (Ordnance Survey, 2013). The quasi-2D SPR models use a participatory stake-holder engagement approach to develop the floodplain system diagrams and gather information about the floodplain. The methodology for model construction however does not make use of formal participatory methodologies such as workshops or questionnaires; rather it relies on the local teams responsible for model construction to ensure effective stakeholder participation. An immediate research need in this context is the use of formal participative methodologies in subsequent applications of the quasi-2D SPR to ensure that all stake-holders have a say when building the initial description of the floodplain state.

Another output of the quasi-2D SPR from the model construction process was the collection and gathering of information about the coastal floodplain. Often during application of the quasi 2D SPR this information was found to be a mix of qualitative knowledge expert opinions and quantitative data pertinent to flood risk analysis (e.g. Narayan et al., 2013). A formal method and framework for organising and storing of this data that is linked to the construction methodology will greatly benefit future flood risk studies. This framework will enable the creation of a database specific to the coastal floodplain that describes existing knowledge about this floodplain which can be used by subsequent flood risk studies and numerical models. Use of an electronic database management system to organise this data will also enable users to update this database as and when new knowledge about the floodplain is obtained.

7.3.2 Further Research: Bayesian Network Model

The main advantages of the Bayesian network model developed in this thesis are the development of a systems understanding and the critical flood pathway analyses. The network models as applied here however use a limited representation of coastal morphological processes such as erosion. Detailed applications of this approach looking specifically at coastal erosion demonstrate the potential capability of the approach in describing these processes (e.g., Plant and Stockdon, 2012, Plant and Holland, 2011b). Better representations of coastal morphology within the existing floodplain network model will help improve our understanding of the influence of these elements on coastal flood risk. Another useful extension of the network model that will improve understanding of flood risk propagation is the inclusion of information on the structural health of flood defences. This will be particularly useful in rapid analysis of complex urban coastal floodplains where flood defences are often the only protection against coastal flooding.

The Bayesian network models allow efficient analysis of the probability distributions of overtopping at specific seawall sections. Currently these volumes drive flood propagation within the rest of the network. Numerical inundation models that use overtopping volumes as inputs generally use a deterministic value of inundation volume for each simulation and require multiple simulations for detailed analyses of the effects of uncertainties in these values (Horritt, 2006). A targeted Bayesian network model that describes only the flood sources, beach and seawall elements for a coastal floodplain can be used to provide detailed information on the probabilistic overtopping volume contributions from specific flood defence sections to subsequent numerical inundation models, reducing the number of variables they need to simulate and potentially increasing numerical model efficiency.

The network models are intended to provide rapid overviews of critical flood pathways and floodplain sensitivities. Currently these models provide information on changes to flood probabilities in response to floodplain state changes. These models can therefore be used to assess the response of the floodplain to changes in the state of a particular floodplain element such as a coastal defence. However Bayesian network models can also be built that specifically support decision-making. Such models have been used to inform decision-making in coastal floodplains vulnerable to sea-level rise (Catenacci and Giupponi, 2013). A key area for further research would be the integration of the current network models for flood probability propagation with Bayesian network models that use so-called 'decision networks' to assess the influence of particular flood risk management measures on the aggregated coastal floodplain. The linking of these two types of network models will also allow formal and complete uncertainty analyses of different flood risk management techniques.

A related avenue for further research would be the application of Bayesian network models for the coastal floodplain at larger scales. Both network models in this thesis have been applied to local-scale coastal floodplains. Depending on data and resource availability larger-scale applications of network models could focus on approximate and/or aggregated analyses of vulnerability and cost estimates of floodplain inundation (also see Section 6.7.4).

The outputs of the network models applied in this thesis can be readily transferred to GIS software for the production of flood extent maps. At present, this coupling is done manually. Automating this process can help improve model efficiency and run-time when communicating the final results.

7.3.3 Further Research: Teignmouth and Portsmouth Coastal Floodplains

The network model application in Teignmouth highlighted some critical knowledge gaps and research needs for integrated flood risk assessments in this floodplain. For instance the model application described here would benefit from a comprehensive survey of the estuarine and coastal defences to establish where these defences exist and their relevant parameters. The sensitivity of the floodplain to estuarine flooding and the recent construction of an estuarine flood defence scheme make this issue even more relevant to future flood risk assessments in this area. Another feature requiring further research that was highlighted by the network model as the main driver of flood propagation uncertainty was the future evolution of the coastal beaches that presently exist in front of the open coast seawall sections. A lack of data on these for the network model application meant that they were driven by a qualitative 'yes' or 'no' sediment input criterion. The condition of these beaches was however seen to be critical to the emergence of new flood pathways along the open coast with increasing sea-level rise and as such warrant more detailed investigation.

Network model application in Portsmouth had access to relatively better and higher resolution data on the flood sources, pathways and floodplain receptors. Due to its topography flooding in Portsmouth is known to be influenced by the urban drainage capacity (Wadey, 2013). More information on the influence of urban drainage is needed to be able to link this variable to flood propagation estimates – both in the Bayesian network model and within 2D numerical inundation models. Another uncertain variable that was modelled as a qualitative 'yes' or 'no' input in the Portsmouth network was the underpasses under a road in the north of Portsea island (see Section 5.3.2). Though its influence on flood propagation model was found to be limited in the Bayesian network model more information is needed on the characteristics and influence of this input. The Bayesian network model for Portsmouth also identified the seawalls as important drivers of flood pathway uncertainty, warranting more detailed investigation.

7.3.4 Further Research: Integrated Systems Analyses of Coastal Floodplains

The quasi-2D SPR and Bayesian network models are applied together in this thesis as a rapid appraisal tool to provide a systems understanding and an integrated assessment of flood propagation, pathways and extents within coastal floodplains. Of the two components of flood risk – probability and consequence (see Equation 2) these outputs are an estimation of the former i.e., probability. Linking this analysis to spatial calculations of the costs and damages due to floodplain inundation (e.g., Burzel et al., 2012), and vulnerability assessments (e.g., McInnes et al., 2013) will provide a complete conceptual model for integrated flood risk assessments that can be used to inform flood risk management policies. One area of flood risk management where improvement is required is in the communication between authorities responsible for managing different aspects of the system (Pitt, 2008b). In this context a linked quasi-2D SPR and/or network model describing the authorities responsible for managing the different floodplain elements and their interactions would be very useful in encouraging an integrated management of the floodplain system.

Damage from coastal flood events like storms and hurricanes almost always includes secondary damage to floodplain infrastructure like energy lines and transport links (Lickley et al., 2013). The quasi-2D SPRs for some floodplains such as the Hafencity and the Dendermonde floodplains include descriptions of infrastructure networks in their system diagrams (see Narayan et al., 2012a). The Bayesian network models in this thesis currently do not describe infrastructure networks in their floodplain state descriptions. A useful extension of this work would be to link these Bayesian network models to network models of infrastructure systems to enable integrated assessments of the resilience infrastructure networks to climate change (e.g., Hall et al., 2012). An advantage of the Bayesian network approach in this respect is the ability to assess the aggregated sensitivities of uncertain complex systems. Dynamic extensions to these Bayesian network models will allow more complete, detailed and sophisticated simulations of the evolution of flood risk within complex floodplains over long time-periods as well as of multiple scenarios of flood source and pathway evolution and floodplain development.

Another potentially valuable area of research would be extension of the rapid appraisal tool to fluvial and pluvial floodplains. This thesis and the discussions here have focused on a tool for coastal floodplains. One reason for this is that coastal floodplains are often characterised by diverse types of interacting elements – wave and water level flood sources, flood pathways such as coastal morphology, ecology, artificial structures and inland floodplain features the integration of which is a significant challenge. In comparison fluvial and pluvial flooding is driven by flood volume sources, artificial defences (in case of fluvial flooding) and inland floodplain features. For these floodplains the quasi-2D SPR and Bayesian network models will need to describe relevant floodplain elements such as the flood defences and urban conveyance features like drainage system networks, channels in agricultural fields and roads.

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Appendices

Appendix 1: Model-builder for Quasi-2D SPR

For applications of the quasi-2D SPR in floodplains with a large number of elements and links, where it would be time-consuming to manually build the system diagram manually, model construction was automated using the Model-Builder functionality in ArcGIS 10.1. Figure 52 below shows an example of the model-builder for the quasi-2D SPR for Portsmouth (see Section 5.3.2).

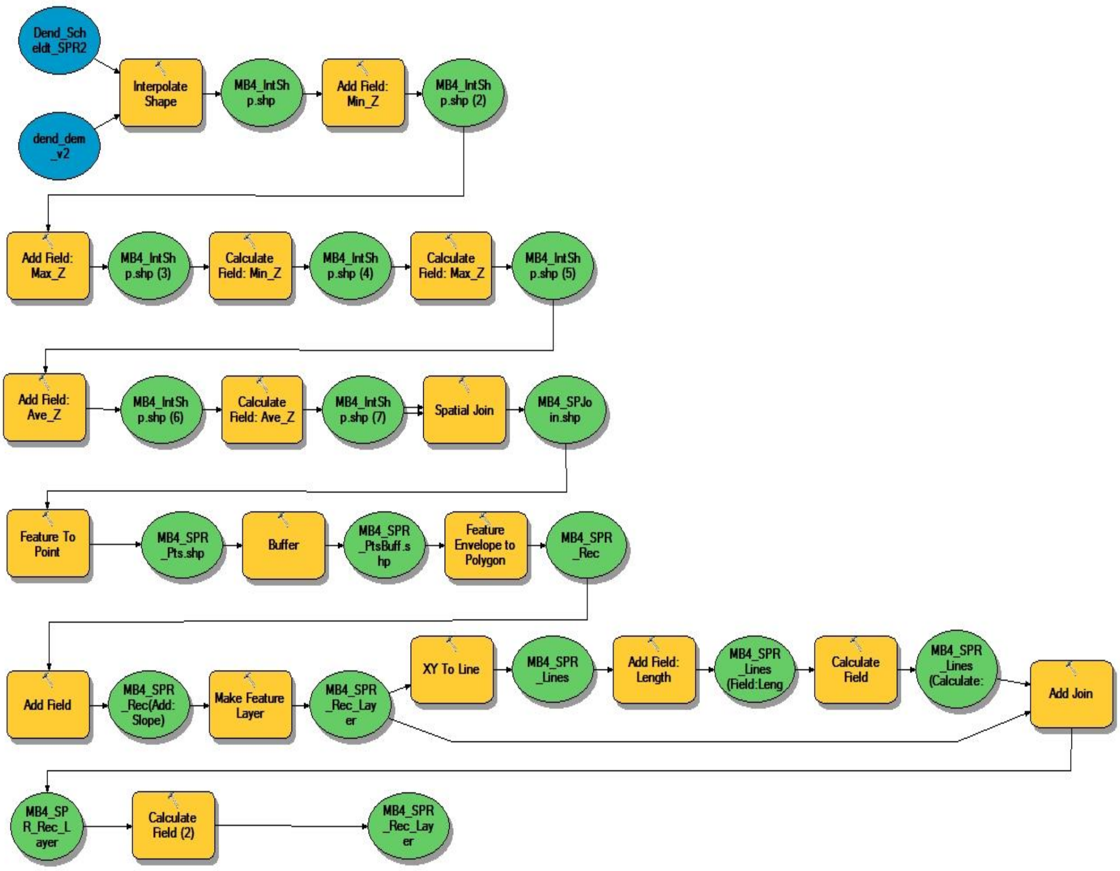

Figure 52: Example model-builder for quasi-2D SPR

Appendix 2: Bayesian Network Node Equations for Teignmouth

The construction of the Bayesian network models in this thesis used logical, empirical and probabilistic equations to describe the relationships between linked nodes. These equations were used to calculate the conditional probabilities of the states of the downstream node, based on the values of its linked upstream nodes (see Section 4.6). This section lists all the equations used to describe the node relationships for the Teignmouth network model (Section 5.2.2). The section also lists the state values for all input nodes for an example simulation. More details on specific equations can be found in (Norsys Software Corp, 2010) and (Norsys Software Corp, 2013).

Node Equations for Teignmouth

```
Beach_Rly (Waves_WL_2, Irribarren_BeachRly) =
(Ht_Beach_Rly <= Waves_WL_2) ? Waves_WL_2 :
Irribarren_BeachRly*Hs_WWL1

Beach_Rly2 (Waves_WL_2, SedimentInput) =
(SedimentInput==absent) ?
2.5:
12.5

Beach_east (Waves_WL_1, SedimentInput) =
(SedimentInput==absent)?2.5:12.5

p (Beach_inside1 | Ht_B_inside1, WaterLevels1) =
NoisyOrDist (Beach_inside1, 0, (Ht_B_inside1<=WaterLevels1), 1)

p (Beach_inside2 | WaterLevels2, Ht_B_inside2) =
NoisyOrDist (Beach_inside2, 0, (Ht_B_inside2<=WaterLevels2), 1)

p (Beach_mouth | WaterLevels2, Ht_B_mouth) =
NoisyOrDist (Beach_mouth, 0, (Ht_B_mouth<=WaterLevels2), 1)

p (Beach_west1 | WaterLevels1, Ht_B_W1) =
NoisyOrDist (Beach_west1, 0,
(Ht_B_W1<=WaterLevels1), 1)

P (Beach_west2 | WaterLevels1, Ht_B_W2) =
NoisyOrDist (Beach_west2, 0, (Ht_B_W2<=WaterLevels1), 1)

p(Harbour | WaterLevels1, Ht_Harbour) =
NoisyOrDist (Harbour, 0, (Ht_Harbour<=WaterLevels1), 1)

Irribarren_BeachRly () =
Slope_Beach_Rly / ((Hs_WWL1 * 2 * 3.14 /
(9.81*Tp_WWL1*Tp_WWL1)) ^ 0.5)

p (NearCoastal1 | Harbour, Beach_inside1, Ht_NearCoastal1) =
NoisyOrDist (NearCoastal1, 0,
(Harbour==1 && Ht_NearCoastal1 <= Ht_Max), Harbour,
```

```
(Beach_inside1==1 && Ht_NearCoastal1 <= Ht_Max), Beach_inside1)

p (NearCoastal2 | Beach_inside1, NearCoastal1, Ht_NearCoastal2) =
NoisyOrDist (NearCoastal2, 0,
(NearCoastal1==1 && Ht_NearCoastal2 <= Ht_Max), NearCoastal1,
(Beach_inside1==1 && Ht_NearCoastal2 <= Ht_Max ), Beach_inside1)

p (NearCoastal3 | NearCoastal5, Beach_mouth, Seawall_76,
Ht_NearCoastal3) =
NoisyOrDist (NearCoastal3, 0,
(NearCoastal5==1 && Ht_NearCoastal3 <= Ht_Max), NearCoastal5,
(Beach_mouth==1 && Ht_NearCoastal3 <= Ht_Max ), Beach_mouth,
(Seawall_76 < 0 && Ht_NearCoastal3 <= Rc_76), 1,
(Seawall_76 < 0 && Ht_NearCoastal3 <= Ht_Max),1,
(Seawall_76 > 50 && Ht_NearCoastal3 <= Rc_76), 1)

p (NearCoastal4 | Seawall_91, Seawall_72, NearCoastal3,
Ht_NearCoastal4) =
NoisyOrDist (NearCoastal4, 0,
(NearCoastal3==1 && (Ht_NearCoastal4 <= Ht_Max)), NearCoastal3,
(Seawall_72 < 0 && Ht_NearCoastal4 <= Rc_72), 1,
(Seawall_72 < 0 && Ht_NearCoastal4 <= Ht_Max),1,
(Seawall_72 > 50 && Ht_NearCoastal4 <= Rc_72),1,
(Seawall_91 < 0 && Ht_NearCoastal4 <= Rc_91), 1,
(Seawall_91 < 0 && Ht_NearCoastal4 <= Ht_Max),1,
(Seawall_91 > 50 && Ht_NearCoastal4 <=Rc_91),1)

p (NearCoastal5 | Beach_inside2, Beach_mouth, NearCoastal2,
Ht_NearCoastal5) =
NoisyOrDist (NearCoastal5, 0,
(NearCoastal2==1 && Ht_NearCoastal5 <= Ht_Max), NearCoastal2,
(Beach_inside2==1 && Ht_NearCoastal5 <= Ht_Max ), Beach_inside2,
(Beach_mouth==1 && Ht_NearCoastal5 <= Ht_Max ), Beach_mouth)

Railway_inside (Harbour, Railway_north, Railway_west, Ht_Rly_IN) =
(Ht_Rly_IN <= Ht_Max && Harbour == 1) ? -100 :
(Ht_Rly_IN <= Ht_Max&& Railway_west == 1) ? -100 :
((Ht_Rly_IN <= Ht_Max) && Railway_north < 0) ? -100 :
(Ht_Rly_IN <= Ht_Rly_n) ? Railway_north : 0

Railway_north (Seawall_Rly3, Seawall_Rly2,Seawall_Rly, Rly_Sign) =
(Ht_Rly_n > Rc3 && Ht_Rly_n > Rc2 && Ht_Rly_n > Rc_Seawall_Rly
&& Ht_Rly_n > Ht_Sign && Ht_Rly_n > Ht_Max) ? 0:
(Seawall_Rly3 < 0 && (Ht_Rly_n <= Ht_Max || Ht_Rly_n <=Rc3))?-100:
(Seawall_Rly2 < 0 && (Ht_Rly_n <= Ht_Max || Ht_Rly_n <=Rc2))?-100:
(Seawall_Rly < 0 && (Ht_Rly_n <= Ht_Max || Ht_Rly_n
<=Rc_Seawall_Rly))?-100:
(Rly_Sign < 0 && (Ht_Rly_n <=Ht_Max || Ht_Rly_n <=Ht_Sign))?-100:
(Seawall_Rly > 50 && Ht_Rly_n <=
Rc_Seawall_Rly)?Seawall_Rly*L_Seawall_Rly*StageDuration:
(Seawall_Rly2 > 50 && Ht_Rly_n <= Rc2)?Seawall_Rly2*L_2*StageDuration:
(Seawall_Rly3 > 50 && Ht_Rly_n <= Rc3)?Seawall_Rly3*L3*StageDuration:
(Rly_Sign > 50 && Ht_Rly_n <= Ht_Sign)?Rly_Sign*L_Sign*StageDuration:0

P (Railway_west | Harbour, Beach_west2, Beach_west1, Ht_Rly_W) =
NoisyOrDist (Railway_west, 0,
(Harbour==1 && Ht_Rly_W <= Ht_Max), Harbour,
(Beach_west2==1 && Ht_Rly_W <= Ht_Max ), Beach_west2,
(Beach_west1==1 && Ht_Rly_W <= Ht_Max), Beach_west1)

Rly_Sign (Waves_WL_3) =
```

```
(Ht_Sign<=Waves_WL_3) ? -10 :
clip(0, 100,
(1000*0.00028 * ((0.1 * (Ht_Sign - Waves_WL_3) /
Hs_WWL1)  ^ (-3.1)) *
(0.1 ^ 2) * ((9.81 * Waves_WL_3) ^ 0.5)))

P (SLR | ) = NormalDist(SLR,0.7,0.2)

Seawall_72 (Beach_east, Waves_WL_1) =
(Beach_east*Beach_Slope>Waves_WL_1 && Rc_72>Waves_WL_1) ? 0 :
(Beach_east*Beach_Slope<waves_wl_1&& rc_72<="Waves_WL_1)" ?="" -
10="" :0="" seawall_76="" (waves_wl_1)="(Rc_76">Waves_WL_1+Hs_WWL1) ?
0 :
clip(-10, 100,
((Rc_76<=Waves_WL_1) ? -10 :
1000*0.00028 * ((0.1 * (Rc_76 - Waves_WL_1) /
Hs_WWL1) ^ (-3.1)) *
(0.1 ^ 2) * ((9.81 * Waves_WL_1) ^ 0.5)))

Seawall_91 (Beach_east,Waves_WL_1) =
(Beach_east*Beach_Slope>Waves_WL_1 && Rc_91>Waves_WL_1) ? 0 :
(Beach_east*Beach_Slope<="Waves_WL_1)" ?="" -10="" :0=""
seawall_rly="" (beach_rly,=""
waves_wl_2)="(Rc_Seawall_Rly<=Waves_WL_2)" :=""
(ht_beach_rly="">Beach_Rly) ? 0:
clip(0, 100,
(1000*0.00028 * ((0.1 * (Rc_Seawall_Rly - Waves_WL_2) /
Hs_WWL1)  ^ (-3.1)) *
(0.1 ^ 2) * ((9.81 * Waves_WL_2) ^ 0.5)))

Seawall_Rly2 (Waves_WL_2) =
(Rc2<=Waves_WL_2) ? -10 :
clip(0, 100,
(1000*0.00028 * ((0.1 * (Rc2 - Waves_WL_2) /
Hs_WWL1)  ^ (-3.1)) *
(0.1 ^ 2) * ((9.81 * Waves_WL_2) ^ 0.5)))

Seawall_Rly3 (Beach_Rly2, Waves_WL_2) =
(Beach_Rly2*Beach_Slope>Waves_WL_2 && Rc3>Waves_WL_2) ? 0 :
(Beach_Rly2*Beach_Slope<="Waves_WL_2)" ?="" -10="" :0="" sourcewl=""
(ht_sourcewl,="" slr)="Ht_SourceWL+SLR" p="" (teignfp_a="" |=""
railway_inside,="" railway_north,=""
ht_teignfp_a)="NoisyOrDist(TeignFP_A," 0,="" ((ht_teignfp_a<="Ht_Max)"
&&="" railway_north="" <="Ht_Rly_n">200), 1,
(Ht_TeignFP_A<=Ht_Max && Railway_inside <-90), 1,
(Ht_TeignFP_A<=Ht_Max && Railway_inside >200), 1)

p (TeignFP_B | Ht_TeignFP_B, NearCoastal1, NearCoastal2, NearCoastal3,
NearCoastal4, NearCoastal5) =
NoisyOrDist(TeignFP_B, 0,
(Ht_TeignFP_B<=Ht_Max),NearCoastal5,
(Ht_TeignFP_B<=Ht_Max),NearCoastal4,
(Ht_TeignFP_B<=Ht_Max),NearCoastal3,
(Ht_TeignFP_B<=Ht_Max),NearCoastal2,
(Ht_TeignFP_B<=Ht_Max),NearCoastal1)

p (TeignFP_Composite | TeignFP_A, TeignFP_B) =
NoisyOrDist(TeignFP_Composite, 0,
(TeignFP_A==1), TeignFP_A,
(TeignFP_B==1),TeignFP_B)
```

```
TeignmouthFP_west (Railway_west, Ht_Teign_W) =
(Ht_Teign_W<=Ht_Max&& Railway_west == 1) ? 1 : 0

WaterLevels1 (SourceWL) =
SourceWL

WaterLevels2(SourceWL) =
SourceWL

Waves_WL_1 (SourceWL) =
SourceWL

Waves_WL_2 (SourceWL) =
SourceWL

Waves_WL_3 (SourceWL) =
SourceWL
```

Example Node Inputs for Teignmouth

Ht_NearCoastal5	3.2	m
Ht_Rly_IN	16	m
Ht_Rly_W	0.4	m
Ht_Rly_n	17	m
Ht_Sign	7	m
Ht_TeignFP_A	11.5	m
Ht_TeignFP_B	2.5	m
Ht_Teign_W	0 to 1.01	m
L3	100	m
L_2	100	m
L_72	150	m
L_76	200	m
L_91	100	m
L_Seawall_Rly	100	m
L_Sign	10	m
Max ESWL	3.78	m
Rc2	3.15	m
Rc3	7.07	m
Rc_72	4.99	m
Rc_76	5	m
Rc_91	5.28	m
Rc_Seawall_Rly	5	m
SLR	0.5	m
Slope_Beach_Rly	0.2	

Steady-state Hs	2.5	m
Steady-state Tp	8	s
StormDuration	4	Hrs

Appendix 3: Bayesian Network Model Equations and Inputs for Portsmouth

This section lists the node equations used for the Portsmouth network model and the node inputs for an example simulation. Details on specific equations can be found in (Norsys Software Corp, 2010) and (Norsys Software Corp, 2013).

Node Equations for Portsmouth

```
p (A2030_3 | MiltonBeach, EasternRoad_A2030) =
NoisySumTableDist(A2030_3,0,
(MiltonBeach<10&&EasternRoad_A2030<10), 1, 1, 0,
(MiltonBeach>6000&&(A2030_3_Ht<miltonbeach_ht||a2030_3_ht<=swl_ht)),
1,1,clip(0,25000,miltonbeach),=""
((a2030_3_ht<="EasternRd_Ht||A2030_3_Ht<=SWL_Ht)&&EasternRoad_A2030">6
000),
1,1,EasternRoad_A2030/EasternRd_Nlinks
)


A2047 (A3_2) =
((A2047_Ht<=A3_2_Ht || A2047_Ht<=SWL_Ht)&&
A3_2>6000)?A3_2/A3_2_Nlinks:0

A27 (FarlingtonMarshes, Farl_Hilsea_Embankment) =
(((A27_Ht<=FM_Ht || A27_Ht<=SWL_Ht)&&
FarlingtonMarshes/FM_Nlinks>10000)?FarlingtonMarshes/FM_Nlinks:0)
+
(((A27_Ht<=FarlHilsEmbank_Ht || A27_Ht<=SWL_Ht)&&
Farl_Hilsea_Embankment>10000)?Farl_Hilsea_Embankment/FarlHils_Nlinks:0
)

A27_2 (HilseaNorthEmbankm, MaxSWL2, Underpass) =
clip(0,100000,
((A27_2_Ht<swl_ht)&&="" hilseanorthembankm="">6000)?
HilseaNorthEmbankm/HilsNEmbank_Nlinks:0)
+
((Underpass==open)?
5*0.6*sqrt(9.81*((abs(MaxSWL2-A27_2_Ht))^3))*1800:0)
)

A288 (A3_2, UrbanDrainageSystem) =
clip(0, 50000,
(((A288_Ht<=A3_2_Ht || A288_Ht<=SWL_Ht)&&
A3_2>6000)?A3_2/A3_2_Nlinks:0)
-
UrbanDrainageSystem/Drainage_Nlinks)

A288_2 (PembrokeGardens, A3_3) =
clip(0,50000,
(((A288_2_Ht<=Pembroke_Ht|| A288_2_Ht<=SWL_Ht)&&
PembrokeGardens/Pembroke_Nlinks>6000)?
PembrokeGardens/Pembroke_Nlinks:0)
+
(((A288_2_Ht<=A3_3_Ht|| A288_2_Ht<=SWL_Ht)&&
A3_3/A3_3_Nlinks>6000)?A3_3/A3_3_Nlinks:0)
```

```
)

P (A3_2 | AlexandraPark_Coll, A27_2) = NoisySumTableDist(A3_2,0,
(A3_2_Ht<=Alexandra_Ht&&AlexandraPark_Coll>6000), 1, 1,
AlexandraPark_Coll/Alexandra_Nlinks,
((A3_2_Ht<=A27_2_Ht||A3_2_Ht<=SWL_Ht)&&A27_2>6000), 1, 1,
A27_2/A27_2_Nlinks
)

A3_3 (GunwharfQuays, PembrokeGardens, ClarencePier) =
((A3_3_Ht<=GW_Quays_Ht&&GunwharfQuays>0.6)?
GunwharfQuays*470000:0)
+
(((A3_3_Ht<=Clarence_Pier_Ht||A3_3_Ht<=SWL_Ht)&&ClarencePier>6000)?
ClarencePier/ClarencePier_Nlinks:0)
+
((A3_3_Ht<=Pembroke_Ht&&PembrokeGardens>6000)?
PembrokeGardens/Pembroke_Nlinks:0)

A3_A2030_Roundabout (Farl_Hilsea_Embankment) =
((Rdbt_Ht<=FarlHilsEmbank_Ht || Rdbt_Ht<=SWL_Ht)&&
Farl_Hilsea_Embankment>10000)?
Farl_Hilsea_Embankment/FarlHils_Nlinks:0


P (AlexandraPark_Coll | HorseaLakesideRd, A27_2, Alexandra_StorVol) =
NoisySumTableDist (AlexandraPark_Coll, 0,
(HorseaLakesideRd<10&&A27_2<10), 1, 1, 0,
((Alexandra_Ht<=HorsLakeRd_Ht||Alexandra_Ht<=SWL_Ht)&&HorseaLakesideRd
>0), 1, 1, HorseaLakesideRd/HorsLakeRd_Nlinks,
((Alexandra_Ht<=A27_2_Ht||Alexandra_Ht<=SWL_Ht)&&A27_2>10000), 1, 1,
A27_2/A27_2_Nlinks,
true,1, 1, neg(Alexandra_StorVol)
)

p (AnchoragePark | HilseaNorthEmbankm, EasternRoad_A2030,
EastPMSWaterfront, Anchorage_StorVol) =
NoisySumTableDist(AnchoragePark,0,
(HilseaNorthEmbankm>0&&EasternRoad_A2030<10&&EastPMSWaterfront<10),1,1
,0,
((Anchorage_Ht<=HilsNEmbank_Ht||Anchorage_Ht<=SWL_Ht)&&HilseaNorthEmba
nkm>6000),
1,1,HilseaNorthEmbankm/HilsNEmbank_Nlinks,
((Anchorage_Ht<=EasternRd_Ht||Anchorage_Ht<=SWL_Ht)&&EasternRoad_A2030
>6000),
1,1,EasternRoad_A2030/EasternRd_Nlinks,
((Anchorage_Ht<=EastPMSWall_Ht||Anchorage_Ht<=SWL_Ht)&&EastPMSWaterfro
nt>6000),
1,1,EastPMSWaterfront/EastPMSWall_Nlinks,
true,1,1,neg(Anchorage_StorVol)
)

P (BransburyPark | EastneyInsideWall, FtCumberlandRd,
Bransbury_StorVol) =
NoisySumTableDist(BransburyPark,0,
(Bransbury_Ht<=EastneyWall_Ht&&EastneyInsideWall>6000), 1, 1,
EastneyInsideWall/EastneyWall_Nlinks,
(Bransbury_Ht<=CumberlandRd_Ht&&FtCumberlandRd>6000),1,1,FtCumberlandR
d/FtCumberRd_Nlinks,
true,1,1,neg(Bransbury_StorVol)
)
```

```
BurrfieldsRd (EasternRoad_A2030, UrbanDrainageSystem) =
clip(0,50000,
(((Burrfields_Ht<=SWL_Ht||Burrfields_Ht<=EasternRd_Ht)&&EasternRoad_A2
030>10000)?
EasternRoad_A2030/EasternRd_Nlinks:0)
-
UrbanDrainageSystem/Drainage_Nlinks)


CentralPMS_North (A2047, A288) =
clip(0,1,
(
(((Central_PMS_Ht<=A2047_Ht||Central_PMS_Ht<=SWL_Ht)&&
A2047/A2047_Nlinks>6000)?
A2047/A2047_Nlinks:0)
+
(((Central_PMS_Ht<=A288_Ht||Central_PMS_Ht<=SWL_Ht)&&
A288/A288_Nlinks>6000)?
A288/A288_Nlinks:0)
)/(332000*0.5))

p(ClarenceBeach | MaxSWL4) =
(ClarenceWall_Ht > MaxSWL4&&Hsig1<0.5) ?
NormalDist(ClarenceBeach,100,1):
(ClarenceWall_Ht > MaxSWL4&&Hsig1>0.5) ?
NormalDist(ClarenceBeach,
sqrt(9.81*Hsig1^3)*0.04/exp(2.6*(ClarenceWall_Ht-MaxSWL4)/Hsig1)
*200*7200/exp((ClarenceWall_Ht/(Hsig1*1.62*0.4))^2),
0.8*200*7200/exp((ClarenceWall_Ht/(Hsig1*1.62*0.4))^2)):

(ClarenceWall_Ht<="SWL_Ht)&&" clarencebeach=""
clarencebeach_nlinks="">10000?
ClarenceBeach/ClarenceBeach_Nlinks:0

ContlFerryPort (FerryPortWall) =
clip(0,1,
(((CF_Port_Ht<=FerryPortWall_Ht|| CF_Port_Ht<=SWL_Ht)
&&FerryPortWall>6000)?
FerryPortWall/(FerryPortWall_Nlinks*363200*0.5):0)+0.0)

Copnor (SalternsPark_Lake, TangierRd, BurrfieldsRd) =
clip(0,1,
(
(((Copnor_Ht<=SalternsLake_Ht||Copnor_Ht<=SWL_Ht)&&
SalternsPark_Lake>10000)?SalternsPark_Lake/SalternsLake_Nlinks:0)
+
(((Copnor_Ht<=TangierRd_Ht||Copnor_Ht<=SWL_Ht)&&
TangierRd>10000)?TangierRd/Tangier_Nlinks:0)
+
(((Copnor_Ht<=Burrfields_Ht||Copnor_Ht<=SWL_Ht)&&
BurrfieldsRd>10000)?BurrfieldsRd/Burrfields_Nlinks:0)
)/(342400*0.5))

Copnor_Hilsea_North (Rly_Line_Hilsea,
HilseaLines_Park, A27_2, A288) =
clip(0,1,
(
(((Copnor_Hils_N_Ht<=Rly_Hils_Ht ||
Copnor_Hils_N_Ht<=SWL_Ht)&&Rly_Line_Hilsea>6000)?
Rly_Line_Hilsea:0)
```

```
+
(((Copnor_Hils_N_Ht<=Hilsea_Lines_Ht|| Copnor_Hils_N_Ht<=SWL_Ht)&&
HilseaLines_Park/HilseaLines_Nlinks>6000)?
HilseaLines_Park/HilseaLines_Nlinks:0)
+
(((Copnor_Hils_N_Ht<=A27_2_Ht
||Copnor_Hils_N_Ht<=SWL_Ht)&&A27_2/A27_2_Nlinks>6000)?
A27_2/A27_2_Nlinks:0)
+
(((Copnor_Hils_N_Ht<=A288_Ht||
Copnor_Hils_N_Ht<=SWL_Ht)&&A288/A288_Nlinks>6000)?
A288/A288_Nlinks:0)
)/(585500*0.5))

CoshamDocks_Urban (M275_1) =
clip(0,1,
(
(((Cosham_Ht<=M275_1_Ht||Cosham_Ht<=SWL_Ht)&&
M275_1>10000) ? M275_1/M275_1_Nlinks:0)
+0.0)/(100000*0.5))

p(EastPMSWaterfront | MaxSWL5) =
(Hsig1<0.5&&EastPMSWall_Ht>MaxSWL5)?
NormalDist(EastPMSWaterfront,100,1):
(Hsig1>0.5&&EastPMSWall_Ht>=MaxSWL5)?
(EastPMSWall_Ht > MaxSWL5) ?
NormalDist(EastPMSWaterfront,
sqrt(9.81*Hsig1^3)*0.04/exp(2.6*(EastPMSWall_Ht-MaxSWL5)/Hsig1)
*200*7200/exp((EastPMSWall_Ht/(Hsig1*1.62*0.4))^2),
0.8*200*7200/exp((EastPMSWall_Ht/(Hsig1*1.62*0.4))^2)):

NormalDist(EastPMSWaterfront,0.06*sqrt(9.81*Hsig1^3)*200*7200,
0.0062*200*7200):

(EastPMSWall_Htmax(EastPMSWall_Ht, SWL_Ht))?0:
(EasternRd_Ht<=EastPMSWall_Ht&&EastPMSWaterfront>6000)?
EastPMSWaterfront/EastPMSWall_Nlinks:
(EasternRd_Ht>EastPMSWall_Ht&&EastPMSWaterfront>6000
&&EasternRd_HtEastneyBeach_Ht)?
2*N_Events:0

EastneyBeachRunup (MaxSWL5,EastneyGroynes) =
(Hsig1<0.5)?0:
(EastneyGroynes==0)?
(4.3-1.6/
sqrt(EastneyBeach_Slope/((Hsig1*2*3.14/(9.81*TP1^2))^0.5)))
*Hsig1:
0.25*((4.3-1.6/
sqrt(EastneyBeach_Slope/((Hsig1*2*3.14/(9.81*TP1^2))^0.5)))
*Hsig1)

p(EastneyInsideWall | MaxSWL5) =
(Hsig1<0.5&&EastneyWall_Ht>MaxSWL5)?
NormalDist(EastneyInsideWall,100,1):
(Hsig1>0.5&&EastneyWall_Ht>=MaxSWL5)?
(EastneyWall_Ht > MaxSWL5) ?
NormalDist(EastneyInsideWall,
sqrt(9.81*Hsig1^3)*0.04/exp(2.6*(EastneyWall_Ht-MaxSWL5)/Hsig1)
*200*7200/exp((EastneyWall_Ht/(Hsig1*1.62*0.4))^2),
0.8*200*7200/exp((EastneyWall_Ht/(Hsig1*1.62*0.4))^2)):
```

```
NormalDist(EastneyInsideWall,0.06*sqrt(9.81*Hsig1^3)*200*7200,
0.0062*200*7200):

(EastneyWall_Ht<="MiltonP_Ht||" eastney_milton_ht<="SWL_Ht)&&"
miltonparkandlakes="">10000)?MiltonParkandLakes/MiltonP_Nlinks:0)
+
(((Eastney_Milton_Ht<=Bransbury_Ht|| Eastney_Milton_Ht<=SWL_Ht)&&
BransburyPark>10000)?BransburyPark/Bransbury_Nlinks:0)
)/(414800*0.5))

p(Esplanade | MaxSWL4) =
(Esplanade_Ht > MaxSWL4&&Hsig1<0.5) ?
NormalDist(Esplanade,100,1):
(Esplanade_Ht > MaxSWL4&&Hsig1>0.5) ?
NormalDist(Esplanade,
sqrt(9.81*Hsig1^3)*0.04/exp(2.6*(Esplanade_Ht-MaxSWL4)/Hsig1)
*200*7200/exp((Esplanade_Ht/(Hsig1*1.62*0.4))^2),
0.8*200*7200/exp((Esplanade_Ht/(Hsig1*1.62*0.4))^2)):

(Esplanade_HtMaxSWL)?
NormalDist(FM_Seawall,100,1):
(Hsig1>0.5&&FM_Seawall_Ht>=MaxSWL)?
(FM_Seawall_Ht > MaxSWL) ?
NormalDist(FM_Seawall,
sqrt(9.81*Hsig1^3)*0.04/exp(2.6*(FM_Seawall_Ht-MaxSWL)/Hsig1)
*200*7200/exp((FM_Seawall_Ht/(Hsig1*1.62*0.4))^2),
0.8*200*7200/exp((FM_Seawall_Ht/(Hsig1*1.62*0.4))^2)):

NormalDist(FM_Seawall,0.06*sqrt(9.81*Hsig1^3)*200*7200,
0.0062*200*7200):

(FM_Seawall_Ht MaxSWL) ?
NormalDist(Farl_Hilsea_Embankment,100,1):
(Hsig1>0.5&&FarlHilsEmbank_Ht >= MaxSWL) ?
(FarlHilsEmbank_Ht > MaxSWL) ?
NormalDist(Farl_Hilsea_Embankment,
sqrt(9.81*Hsig1^3)*0.04/exp(2.6*(FarlHilsEmbank_Ht-MaxSWL)/Hsig1)
*200*7200/exp((FarlHilsEmbank_Ht/(Hsig1*1.62*0.4))^2),
0.8*200*7200/exp((FarlHilsEmbank_Ht/(Hsig1*1.62*0.4))^2)):

NormalDist(Farl_Hilsea_Embankment,0.06*sqrt(9.81*Hsig1^3)*200*7200,
0.0062*200*7200):

(FarlHilsEmbank_Ht<="FM_Seawall_Ht&&FM_Seawall">10000)?
FM_Seawall/(FM_Seawall_Nlinks*253900*0.5):0)
+
(((Farlington_Ht<=FM_Ht||Farlington_Ht<=SWL_Ht)&&
FarlingtonMarshes>10000)?
FarlingtonMarshes/(FM_Nlinks*253900*0.5):0))

FarlingtonMarshes (FM_Seawall, FM_StorVol) =
(FM_Ht>FM_Seawall_Ht&&FM_Ht>SWL_Ht)?0:
(FM_Seawall>6000)?
FM_Seawall-FM_StorVol:0

p(FerryPortWall | MaxSWL3) =
(Hsig1<0.5&&FerryPortWall_Ht >MaxSWL3) ?
NormalDist(FerryPortWall,100,1):
(Hsig1>0.5&&FerryPortWall_Ht >=MaxSWL3) ?
(FerryPortWall_Ht > MaxSWL3) ?
```

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NormalDist(FerryPortWall,
sqrt(9.81*Hsig1^3)*0.04/exp(2.6*(FerryPortWall_Ht-MaxSWL3)/Hsig1)
*200*7200/exp((FerryPortWall_Ht/(Hsig1*1.62*0.4))^2),
0.8*200*7200/exp((FerryPortWall_Ht/(Hsig1*1.62*0.4))^2)):

NormalDist(FerryPortWall,0.06*sqrt(9.81*Hsig1^3)*200*7200,
0.0062*200*7200):

(FerryPortWall_Ht<="CumberlandRd_Ht||" ft_cumberland_ht<="SWL_Ht)&&"
ftcumberlandrd="">10000)?
FtCumberlandRd/FtCumberRd_Nlinks:0)
+
((Ft_Cumberland_Ht<swl_ht&&southseabeach<="Esplanade_Ht||"
ft_cumberland_ht<="SWL_Ht)&&" esplanade="">10000)?
Esplanade/Esplanade_Nlinks:0)
)/(134400*0.5))

FtCumberlandRd (EastneyBeach) =
((EastneyBeach<3.33&&CumberlandRd_Ht MaxSWL4) ?
NormalDist(GQWall,100,1):
(Hsig1>0.5&&GQWall_Ht >= MaxSWL4) ?
(GQWall_Ht>MaxSWL4)?
NormalDist(GQWall,
sqrt(9.81*Hsig1^3)*0.04/exp(2.6*(GQWall_Ht-MaxSWL4)/Hsig1)
*200*7200/exp((GQWall_Ht/(Hsig1*1.62*0.4))^2),
0.8*200*7200/exp((GQWall_Ht/(Hsig1*1.62*0.4))^2)):

NormalDist(GQWall,0.06*sqrt(9.81*Hsig1^3)*200*7200,
0.0062*200*7200):

(GQWall_Ht<="GQWall_Ht||" gw_quays_ht<="SWL_Ht)&&"
gqwall="">6000)?GQWall/(357600*0.5):0)
+
0.0)

Highbury (Highbury_College, A27) =
clip(0,1,
(Highbury_College==1)?1:
(((Highbury_Ht<=A27_Ht||Highbury_Ht<=SWL_Ht)&&
&&A27>6000)?A27/(A27_Nlinks*483600*0.5):0)+0.0)


HighburyEast (A3_A2030_Roundabout, Rly_Line_Cosham) =
clip(0,1,
(
(((Highbury_East_Ht<=Rly_Cosham_Ht||Highbury_East_Ht<=SWL_Ht) &&
Rly_Line_Cosham>10000)?
Rly_Line_Cosham/Rly_Cosham_Nlinks:0)
+
((Highbury_East_Ht<=Rdbt_Ht&&A3_A2030_Roundabout>10000)?
A3_A2030_Roundabout/A2030Rdbt_Nlinks:0)
)/(164000*0.5))

Highbury_College (A27) =
clip(0,1,
(((Highbury_Coll_Ht<=A27_Ht||Highbury_Coll_Ht<=SWL_Ht)&&
A27>6000)?A27/(A27_Nlinks*74000*0.5):0)+0.0)

HilseaIndustrial (NorwayRd, BurrfieldsRd,
EasternRoad_A2030, SalternsPark_North) =
clip(0,1,
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(
(((Hilsea_Indust_Ht<=NorwayRd_Ht||Hilsea_Indust_Ht<=SWL_Ht)&&
NorwayRd>10000)?NorwayRd/Norway_Nlinks:0)
+
(((Hilsea_Indust_Ht<=Burrfields_Ht||Hilsea_Indust_Ht<=SWL_Ht)&&
BurrfieldsRd>10000)?BurrfieldsRd/Burrfields_Nlinks:0)
+
(((Hilsea_Indust_Ht<=NorwayRd_Ht||Hilsea_Indust_Ht<=SWL_Ht)&&
EasternRoad_A2030>6000)?EasternRoad_A2030/EasternRd_Nlinks:0)
+
(((Hilsea_Indust_Ht<=SalternsNorth_Ht||Hilsea_Indust_Ht<=SWL_Ht)&&
SalternsPark_North>10000)?SalternsPark_North/SalternsN_Nlinks:0)
)/(762100*0.5))

HilseaLines_Park (HilseaNorthEmbankm,
HilseaLines_StorVol) =
((Hilsea_Lines_Ht<=HilsNEmbank_Ht || Hilsea_Lines_Ht<=SWL_Ht)&&
HilseaNorthEmbankm>6000)?
HilseaNorthEmbankm/HilsNEmbank_Nlinks -
HilseaLines_StorVol :0

p(HilseaNorthEmbankm | MaxSWL) =
(Hsig1<0.5&&HilsNEmbank_Ht>MaxSWL)?
NormalDist(HilseaNorthEmbankm, 100,1):
(Hsig1>0.5&&HilsNEmbank_Ht>=MaxSWL)?
(HilsNEmbank_Ht> MaxSWL) ?
NormalDist(HilseaNorthEmbankm,
sqrt(9.81*Hsig1^3)*0.04/exp(2.6*(HilsNEmbank_Ht-MaxSWL)/Hsig1)
*200*7200/exp((HilsNEmbank_Ht/(Hsig1*1.62*0.4))^2),
0.8*200*7200/exp((HilsNEmbank_Ht/(Hsig1*1.62*0.4))^2)):

NormalDist(HilseaNorthEmbankm,0.06*sqrt(9.81*Hsig1^3)*200*7200,
0.0062*200*7200):

(HilsNEmbank_HtMaxSWL2)?
NormalDist(HorseaLakesideRd, 100, 1):
(Hsig1>0.5&&HorsLakeRd_Ht>=MaxSWL2)?
(HorsLakeRd_Ht > MaxSWL2) ?
NormalDist(HorseaLakesideRd,
sqrt(9.81*Hsig1^3)*0.04/exp(2.6*(HorsLakeRd_Ht-MaxSWL2)/Hsig1)
*200*7200/exp((HorsLakeRd_Ht/(Hsig1*1.62*0.4))^2),
0.8*200*7200/exp((HorsLakeRd_Ht/(Hsig1*1.62*0.4))^2)):

NormalDist(HorseaLakesideRd,0.06*sqrt(9.81*Hsig1^3)*200*7200,
0.0062*200*7200):

(HorsLakeRd_Ht<="SWL_Ht" &&horseaseawall="">10000)?
HorseaSeawall:0)
+
((HorseaMarina_Ht<=M275_1_Ht&&M275_1>10000)?
M275_1/2:0)
)/(120000*0.5))

p(HorseaSeawall | MaxSWL2) =
(Hsig1<0.5&&HorseaWall_Ht>MaxSWL2)?
NormalDist(HorseaSeawall,  100, 1):
(Hsig1>0.5&&HorseaWall_Ht>=MaxSWL2)?
(HorseaWall_Ht >MaxSWL2)?
NormalDist(HorseaSeawall,
sqrt(9.81*Hsig1^3)*0.04/exp(2.6*(HorseaWall_Ht-MaxSWL2)/Hsig1)
*200*7200/exp((HorseaWall_Ht/(Hsig1*1.62*0.4))^2),
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0.8*200*7200/exp((HorseaWall_Ht/(Hsig1*1.62*0.4))^2)):

NormalDist(HorseaSeawall,0.06*sqrt(9.81*Hsig1^3)*200*7200,
0.0062*200*7200):

(HorseaWall_HtMaxSWL3)?
NormalDist(LandportWall,100,1):
(Hsig1>0.5&&LandportWall_Ht>=MaxSWL3)?
(LandportWall_Ht > MaxSWL3) ?
NormalDist(LandportWall,
sqrt(9.81*Hsig1^3)*0.04/exp(2.6*(LandportWall_Ht-MaxSWL3)/Hsig1)
*200*7200/exp((LandportWall_Ht/(Hsig1*1.62*0.4))^2),
0.8*200*7200/exp((LandportWall_Ht/(Hsig1*1.62*0.4))^2)):

NormalDist(LandportWall,0.06*sqrt(9.81*Hsig1^3)*200*7200,
0.0062*200*7200):

(LandportWall_Ht<="LandportWall_Ht||" landp_wharf_ht<="SWL_Ht)&&"
landportwall="">6000)?
LandportWall/(217000*0.5):0)
+
(((Landp_Wharf_Ht<=M275_2_Ht|| Landp_Wharf_Ht<=SWL_Ht)&&
M275_2/M275_Nlinks>6000)?
M275_2/(M275_Nlinks*217000*0.5):0))

LockLakeMarina (FtCumberlandRd,MaxSWL5) =
((LockLake_Marina_Ht<=MaxSWL5||
(LockLake_Marina_Ht<=CumberlandRd_Ht&&FtCumberlandRd>10000))?
FtCumberlandRd/FtCumberRd_Nlinks:0)+0.0

M275_1 (MaxSWL2) =
((M275_1_Ht<="SWL_Ht)&&" stamshawbeach=""
stamshawwall_nlinks="">6000)?
StamshawBeach/StamshawWall_Nlinks:0

MaxSWL (MaxSWL_Source) =
MaxSWL_Source+RSLR

MaxSWL2 (MaxSWL_Source) =
MaxSWL_Source+RSLR

MaxSWL3 (MaxSWL_Source) =
MaxSWL_Source+RSLR

MaxSWL4 (MaxSWL_Source) =
MaxSWL_Source+RSLR

MaxSWL5 (MaxSWL_Source) =
MaxSWL_Source+RSLR

p (MaxSWL_Source | ) =
WeibullDist(MaxSWL_Source,1,1/9.752)*8*10^10/9.752

p(MiltonBeach | MaxSWL5) =
(Hsig1<0.5&&MiltonBeach_Ht > MaxSWL5) ?
NormalDist(MiltonBeach,100,1):
(Hsig1>0.5&&MiltonBeach_Ht >= MaxSWL5) ?
(MiltonBeach_Ht > MaxSWL5) ?
NormalDist(MiltonBeach,
sqrt(9.81*Hsig1^3)*0.04/exp(2.6*(MiltonBeach_Ht-MaxSWL5)/Hsig1)
*200*7200/exp((MiltonBeach_Ht/(Hsig1*1.62*0.4))^2),
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0.8*200*7200/exp((MiltonBeach_Ht/(Hsig1*1.62*0.4))^2)):

NormalDist(MiltonBeach,0.06*sqrt(9.81*Hsig1^3)*200*7200,
0.0062*200*7200):

(MiltonBeach_Ht<="EastneyWall_Ht&&EastneyInsideWall">6000), 1, 1,
EastneyInsideWall/EastneyWall_Nlinks,
(MiltonP_Ht<=A2030_3_Ht&&A2030_3>6000),1,1,A2030_3/A2030_3_Nlinks,
true,1,1,neg(MiltonP_StorVol)
)

Milton_Residential (A2030_3, TangierRd) =
clip(0,1,
(
(((Milton_Res_Ht<=A2030_3_Ht|| Milton_Res_Ht<=SWL_Ht)&&
A2030_3>6000)?
A2030_3/A2030_3_Nlinks:0)
+
(((Milton_Res_Ht<=TangierRd_Ht|| TangierRd_Ht<=SWL_Ht)&&
TangierRd>10000)?TangierRd/Tangier_Nlinks:0)
)/(228300*0.5))

NavalBase (FerryPortWall) =
clip(0,1,
(((Naval_Base_Ht<=FerryPortWall_Ht|| Naval_Base_Ht<=SWL_Ht)
&&FerryPortWall>6000)?
FerryPortWall/(FerryPortWall_Nlinks*233000*0.5):0)+0.0)

NorthernParade (A27_2, A2047, AlexandraPark_Coll) =
clip(0,1,
(
(((North_Parade_Ht<=A27_2_Ht || North_Parade_Ht<=SWL_Ht)&&
A27_2/A27_2_Nlinks>6000)?
A27_2/A27_2_Nlinks:0)
+
(((North_Parade_Ht<=A2047_Ht ||
North_Parade_Ht<=SWL_Ht)&&A2047/A2047_Nlinks>6000)?
A2047/A2047_Nlinks:0)
+
(((North_Parade_Ht<=Alexandra_Ht||North_Parade_Ht<=SWL_Ht)&&
AlexandraPark_Coll/Alexandra_Nlinks>6000)?
AlexandraPark_Coll/Alexandra_Nlinks:0)
)/(276000*0.5))

NorwayRd (EasternRoad_A2030, AnchoragePark) =
(
(((NorwayRd_Ht<=Anchorage_Ht||NorwayRd_Ht<=SWL_Ht)&&
AnchoragePark>6000)?AnchoragePark/Anchorage_Nlinks:0)
+
(((NorwayRd_Ht<=EasternRd_Ht||NorwayRd_Ht<=SWL_Ht)&&
EasternRoad_A2030>6000)?EasternRoad_A2030/EasternRd_Nlinks:0)
)

OldPMS (ClarencePier, A3_3) =
clip(0,1,
(((Old_PMS_Ht<=Clarence_Pier_Ht|| Old_PMS_Ht<=SWL_Ht)&&
ClarencePier>6000)?
ClarencePier/(ClarencePier_Nlinks*162300*0.5):0)
+
(((Old_PMS_Ht<=A3_3_Ht|| Old_PMS_Ht<=SWL_Ht)&&
A3_3/A3_3_Nlinks>6000)?
```

```
A3_3/(A3_3_Nlinks*162300*0.5):0))

P(PembrokeGardens | Esplanade,ClarenceBeach, Pembroke_StorVol) =
NoisySumTableDist (PembrokeGardens, 0,
(ClarenceBeach<10&&Esplanade<10), 1, 1, 0,
(Pembroke_Ht>max(ClarenceWall_Ht,Esplanade_Ht,SWL_Ht)), 1, 1, 0,
((Pembroke_Ht<=ClarenceWall_Ht||Pembroke_Ht<=SWL_Ht)&&ClarenceBeach>60
00), 1, 1, ClarenceBeach/ClarenceBeach_Nlinks,
((Pembroke_Ht<=Esplanade_Ht||Pembroke_Ht<=SWL_Ht)&&Esplanade>6000), 1,
1, Esplanade/Esplanade_Nlinks,
true,1, 1, neg(Pembroke_StorVol)
)

Rly_Ferry (FerryPortWall) =
clip(0,1,
(((Rly_Ferry_Ht<=FerryPortWall_Ht|| Rly_Ferry_Ht<=SWL_Ht)&&
FerryPortWall>6000)?
FerryPortWall/(FerryPortWall_Nlinks*40000*0.5):0))

Rly_Line_Cosham (Highbury, CoshamDocks_Urban,
Farlington) =
clip(0,50000,
((Rly_Cosham_Ht<=Highbury_Ht&&Highbury>0.1)?
Highbury*0.1*483600:0)
+
((Rly_Cosham_Ht<=Cosham_Ht&&CoshamDocks_Urban>0.1)?
CoshamDocks_Urban*0.1*100000:0)
+
((Rly_Cosham_Ht<=Farlington_Ht&&Farlington>0.1)?
Farlington*0.1*253900:0))

Rly_Line_Hilsea (AnchoragePark, HilseaLines_Park) =
clip(0,50000,
(
(((Rly_Hils_Ht<=Hilsea_Lines_Ht|| Rly_Hils_Ht<=SWL_Ht)&&
HilseaLines_Park>6000)?
HilseaLines_Park/HilseaLines_Nlinks:0)
+
(((Rly_Hils_Ht<=Anchorage_Ht|| Rly_Hils_Ht<=SWL_Ht)&&
AnchoragePark>6000)?
AnchoragePark/Anchorage_Nlinks:0)
))

Rly_Triangle (Rly_Line_Cosham, A3_A2030_Roundabout) =
clip(0,1,
(
(((Rly_Triangle_Ht<=Rly_Cosham_Ht||Rly_Triangle_Ht<=SWL_Ht) &&
Rly_Line_Cosham>10000)?
Rly_Line_Cosham/Rly_Cosham_Nlinks:0)
+
((Rly_Triangle_Ht<=Rdbt_Ht&&A3_A2030_Roundabout>10000)?
A3_A2030_Roundabout/A2030Rdbt_Nlinks:0)
)/(75000*0.5))

SSeaBeachErosion (SSeaBeachRunup) =
(SSeaBeachRunup>SSeaBeach_Ht)?
2*N_Events:0

SSeaBeachRunup (MaxSWL4,SouthseaGroynes) =
(Hsig1<0.5)?0:
(SouthseaGroynes==0)?
```

```
(4.3-1.6/
sqrt(SouthseaBeach_Slope/((Hsig1*2*3.14/(9.81*TP1^2))^0.5)))
*Hsig1:
0.25*((4.3-1.6/
sqrt(SouthseaBeach_Slope/((Hsig1*2*3.14/(9.81*TP1^2))^0.5)))
*Hsig1)

SSeaGolfLinks (SSeaGolf_StorVol, Esplanade, A288_2) =
clip(0,50000,
(((SSea_Golf_Ht<=Esplanade_Ht|| SSea_Golf_Ht<=SWL_Ht)&&
Esplanade>10000)?
Esplanade/Esplanade_Nlinks:0)
+
(((SSea_Golf_Ht<=A288_2_Ht||SSea_Golf_Ht<=SWL_Ht)&&A288_2>10000)?
A288_2/A288_2_Nlinks:0)
-
SSeaGolf_StorVol)

SalternsPark_Lake (EasternRoad_A2030, SalternsLake_StorVol) =
clip(0,50000,
(((SalternsLake_Ht<=EasternRd_Ht||SalternsLake_Ht<=SWL_Ht)&&
EasternRoad_A2030>6000)?
EasternRoad_A2030/EasternRd_Nlinks:0)
-
SalternsLake_StorVol)

p (SalternsPark_North | EasternRoad_A2030, SalternsN_StorVol) =
NoisySumTableDist(SalternsPark_North,0,
(EasternRoad_A2030<10),1,1,0,
(EasternRoad_A2030>6000&&(SalternsNorth_Ht<=NorwayRd_Ht||SalternsNorth
_Ht<=SWL_Ht)),
1,1,EasternRoad_A2030/EasternRd_Nlinks,
true,1,1,neg(SalternsN_StorVol)
)

SluiceLakeQuay (EastPMSWaterfront) =
((SluiceQuay_Ht<=EastPMSWall_Ht||SluiceQuay_Ht<=SWL_Ht)&&
EastPMSWaterfront/130000>0.1)?1:0

Southsea (A288_2, A3_3) =
clip(0,1,
(
(((Southsea_Ht<=A288_2_Ht|| Southsea_Ht<=SWL_Ht)&&
A288_2>10000)?A288_2/A288_2_Nlinks:0)
+
(((Southsea_Ht<=A3_3_Ht|| Southsea_Ht<=SWL_Ht)&&
A3_3>10000)?A3_3/A3_3_Nlinks:0)
)/(1128000*0.5))

SouthseaBeach (SSeaBeachErosion) =
clip(0,10,SSeaBeach_InitialW-SSeaBeachErosion)

SouthseaPark (SouthseaWall, Southsea_StorVol) =
((SSea_Park_Ht<=SSeaWall_Ht|| SSea_Park_Ht<swl_ht)&&
southseawall="">6000)?
SouthseaWall - Southsea_StorVol:0

p(SouthseaWall | MaxSWL4) =
(SSeaWall_Ht > MaxSWL4&&Hsig1<0.5) ?
NormalDist(SouthseaWall,100,1):
(SSeaWall_Ht > MaxSWL4&&Hsig1>0.5) ?
```

```
NormalDist(SouthseaWall,
sqrt(9.81*Hsig1^3)*0.04/exp(2.6*(SSeaWall_Ht-MaxSWL4)/Hsig1)
*200*7200/exp((SSeaWall_Ht/(Hsig1*1.62*0.4))^2),
0.8*200*7200/exp((SSeaWall_Ht/(Hsig1*1.62*0.4))^2)):

(SSeaWall_Ht<="StamshawWall_Ht||" stamshaw_ht<="SWL_Ht)&&"
stamshawbeach="">6000)?
StamshawBeach/StamshawWall_Nlinks:0)
+
(((Stamshaw_Ht<=M275_2_Ht|| Stamshaw_Ht<=SWL_Ht)&&
M275_2>6000)?
M275_2/M275_Nlinks:0)
+
(((Stamshaw_Ht<=Alexandra_Ht|| Stamshaw_Ht<=SWL_Ht)&&
AlexandraPark_Coll>6000)?
AlexandraPark_Coll/Alexandra_Nlinks:0)
)/(197300*0.5))

p(StamshawBeach | MaxSWL3) =
(Hsig1<0.5&&StamshawWall_Ht>MaxSWL3)?
NormalDist(StamshawBeach,100,1):
(Hsig1>0.5&&StamshawWall_Ht>=MaxSWL3)?
(StamshawWall_Ht > MaxSWL3) ?
NormalDist(StamshawBeach,
sqrt(9.81*Hsig1^3)*0.04/exp(2.6*(StamshawWall_Ht-MaxSWL3)/Hsig1)
*200*7200/exp((StamshawWall_Ht/(Hsig1*1.62*0.4))^2),
0.8*200*7200/exp((StamshawWall_Ht/(Hsig1*1.62*0.4))^2)):

NormalDist(StamshawBeach,0.06*sqrt(9.81*Hsig1^3)*200*7200,
0.0062*200*7200):

(StamshawWall_Ht<="SalternsLake_Ht||TangierRd_Ht<=SWL_Ht)&&SalternsPar
k_Lake">10000)?
(SalternsPark_Lake)/SalternsLake_Nlinks:0)
+
(((TangierRd_Ht<=EasternRd_Ht||TangierRd_Ht<=SWL_Ht)&&EasternRoad_A203
0>6000)?
EasternRoad_A2030/EasternRd_Nlinks:0)
-
((SalternsPark_Lake<0)?SalternsPark_Lake/SalternsLake_Nlinks:0)
-
UrbanDrainageSystem/Drainage_Nlinks)

Tipner (TipnerSeawall, Stamshaw, HorseaLakesideRd,
AlexandraPark_Coll) =
clip(0,1,(
(((Tipner_Ht<=TipnerWall_Ht|| Tipner_Ht<=SWL_Ht)&&
TipnerSeawall>6000)?TipnerSeawall:0)
+
(((Tipner_Ht<=HorsLakeRd_Ht|| Tipner_Ht<=SWL_Ht)&&
HorseaLakesideRd>6000)?
HorseaLakesideRd/HorsLakeRd_Nlinks:0)
+
(((Tipner_Ht<=Stamshaw_Ht||Tipner_Ht<=SWL_Ht)&&
Stamshaw>0.3)?197300*0.1:0)
+
(((Tipner_Ht<=Alexandra_Ht|| Tipner_Ht<=SWL_Ht)&&
AlexandraPark_Coll>6000)?
AlexandraPark_Coll/Alexandra_Nlinks:0)
)/(278000*0.5))
```

```
p(TipnerSeawall | MaxSWL3) =
(Hsig1<0.5&&TipnerWall_Ht>MaxSWL3)?
NormalDist(TipnerSeawall,100,1):
(Hsig1>0.5&&TipnerWall_Ht>=MaxSWL3)?
(TipnerWall_Ht > MaxSWL3) ?
NormalDist(TipnerSeawall,
sqrt(9.81*Hsig1^3)*0.04/exp(2.6*(TipnerWall_Ht-MaxSWL3)/Hsig1)
*100*7200/exp((TipnerWall_Ht/(Hsig1*1.62*0.4))^2),
0.8*100*7200/exp((TipnerWall_Ht/(Hsig1*1.62*0.4))^2)):

NormalDist(TipnerSeawall,0.06*sqrt(9.81*Hsig1^3)*100*7200,
0.0062*100*7200):

(TipnerWall_Ht<MaxSWL3)?
NormalDist(TipnerSeawall, clip(0,50000,
0.6*sqrt(9.81*((MaxSWL3-TipnerWall_Ht)^3))*100*7200),
clip(0,5000,0.1*100*7200)):0
```

Node Input Values for Example Simulation

A2030Rdbt_Nlinks	2	
A2030_3_Ht	3	m
A2030_3_Nlinks	2	
A2047_Ht	2.01	m
A2047_Nlinks	1	
A27_2_Ht	2.01	m
A27_2_Nlinks	4	
A27_Ht	3.2	m
A27_Nlinks	2	
A288_2_Ht	3.1	m
A288_2_Nlinks	1	
A288_Ht	2.01	m
A288_Nlinks	1	
A3_2_Ht	2.01	m
A3_2_Nlinks	2	
A3_3_Ht	3.94	m
A3_3_Nlinks	3	
Alexandra_Ht	2.91	m
Alexandra_Nlinks	4	
Alexandra_StorVol	0	m3
Anchorage_Ht	2.94	m
Anchorage_Nlinks	3	
Anchorage_StorVol	0	m3
Bransbury_Ht	1.33	m

Bransbury_Nlinks	1	
Bransbury_StorVol	0	m3
Burrfields_Ht	2.55	m
Burrfields_Nlinks	2	
CF_Port_Ht	2	m
Central_PMS_Ht	3	m
ClarenceBeach_Nlinks	2	
ClarencePier_Nlinks	2	
ClarenceWall_Ht	4	m
Clarence_Pier_Ht	0	m
Copnor_Hils_N_Ht	3.71	m
Copnor_Ht	3.27	m
Cosham_Ht	4.45	m
CumberlandRd_Ht	2.49	m
Drainage_Nlinks	3	
EastPMSWall_Ht	3.2	m
EastPMSWall_Nlinks	2	
EasternRd_Ht	0	m
EasternRd_Nlinks	8	
EastneyBeach_Ht	1.25	m
EastneyBeach_InitialW	8	m
EastneyBeach_Slope	0.15	
EastneyWall_Ht	3.2	m
EastneyWall_Nlinks	2	
Eastney_Marina_Ht	1.71	m
Eastney_Milton_Ht	2	m
Esplanade_Ht	4.26	m
Esplanade_Nlinks	3	
FM_Ht	2.21	m
FM_Nlinks	2	
FM_Seawall_Ht	2	m
FM_Seawall_Nlinks	2	
FM_StorVol	0	m3
FarlHilsEmbank_Ht	3.7	m
FarlHils_Nlinks	2	
Farlington_Ht	1.28	m
FerryPortWall_Ht	3.25	m
FerryPortWall_Nlinks	3	

FtCumberRd_Nlinks	3	
Ft_Cumberland_Ht	2.25	m
GQWall_Ht	4.5	m
GW_Quays_Ht	3.76	m
Highbury_Coll_Ht	1.86	m
Highbury_East_Ht	1.94	m
Highbury_Ht	1.49	m
HilsNEmbank_Ht	3.3	m
HilsNEmbank_Nlinks	3	
HilseaLines_Nlinks	3	
Hilsea_Indust_Ht	2.5	m
Hilsea_Lines_Ht	1.84	m
HorsLakeRd_Ht	3.2	m
HorsLakeRd_Nlinks	2	
HorseaMarina_Ht	4.05	m
HorseaWall_Ht	3.7	m
Hsig1	0	m
Landp_Wharf_Ht	3.63	m
LandportWall_Ht	3	m
LockLake_Marina_Ht	1.11	m
M275_1_Ht	1.86	m
M275_1_Nlinks	2	
M275_2_Ht	6.13	m
M275_Nlinks	2	
MaxSWL_Source	3.12	m
MiltonBeach_Ht	2.26	m
MiltonP_Ht	1.81	m
MiltonP_Nlinks	1	
MiltonP_StorVol	0	m3
Milton_Res_Ht	3.74	m
N_Events	4	
Naval_Base_Ht	5	m
North_Parade_Ht	3.45	m
NorwayRd_Ht	1.64	m
Norway_Nlinks	1	
Old_PMS_Ht	3.77	m
Pembroke_Ht	2.58	m
Pembroke_Nlinks	2	

Pembroke_StorVol	0	m3
RSLR	one	m
Rdbt_Ht	2.86	m
Rly_Cosham_Ht	2.5	m
Rly_Cosham_Nlinks	2	
Rly_Ferry_Ht	3.47	m
Rly_Hils_Ht	4.02	m
Rly_Triangle_Ht	1.44	m
SSeaBeach_Ht	1.91	m
SSeaBeach_InitialW	8	m
SSeaGolf_Nlinks	1	
SSeaGolf_StorVol	0	m3
SSeaWall_Ht	4.5	m
SSea_Golf_Ht	1.98	m
SSea_Park_Ht	1.98	m
SWL_Duration	12	hrs
SWL_Ht	3.12	m
SalternsLake_Ht	2	m
SalternsLake_Nlinks	3	
SalternsLake_StorVol	0	m3
SalternsN_Nlinks	3	
SalternsN_StorVol	0	m3
SalternsNorth_Ht	2	m
SluiceQuay_Ht	3	m
SouthseaBeach_Slope	0.15	
Southsea_Ht	0.67	m
Southsea_Nlinks	1	
Southsea_StorVol	0	m3
StamshawWall_Ht	2	m
StamshawWall_Nlinks	2	
Stamshaw_Ht	3.94	m
TP1	12	s
TangierRd	0 to 10000	m3
TangierRd_Ht	3.66	m
Tangier_Nlinks	2	
TipnerWall_Ht	3.1	m
Tipner_Ht	3.82	m
Underpass	close	

UrbanDrainageSystem	0to10000	m3

Appendix 4: Example Programme Code for Bayesian Networks in Netica

The commercial version of the Netica Bayesian network model provides additional programming functionalities via an Application Programming Interface (API) (Norsys Software Corp, 2010). This functionality has been used in this thesis to automate the provision of inputs, running and compiling of a network once it is built. This section provides an example code to perform these functions for the Teignmouth network, using a pre-defined case-file with inputs like the ones described in Appendix 2. This code is programmed in C using the Microsoft Visual Studio Compiler.

```
/*
 *  Teign_Example.c
 * This program provides an example code in the Netica API for:
 * i. retrieving nodes of a network from a Netica network file and printing the current
state probabilities for specific nodes
 * ii. copying the nodes to a new network and clearing all calculated state probability
values
 * iii. reading inputs from a user-specified case-file, compiling the net and calculating
the new state probabilities
 * iv. printing the new state probabilities for specific nodes
 */

#define _CRT_SECURE_NO_DEPRECATE /* for using fopen, fprintf and fclose functions
*/
#include<time.h>
#include <stdio.h>
#include <stdlib.h>
#include "Netica.h"
#include "NeticaEx.h"

#define CHKERR  {if (GetError_ns (env, ERROR_ERR, NULL))  goto error;}

environ_ns* env;

int main (void){
	net_bn* net = NULL, *learned_net = NULL;
	const nodelist_bn* net_nodes;
	caseposn_bn caseposn = FIRST_CASE;
	nodelist_bn* dup_net_nodes = NULL;
	prob_bn* probs;
	const prob_bn *prs;
	node_bn *Beach_east;
	stream_ns *casefile, *writefindings;
	double belief_FP, belief_west, belief_harbour, belief_rly_west,
probs_beach_rly[8] ={0.0}, start, end;
	double nodevalues [79] = {0}; // make sure nodevalues [size] is >= no. of nodes
in net
	char mesg[MESG_LEN_ns];
	const char *nodename, *statename, *equation = {0};
	int res, numnodes, i, num_entries;
	FILE *nodefile;
```

```
        report_ns* err;

        // INITIALIZE NETICA ENVIRONMENT AND ERROR CHECKING
        start = clock();
        env = NewNeticaEnviron_ns ("+Lic1/USouthampton/120,310-6-A/28951", NULL,
NULL);
        res = InitNetica2_bn (env, mesg);
        printf ("%s\n", mesg);
        if (res < 0)  exit (-1);

        // READ NET AND NODES AND COMPILE
        net = ReadNet_bn ( NewFileStream_ns ("Data Files\\Teign_Full_v1.dne", env,
NULL), NO_VISUAL_INFO);
        net_nodes = GetNetNodes_bn (net);
        numnodes = LengthNodeList_bn (net_nodes);
        SetNetAutoUpdate_bn (net, BELIEF_UPDATE);
        CHKERR

        CompileNet_bn (net);

        // GET BELIEFS FROM ORIGINAL NET
        belief_FP = GetNodeBelief ("TeignFP_Composite", "true", net);
        belief_west = GetNodeBelief ("TeignmouthFP_west", "true", net);
        belief_rly_west = GetNodeBelief ("Railway_west", "true", net);
        belief_harbour = GetNodeBelief ("Harbour", "true", net);
        printf ("\nThe current probability of flooding for Railway West is %g\n",
belief_rly_west);
        printf ("The current probability of flooding for Teign west is %g\n", belief_west);
        printf ("The current probability of flooding for the Harbour is %g\n",
belief_harbour);
        printf ("The current probability of flooding for Teign FP is %g\n", belief_FP);


        // DUPLICATE NODES AND COPY INTO NEW NET
        learned_net = NewNet_bn ("Learned_Teign_Full_v1", env);
        dup_net_nodes = CopyNodes_bn (net_nodes, learned_net, NULL);
        numnodes = LengthNodeList_bn (dup_net_nodes);
        WriteNet_bn (learned_net,  NewFileStream_ns ("Data
Files\\Learned_Teign_Full_v1.dne", env, NULL));


        // RETRACT FINDINGS AND DELETE NODE TABLES OF DUPLICATE NODES
        for (i = 0; i < numnodes; i++){
                DeleteNodeTables_bn (NthNode_bn (dup_net_nodes, i));
                RetractNodeFindings_bn (NthNode_bn (dup_net_nodes, i));
        }

        // REVISE TABLES OF DUPLICATE NODES BY FINDINGS FROM CASE FILE
        casefile = NewFileStream_ns ("Data Files\\Teign_Full_cases_real_1.txt", env,
NULL);
        while (1) {
                ReadNetFindings2_bn (&caseposn, casefile, FALSE, dup_net_nodes,
NULL, NULL);
                if (caseposn == NO_MORE_CASES) break;
                ReviseCPTsByCaseFile_bn (casefile, dup_net_nodes, 0, 1.0);
                caseposn = NEXT_CASE;
                CHKERR
        }
```

```
	// UPDATE TABLES OF NODES WITH EQUATIONS OF DUPLICATE NODES AND
COMPILE NEW NET
	for (i = 0; i < numnodes; i++){
		equation = GetNodeEquation_bn (NthNode_bn (dup_net_nodes, i));
		if (equation[0]!=0)
			EquationToTable_bn (NthNode_bn (dup_net_nodes, i), 500,
FALSE, FALSE);
	}

	CompileNet_bn (learned_net);
	for (i = 0; i<numnodes; i++) {
		if (GetNodeKind_bn (NthNode_bn (dup_net_nodes, i)) !=
CONSTANT_NODE)
			GetNodeBeliefs_bn(NthNode_bn (dup_net_nodes, i));
	}
	/* FOR DUPLICATED NODES; GET OUTPUT NODE VALUES (BELIEFS) FOR NODES
WITH EQUATIONS AND
	PRINT INPUT NODE VALUES (FINDINGS) FOR NODES WITHOUT EQUATIONS AND
WRITE TO FILE */
	nodefile = fopen ("Teign_Full_nodes_real_1.txt","w");
	CHKERR
	for (i = 0; i < numnodes; i++){
		equation = GetNodeEquation_bn (NthNode_bn (dup_net_nodes, i));
		if (equation[0]!=0)
			nodevalues[i] = GetNodeExpectedValue_bn (NthNode_bn
(dup_net_nodes, i), 0, 0, 0);
		else
			nodevalues[i] = GetNodeValueEntered_bn (NthNode_bn
(dup_net_nodes, i));
		nodename = GetNodeName_bn (NthNode_bn (dup_net_nodes, i));
		fprintf(nodefile, "%d\t%s\t%g, %g\n", i, nodename, nodevalues[i]);
	}
	fclose (nodefile);

	// INITIALISE node_bn* Beach_Rly; prob_bn* probs; AND ASSIGN CPs OF
Beach_Rly TO probs
	Beach_east = GetNodeNamed_bn ("Beach_east", learned_net);
	num_entries = SizeCartesianProduct (GetNodeParents_bn (Beach_east)) *
GetNodeNumberStates_bn (Beach_east);
	probs = (prob_bn*) malloc (num_entries * sizeof (probs));

	prs = GetNodeBeliefs_bn (Beach_east);
	if (prs)
		for (i = 0;  i < num_entries;  ++i)  probs[i] = prs[i];
	nodefile = fopen ("Teign_Full_nodes_real_1.txt", "a");
	fprintf (nodefile, "\nBeach_east CPs\n");
	for (i = 0; i<(GetNodeNumberStates_bn (Beach_east)); ++i) {
		statename = GetNodeStateName_bn (Beach_east, i);
		fprintf (nodefile, "\nState %s:\t%g", statename, probs[i]);
	}
	fclose (nodefile);

	// WRITE DUPLICATE NODE FINDINGS TO NEW CASEFILE - CASEFILE SHOULD BE
DELETED FOR OVERWRITING FINDINGS
	writefindings = NewFileStream_ns ("Data Files\\Teign_Full_real_1_findings.cas",
env, NULL);
	WriteNetFindings_bn (dup_net_nodes, writefindings, -1, -1);
	CHKERR
```

```
        // GET BELIEFS FROM NEW NET
        belief_FP = GetNodeBelief ("TeignFP_Composite", "true", learned_net);
        belief_west = GetNodeBelief ("TeignmouthFP_west", "true", learned_net);
        belief_harbour = GetNodeBelief ("Harbour", "true", learned_net);
        belief_rly_west = GetNodeBelief ("Railway_west", "true", learned_net);
        printf ("\nThe current probability of flooding for Railway West is %g\n",
belief_rly_west);
        printf ("The revised probability of flooding for Teign west is %g\n", belief_west);
        printf ("The revised probability of flooding for the Harbour is %g\n",
belief_harbour);
        printf ("The revised probability of flooding for Teign FP is %g\n\n", belief_FP);
        printf ("This net has %d", numnodes);
        printf (" nodes\n");
        PrintNodeList (dup_net_nodes);

        CompileNet_bn (learned_net);
        for (i = 0; i<numnodes; i++) {
                if (GetNodeKind_bn (NthNode_bn (dup_net_nodes, i)) !=
CONSTANT_NODE)
                        GetNodeBeliefs_bn(NthNode_bn (dup_net_nodes, i));
        }
        end = clock();
        printf("\nTime taken: %g\n", (end - start)/CLOCKS_PER_SEC);


end:
        DeleteNodeList_bn (dup_net_nodes);
        DeleteStream_ns (casefile);
        DeleteStream_ns (writefindings);
        DeleteNet_bn (net);
        DeleteNet_bn (learned_net);
        res = CloseNetica_bn (env, mesg);
        printf ("%s\n", mesg);
        printf ("Press <enter> key to quit ", mesg);
        getchar();
        return (res < 0 ? -1 : 0);

error:
        err = GetError_ns (env, ERROR_ERR, NULL);
        fprintf (stderr, "TeignNet: Error %d %s\n",
               ErrorNumber_ns (err), ErrorMessage_ns (err));
        goto end;
}
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Appendix 5: Peer-reviewed Journal Publications

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Risk assessment of estuaries under climate change: Lessons from Western Europe

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ABSTRACT

Climate change with rising sea levels and possible changes in surge levels and wave climate will have a large impact on how we protect our coastal areas and cities. Here the focus is on estuarine locations not only affected by tide and surge propagation, but also potentially influenced by freshwater discharge. Mitigation measures might be diverse ranging from pure hard 'engineering' solutions all the way to significant realignment. The variation in the type/origin and extent of the flood sources greatly influences subsequent risk management measures. At the same time, society is increasingly demanding that we take a holistic view on risk management, embracing and balancing safety, ecological and socio-economic aspects. This requires that all these diverse factors need to be considered together and integrated. In this context, the Source–Pathway–Receptor (SPR) approach offers a powerful holistic tool to investigate changing risk connected to extreme events.

The traditional SPR approach with a consecutive treatment of the flood, pathway and receptor is well understood and is widely used in coastal flood risk analysis. Here an enhanced 2D conceptual version of the SPR method is used to better describe the system and to allow flexibility in considering multiple scales, flood sources and pathways. The new approach is demonstrated by three estuarine case studies in western Europe: the Gironde estuary, France; the Dendermonde region in the Scheldt estuary, Belgium; and HafenCity (Hamburg) in the Elbe estuary, Germany. They differ considerably in the surface area considered, in the type of flood sources, and hence also in the SPR configuration. After a brief introduction of the typical characteristics of the three study sites including some lessons learned from past flood protection measures, the differences in application and results of the SPR approach are discussed. Emphasis is on the specific aspects for each study site, but embedded in a generic SPR framework. The resulting generic lessons learned about the flood sources and how this shapes subsequent analysis are transferable to numerous important estuaries worldwide.

1. Introduction

Estuaries and coastal areas are ecologically rich, often densely populated and of vital economic and social importance across Europe and the world. They are directly affected by sea-level rise, leading to higher extreme water levels. Also other aspects of climate change may have a significant additional impact on coastal flood risk (positive or negative). Possible changes in atmospheric circulation, related sea level pressure patterns and wind climate may result in changes of (extreme) wave conditions and storm surges. Typically estuaries combine threats from the terrestrial and the ocean side. The effects of changes in sea level interact with changes in rainfall and evapotranspiration patterns and consequent inland run-off in a non-linear way. The tide propagation characteristics may be altered and the location where a negative impact occurs is not necessarily at the location of the change. In addition, non-climate effects may be important such as localized subsidence of low-lying land (increasing potential flood depths and hence flood consequences) and capital dredging for navigation which will increase water depths and allow the tide and surges to propagate further upstream. Winterwerp (2013) gives 5 examples of 5 European ports (Antwerp on the Scheldt, Bremen on the Weser, Hamburg on the Elbe, Nantes on the Loire and Papenburg on the Ems) situated more than 50 km from the mouth of the estuary where the tidal range has increased in the last 100 years due to deepening and canalization. The increase of tidal range necessarily needs to have an effect on low and/or high water levels but to which extent high waters increase and low waters decrease depends on the shape of the estuary (Van Rijn, 2010,

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2011). Wherever the site, all these factors need to be considered and the Source–Pathway–Receptor–(Consequences) SPR(C) methodology facilitates such an approach (Evans et al., 2004; Narayan et al., 2012, this volume). The C (Consequence) part of the SPRC methodology falls outside the scope of this paper and will – with the exception of the Gironde study site – not be discussed in detail.

The only certainty of what the future will bring us is uncertainty. Exploring this uncertainty is now widely accepted as good practice to study potential impacts of climate change, to investigate the effect of different mitigation options and to develop appropriate management plans. Global and regional climate model studies incorporate uncertainty in their model output through ensemble modeling, either through a perturbation of physics approach of an individual model or through ensembles of different models, illustrated by Lowe et al. (2009) and Grabemann and Weisse (2008), respectively. Weisse et al. (2014) give an assessment of the climate projections at the THESEUS study sites, including those considered in this paper.

This paper demonstrates the application benefits of the SPR(C) approach to investigate the possible impact of climate change on three specific areas that are situated in large European estuaries, with a focus on flood sources. For the Scheldt estuary the area of Dendermonde, Belgium, is chosen because of its particular sensitivity to the combined effect of rainfall-induced runoff (upstream discharge) and downstream surge levels including sea-level rise (Ntegeka et al., 2012). Surge levels, sea level rise and rainfall are all potentially affected by climate change. HafenCity in Hamburg on the Elbe, Germany, is an attractive residence and commercial area developed outside the dikes on an old port area and hence the impacts of increased water levels because of sea level rise and storm surges are directly and immediately felt. For the Gironde, France, the area downstream of Bordeaux is considered. The first two case studies consider rather small areas more upstream the estuary. In contrast, the Gironde case has a much larger extent both in space as in terms of variety of challenges. Contrary to the other sites, it also contains the lower part of the estuary where next to sea level rise and storm surge, also wave action is important.

Although the three sites are nearby in planetary terms, it proved impossible in practice to use the same tools and to come up with a homogeneous set of climate scenarios. The difference in traditions (existing flood protection plans and flood protection philosophy and strategy), in historical choices (choice of values for sea level rise by local stakeholders or decision for urban development outside the existing dike system as in HafenCity), in system characteristics (small versus large spatial scale, differences in dominant flood sources), in previous experience and knowledge (existing hydrodynamic model implementations, previous experience with climate scenario's for rainfall-run-off in the Dender basin) and in stakeholder needs at the different study sites (e.g. implementation of a Decision Support System for the Gironde during the THESEUS project, added value of combined rainfall-runoff and tide-surge climate scenarios study for the Dendermonde area), led to differences in the details of the climate scenarios used including differences in the assumption on sea level rise and difference in the tools (hydrodynamic and wave models) used. Details about this are given when describing the different sites. It can however be considered a strength of the SPR(C) approach is that it on the one hand could still be applied and on the other hand added insight in the risk assessment notwithstanding the various spatial scales and different amounts of detail in each of the study sites.

2. The SPR approach

The Source–Pathway–Receptor (SPR) approach is a well understood and widely used approach in coastal flood risk analysis. It was first adopted from pollution studies by the Foresight Future Flooding project in the UK and has been used in several flood risk assessments since Evans et al. (2004). The traditional use of the approach is a straightforward consecutive (1D) treatment of the coastal floodplain, consisting of a flood source leading through pathways to flood receptors. In this paper an enhanced 2D conceptual version of the SPR method is used to better describe the system and allow flexibility in considering multiple scales, flood sources and pathways (Narayan et al., 2012, this volume). The approach towards the application of this conceptual model was the same for all three estuaries: a large-scale SPR model applied to the estuary as a whole provides a way to identify main units within the estuary, and a more detailed small-scale SPR model for the specific unit of interest. In the Scheldt estuary the SPR results on the affected areas are compared with existing flood maps. In the Gironde, the SPR methodology is linked to a full-scale Decision Support System that maps and quantifies risk.

The 2D SPR model diagrams for each site are built for the natural floodplain of the maximum considered event. This can be done manually using e.g. Microsoft Publisher 2010, a standard program in Microsoft Office 2010, but can also be automated in a GIS environment. From these diagrams, system-level information is extracted about each floodplain and its flood sources. One such metric that is described here is the relative exposure of floodplain elements. The elements are classified in terms of exposure based on their distance away from the flood source expressed in number of links. Elements that are less than two links away from the flood source — i.e., elements that have one or zero intervening elements between themselves and a flood source, are classified as exposed. Elements further than two links away from sources are termed ‘far elements’. The choice of two links is an arbitrary choice to differentiate element exposure, based on the reasoning that in most urban floodplains the first element encountered would function as a flood defense. The validity of this assumption should be verified for each study site. In this paper we have limited the discussion to two links. Three aspects of the floodplain are analyzed in each site: a) the relative percentages of different land-uses across the most exposed elements; b) the average number of flood sources per floodplain element and; c) the critical direction of flooding corresponding to maximum exposure of floodplain elements.

The direction of flooding is calculated based on flood source — floodplain element links as follows:

1. Using a coordinate system with the regular convention of N–S as the y-axis and the center of the floodplain as the origin, the flood sources are categorized as North (N), South (S), East (E) or West (W).
2. The number of floodplain elements exposed to each source is tallied. Only floodplain elements at most two links away from the source are taken into consideration. The numbers obtained are used to calculate the coordinates of a point: the x-coordinate being the difference between W vs E and the y-coordinate the difference between N vs S.
3. The critical direction of flooding is estimated as the angle of the arctangent line from the origin to the calculated point. Since the flood sources are discretized into North, South, East or West in the SPR, the dominant flood direction indicates the predominant source in terms of the number of linked, exposed floodplain elements. Note that this is a way to visualize the dominant flooding direction (flood source) but that the resulting direction is not connected to real world co-ordinates.

To illustrate the procedure, we refer to Fig. 6 for a simple example. In this example there are seven floodplain elements and two sources. Source S1 (North) is connected to four floodplain elements that are maximum two links away: floodplain elements 24, 25 and 26 are 1 link away and floodplain element 27 is two links away. Source S2 (East) is connected to seven floodplain elements: floodplain elements 26, 27, 28, 29 and 30 are 1 link away and floodplain elements 25 and 24 (linked via element 27) are two links away. The arctangent of 7 pointing west and 4 pointing south, gives a dominant flood direction of 240° from North.

Extreme coastal water level is a key parameter for assessing coastal flood risk and changes in the future climate. It is the superposition of a slowly changing mean sea level, astronomical tides and storm induced surge.[1] River flow and waves are, depending on the local situation, two other possible sources of flooding in an estuary. The influence of river flow rate will depend on the ratio between tidal flow and river flow. It will be important in those locations where fresh water exchange is considerable with respect to the tidal exchange flow. Waves influence flooding by set-up and overtopping/breaching mechanisms. They can become important in situations where there is a large fetch which is typical in the downstream parts of an estuary. All these are called source drivers in the SPR approach:

1. Mean sea level — the effect of mean water level change on extreme water level change. Note that where land movement is thought to be an important coastal process, it could be treated as a separate Source Driver and added to the effect of climate-induced oceanic changes. Sea level rise (SLR) due to climate change was found to be relevant in all three sites.
2. Wave height — the direct change in extreme wave height due to changing wind characteristics and the indirect change due to depth change produced by mean sea-level change described above.
3. Surges — the change in extreme sea level due to direct change in the surge component caused by changing storm characteristics (this is separate from the effect of mean sea-level change).
4. River flow — the change in extreme river volume/flow due to change in inland precipitation, if appropriate.

3. The Scheldt estuary

3.1. Current characteristics

The Scheldt estuary is part of the Scheldt basin (Fig. 1). The estuary is characterized by a multi-channel system in the downstream part with many sandbanks. More upstream it is a one channel system. The intertidal areas are of high nature value, with potentially high primary productivity. Migrating birds are therefore attracted to this excellent habitat. The Scheldt also serves as shipping route to the major harbor of Antwerp. The part of the estuary in The Netherlands is essential rural, whereas its part in Belgium is more densely populated and known for its intense industrial activities. From the mouth of the Scheldt near Vlissingen in the Netherlands, the tide propagates 160 km to Ghent in Belgium, where it is artificially stopped by a lock weir. Due to the geometric characteristic of the estuary the tidal amplitude increases all the way to Rupelmonde (by a factor around 1.4 some 15 km upstream of Antwerp at km 110 from the mouth). From there the amplification factor decreases to become approximately 1 near Dendermonde (at km 130) and then further decreases until Ghent (amplification factor of 0.55 at km 160 from the Vlissingen mouth) (Van Rijn, 2010, 2011).

3.2. History and functions

Land reclamation starting in the middle ages, capital and maintenance dredging on behalf of navigational needs and sea level rise have continuously increased tidal range and storm surge levels. For example the mean tidal range has increased by more than 1 m between 1900 and 2010 (from 4.4 to 5.3 m in Antwerp; Van Rijn, 2010, 2011). The largest portion (roughly 75%) of this increase in tidal range is seen as an increase in mean high water level, the remaining part (about 25%) is due to lowering of the mean low water level. The location of the highest mean water level has also moved upstream. VNSC (2010) has included water level as an indicator for assessing safety against flooding and gives detailed curves regarding the changes in high and low water levels along the estuary. More detailed physical interpretation using the theoretical principles of tide and tide propagation theory can be found in Pieters et al. (2005). Several important floods have hit the area. Still in recent memory are the disastrous flood of 1953 mainly in the Netherlands and the flood of 1976 which mainly hit Flanders. They led to the major coastal defense plans of the Delta Works in the Netherlands, completed by the installation of the storm surge barrier (Maeslandkering — used for the first time in 1997[2] on the Nieuwe Waterweg (Rotterdam area) and to the implementation of the Sigma Plan in Belgium. Execution of such plans takes decades, and these coastal defense plans have been revised along the way. The original intention of the Delta works was the closure of all mouths (except for the Western Scheldt). Largely due to ecological pressure, plans for the Eastern Scheldt were changed by building a gated storm surge barrier. Also the original Sigma Plan has been revised fairly recently based on a social cost benefit analysis, and new insights based on the creation of room for water (flood areas) have been integrated with the need for safety, nature and economic activity. Largely because of the economic activities in the harbor of Antwerp the fairway has been deepened and widened (most of it since 1970). In order to deal with the complex management of this estuarine system with on first view opposing interest of nature development, safety and economic development, there is an international Flemish–Dutch Scheldt Commission. A long term vision 2030 and an intensive monitoring strategy have been worked out to follow up on a set of indicators (LTV 2030; VNSC, 2013).

3.3. Fresh water input

The Scheldt basin is a relatively small catchment (nearly 22,000 km^2). Polder areas that drain directly into the sea are part of the basin but do as such not contribute to the discharge of the Scheldt. The Scheldt river itself has an average discharge of about 120 m^3/s. This is small in comparison with the tidal discharges at the mouth. Therefore fresh water flow does not influence water levels towards the downstream end. However more upstream the combination of high rainfall-runoff discharges and high tidal water levels may be important. This is particularly the case for the Dendermonde area (Fig. 1) where the combination of both leads to higher risk levels.

3.4. Climate change scenarios

Three future climate scenarios were selected for impact studies for the Dendermonde region in the 2080s: i) an extreme scenario (S1) combining an extreme SLR of 2 m with an increase in surge levels of 21% and an increase of 30% in upstream flow discharges; ii) a high scenario (S2) only differing from the extreme in the assumption on SLR (now set at 0.6 m); and a mean scenario (S3) where a SLR of 0.6 m is combined with a more moderate estimate of 6% for the surge levels and 16% for the upstream flow discharges. For the Dendermonde area in Scheldt estuary both rainfall-runoff and tide-surge propagation are important sources for flooding risk. These scenarios result from considerable experience with possible effects of climate change on rainfall-runoff for the Dendermonde area. They are based on detailed analysis and downscaling of PRUDENCE, ENSEMBLES and CERA databases containing several global and regional climate models and scenarios (see Ntegeka et al., 2012; Weisse et al., 2014, for more details). Running all of these scenarios is impossible or at least very impractical for further detailed analysis. Therefore a reduced set has been used to do the detailed hydrodynamic model calculations and in depth analysis. In this case study the existing experience of possible future climate effects on rainfall-runoff, has been extended with original work on possible climate effects on surge and surge propagation in the Scheldt estuary. The extension takes into account the correlation between surge and rainfall in the different scenarios used.

[1] Astronomical tides are assumed unchanged.

[2] http://www.rijkswaterstaat.nl/water/feiten_en_cijfers/dijken_en_keringen/europoortkering/maeslantkering/.

Fig. 1. The Scheldt basin district and the location of the Dendermonde area.
Adapted from International Scheldt commission.

3.5. Flood protection and hazards

The focus here is on the Dendermonde section of the Scheldt estuary only, a small area of some 30 km^2. However, the area is flood prone area at the confluence of the Scheldt river and its main tributary river, the river Dender. The Dender and Scheldt water levels are in that area influenced by the bi-directional interactions that exist between both rivers. There are many dense urban subareas and infrastructures in that region, which makes the region very vulnerable to flooding (Fig. 2). The Dender has very strong temporal river flow fluctuations. It is a river that responds very quickly to rainfall over the upstream catchments. In Dendermonde, the flow can be as low as 10 m^3/s in dry summer periods and can rise to more than 100 m^3/s in wet winter periods. To improve navigation, the tidal effects downstream the Dender were reduced by a lock weir, built at Dendermonde mid-19th century, and the river was canalized (starting from the 17th century) by several other lock weirs along the river. During high tide, the weir of Dendermonde is closed and together with two more weirs upstream, carefully regulated. During high tide periods, the upstream flow volumes are stored in the river stretches between the weirs. The river stretches act then as storage reservoirs. The stored volumes are released during low tide periods to the Scheldt, however still maintaining minimum water levels. During periods with extremely high tidal levels in the Scheldt and/or extremely high upstream Dender flows, floods can occur due to: i) Scheldt levels exceeding the Scheldt dike crests (or breaching), or ii) water storage along the Dender exceeding the river's storage capacity (Dender dike overtopping). The latter can be due to prolonged high tidal levels (hence long closure of the downstream Dender weirs), or high upstream Dender flows, or to both effects combined.

3.6. Hydrodynamic and flood model

In order to translate changes in downstream surge levels including SLR and changes in upstream discharge to changes in river water level and inundation related variables, a technical translation is needed in the form of a hydrodynamic or conceptual river model accompanied with an inundation model. For the river part, two types of models were considered: i) a full hydrodynamic model of the Scheldt and Dender rivers, implemented in the MIKE11 modeling platform of DHI Water & Environment; ii) a simplified conceptual river model for 7 points along the Scheldt and 3 points along the Dender, following the spatial discretization of the flood sources (hydraulic loading) in the SPR framework. For translating the river water levels simulated with those models to inundation related variables (inundation levels, spatial extent), the same two types of models were considered: (i) a quasi-2D floodplain model, implemented in the MIKE11/MIKE-GIS platform, where the flood plains along the river are represented by a network of flood branches and spills. The spill levels are determined by the topographical elevations in contrast to the flood branches which are topographical depressions (Willems et al., 2002; Willems, 2013); ii) a

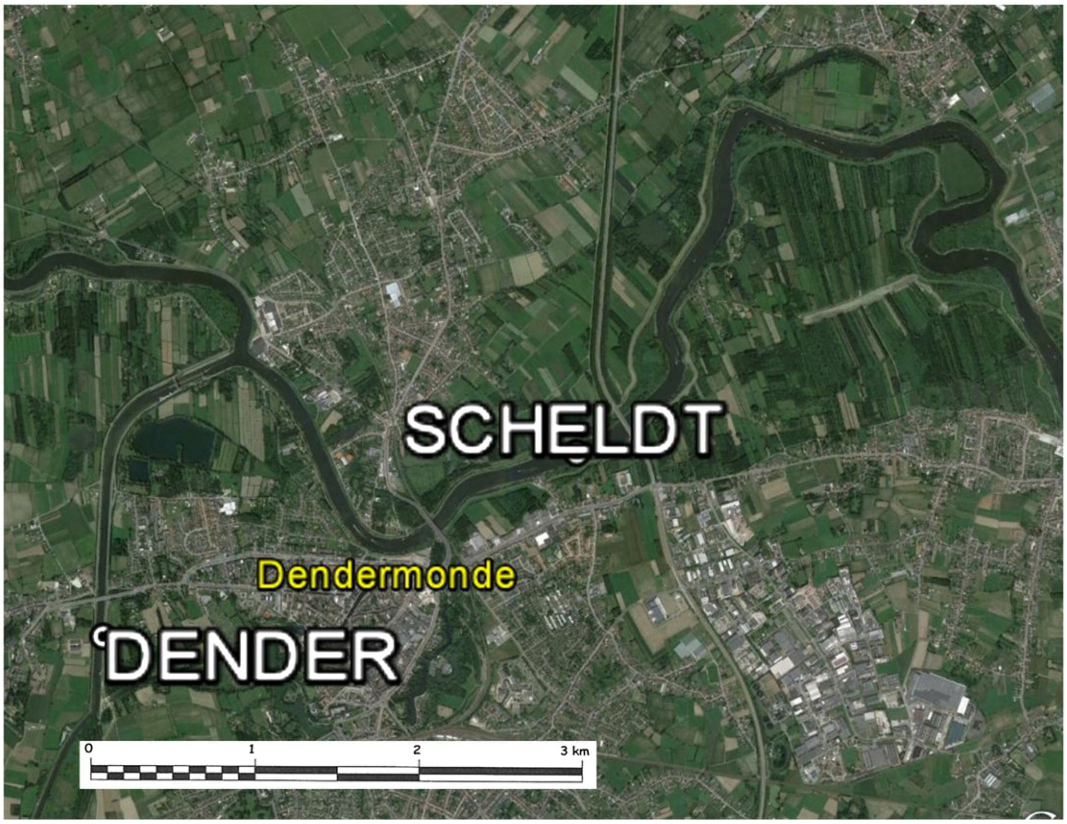

Fig. 2. Aerial view of the Dendermonde area located at the confluence of the rivers Scheldt and Dender.

simplified conceptual inundation model, considering the pathway elements in the SPR framework. In both cases, the simplified model was calibrated to the full hydrodynamic model. The full hydrodynamic model allows us to consider the most relevant physical processes, whereas the conceptual model has a reduced computational time and is better suited for integration in the SPR framework. The conceptual inundation model uses a linked-storage-cell approach where each element of the SPR is considered as a reservoir with an average elevation and a storage volume based on a storage depth variable which is used to calibrate the model. Flood water from the source(s) is spread across the floodplain through these elements until all the elements are full. The method is simple and provides rapid, basic information on flood extent and depth. The accuracy of the model is dependent on the resolution of the 2D SPR elements.

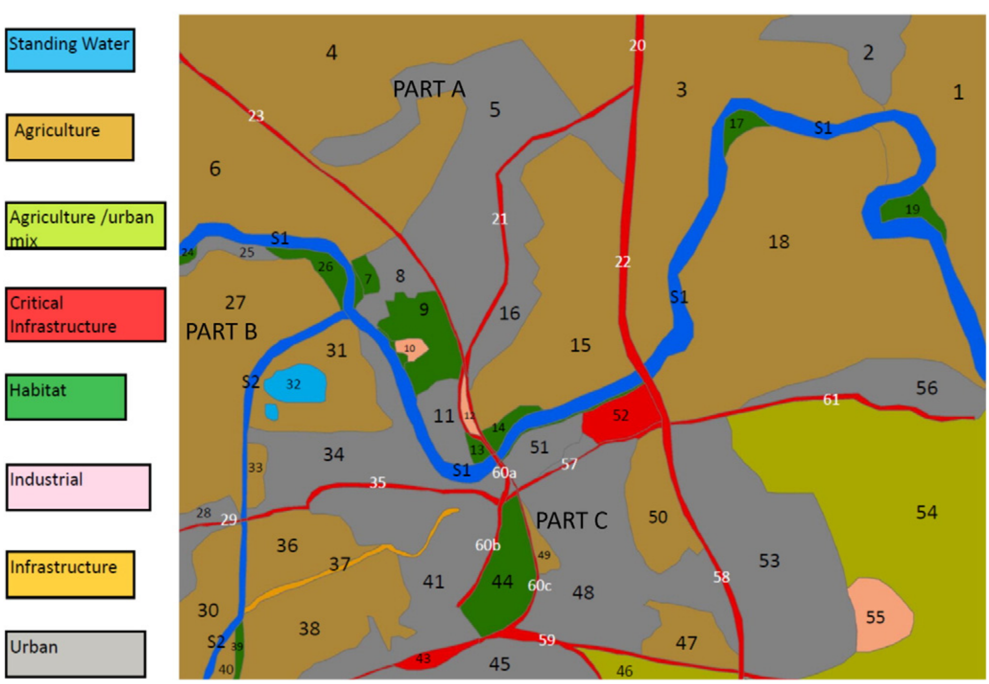

Fig. 3. Land use map of the Dendermonde area.

3.7. Schematic representation of the SPR model

The 2D SPR model for the Dendermonde area is built using two basic inputs: a map of the floodplain indicating the maximum flood extent and the constituent land-use polygons and a digital elevation model. The digital elevation model is used to record data on polygon elevations for use in the quantitative SPR analyses. The land-use map is typically to be created by the users. This gives these users flexibility in defining specific floodplain elements of non-local scale resolution that are known to be relevant to flood risk within the floodplain, such as defense elements, natural coastal elements or inland features such as roads or pumping stations. Fig. 3 shows the land-use map for the Dendermonde area.

The construction of the 2D SPR is flexible in terms of data requirements and element representation. The detail and type of elements represented reflect existing knowledge of the floodplain. While a degree of spatial representation is maintained to be able to map the elements onto a floodplain map, the key aspects that are preserved in the SPR system diagram are the topology and links. Elements can be modified and links added or removed when this knowledge is improved. For instance a link may be added between non-adjacent critical infrastructure elements, such as a power plant and a pumping station. The combination of the digital elevation model (DEM) with the 2D SPR serves as an effective way of ensuring that key floodplain elements are not missed due to resolution issues. Furthermore, since all mapped elements are represented in the model, assumptions about individual elements become explicit to users. Note that the system diagram presented here is manually constructed from a GIS-based land-use map. 2D SPR construction for this site has also been automated in ArcGIS for subsequent integration with flood mapping models. However a manually constructed map was found to be better for visualization and to facilitate a participatory mapping approach.

3.8. Findings

The 2D SPR in Fig. 4 represents part C of the Dendermonde area in Fig. 3. It highlights the two flood sources to the Dendermonde floodplain elements. It contains the area to the South of the Scheldt and to the East of the Dender in Fig. 3. Most elements are directly exposed to one source, though the maximum is two. The dominant flood direction is 66° below the W–E axis indicating the slight dominance of the northern source over the western source in terms of number of flood source — floodplain element links. Fig. 5 shows the relative percentage distributions of the different land-uses classes across the exposed elements.

As it is situated on relatively high ground, the frequency of flooding is rather limited for the city of Dendermonde. It is relatively safe from flooding. However, if floods occur, the consequences are severe. The 2D SPR makes assumptions explicit and structures understanding of the complex Scheldt-Dender system, the different flood sources and pathways (as described above) and the interactions. Since flooding in Dendermonde is driven predominantly by elevation rather than land-use, the 2D SPR by itself did not add knowledge regarding the flood risk. The construction of the 2D SPR did, however, provide knowledge regarding regional differences and severity of the consequences. For example, the region to the south-west of the Scheldt-Dender conjunction (part B in Fig. 3) was highlighted in the SPR and the flood model as being more flood-prone. Though the land-use map shows this floodplain to contain assets of relatively lower economic value (Fig. 3). The DEM identifies the floodplain as lying below river flood levels therefore making it more susceptible to flooding. The 2D SPR for this floodplain area is shown in Fig. 6.

This SPR conceptual model represents elements across a wide range of spatial resolution — as small as 15 m for the road and as large as 2000 m for the agricultural areas. The floodplain extent as well as

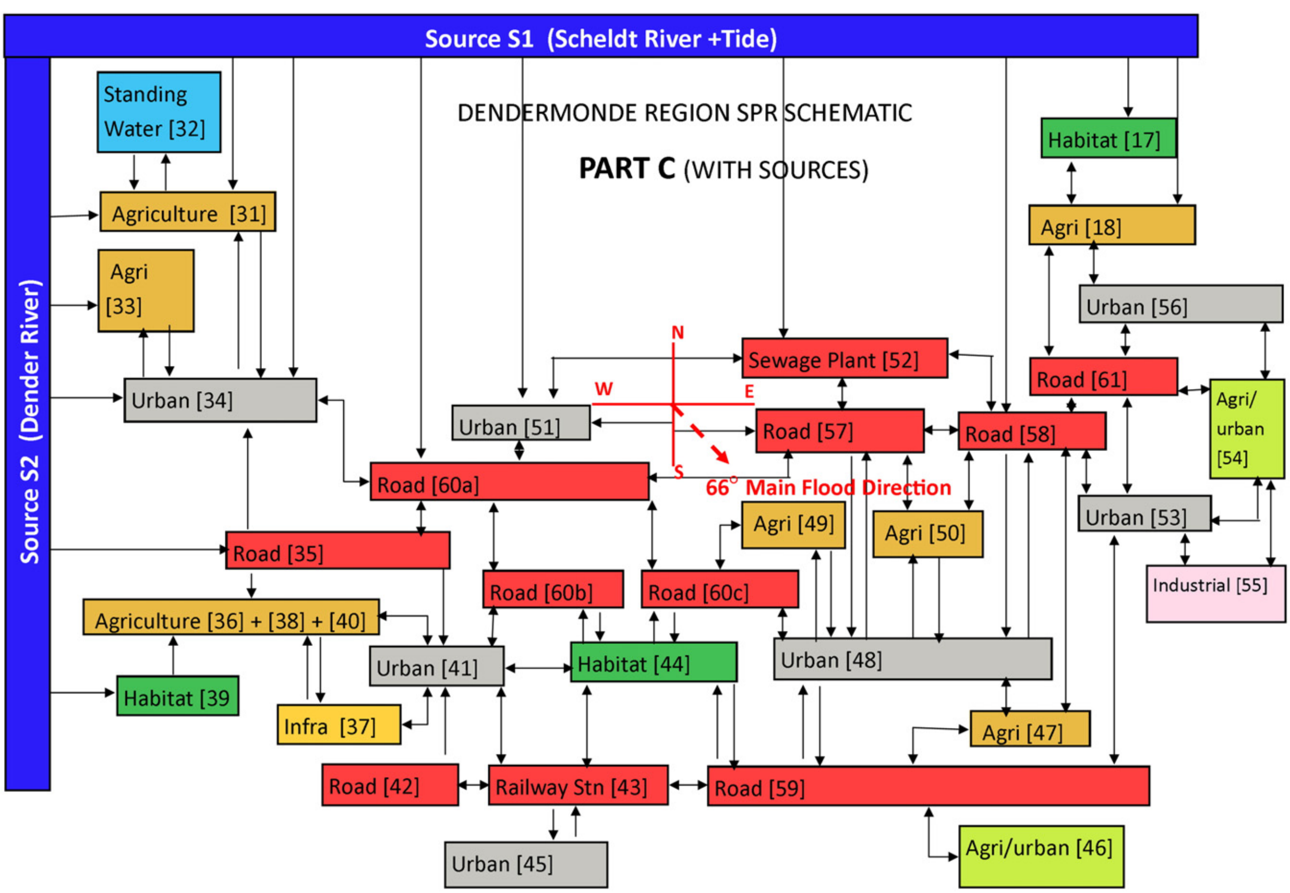

Fig. 4. Dendermonde city 2D SPR system diagram (red coordinates, arrows and text indicate critical flood direction).

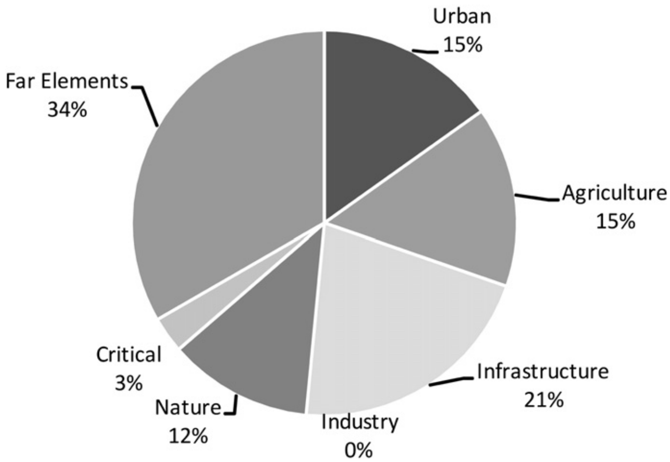

Fig. 5. Land-use distribution of exposed elements in the Dendermonde city floodplain from the 2D SPR (far elements are considered less exposed and their division in terms of land use is omitted).

elevations are less than that of Dendermonde city. All floodplain elements are directly connected to at least one flood source and are exposed on average to 2 flood sources, compared to the average of one source per element for Dendermonde city. The agriculture element in the north is seen as most critical since it forms the pathway to four out of the six floodplain elements. Adequate measures preventing the agricultural element 27 from acting as a flood pathway can therefore effectively serve as flood protection for the surrounding linked elements. From the DEM it can be seen that the road and urban areas are safe from flood levels less than 3 m. This 2D SPR was constructed relatively quickly and provides more insight than a basic bath-tub model, structuring understanding of the floodplain system and its relationship to the flood sources. This understanding can then inform and direct scenario selections in more detailed numerical inundation modeling.

4. The Elbe estuary

4.1. Current characteristics

The Elbe River reaches from the Karkonosze Mountains in the Czech Republic to the German Bight, North Sea. With a length of about 1094 km and a catchment area of 148,268 km^2 the Elbe River is one of the major rivers in Europe. The tidally influenced part, the Elbe estuary, extends from the tidal weir in Geesthacht to the North Sea and has a length of about 142 km (see Fig. 7).

The hydrodynamics in the German Bight dominate the hydrodynamic and morphodynamic processes in the Elbe estuary. The amplitudes and phases of the North Sea tides are heavily modified by the basin bathymetry and already get deformed by the reflection in the German Bight (Fickert and Strotmann, 2007; Nichols and Biggs, 1985). As a result of the interplay between the external forcing and the geometrical and topographical characteristics of the system, storm surges within an estuary exhibit a more complex behavior than at the open coastline. For the Elbe estuary the most important influences are those from the seaward boundary, e.g. tides, wind set-up, external surge, long-term sea level rise and to a lesser extent the freshwater runoff at the head of the estuary, mainly for the innermost part of the estuary between the weir and Hamburg.

The main characteristics of the estuary, which influence the development of a storm surge are:

- geometry of the estuary (length, depth, width, cross-sections) and roughness;
- civil engineering works (dikes, weirs, barriers, cutting off of tributaries);
- local modifications of the wind field.

4.2. History and functions

Diking, deepening and loss of intertidal area have led to a marked increase in maximum storm surge water levels along the estuary of 0.2 m to 1 m from the 1950s to the 1980s. This is accompanied by an increase

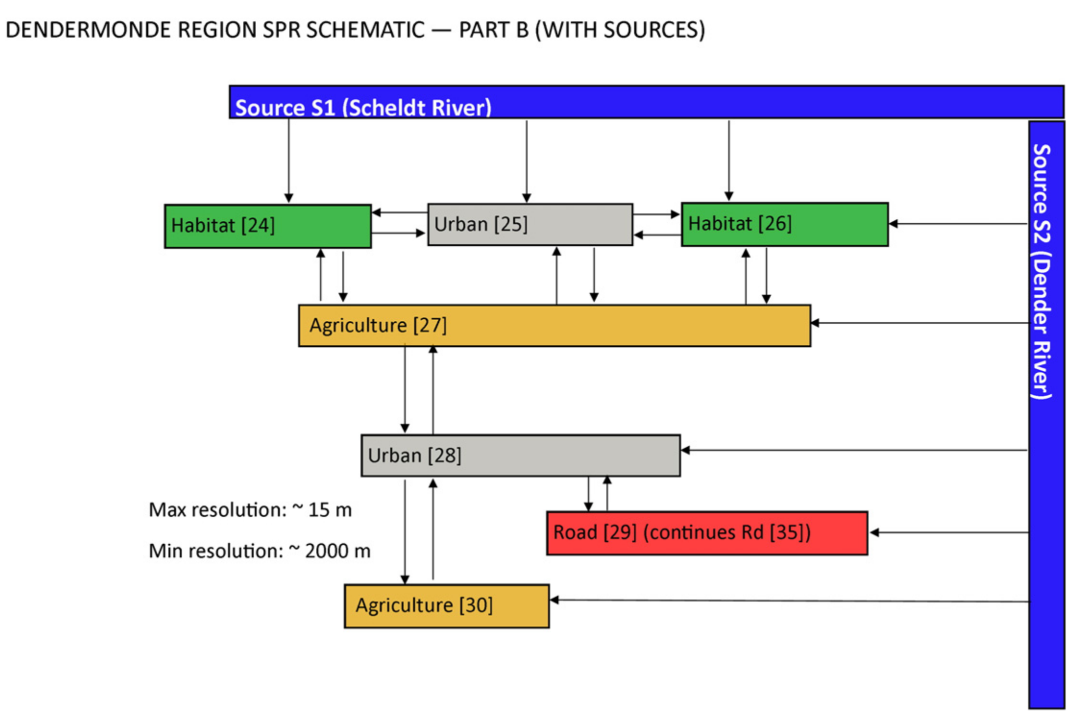

Fig. 6. 2D SPR for the floodplain to the south-west of the Scheldt-Dender confluence.

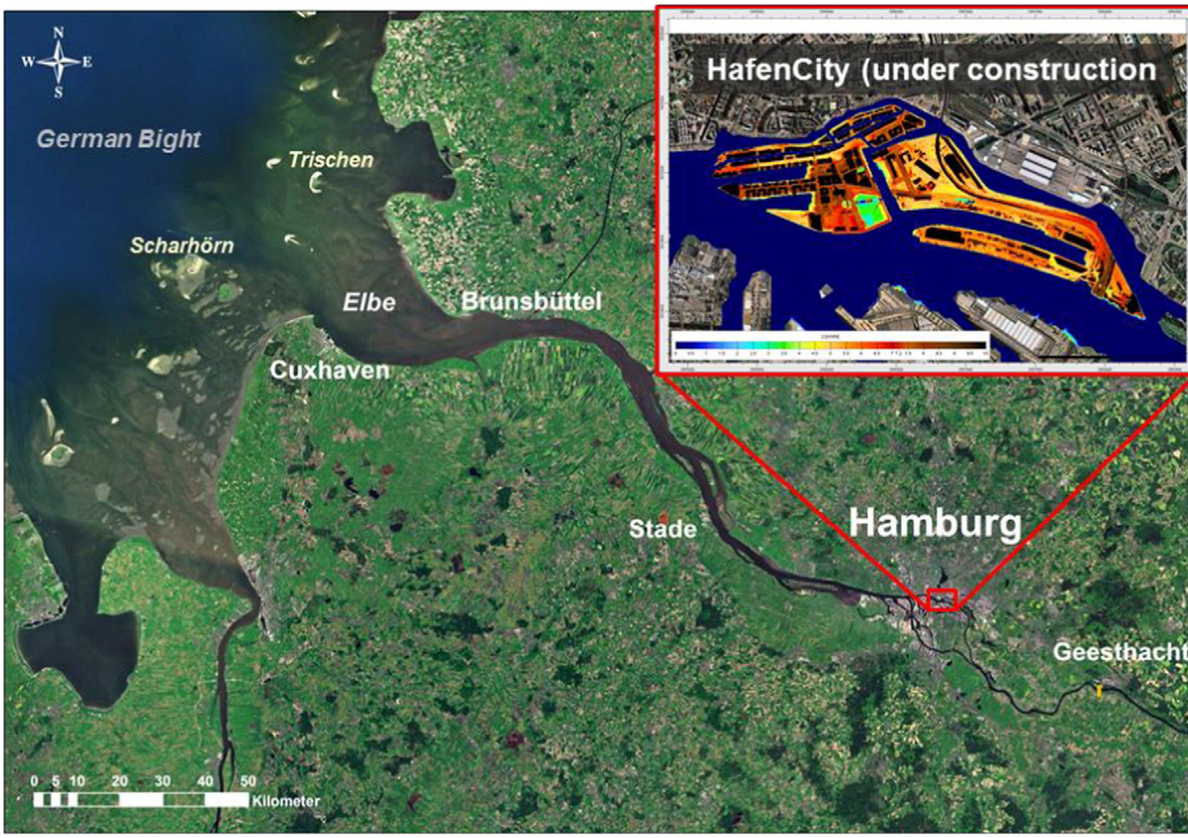

Fig. 7. Hamburg HafenCity within the Elbe estuary. (Source: Brockmann Consult, (c) 2003).

of the difference of maximum water levels in Hamburg and at the mouth of the estuary (Cuxhaven) by some 0.6 m and a decrease of propagation time of the storm surge from Cuxhaven to Hamburg by 1 h (Fickert and Strotmann, 2007). During the 1962 flood extended inundations occurred in Hamburg, after which massive investments in coastal defense infrastructure were made; dykes were raised to 7.20 m above German datum (NN (Normal Nul) = mean sea level around 1900). Due to advanced investigations and reviews dykes were raised further to a level between 8 m and 9.3 m above German datum beginning in the 1990s. Since 1962 several high storm surges occurred with heights between 5.5 m and 6.5 m above German datum, but only resulting in minor damages (Rohde, 1971).

The natural development of the estuary, including the adjustment to sea level rise, was interfered with by canalisation and the construction of controls such as dikes and barriers. Without such interference, the marshlands would have increased across the whole cross section. Dewatering the land behind the dikes led to consolidation. With the absence of sedimentation the hinterland ground level could not rise to match the rate of the constantly rising water level of the Elbe River.

The drainage of the hinterland has become more and more difficult. Since 1950 foreshore areas and flood plains of the Tidal Elbe River were reduced by 180 km^2. And with the construction of river barriers, the foreshore areas of the tributaries were also no longer available as flood plains. This meant that even more ecologically valuable intertidal areas had disappeared. Although some measures within the mouth of the estuary helped to restrict storm surges, Siefert and Havnoe (1988) showed that all diking measures together led to an increase of the maximum peak water level of almost half a meter at Hamburg during storm surges.

Apart from the historic development of coast protection and the cutting off of the tributaries by constructing barriers, the Tidal Elbe River has also seen large-scale changes as an important navigable waterway. As a result of the industrialization and the growing needs of a changing merchant fleet at the beginning of the 20th century, river engineering measures were necessary. These included the construction of training walls, alteration of cross-sections and the expansion of the ports of Hamburg, Cuxhaven, Brunsbüttel and Stade. These added to the natural changes in hydrodynamics over several centuries such as expanding channels, formation of new channels, migration of channels, sea level rise and those induced by geological and meteorological changes.

The hydrodynamic development of the tidal parameters is therefore characterized by an increase in the high water level and a decline of the low water level. This development is more significant further upstream. Along the estuary the maximum tidal amplitude is attained at the tide gage St. Pauli in Hamburg. The current avarage is about 3.6 m. 150 years ago the tidal range was about 2.0 m in St. Pauli (Fig. 8). The increase in tidal range is mostly due to the decline of the low water level making up about 2/3 of the variance. Note that this is different from the Scheldt estuary where the increase in tidal amplitude is mostly visible as an increase of the high water levels (see Section 3.2).

4.3. Fresh water input

The freshwater inflow from the catchment varies throughout the year, with maximum values generally in spring (>1500 m^3/s) and minimum values in summer or autumn (<300 m^3/s). The long-term mean of the freshwater run-off is about 709 m^3/s (Deutsches Gewässerkundliches Jahrbuch, 2008). Although there is a considerable variation in fresh water discharge [minimal discharge: 145 m^3/s (1947) and maximal discharge 3630 m^3/s (1940)], the effect on water-levels in the receptor area amounts to only some 10–15 cm, which is only 2.5% of the maximum storm surge contribution of 5.0 m.

4.4. Climate change scenarios

For the Elbe study site, only the IPCC scenario A1B is evaluated. Following Weisse et al. (2014) a sea level rise in the German Bight of 30 cm

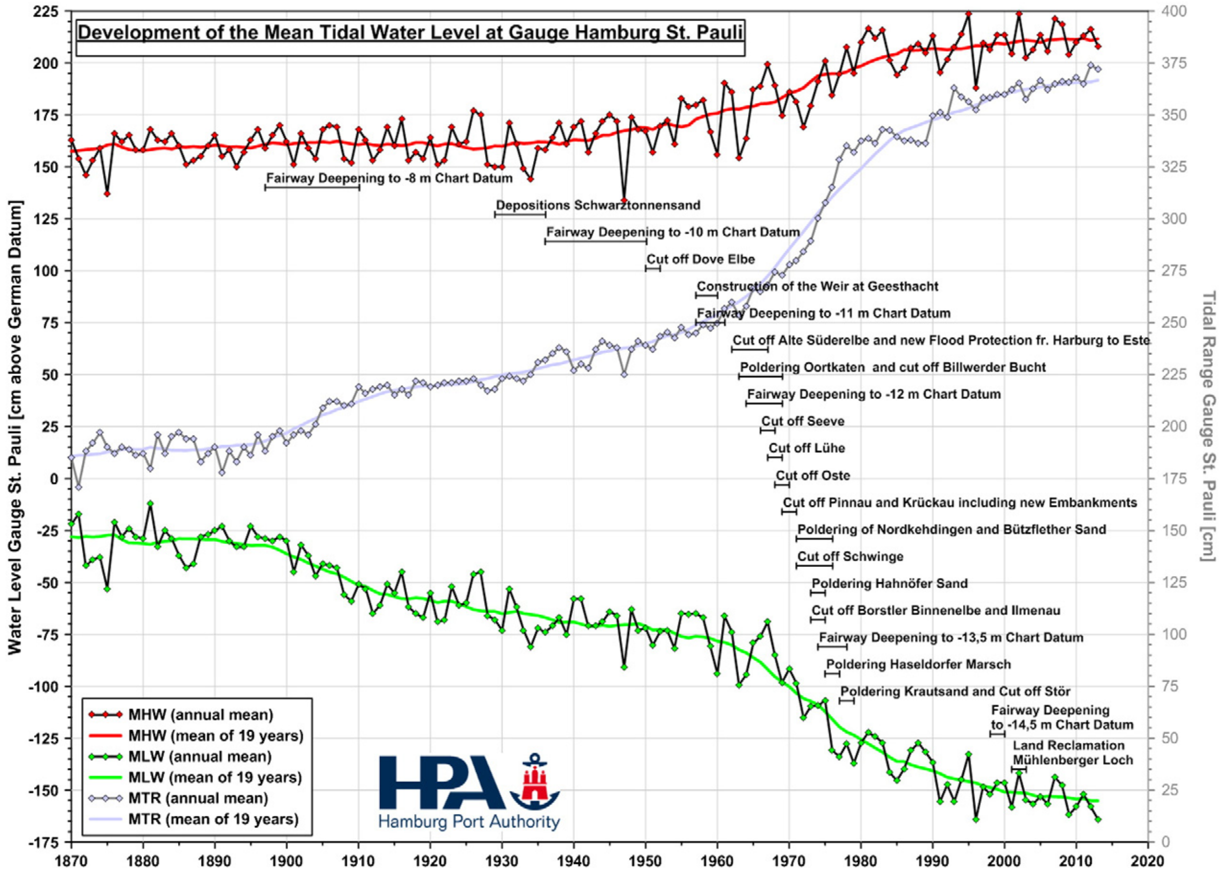

Fig. 8. Development of the mean high water and mean low water as annual values and 19-year-average values at the tide gage St. Pauli in Hamburg. Source: Hamburg Port Authority.

(2025), 50 cm (2055) and 90 cm (2085) is assumed. In this often used scenario there will be no significant changes (exceeding the natural variability) in waves and surges. The river flow will not significantly be altered, but its seasonality will change (higher flow in winter, lower in summer). For the receptor area of HafenCity in Hamburg only the sea-level rise will give a higher flood risk in the future. For this study site the 1/100 year event is considered as the extreme event.

4.5. Flood protection and hazards

Flood protections in the Elbe estuary are designed for a predicted storm surge in the year 2085 including climate changes (see Section 4.4). Since the receptor area HafenCity is located 100 km upstream of estuary mouth, it is quite sheltered from wave action and is mainly affected by storm surges. The HafenCity district is located between the main Elbe river and the public flood protection line along the river banks (Fig. 7) and its surface area is only a couple of square kilometers. The elevation of the area ranges from +4.4 m to +7.2 m above German datum, and is thus within the potential flooding area of the Elbe.

The conversion of the harbor areas into an inner city quarter is still in the construction phase and requires the development of structural and organizational solutions to protect people and buildings from flooding and also requires the listing of routes that enables the fire and rescue services to gain unlimited access in the event of flooding. Therefore it was decided to apply a new flood protection concept, putting new buildings on dwelling mounds well above the highest expected flood level. A previous study indicated a required minimum level of +7.5 m above German datum of the dwelling mound. The flood protection of single buildings is achieved by an ever increasing number of flood gates in the lower levels of the buildings. Providing this protection is left to the land owners.

The HafenCity site will be realized in development and building stages of various scales. The artificial dwelling mound solution is a suitable solution for phased development, because even single mounds provide complete protection. On the other hand not all buildings and street connections can be shifted onto an artificial dwelling mound, so that flood protection measures at single buildings have to be installed and inundations of streets and infrastructures cannot be avoided (Fig. 9).

4.6. Hydrodynamic and flood model

Flood maps for the HafenCity area were generated by using the numerical model FVCOM (Finite Volume Coastal and Ocean Model). FVCOM is a prognostic, unstructured-grid, finite-volume, free-surface, 3-D primitive equation coastal ocean circulation model developed by joint efforts of UMASSD and WHOI. The details and results of the flood simulations are given in Ge et al. (2013). Two historical storm-induced flood events were simulated. The results showed a significant flooding situation under the strong storm process, such as the 1999 storm. The extent of flooding in HafenCity will be significantly increased under short-, middle- and long-term sea-level rise (SLR) scenarios of 0.3 m, 0.5 m, and 0.9 m. Most of the additional flooding occurs in areas that are already flooded under present conditions. These areas are intentionally exposed to flooding and consist of streets, low-lying canals, embankments and historical buildings, which cannot be shifted to the artificial dwelling mounds. The additional impacts of the mid- and long-term scenarios result in higher water depths in the already flooded areas. The relatively highest increase of flooded area results from a SLR of 0.3 m. The maximum flood water level in the 2085

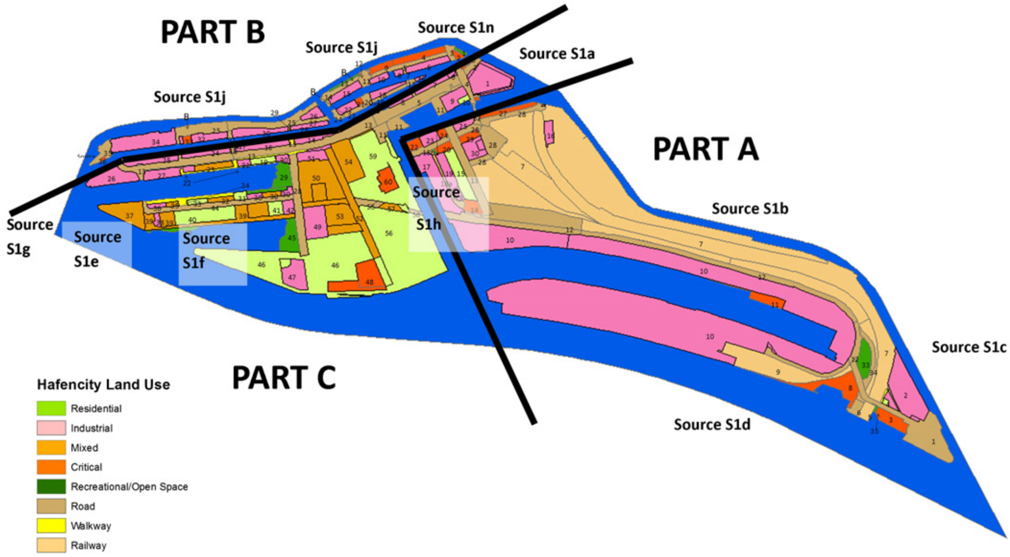

Fig. 9. 2D SPR Land-Use map for HafenCity area, based on the development scheme and land-use plan (year 2010).

scenario (SLR = 0.9 m) is 6.80 m above German datum. In summary, the peak flood levels will rise according to the respective SLR, while the flooded area will increase by 18% (2025), 34% (2055) and 54% (2085). The absolute values are 0.266 km^2 (present), 0.314 km^2 (2025), 0.356 km^2 (2055), and 0.410 km^2 (2085).

In contrast to the Dendermonde study site where a full 1D hydrodynamic model was used in combination with a conceptual river model and accompanied by a separate inundation model, the hydrodynamical modeling for the HafenCity study site was done with the 2D hydrodynamic model FVCOM. The main reason for this was the fact that 2D flooding maps for the different parts of HafenCity were required. The disadvantage of using this approach is that only a few selected events (here two strong storms) can be simulated because of computational demands.

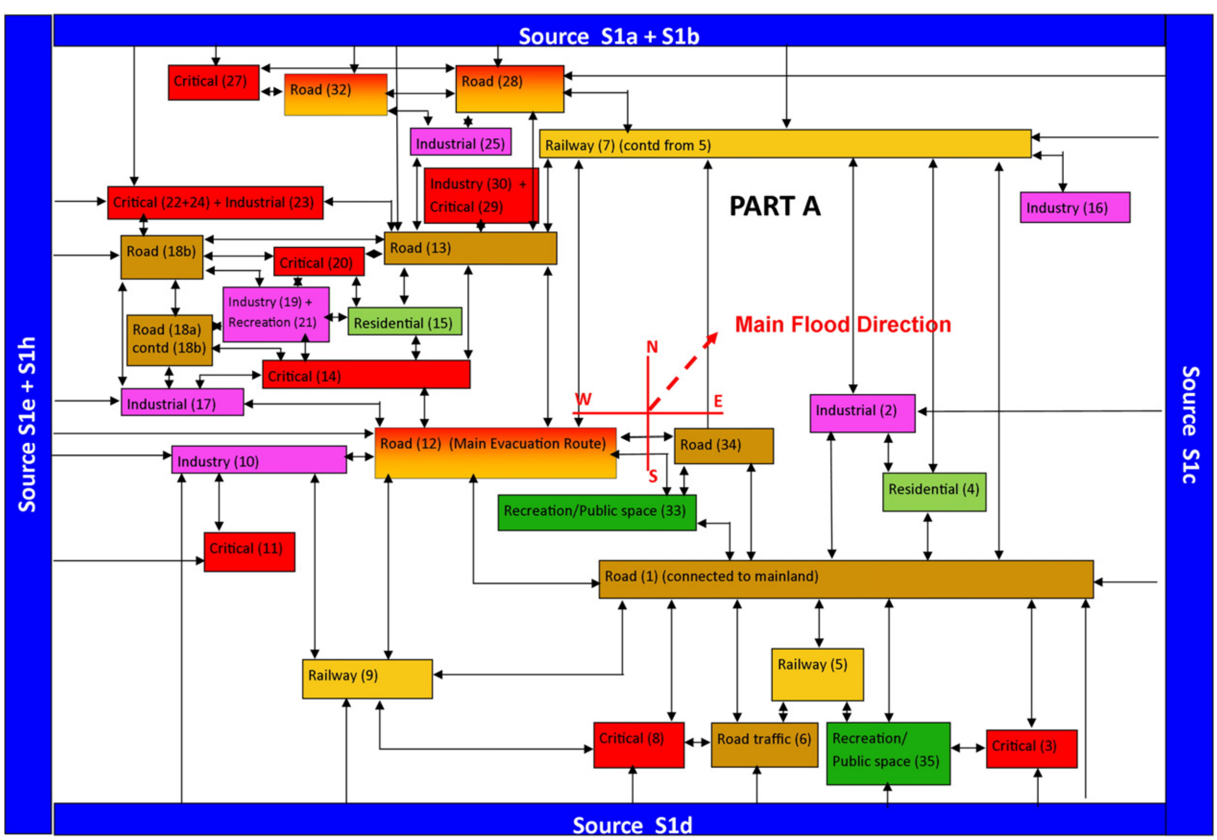

Fig. 10. SPR for Part A of the HafenCity area (right side island on land-use map, Fig. 9).

4.7. Schematic presentation of the SPR model

As already mentioned, the SPR approach focused on an area with readily available data and where flooding can occur. This led to the construction of a small-scale SPR model of the HafenCity, focusing on critical infrastructure and evacuation routes.

For this the HafenCity was divided into three parts (A, B and C — see Fig. 9). The SPR for the Part A is illustrated in Fig. 10. For the implementation of this schematic and linkage diagram, the following information was utilized:

- land-use map and development scheme of the year 2010;
- flood maps for present and future scenarios;
- defense and evacuation plans;
- relevant administration boundaries.

Roads, railways and evacuation routes are seen as critical for the flood safety of this part. Since the HafenCity region is still under construction, a validation of the flood model is not possible. The SPR model offers an alternative way of verifying flood model results based on expert opinion and local knowledge. For instance, the FVCOM numerical model results for Part A of the HafenCity does not indicate flooding in the region of Elements 2–4, though these are shown as linked to flooded zones across Element 1 (road/evacuation route). The FVCOM numerical model however does not resolve all small-scale canals and structures.

4.8. Findings

The HafenCity floodplain is unique amongst the three sites in that it is a series of connected islands. The SPR analysis for Part A of the HafenCity floodplain (Fig. 10) indicates an average of two flood sources for every exposed element and a maximum of four. The dominant direction of flooding is 56° (clockwise from North — red arrow in Fig. 10). In contrast the most vulnerable areas are affected by northern and eastern flood sources. Fig. 11 shows the distribution of land-uses across these elements.

Global (climate change, e.g. sea level rise) and local (civil engineering, e.g. flood defense, fairway adaptation) effects influence the flood risk in the Elbe estuary and the receptor area HafenCity in the same order of magnitude. This holds for the normal (mean) and storm surge conditions.

The SPR model of HafenCity highlights the sensitive receptors, which in some cases were not identified in the flood maps generated by the FVCOM numerical model. This reflects the fact that it is virtually impossible to include all the linkages and small-scale structures of the SPR model within the numerical model layout. The SPR approach can enable a better assessment of possible consequences of floods.

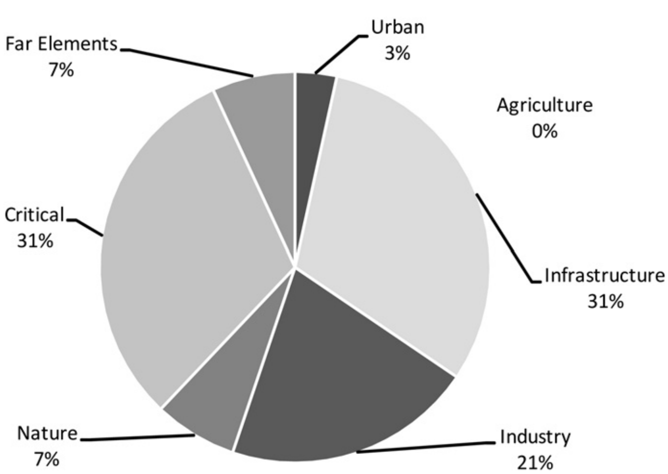

Fig. 11. Land-use distribution of exposed elements in HafenCity Part A (far elements are considered less exposed and division in terms of land use is omitted).

The sensitivity analysis of the receptor area can also be useful for the optimization of evacuation routes and plans. Moreover the results of the SPR analysis can be utilized in the next construction stages of HafenCity.

5. The Gironde estuary

5.1. Current characteristics

The Gironde is the largest estuary in Europe with a surface area of 635 km^2. Saline water flows upstream up to the confluence of the two rivers Garonne and Dordogne near Ambès. The distance from there to the mouth of the estuary is about 75 km. However, tidal waves are felt farther upstream, up to 170 km from the mouth, near La Réole (Fig. 12).

Due to the funnel shape of the estuary, the tidal amplitude increases when it propagates towards the continent. For average tides, the amplitude is about 3.1 m at the mouth and goes up to 4.2 m in Bordeaux before decreasing again. The wave is strongly asymmetric, all the more so upstream, with the ebb tide lasting for about 2/3 of the semi-diurnal period.

5.2. History and functions

The risk of flooding has always been a major concern of authorities along the estuary. Champion (1862) show that it was the case at least since the 13th century with several consecutive floods of the Garonne and Dordogne in 1212, 1310, 1425, 1523, 1536, and 1542. The most damaging flood occurred in April 1770, when about 24,000 km^2 were covered by water along the Garonne and Gironde, causing enormous damage in the city of Bordeaux. Special aid was offered by the king to help in the rehabilitation of the city. From this point, measures were taken to limit the consequences of flooding. However, they did not prevent new strong floods to occur in 1835 and in the following years, 1855 and 1856 and above all 1875 when 500 people lost their lives. In 1930 again, floods caused the destruction of 1000 houses and more than 300 human lives were claimed. In the last decades, three main events are burnt in the memories of people: one in December 1981 mainly due to strong river discharges in combination with high tidal amplitude, then the Lothar and Martin storms in 1999 and most recently the storm Xynthia in 2010.

Repetitive floods led to an early adoption of preventive policies and protection measures. However, previous experience show that those policies still lack coordination at the scale of the estuary (de Vries et al., 2010).

Contrary to other European estuaries, the estuary of Gironde still relies very heavily on its natural functioning with a unique ecosystem that allows for the growth of special species of fishes which are not found elsewhere in France, like the European sea sturgeon. Those species are threatened today by the contamination of river water and by strong anthropogenic pressure. Fishing is commonly adopted along the estuary and it contributes to 6% of the total fishing activity in France. A large part of the coastal area is dedicated to vineyards. Industry is quite well developed upstream of the estuary, with oil refineries and chemical industries near Ambès and a nuclear power plant near Blaye. Activities in the tertiary sector are well developed near and in Bordeaux.

The morphodynamic evolution of the bottom of the estuary which is responsible for the creation of new islands and for the displacement of current ones, has made navigation difficult, but this did not prevent Bordeaux from being the first French harbor until the nineteenth century. Today, two channels are dredged to allow for the arrival of ships in Bordeaux, Pauillac and Verdon.

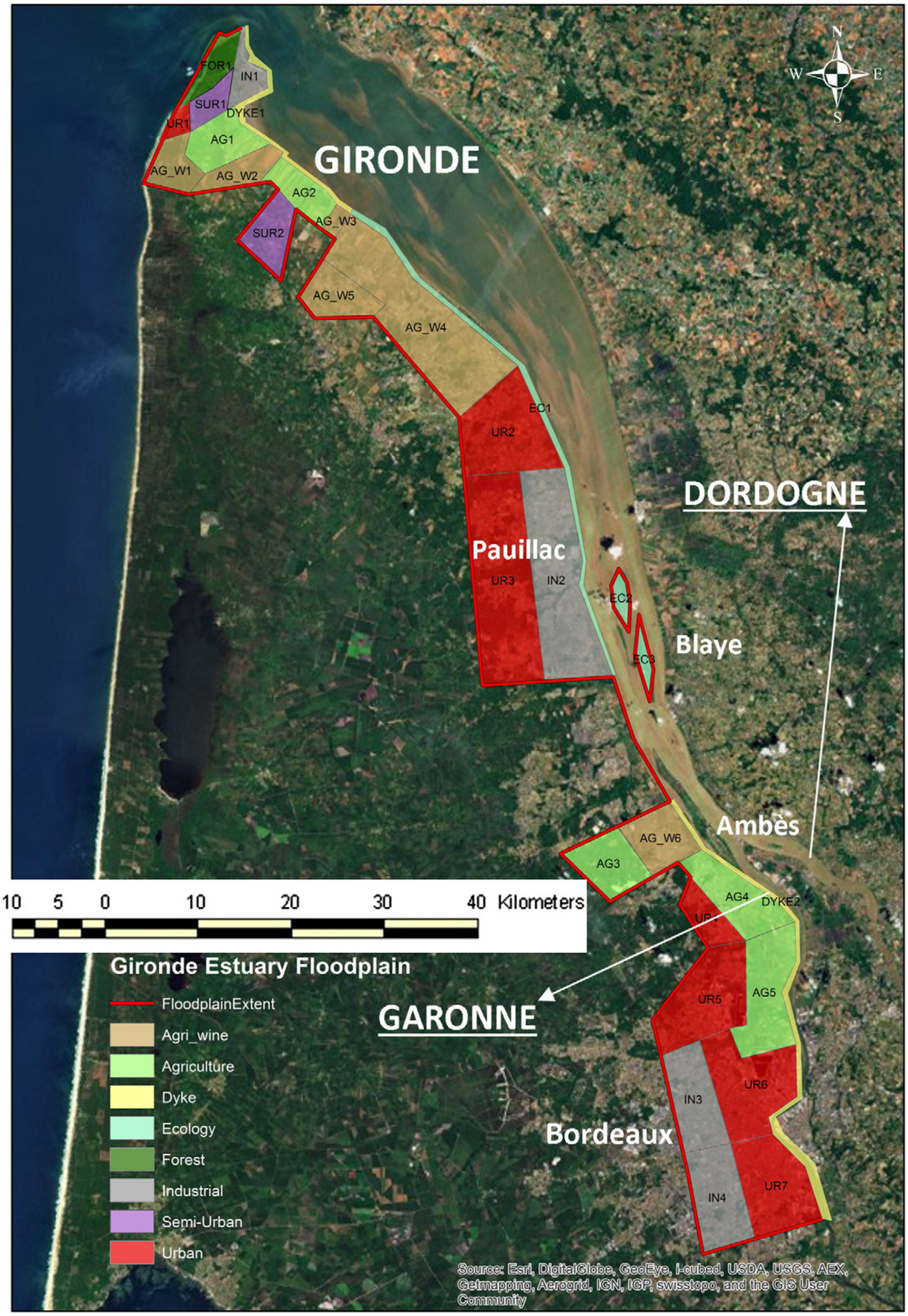

Fig. 12. View on the Gironde estuary. Land use is superimposed for the left bank only.

5.3. Fresh water input

At the mouth of the estuary, the total oscillating volume during a tide is about 1.75 billion m^3 and it decreases according to an exponential law with respect to the distance to the mouth (Mignot, 1969). At the confluence, some 75 km upstream, this is reduced to 80 million m^3 among which 52 million m^{3}flow to the Garonne and 28 million m^3 flow to the Dordogne. In one year, it can be estimated that about 900 billion m^3 enter in the estuary at the mouth, and about 35 billion m^3 flow through a transverse section in Bordeaux.

In comparison, the average combined river discharges of Garonne and Dordogne is 30 billion m^{3}per year at the confluence in Ambès. At

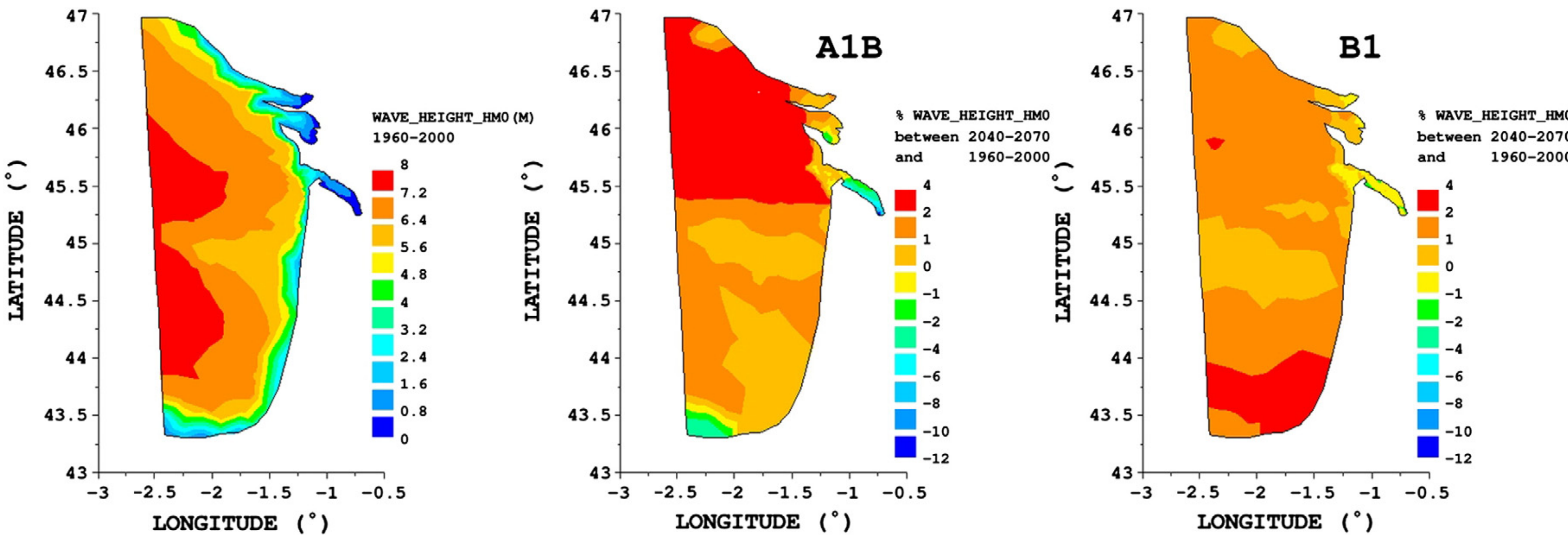

Fig. 13. 100-year return period wave heights for present conditions, and change in % for the future period 2040–2070 under climate change scenarios A1B and B1.

this point, the river discharge is in the same range of value as the tidal oscillating volume. The discharge of Garonne may exceptionally reach a value of 8000 to 9000 m^3/s, but usually does not exceed 4000 m^3/s with an average discharge of 620 m^3/s. In summer, low flows may lead to discharges under 200 m^3/s. Dordogne's discharges are lower and seldom exceed 2000 m^3/s with a yearly average value of 270 m^3/s in Bergerac.

The above figures show that the discharges of Garonne and Dordogne rivers contribute in a substantial way to the level of flood risk along the estuary, especially upstream from the confluence of the two rivers in Ambès. During an interview at the beginning of the Theseus project, the chief fireman of the Gironde department in Bordeaux indeed stated that the risk is due to the addition of four components: high storm surges, high tides, strong winds and high river discharges. Major events in the last three decades resulted from the combination of three of those factors, but an extreme event combining all four causes can still be expected.

5.4. Climate change scenarios

Climate change is expected to have an impact on the hydraulic loads on the mouth of the estuary. One of its main consequences will be a rise in the average level of sea. According to the French office for studies on climate change (ONERC, 2010), three scenarios have to be considered: an optimistic one with a sea level rise of 0.40 m, a pessimistic one with a rise of 0.60 cm, and an extreme one with a rise of 1 m, all rises by the end of the century.

Waves and storm surges may also vary due to a change in the surface winds on the Atlantic Ocean. Waves only have an influence on the rather rural territories near the mouth of the estuary. For this source, two hydraulic models were built using the Tomawac software, one over the full Gascogne Golfe, the other centered on the Gironde estuary (Morellato, 2010). Its resolution is between 1° offshore and 0.25° nearshore. The model was forced with winds from both a global climate model (ECHAM5) and the European one provided through the Theseus

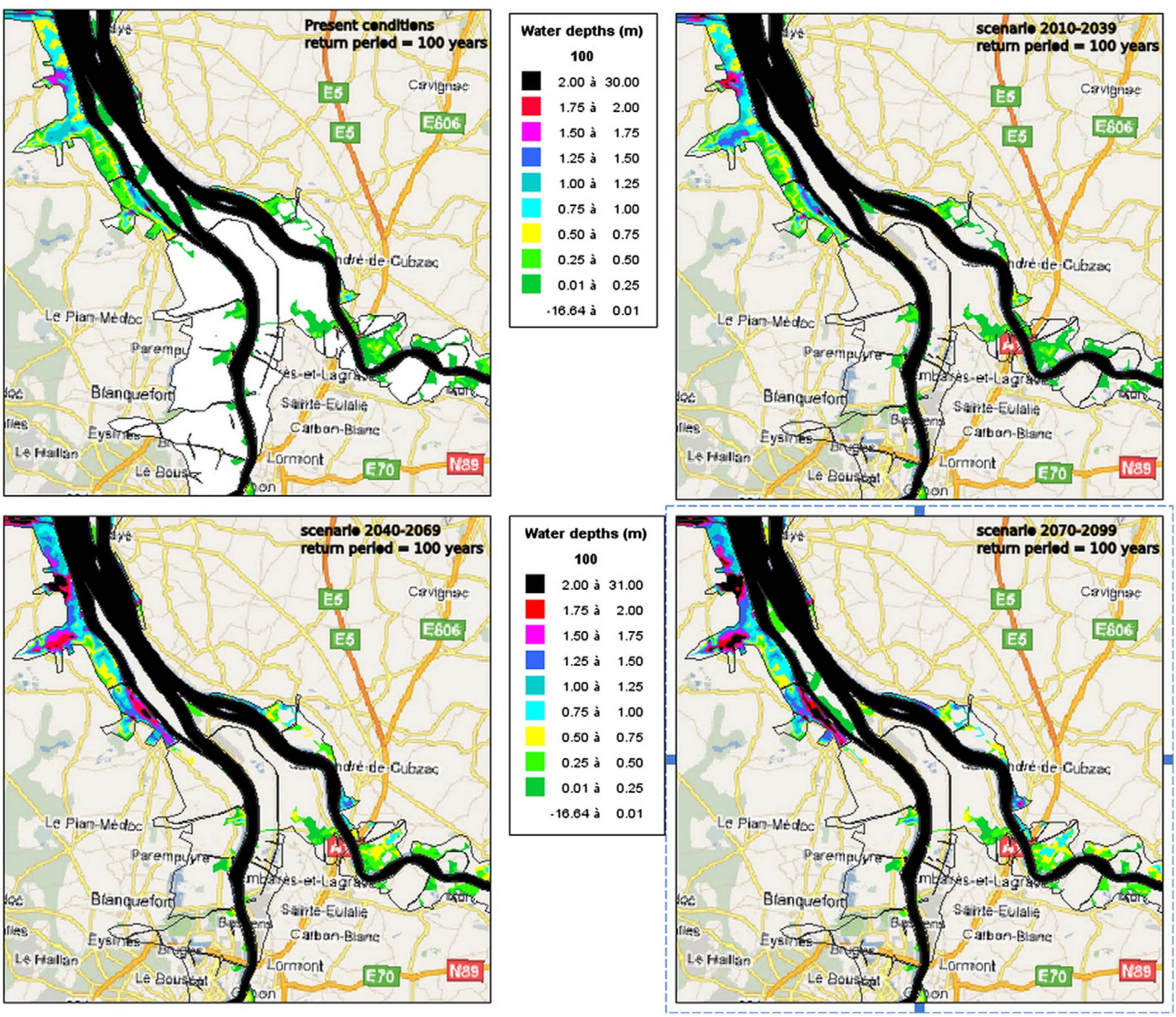

Fig. 14. Water levels for 100-year return period flood, near the confluence of the two rivers, for present conditions and three future time slices.

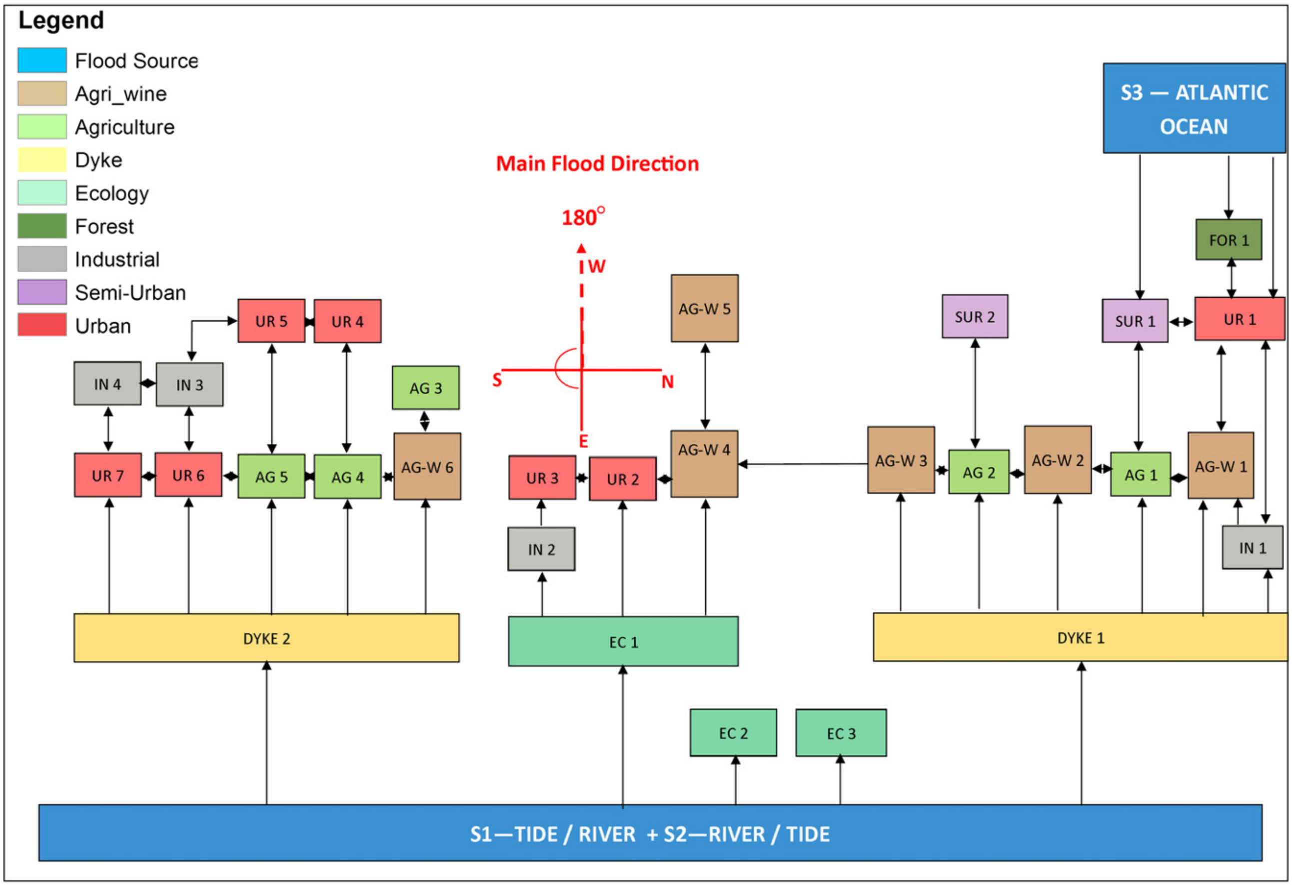

Fig. 15. Large-scale SPR for Gironde estuary.

project (Weisse et al., 2014). Simulations were made for two time slices: 1960–2000 to calibrate the model, and 2001–2100 to evaluate how conditions will change. For the future period, two global climate change scenarios from IPCC were used: A1B and B1. A1B has a more economic focus with a balance between fossil and non-fossil energy resources, while B1 has a more environmental focus. The results, partially presented in Fig. 13, show that the average wave height tends to decrease until 2100, but variations are generally slight (between −10% and −4%). The number of storms decreases a little while extreme wave heights slightly increase (up to 3% for A1B scenario, 1% for B1 scenario). These changes are quite small but seasonal analysis shows larger variations, with a 10% increase of wave heights during winter and a 25% decrease during summer.

Storm surges were correlated with local wind data near the mouth of the estuary through a simple relation where the storm surge is a sum of three terms, one proportional to the square velocity of the wind, the second proportional to the pressure, and a third constant term (Laborie et al., 2012).

The coefficients of this correlation were calculated on a set of 10 selected extreme events with an average duration of two weeks each. The correlation function was then run for the next century, using as input the CLM/SGA database for future winds (Weisse et al., 2014). Those calculations led to the conclusion that extreme storm surges generally decrease in the future. 50 and 100-year return period surges decrease by about 5 cm by 2050 and 8 cm by 2100.

There is more uncertainty about the change in river discharges in the future. In the absence of more detailed information, the discharges of Garonne and Dordogne were considered stationary during the next century in the Theseus risk assessment.

5.5. Flood protection and hazards

According to de Vries et al. (2010), dike management is very fragmented along the estuary with for example more than 400 owners for a stretch of 20 km. In total, there are 433 km of dikes with different levels of protection on the study site. SMIDDEST, a syndicate of municipalities and local authorities, was established in 2001 with as main aim building a consensual strategy for risk mitigation shared by all stakeholders on the estuary. One of the first actions of SMIDDEST supported

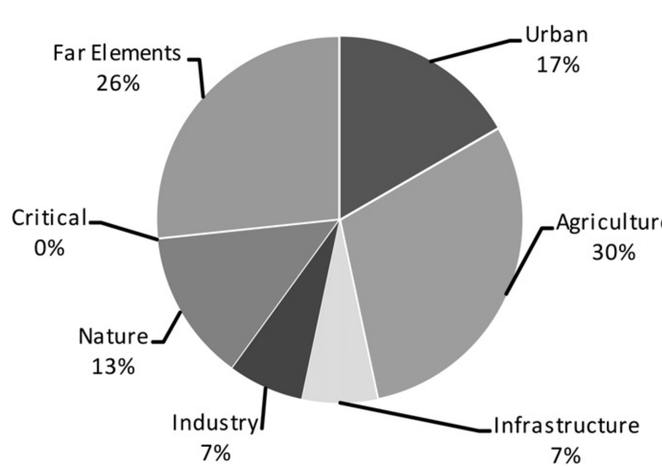

Fig. 16. Relative distribution of land-uses of exposed elements in Gironde FP (far elements are considered less exposed and division in terms of land use is omitted).

by national government was the development of a large flood database on the Gironde (RIG), including a risk assessment and a numerical model of the estuary. This tool served as a basis for the preparation of the action plan for the prevention of flooding (PAPI) which is a first co-ordinated policy for the reduction of the risk, including structural mitigation measures and non-structural options to limit the vulnerability of the exposed areas. Now, 32% of dikes along the estuary are managed by SMIDDEST and other syndicates of municipalities in a more homogeneous way (de Vries et al., 2010).

(Un)fortunately, recent events and especially the Xynthia storm raised awareness of the need for a joint approach of risk mitigation. In the aftermath of this Xynthia event, a global inspection of the state of all dikes along the estuary was carried out. This showed that the state of dikes varies a lot, with about 50% of them in good condition, 30% in moderately-good condition and 20% in poor condition.

5.6. Hydrodynamic and flood model

The numerical model of the estuary developed in the framework of the RIG (see above) was used to delineate the extent of extreme floods in the estuary for present and future conditions. The model is a 2D shallow-water model based on the Télémac software. It was adapted to take into account dikes overflowing and to simulate the flood dynamics in the flood plain. It is however assumed that existing dikes do not break during a flood event. The model was calibrated over real observations between 1960 and 2000, and run between 2000 and 2100 using as input the hydraulic loads established in the previous stage of the project (see climate change section above).

Flood extents corresponding to different return periods between 1 year and 100 years were calculated for three future periods (2011–2040, 2041–2070 and 2071–2100) by applying a peak-over-threshold statistical analysis on the raw results of the simulation for each of the 13,621 nodes of the finite-element model. Outside the river bed, a threshold of 1 cm was used, so that an event is qualified as extreme as soon as there actually is water in the floodplain. A Gumbel distribution was used to fit the number of occurrences of extreme flood events.

The Gironde Estuary is a very large area. Water levels corresponding to return periods of 2, 5, 10, 20, 50 and 100 years have been mapped for three specific sites of interest. Those are located at the maritime frontier of the model in the neighborhood of Le Verdon, at the confluence between Dordogne and Garonne rivers and in Bordeaux and its surroundings. As an example the extent of the 100 year return period flood is illustrated in Fig. 14.

5.7. Schematic presentation of the SPR approach

The Gironde is an example of a much larger-scale application. In Fig. 12 the large scale land use has construction of the SPR model (Fig. 15). Only the left bank is shown here. It covers the length of the Gironde estuary from the mouth to the city of Bordeaux and this is mapped in the SPR model with the estuary as the main source of flooding. Historic coastal recession data and shoreline models identify a potential breach location on the Atlantic Ocean side of the floodplain. This is mapped as an additional source of flooding which becomes more likely as sea levels rise. The large-scale SPR (Fig. 15) is used to identify the regions threatened by the potential breach. In addition, a detailed small-scale model SPR was developed (not shown) using existing local knowledge of designated flood pathways to describe the floodplain in case of the Atlantic Ocean breach. This full model has 97 receptors, 5 sources, and more than 200 pathways: it was used as the basis of a Decision Support System as explained below.

In the large scale model, the sources are the ocean and the two rivers. The ocean has two types of impacts: it can lead to the direct flooding of the areas west of the estuary (source S3), but tides and storm surges that propagate into the estuary are secondary sources (S1 and S2). These sources are always combined with the one originating from the river discharges. The influence of tides is predominantly downstream while the influence of river discharges is more important upstream. Waves are only important right at the mouth of the estuary. Further upstream, only water levels are involved in the flooding processes.

5.8. Findings

Analysis of the large-scale 2D SPR indicates an average of one flood source per exposed element though the maximum is three. What is most distinct in Fig. 15 is that the predominant flood direction is directly westward due to the dominance of the two riverine flood sources. However elements IN 1, AG-W 1 and AG 1 at the downstream end are affected by all 3 sources. Fig. 16 indicates the relative land-use distribution of the exposed elements.

The SPR approach showed the variety of land-use configurations that are exposed to flooding in the estuary. It helped to identify the critical elements that were threatened, which are located in the city of Bordeaux and in the industrial areas north of Bordeaux near Ambès. Moreover, it showed those sections that are exposed to three sources. Local authorities therefore might need to prepare for a catastrophic event stronger than the ones they have encountered so far, resulting from the combination of the three sources. The SPR approach identified the elements at stake. These should get the highest priority in the risk mitigation policies.

The Gironde is one of the pilot sites of the Theseus project for the implementation of the decision-support system (DSS), a software aimed at informing coastal managers and decision makers about the costs and consequences of different scenarios of risk mitigation, including structural protection measures and socio-economic policies (Zanuttigh et al., 2013). The SPR approach developed here is used to define the elements in the DSS. For each receptor unit in the SPR approach, a cost is associated to a flood event and is made of three components: a monetary cost of material damages, the number of lives lost and an environmental value index variation. Pathways are implemented in the software through transfer functions which establish a relation between the source (usually hydraulic variables such as water levels, water velocities, specific wave heights,…) and the receptor (e.g. aggregated flood depth due to overtopping).

A mitigation measure comprises a list of possible actions taken by the local authorities which have an impact either on the pathways in the SPR model (mostly for structural measures), or on the receptor units (mainly socio-economic policies). The source inputs remain the same, whatever the measures.

The DSS allows a comparison of different mitigation measures. In the Gironde area, the mitigation measures tested are both measures already proposed by the local authorities in the framework of the action plan for the prevention of flooding (PAPI) (usually raising the level of dikes or building new dikes), and new innovative measures using the technologies developed by the Theseus project (wave energy converters, reinforcement of dikes, managed realignment).

6. Discussion and conclusions

All three SPRs focus on the sources of flooding when representing the floodplain. The 2D SPRs show that the sites have potential flood sources, and therefore flood pathways, coming from multiple directions. Though all three sites are estuarine coastal regions, the nature of the considered flood sources and the subsequent risk analyses differ greatly. Flood sources along the Scheldt combine extreme surge and river runoff and these are considered also in the future climate scenarios. On the other hand, the Gironde estuary SPR showed the potential emergence of a third distinct flood source from the open ocean which has not yet been observed in past flood events, but becomes more likely as sea levels rise. In the Elbe estuary, the SPR identifies the HafenCity area as vulnerable due to the nature of the existing defenses and the consequences of a potential flood event. All three estuaries are therefore seen to be distinct in their characteristics and in the nature and purpose of their flood risk assessments. Application of the SPR to these sites provided a common, structured methodology within which users can frame their flood risk analyses and models.

In all study sites emphasis has been on probability of flooding without consideration of dike failure. i.e. it is assumed that dikes do not fail. The methodology can be extended to include dike failure provided that probabilistic information for dike failure is available.

Although the sites are relatively close in planetary terms, it proved impossible in practice to homogenize assumption on climate change and sea level rise. The scenarios used for assessing the impact of climate change but also the tools used to work out the hydrodynamics differed from site to site. The main reason for this is that the study sites are quite different in concept, history and development of plans for protection of coastal flooding.

For the Dendermonde site use could be made of full hydrodynamic models and simpler conceptual models for flood propagation in the river basins of the Scheldt and Dender. Conceptual models are calibrated to the full hydrodynamic models and allow for fast calculations of different scenarios. For the Elbe river, a full 2D hydrodynamic model has been used to study the details of flood propagation in HafenCity. Similarly the experience with the TELEMAC hydrodynamic software and the TOMAWAC wave model, made it logical to choose these models for flood and wave impact studies in the Gironde estuary.

The expected effect of sea level rise is for all sites considered as the most important source of worry for the future. In all sites a change in tidal propagation along the river is expected that can be attributed to sea level rise and expected changes in storminess and surge elevations. Changes in tidal propagation are clearly visible from historic records where both sea level rise and deepening for navigation purposes, have increased the tidal range considerably, especially in the Elbe and the Scheldt estuary. Due to the geometry of the estuary the dominant effect is an increase of the high water levels along the Scheldt and a decrease of the low water levels along the Elbe.

The application and analysis of the 2D SPR methodology revealed in each of the study sites additional information relevant to flood risk evaluation. For the Scheldt estuary complete coastal flood protection plans have been developed and are expected to provide adequate protection for the next few decades at least. The Dendermonde area falls under the Sigma plan which is a comprehensive flood defense plan including a social cost benefit analysis. Nevertheless the Scheldt SPR exercise brought insight and structure to the flood risk analysis which is shaped by a complex interplay and impact of downstream (coastal) and upstream (inland) controlled sources. For the Dendermonde study site, the climate related expected changes in rainfall-runoff and in downstream surge levels will have a combined impact on the area of Dendermonde. The SPR approach ensured that basic assumptions about the floodplain are made explicit. The HafenCity floodplain is unique among the three sites in that even though the flood sources are estuarine, the floodplain itself is an island. The SPR analysis mapped some elements as potentially flooded, which were not identified in the 2D flood model. This is reflected in the greater number of flood sources (an average of two per exposed element with a maximum of four). The land-use pie chart for this floodplain not only showed the expected high degree of urbanization but also a large percentage of critical elements including evacuation routes exposed to the flood sources. In contrast in the Gironde case study, the SPR was very effective in mapping different designated and non-designated flood pathways as a result of estuary flooding and Atlantic Ocean breach succinctly. The SPR method proved to be a quick and effective way of combining and mapping diverse information.

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The SPR systems model as a conceptual foundation for rapid integrated risk appraisals: Lessons from Europe

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ABSTRACT

Coastal floodplains are complex regions that form the interface between human, physical and natural systems. This paper describes the development, application and evaluation of a conceptual foundation for quantitative integrated floodplain risk assessments using the recently-developed SPR systems model. The SPR systems model is a conceptual model that combines the well-established Source–Pathway–Receptor (SPR) approach with the concept of system diagrams. In comparison to the conventional approach, the systems model provides spatially explicit quasi-2D descriptions of the floodplain in terms of constituent elements and possible element linkages. The quasi-2D SPR, as it will henceforth be referred to in this paper, is not the final product of this work, but is an important intermediate stage which has been pursued as part of a wider European flood risk project THESEUS (www.theseusproject.eu). Further research is currently on-going to provide full quantification of the quasi-2D SPR, and to add further refinements such that hydraulic assessments could follow on easily and rapidly from the results of these appraisals.

The first part of the paper synthesises current conceptual treatment of coastal floodplains and identifies areas for improvement in describing coastal floodplains as complex systems. The synthesis demonstrates that the conceptual foundation of a 'typical' flood risk study often achieves a less comprehensive and integrated description of the floodplain than the quantitative models which it informs. From this synthesis, the quasi-2D SPR is identified as a more robust and informative conceptual foundation for an integrated risk assessment. The quasi-2D SPR has been applied to seven European coastal floodplains as part of the THESEUS project. The second part of the paper discusses in detail the application of the quasi-2D SPR to three contrasting floodplain systems — an estuary, a coastal peninsula and a mixed open coast/estuary site. The quasi-2D SPR provides a consistent approach for achieving comprehensive floodplain descriptions that are individual to each coastal floodplain. These are obtained through a robust, participatory model-building exercise, that facilitates developing a shared understanding of the system. The constructed model is a powerful tool for structuring and integrating existing knowledge across multiple disciplines. Applications of the quasi-2D SPR provide key insights into the characteristics of complex coastal floodplains — insights that will inform the quantification process. Finally, the paper briefly describes the on-going quantitative extension to the quasi-2D SPR.

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1. Introduction

Extreme events in the past decade, such as Hurricane Sandy (Schultz, 2013) and Hurricane Katrina (Seed et al., 2008) in the US and Storm Xynthia in France (Kolen et al., 2010), have demonstrated that it is impossible to completely control or prevent damage due to a flood event. Coastal floodplains world-wide are focal points for human settlement (McGranahan et al., 2007; Small and Nicholls, 2003) and often span large areas crossing administrative and geo-political boundaries (de Moel et al., 2009; EXCIMAP, 2007). They form the interface between human, physical and natural systems, which are in turn influenced by multiple natural (Friess et al., 2012; Gibson et al., 2007) and human-induced pressures and drivers (Hallegatte et al., 2013; Nicholls and Klein, 2005).

Several large-scale flood risk studies recognise that for effective strategic flood risk management, coastal floodplains should be analysed as regions of interacting physical, socio-economic and ecological systems (Hanson and Nicholls, 2012; Mokrech et al., 2011; Safecoast, 2008). Flood risk studies also recognise the need for expanding the spatial and temporal scales across which floodplains are studied (Dawson et al., 2009). Strategic flood risk management therefore requires risk appraisal models that are rapid as well as comprehensive. An exploratory risk appraisal model is currently being developed for the initial stages of a flood risk study, to identify the need for more detailed assessments. For the model to be comprehensive, a robust conceptual understanding of the floodplain is necessary. A strong conceptual foundation is an essential step to understanding the floodplain, framing the study problem and identifying knowledge gaps (Robinson, 2007). To ensure integration within the flood risk study, and ensure ownership of the problem by multiple stakeholders, this conceptual foundation will need to encourage a participatory approach to floodplain mapping (Priest et al., 2012). Narayan et al. (2012a) combined the Source–Pathway–Receptor (SPR) approach with system diagrams to provide an alternative conceptual model for descriptions of coastal floodplains. This conceptual model, referred to in this paper as the quasi-2D SPR, facilitates the development of a shared, comprehensive understanding of coastal floodplain systems.

This paper describes the development, application and evaluation of the quasi-2D SPR as the conceptual foundation for a probabilistic rapid risk appraisal model. The first part of this paper synthesises current conceptual treatment of coastal floodplains within large-scale integrated flood risk studies. The synthesis highlights the necessity for an integrated and comprehensive conceptual model of the coastal floodplain and the relevance of the quasi-2D SPR in this context. The second half of the paper describes the application of the quasi-2D SPR to three exemplary coastal floodplains, out of a total of seven sites, representative of a peninsula, an estuary and a mixed open coast/estuary. Lessons learnt regarding coastal floodplain systems are discussed and the model is evaluated with regard to its consistency, usefulness and universality across the seven pilot sites. The quasi-2D SPR is demonstrated in its applications to be a robust and useful conceptual foundation for further quantitative assessments. In conclusion, the paper also briefly discusses the use of the quasi-2D SPR in the next stages of development of the quantitative risk appraisal model.

2. Coastal floodplain conceptualisation in flood risk assessments

2.1. Conceptual models and frameworks for coastal floodplains

Risk has long been recognised as a central concept in coastal flood protection (Evans et al., 2006; Sayers et al., 2002). Coastal flood risk studies – which focus on the evaluation of coastal flood impacts on human assets – conceptualise the coastal floodplain in terms of two components: 1) flood defences that prevent or reduce the ingress of flood water; and 2) the floodplain behind the defences comprising all features considered to be at risk from flooding (Bakewell and Luff, 2008; FLOODSite Consortium, 2008; Naulin et al., 2012). The quantitative evaluation of risk in these studies is usually performed using numerical hydraulic models. Most flood risk estimation methods break the process down into four components — occurrence *probability* of an event; degree/extent of *exposure*; *susceptibility* of exposed assets to damage and; *value* of a harmed asset (Gouldby and Samuels, 2005).

Large-scale integrated flood risk assessments use conceptual frameworks to describe the relationship of the coastal floodplain system to external drivers and pressures (e.g., Evans et al., 2004; FLOODSite Consortium, 2009; Safecoast, 2008; North Carolina Division of Emergency Management, 2009; Naulin et al., 2012). In all of these studies, the state of the coastal floodplain is described using a well-established concept — the Source–Pathway–Receptor–Consequence (SPRC) conceptual model (Gouldby and Samuels, 2005). The SPRC model describes the floodplain in terms of the process of flood risk propagation — the initiation of a hazard at the shoreline, and its propagation through a flood pathway to a receptor with particular (negative) consequences (Fig. 1). The model was first used in the environmental sciences to describe the movement of a pollutant from a source, through a conducting pathway to a potential receptor (Holdgate, 1979) and was first adapted for coastal flooding in the UK by the Foresight: Future Flooding study (Evans et al., 2004).

The SPRC model presents a snapshot of the floodplain state. This is in turn is driven by inputs operating at a range of spatial and time-scales such as off-shore water levels and waves, climate change effects, and human influences such as coastal zone management decisions and actions. Therefore the model is usually nested within broader frameworks such as the Driver–Pressure–State–Impact–Response (DPSIR) that conceptualise the influence of pressures and drivers external to the floodplain (Kristensen, 2004). In this manner cause–effect feedbacks between the floodplain system and external influences can be conceptualised and described. Fig. 2 shows the relationship between the DPSIR framework and the SPRC model. Fig. 2 illustrates that the SPRC model can be divided into two components based on its nesting within the DPSIR — a floodplain state description (S–P–R) and a description of the consequences to changes in this state (C). Flood risk assessments typically follow this division, using the S–P–R model to assess flood probabilities of elements within the floodplain and separate economic models to evaluate flood consequences. This paper also focuses on describing the floodplain state and will henceforth only discuss the SPR model.

2.2. The SPR model: role and function in floodplain risk assessments

One reason for the popularity of the SPR as a conceptual model for floodplain state descriptions is that it readily translates to the components of risk estimation (see Fig. 3).

The SPR model describes flood risk propagation across the floodplain as a linear process from Source to Receptor although it allows conceptualisation of far more than just risk propagation. In practice, specific and often detailed, numerical models and analysis techniques exist for individual floodplain systems and elements and each step of the process

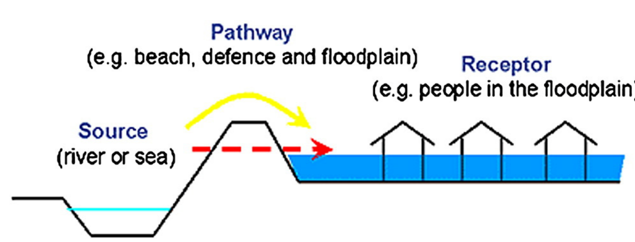

Fig. 1. 1D SPR-C model for coastal flooding. (FLOODSite Consortium, 2009).

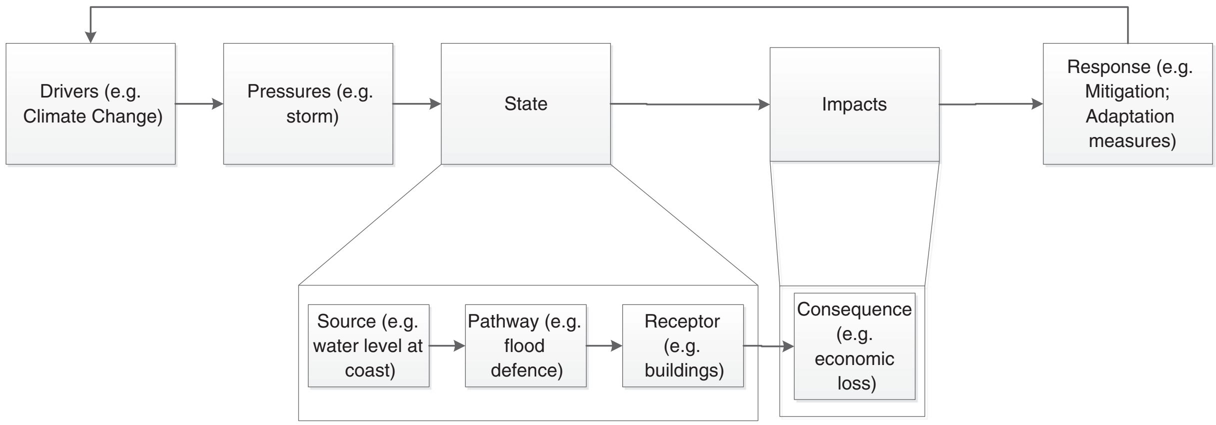

Fig. 2. Nesting of SPR-C model within DPSIR framework.
(Based on Evans et al., 2004).

often involves inputs from specialised and diverse numerical models. Fig. 4 unpacks the role of the SPR model by mapping it to the numerical modelling process of a 'typical' flood risk assessment and its associated inputs.

Due to the linearity of their conceptual model, flood risk assessments have hitherto limited their conceptual description of the floodplain state. However, in practice, a typical flood risk assessment uses a range of diverse models and inputs to describe and analyse the state of the coastal floodplain. Furthermore, the types and nature of models and inputs may differ depending on the scale and extent of detail of a particular assessment. Fig. 5 illustrates the possible range and diversity across scales and levels of detail within typical flood risk assessments — all of which use the linear SPR model described above to conceptualise the coastal floodplain.

Though the flood risk assessment may capture all relevant inputs and processes within its numerical models the SPR itself does not describe the floodplain or the elements being analysed. For instance, the SPR lumps descriptions of all structural and non-structural coastal defences within the 'Pathway' component. Though often accounted for within numerical models (Buijs et al., 2005; Wadey et al., 2012), the role of non-structural floodplain elements such as beaches, spits and coastal habitats is ignored within the conceptual model resulting in a potentially incomplete description of the coastal floodplain.

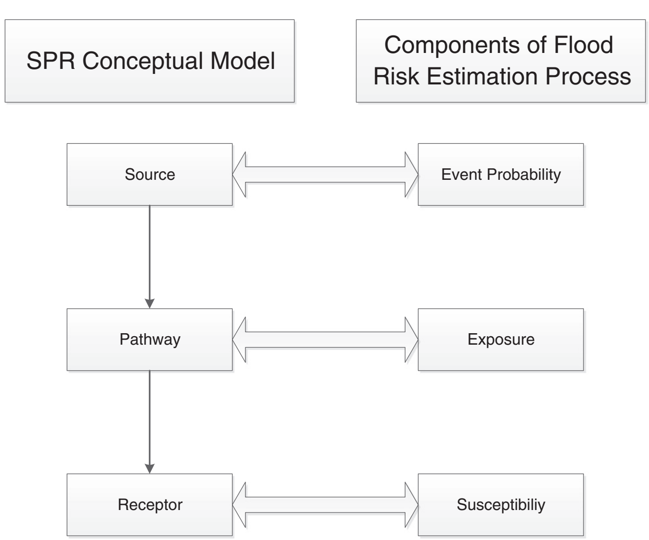

Fig. 3. Mapping SPR model to flood risk estimation components.
(Adapted from FLOODSite Consortium, 2009).

2.3. Relevance and position of the quasi-2D SPR within flood risk assessments

The SPR's effectiveness and popularity as the conceptual approach of choice for coastal floodplain descriptions arises from its simplicity in describing the risk propagation process — from a source of flooding, through a pathway, to a receptor. This description of the floodplain state in terms of the risk assessment process is sufficient when floodplain state description forms one aspect of a larger-scale flood risk analysis. However the synthesis of conceptual treatment of coastal floodplains reveals that quantitative models within flood risk studies often treat the floodplain in a detailed and spatially explicit manner. As a result, the conceptual SPR model provides a far less comprehensive description of the floodplain state in comparison to the rest of the flood risk study. Though widely used as the conceptual basis of flood risk studies the conventional SPR does not achieve a full, integrated description of the floodplain at the start of the study. The new SPR – described in detail in Narayan et al. (2012a) – is one way of filling this gap in the conceptual basis of integrated flood risk assessments. The quasi-2D SPR provides a descriptive, spatial approach to floodplain characterisation and emphasises the relative role of floodplain elements as pathways and/or receptors. This aims to achieve a comprehensive description of the floodplain as consisting of multiple possible source–pathway–receptor linkages, while still describing the risk assessment process in terms of the conventional SPR approach. This comprehensive conceptual description of the floodplain is also useful when evaluating the response of the floodplain to external influences within, for instance, the broader DPSIR or THESEUS conceptual framework.

Since the quasi-2D SPR is an extension of the SPR approach, it is ideally placed as a descriptive conceptual model for application at the initial stage of flood risk assessment. The next part of this paper applies the quasi-2D SPR at the initial stage of flood risk studies for a range of coastal floodplains and evaluates its usefulness and effectiveness as an integrated, participatory and descriptive conceptual model for coastal floodplain systems. The objectives of this application will be to a) gain a shared understanding the flood system, b) facilitate understanding and ownership amongst diverse stakeholders of relevant flood risk issues and problems, and c) inform subsequent quantitative risk analyses of the floodplain.

3. The SPR and system diagrams: a descriptive conceptual model for coastal floodplains

3.1. The SPR and system diagrams model

The quasi-2D SPR describes the coastal floodplain as a system of spatially distributed, interacting elements. Based on the principles of the Risk Assessments for Strategic Planning (RASP) (HR Wallingford and

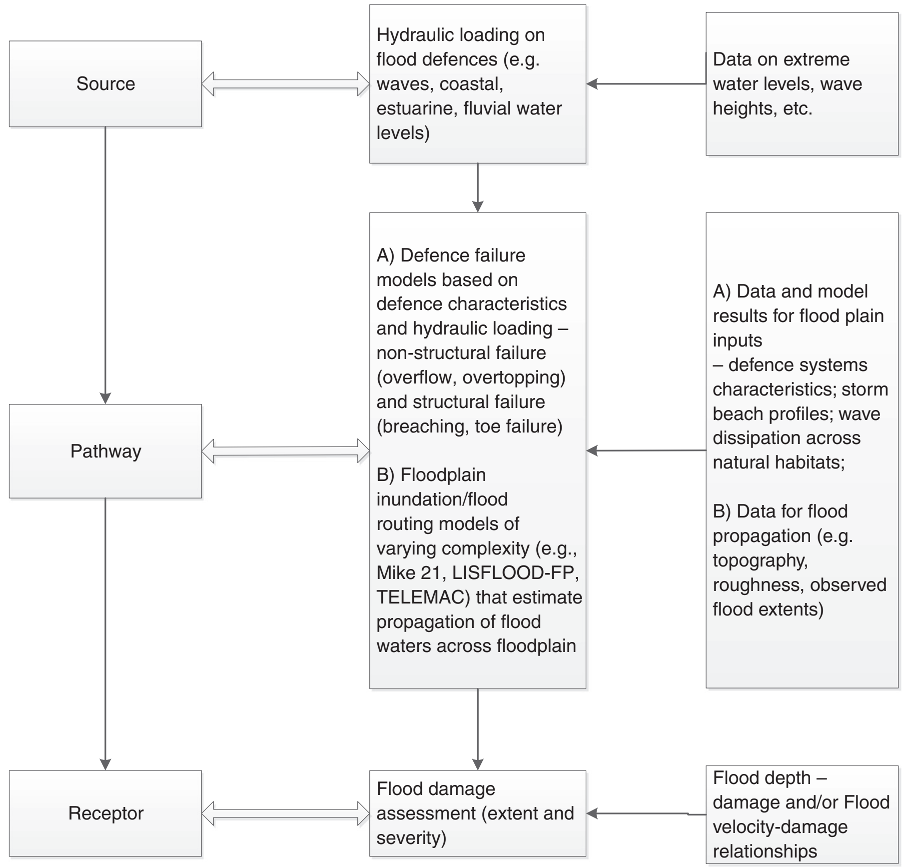

Fig. 4. Application of SPR in flood risk estimation models.
(Based on Oumeraci et al., 2012; FLOODSite Consortium, 2009; North Carolina Division Of Emergency Management, 2009; Gouldby et al., 2008; Bates and De Roo, 2000).

University of Bristol, 2004), Foresight: Future Flooding (Evans et al., 2004) and the EA/DEFRA Coastal Geomorphology (Whitehouse et al., 2009) projects, it was developed with the following objectives:

1. *Participatory construction methodology*: A methodology in which the conceptual framework and model are built by users and stakeholders from diverse genres across the assessed floodplain system in a participatory process;
2. *Capturing local knowledge*: Develop a conceptual framework and model that are capable of capturing relevant local knowledge across floodplain elements in a formalised and structured manner;
3. *Description of large, complex, floodplains*: Ensure that the conceptual framework and model can rapidly and readily describe large and complex coastal floodplains;
4. *Easy and consistent application*: Ensure that the methodology and framework are easy and consistent in their application and help develop a shared understanding of the coastal floodplain system amongst the involved users and stakeholders.

The quasi-2D SPR is built in four steps.

Step 1: The landward boundaries of the coastal floodplain system are first decided using a planar water level model for the most extreme water level being considered. This is done under the assumption of a worst-case scenario where complete failure (or absence) of defences is assumed. This assumption will indicate the full extent of the natural floodplain system and ensure that all system elements are included in subsequent analyses. The seaward boundary of the floodplain system is placed at Mean Low Water Neaps to ensure inclusion of all inter-tidal floodplain elements seaward of the coastline.

Step 2: Once the natural system extent is defined all floodplain elements, including flood defences, are mapped as unique entities classified based on land-use (Fig. 6). Using land-use classification provides a platform for future integration of any analysis with the socio-economic aspects of a flood event, such as economic consequences or land-use planning scenarios.

Step 3: Then the relationships between the identified elements are defined. The quasi-2D SPR emphasises the relative role of a floodplain element as a receptor in its own right, and a pathway to linked downstream elements. A link is identified between any two elements if the elements share a geographical boundary. Links between engineered flood defences and the rest of the system are also identified on the same basis. Flood compartments created by these defences can therefore be studied as part of the bigger natural floodplain system, rather than as isolated sub-systems. The elements and links are then schematised to obtain a systems diagram (Fig. 7). The move from a geographical map to a systems map allows easy, quick and comprehensive analyses of the topological relationships between different elements regardless of their location or size.

Step 4: Once the system diagram is built, all the sources of flooding are identified at the boundaries and, if necessary, within the system boundaries. These sources are also schematised and all links between them and directly connected system elements are identified.

A key strength of the model is the involvement of stakeholders in the model construction process (de Vries et al., 2011). All stakeholders work together to create their version of the system functionality and identify linkages that will permit ingress and movement of floodwater. The

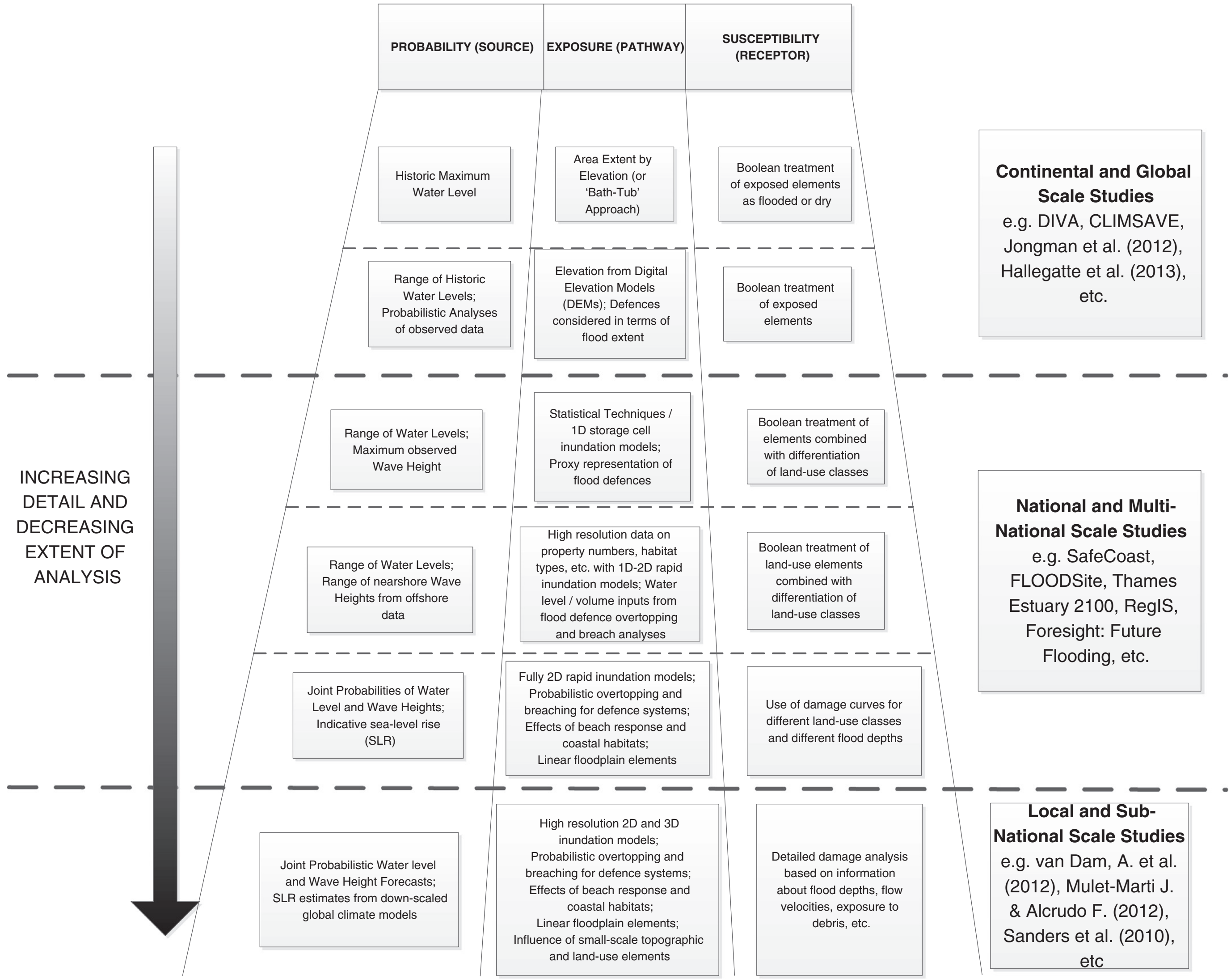

Fig. 5. Types of flood risk studies in terms of SPR model.
(Sources: Evans et al., 2004; Hallegatte et al., 2013; Harrison et al., 2013; Hervouet, 2000; Hinkel and Klein, 2009; Jongman et al., 2012; Klijn et al., 2008; Mokrech et al., 2008; Mulet-Marti and Alcrudo, 2012; Ramsbottom et al., 2012; Safecoast, 2008; Sanders et al., 2010; Syme, 2001; The Environment Agency, 2012; van Dam et al., 2012).

initial model is studied by the team of stakeholders to ensure that all elements of interest have been represented. Floodplain elements may then be added removed or modified in the original model. A lesser flood event may result in a modification of extent and element links depending on the relative flood depth for that event. The ordered progression of systems analysis from the most extreme events to lesser flood events ensures that key receptors and flood pathways are not omitted during flood risk analyses. The process, shown in Fig. 8, is repeated until consensus is reached amongst users that the model captures all the present understanding concerning the coastal floodplain. In this way a map of the natural floodplain is obtained that includes all elements under consideration. The SPR is derived from this map using the concept of system diagrams and provides a comprehensive, spatial description of the state of a coastal floodplain. Once applied, this quasi-2D SPR will be integrated with a larger-scale framework like the ones discussed in Section 2.2 for a full and rigorous flood risk assessment.

3.2. Quasi-2D SPR application: case studies

The EU FP7 THESEUS project (www.theseusproject.eu) is developing innovative solutions for consistent and integrated flood risk management of Europe's varied coastal zones. The quasi-2D SPR is used in the project to describe the state of the coastal floodplain, nested within a larger conceptual framework as shown in Fig. 9 (THESEUS Consortium, 2009). With the project's focus on local coastal flood risk management, the SPR model is set within a DPSIR based framework identifying where and how the management decisions and techniques discussed elsewhere in this volume have the ability to change flood risk in response to a changing climate (see Fig. 9). Though based on the DPSIR, the conceptual framework shown in Fig. 9 differs from the DPSIR framework in omitting a feedback between the floodplain receptors and the boundary conditions affecting it. This feedback would be due to climate mitigation which is a global scale activity and beyond the scope of this study.

The SPR is applied to seven diverse European coastal zones listed in Table 1. Three of these sites were selected in this paper to illustrate the development of the SPR system maps across a range of coastline types, flood risk challenges and management policies; 1) the Hel Peninsula (spit), 2) Medoc (open coast/estuary) and 3) Teign (open coast/estuary). The diversity and complexity of these systems make them ideal for testing the SPR methodology. Each site had a local team of experts and stakeholders covering decision makers and local residents/businesses as well as scientists from engineering, ecology, economics and the social

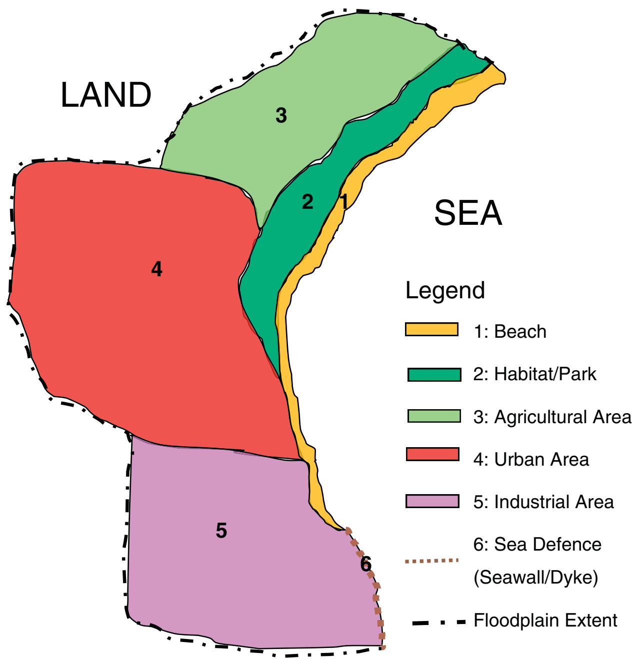

Fig. 6. Land-use map and floodplain extent for generic coastline.

sciences. Supported by project members, each team were asked to apply the approach and develop an SPR relevant for each site. For one case study (the Medoc) this process resulted in the development of two quasi-2D SPRs at different scales to more fully capture the nature of the flood system. Application of the SPR at different scales is discussed further in Narayan et al. (2012b). A more detailed consideration of the flood sources, pathways and receptors for three estuaries using the SPR — The Elbe, Scheldt and Gironde can be found in Monbaliu et al. (in review).

3.2.1. Hel Peninsula, Gdansk, Poland

The Hel Peninsula is a 35 km peninsula located in northern Poland between the open Baltic coast and Puck Bay (see Fig. 10). The peninsula is a long and narrow natural formation and as a result it is highly exposed to coastal erosion and flooding by breaching. Due to its geography and shape, the peninsula is vulnerable to breaching by waves and inundation due to storm surges and rising sea-levels. Most of the peninsula is low elevation, except for a high dune-belt along the open coast whose highest point is 15 m above sea-level. An extreme 100 year return period water level for the region, accounting for sea-level rise is estimated to be around 1.4 m at present and predicted up to 2.78 m by AD 2100 (THESEUS Consortium, 2012). The region has a resident population of around 18,000 and receives more than 100,000 tourists at a time during summer for its wide sandy beaches and world-renowned kite-surfing and wind-surfing sites (THESEUS Consortium, 2012). The peninsula has a number of camping sites and four fishing ports. A road and railway track providing essential transport especially during the tourist season run through the length of the peninsula. Though the entire region is vulnerable to flooding, this case-study focuses on the north-eastern tip as this is the most vulnerable to flooding as well as the most important region in terms of potential consequences. The northern coastline of the peninsula is maintained by annual sand nourishment of around 400,000 m^3.

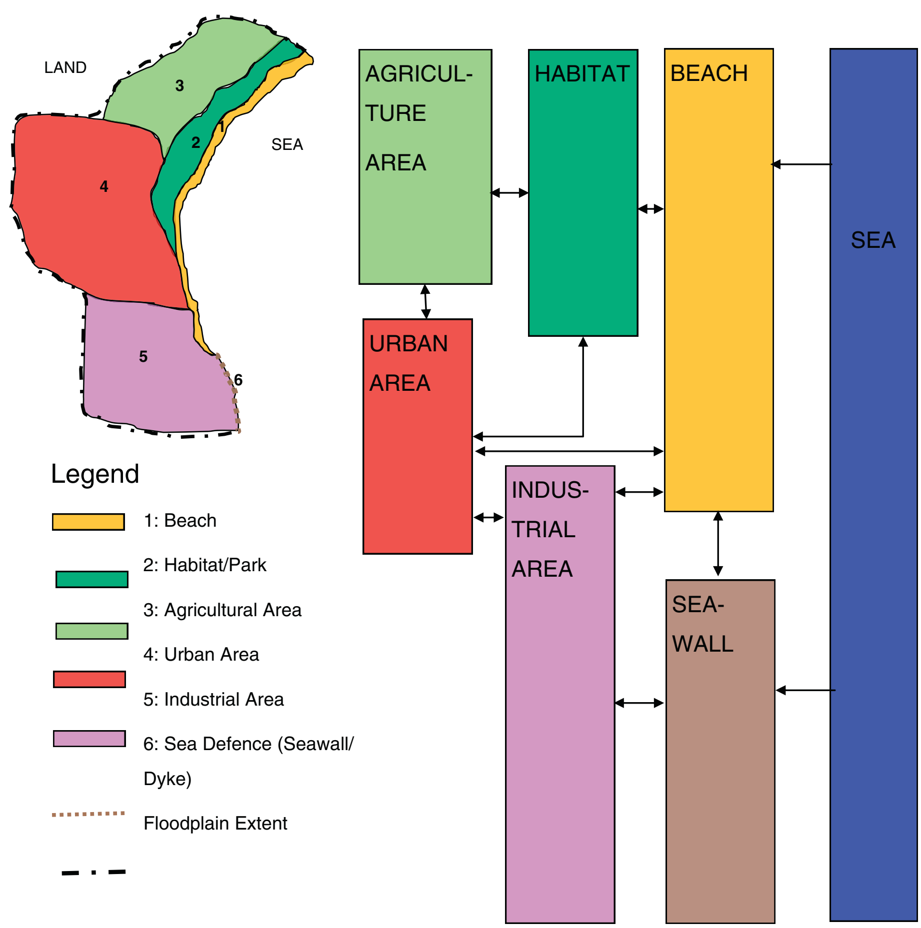

Fig. 7. Generic example of quasi-2D SPR for floodplain system in Fig. 6 (Steps 3–4).

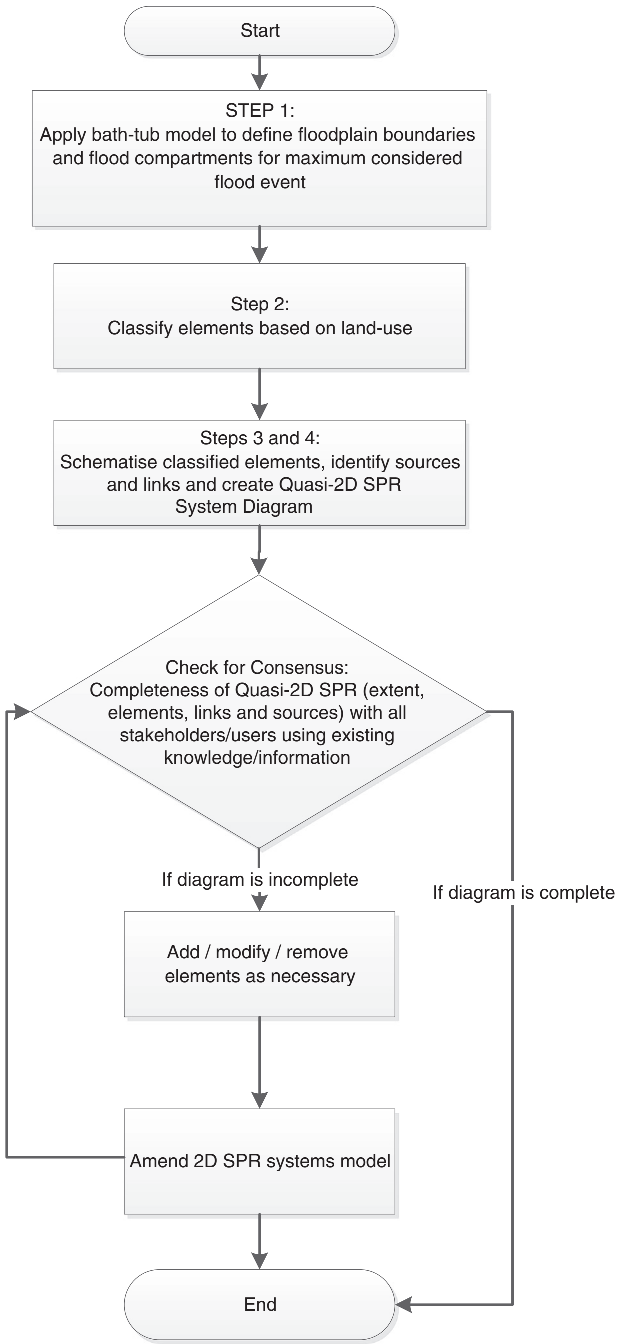

Fig. 8. Algorithm for iterative construction of quasi-2D SPR.

The quasi-2D SPR is applied to the north-eastern segment of the Hel Peninsula. The floodplain extent this case was defined as the 100 year flood extent based on observed flood events and sea-level rise predictions. Examination of past events and the concentration of key elements near the base resulted in the SPR diagram for the site being limited to a 10 km stretch at the landward end of the peninsula. Data for constructing the model used available information on past flood events obtained from the Maritime Office – the government authority in charge of management of the peninsula – and from land-use charts prepared by the local community. The SPR system diagram is built to reflect the dominantly bi-directional nature of flooding in the region — one flood source from the open coast to the north, and the other from the Puck Bay to the south. Model construction and problem-framing were a multi-disciplinary approach necessitating the involvement of sociologists, economists, hydraulic engineers, coastal geomorphologists, local authorities, local businesses and residents. The involvement of professional maritime stakeholders and the local community in building the systems model helped in mapping different floodplain elements from a range of perspectives. Model construction also let the stakeholders identify particular floodplain elements, interactions and flood routes between these elements (see de Vries et al., 2011).

The Hel Peninsula is currently maintained by a range of hard coastal defence structures as well as beach nourishment programmes. The root of the peninsula consists of a heat and power generating factory. This critical infrastructure is protected by a seawall and a gabion revetment built into an artificial dune. There are several other commercial and urban areas in the region. The beach along the open coast is nourished in some parts and has a continuous groyne system along its length. The Puck Bay side of the peninsula consists of natural green areas, camping sites on beaches and revetment flood defences. Three different types of green areas can be distinguished in the region from the system diagram — forests that protect the dunes, natural green areas and insulation green areas. The insulation green areas protect the road and railway lines which run along the centre of the peninsula. With regard to flooding from Puck Bay, the system diagram shows that the road and railway elements could themselves function as highly effective flood barriers.

3.2.2. Medoc region, Gironde estuary, France

The Gironde is the largest estuary in Europe with a high tide water surface area of 645 km^2. The estuary is created by the confluence of the Garonne and Dordogne rivers which merge near Ambès. The length of the estuary from there to the mouth is 75 km. The estuary is tide-dominated with mean tidal amplitude varying from 3.2 m at the mouth to 4.2 m at Bordeaux. The risk of flooding has always been a major concern in the region. Historical records show frequent annual flooding from AD 1212 to AD 1770 when flood defences were built after a significant flood at Bordeaux. However, more damage occurred again in the years 1835, 1855 and 1856. The biggest flood events of the last half century have been river flooding combined with high tidal amplitude in December 1981, the storms Lothar and Martin in 1999, and more recently, storm Xynthia in 2010. The largest part of the estuarine floodplain consists of agricultural fields, of which several are high value wine crops representing 80% of the vineyard region of Bordeaux. Industrial assets notably include a nuclear plant at Le Blayais, on the northern shore of the estuary which was partly flooded during the 1999 storms. The floodplain additionally consists of urban areas including Bordeaux, forests and wetlands, some of which are listed under the framework of the European Directive Natura 2000 (THESEUS Consortium, 2012).

The team in the Gironde case study consisted mainly of flood defence managers and scientists. Since Gironde is a large estuary with very different stakeholders and configurations, building a full SPR model at high resolution is a difficult task. Thus two models are constructed, one at an estuary-wide level which aimed to identify those flood-prone areas that require detailed investigation, and a smaller-scale model studying the identified region in greater detail for both flooding and erosion.

The first is a large-scale model for the region between the estuary and the Atlantic Ocean, from the estuary mouth up to the city of Bordeaux. The maximum flood extent is assumed as the present 100 year flood event. This is based on a planar water level model using the maximum value of tidal amplification along the length of the estuary. The inland extent of the floodplain for this water level varies between 3 and 5 km along the length of the estuary. Fig. 11 shows a map of the region and Fig. 12 shows a schematic built according to the first two steps of the procedure outlined in Section 3.1. The schematic indicates the extent of the flood system along the length of the estuary, the delineated land-use units on the left bank, the indicative towns and cities and the sources of flooding. Steps 3 and 4 of the procedure in Section 3.1 are used to derive the large-scale SPR model for the

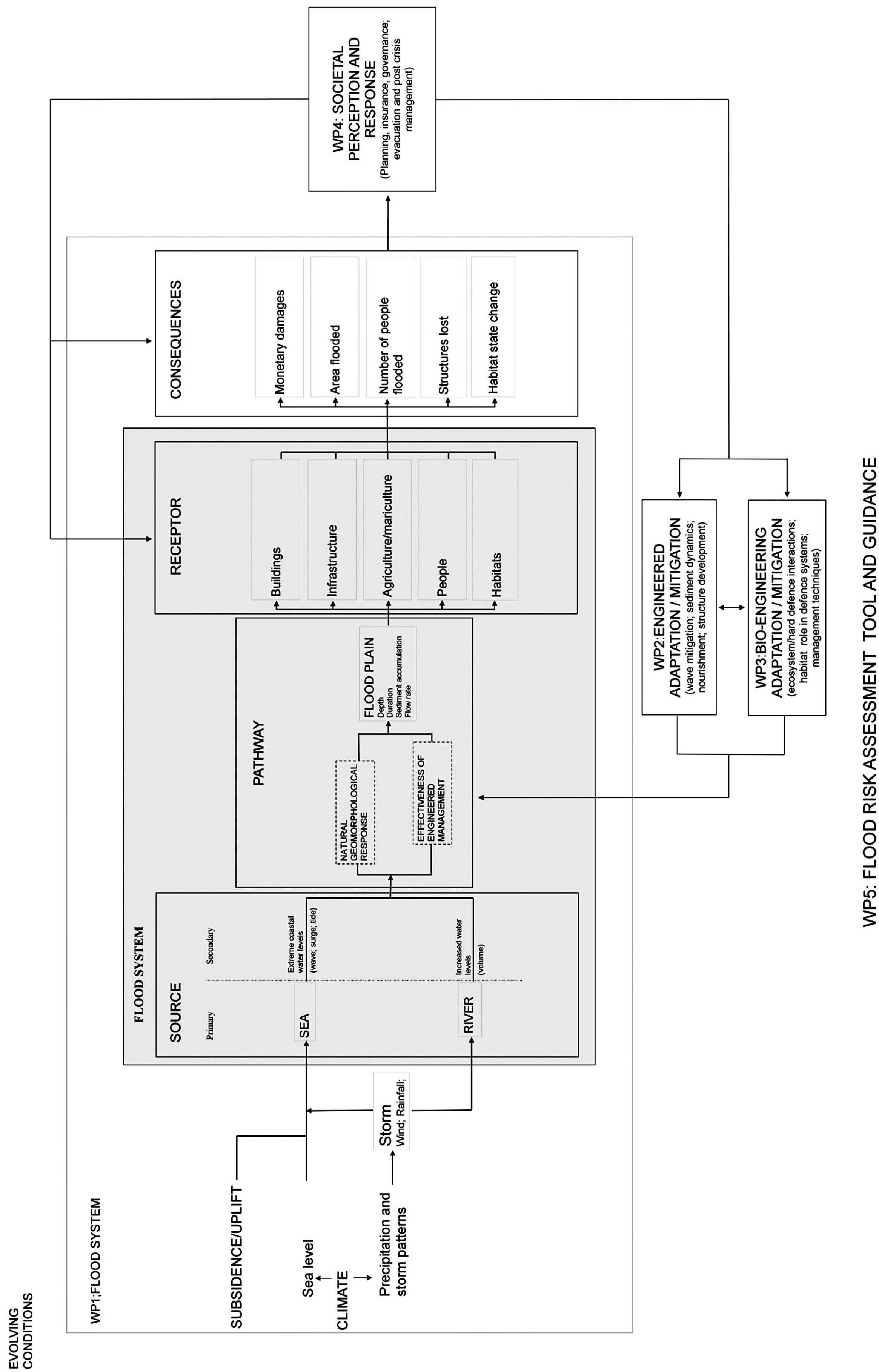

Fig. 9. Conceptual framework for the THESEUS project. (Hanson, 2010 in de Vries et al., 2011).

Table 1
Quasi-2D SPR case study sites (*: sites discussed in detail in this paper).

Case-study site	Region	Coastal classification
Medoc region, France*	Gironde estuary and Atlantic Ocean	Open coast and estuary
Teign estuary, England*	South Devon, English Channel	Open coast and estuary
Dendermonde, Belgium	Scheldt River and estuary	Estuary
Hafen City, Germany	Elbe River and estuary	Estuary
Cesenatico, Italy	Mediterranean Sea	Open coast
Hel Peninsula, Poland*	Baltic Sea, Bay of Puck	Spit
Varna, Bulgaria	Black Sea	Open coast

left bank of the estuary, from the schematic in Fig. 11. The floodplain elements are classified based on their predominant land-use. Homogenous dyke sections — i.e., sections with one owner and uniform crest height are identified in this SPR. The large-scale SPR model is shown in Fig. 12 (Narayan et al., 2012b).

From this SPR, for the Atlantic Ocean flood source, historical data and maps from the Aquitaine Coastal Observatory identified the most likely location of a breach during a storm in 2100 that would result in flooding from the ocean (Aubié and Tastet, 2000) for which a more detailed SPR would be beneficial. A more detailed quasi-2D SPR is subsequently constructed for the Medoc region. The main purpose of the detailed SPR is to identify specific local-scale flood pathways and flood zones, both current and anticipated, based on existing knowledge of flood pathways, and erosion and breach scenarios.

Current knowledge indicates that the Atlantic coast in this region is subject to long-term coastal erosion due to the effects of a northward alongshore current from Pointe de la Négade (south of Soulac) to the Pointe de la Grave (Aubié and Tastet, 2000). Accelerated erosion of the coastal dune in this area could result in the opening of a new pathway from the Atlantic Ocean to the floodplain in the future if no preventive measures are taken. Such a scenario would be consistent with the Holocene history of shoreline retreat in this area (Lesueur et al., 2002). The breach is considered possible as a consequence of sea level rise and continued shoreline erosion along with an extreme event and corresponds to a management scenario where nothing is done to prevent on-going erosion.

A major difference in the localised SPR developed here to the Hel Peninsula is the basis for defining the receptors. Rather than using land-use, the team used the French planning regulations for risk prevention (PPRI) which define three zones (see Fig. 13):

1. Zones where building is forbidden.
2. Zones where building is allowed provided some conditions are met, mainly to raise the standard of protection of existing buildings and ensure that new buildings will withstand the more common flood events.
3. Zones where building is allowed without restriction.

In the PPRI, a significant portion of the floodplain is classified as zone 1, which means only small parts of the floodplain can be built upon. The management of flood defence structures at present does not have a homogenous structure. Some stretches of dykes along the estuary have more than 400 owners and subsequently, no uniform crest height or maintenance standards. An inventory of existing defence types and their characteristics is currently on-going in the region. Since the detailed quasi-2D SPR describes a specific breach as definitely occurring, it does not represent any other defences. The floodplain is mainly subject to flooding, with erosion only occurring on the Atlantic coast near the estuary mouth. Flooding itself may be caused by tidal water levels, waves, upstream river discharge, or a conjunction of these.

Fig. 13 shows a map of the Medoc floodplain indicating the possible sources and pathways of flooding from the estuary and the Atlantic Ocean. Fig. 14 shows the small-scale quasi-2D SPR and the new flood pathways resulting from a breach on the Atlantic Ocean coast. The large-scale SPR is rapidly built and gives an overview of the large-scale floodplain, highlighting the sensitivity of the Medoc region to bi-directional flooding using existing information. This informs the

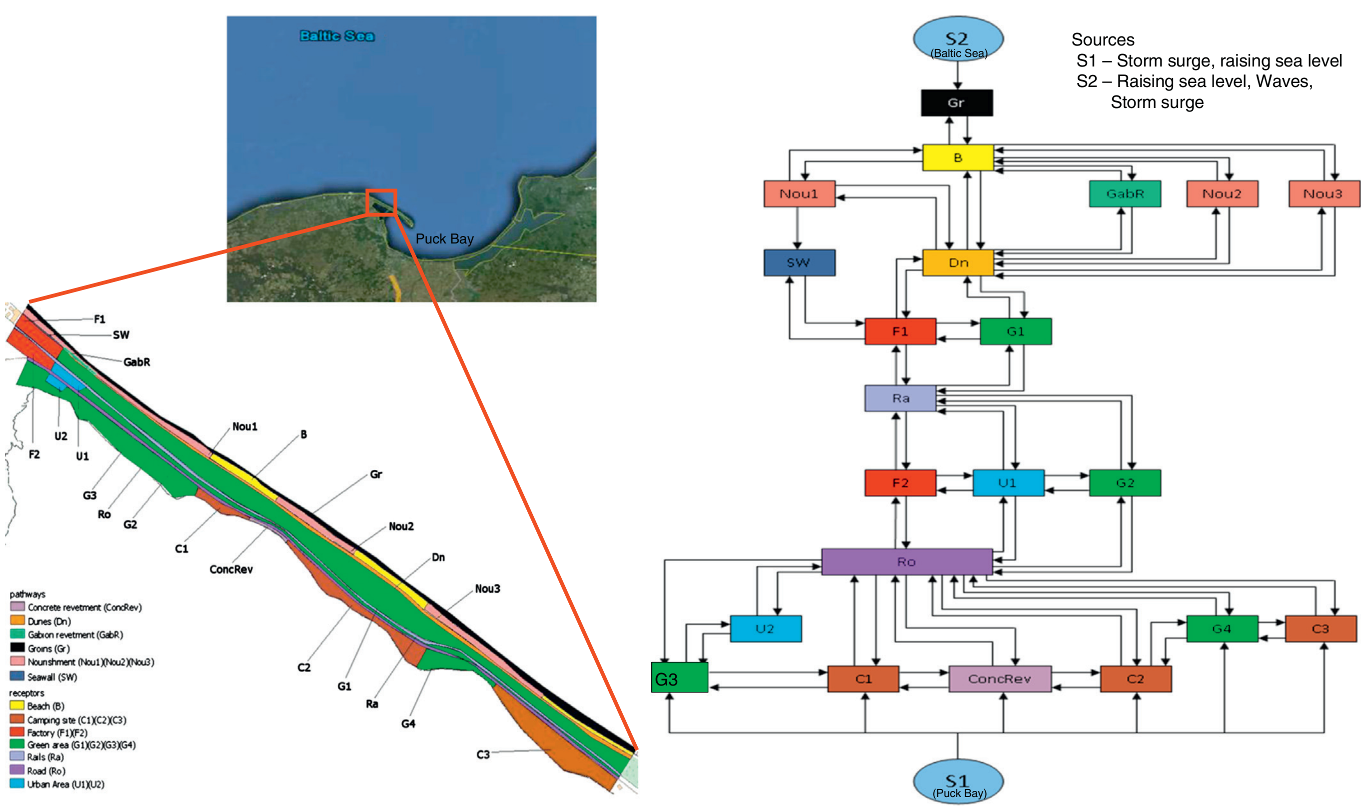

Fig. 10. Land-use map and quasi-2D SPR for the Hel Peninsula (inset — site location).

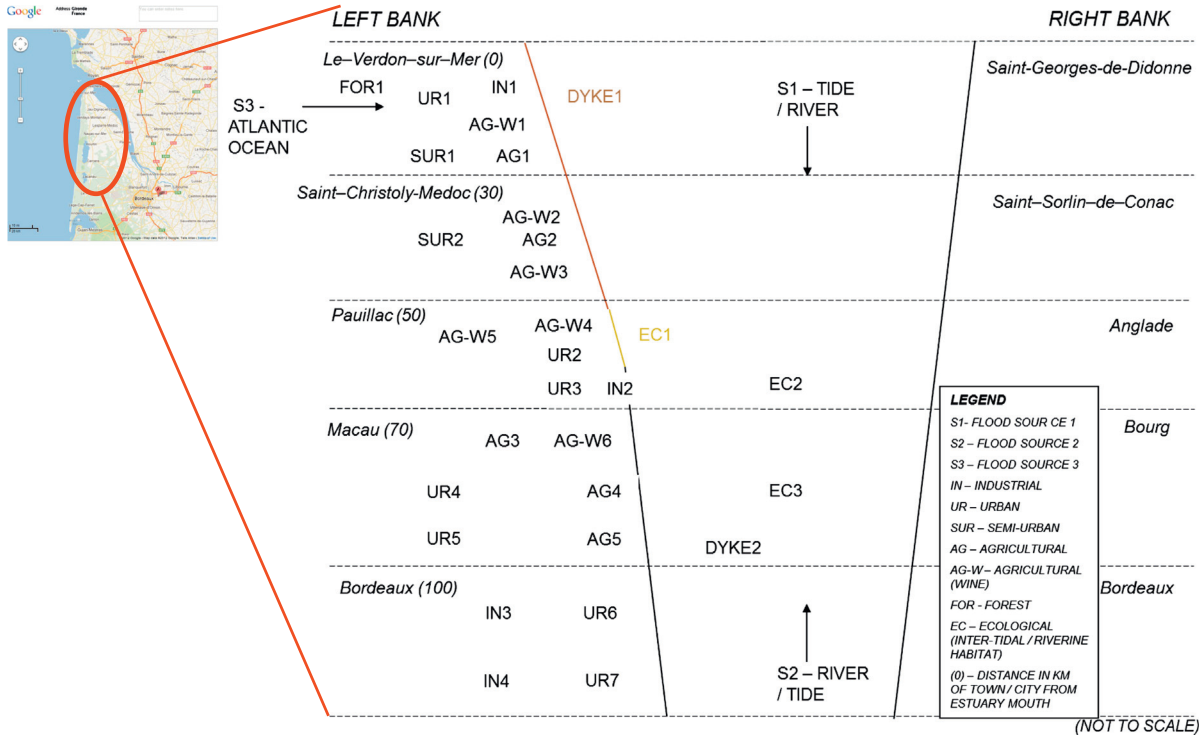

Fig. 11. Schematic map of the Gironde estuary floodplain (inset: map of Gironde region).

downscaling process and the decision to focus on the administrative region of Medoc for the small-scale SPR. The Medoc SPR contains more specific information as it is lesser in extent and more homogenous in terms of data availability. This model gives detailed information on potential new flood pathways as a result of a potential breach on the Atlantic Ocean side. The southern floodplain boundary is decided based on the expected maximum extent of flooding due to the breach at South Le-Royannais.

3.2.3. Teign estuary, South Devon, UK

The Teign estuary is located in southwest England. Similar to the Hel and Gironde models, the quasi-2D SPR for the Teign estuary represents a

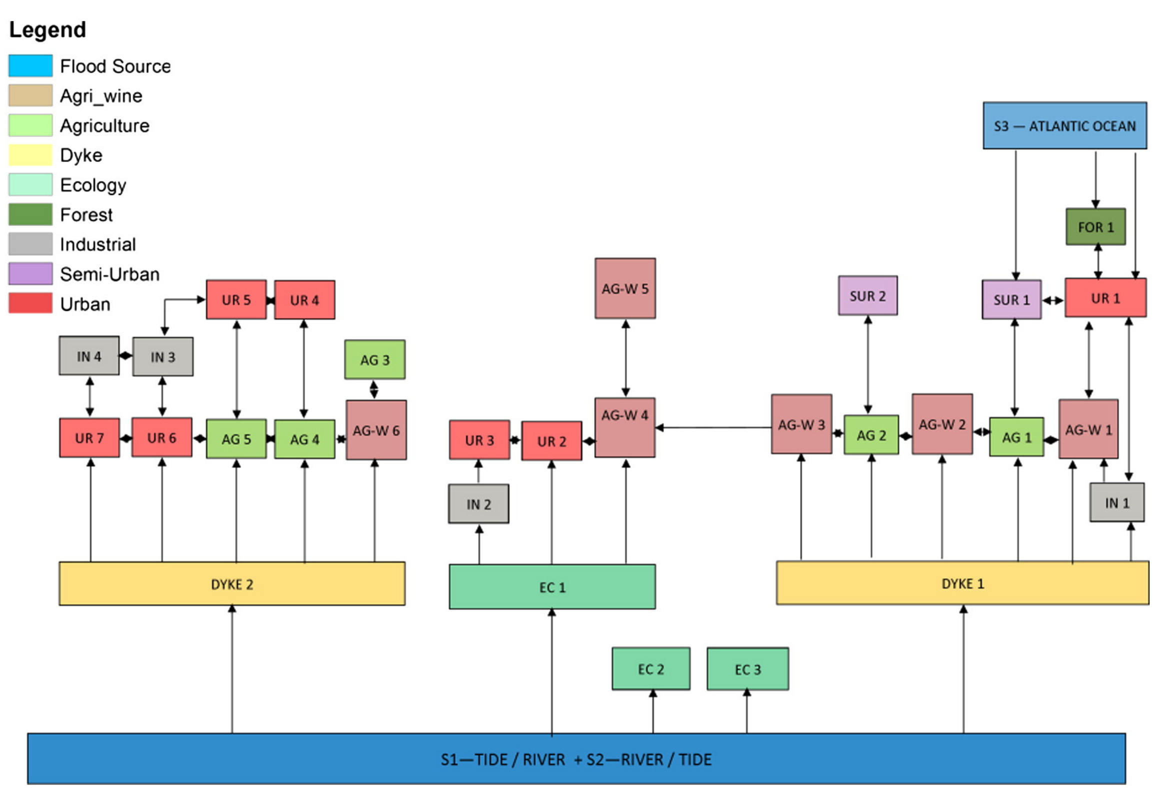

Fig. 12. Quasi-2D SPR for the Gironde estuary.

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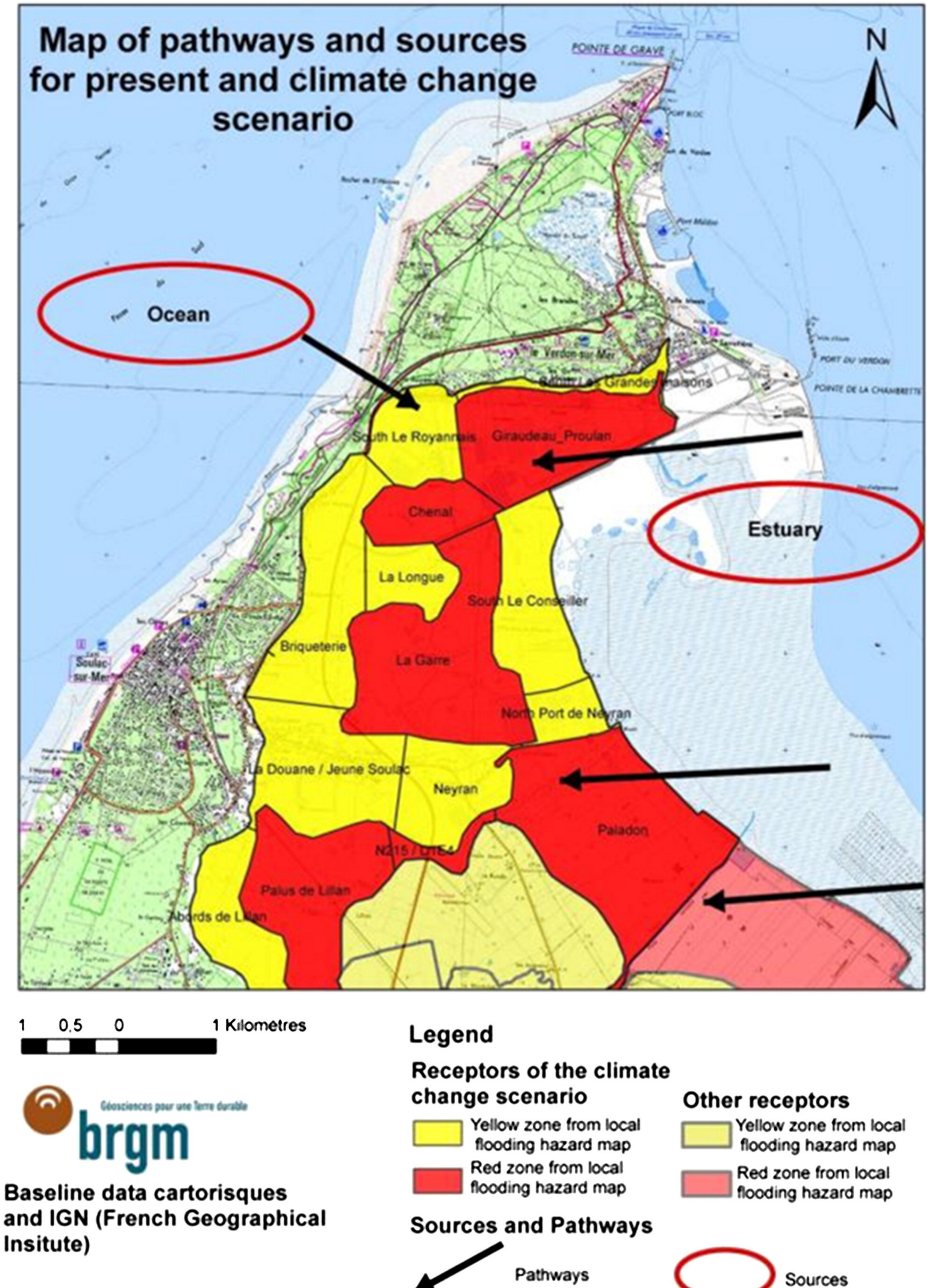

Fig. 13. Floodplain map and flood pathway scenarios for the Medoc region. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

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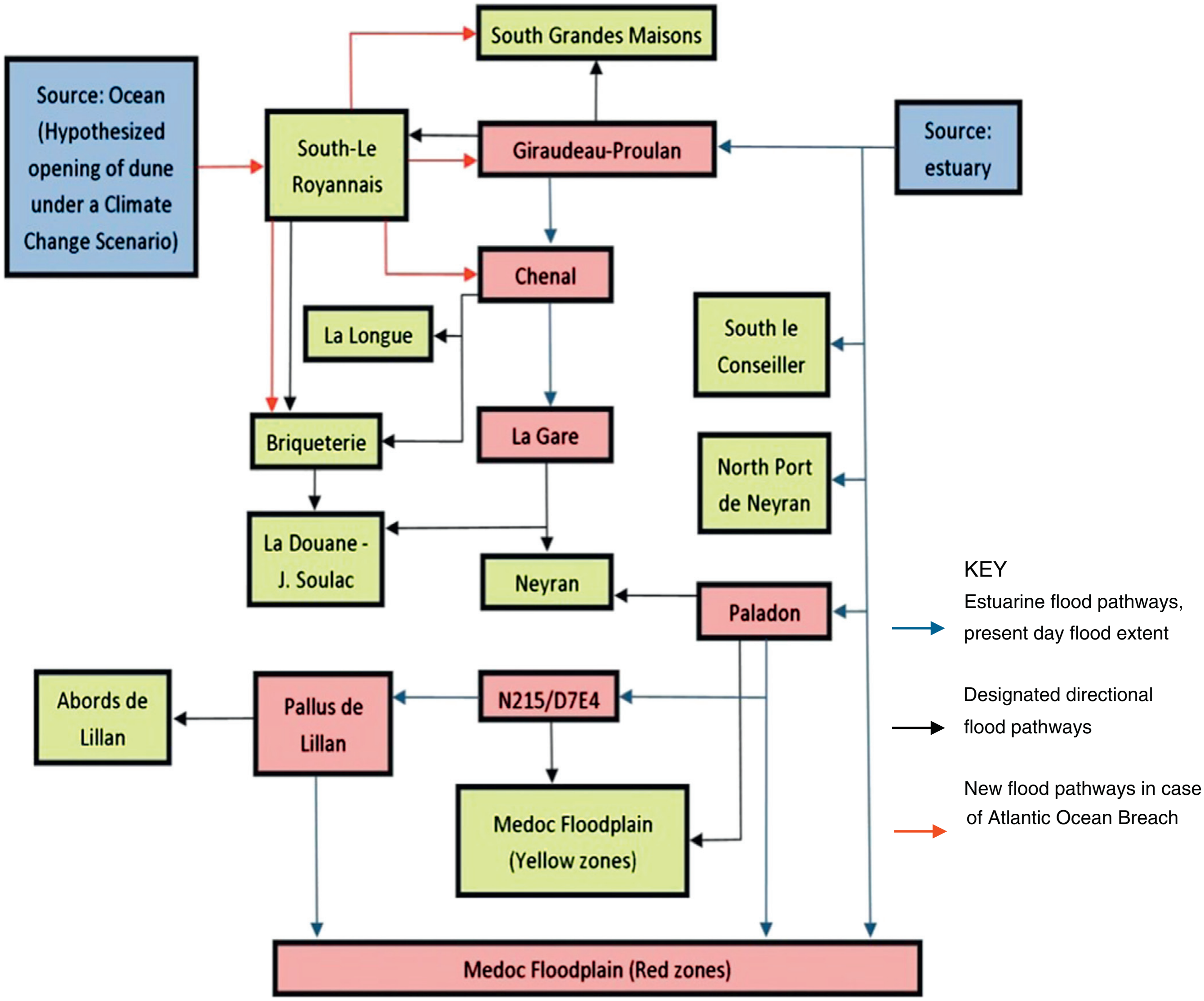

Fig. 14. Quasi-2D SPR for the Medoc region (see Fig. 13).

nested model within a larger case study (Plymouth Sound to the Exe estuary, see Fig. 15 inset).

Due to the geography of the site – consisting of isolated flood compartments – model construction resulted in several isolated SPRs. This case-study example focuses on the Teign estuary SPR. The study site features several urban flood compartments including the historic port city of Teignmouth and a range of important and sensitive habitats. A key artificial coastal element is the railway line running along the site from Teignmouth at the mouth of the estuary to Newton Abbot upstream. Coastal defence lines that protect this critical transport link have had an impact on coastal processes in the region (Halcrow Group, 2011). Flood source characterisation for the site is based on a detailed assessment of wave and water-level conditions on the open coast and within the estuary. Unlike the Hel and Gironde sites where all elements are exposed to flooding from multiple directions, seven of the nine Teign estuary flood compartments flood from a single direction. The flood sources are represented to a higher detail than in the Hel and Gironde sites and are distinguished by the relative contributions of waves and tides and the changing nature of sources from the estuary mouth to the upstream artificial tidal limit at the city of Newton Abbot. The maximum water levels at the mouth of the Teign estuary vary between 2.6 m for a 1 in 2 year return period and 3.44 m for a 1 in 1000 year return period. The estuarine floodplain is defined on the basis of the current 100 year flood applied along with the predicted relative sea-level rise for the year 2100. The quasi-2D SPR for the 6 km long Teign estuary is shown in Fig. 15.

In the Teign quasi-2D SPR, floodplain elements are classified based on their location within flood compartments. The elements are further distinguished as floodplain elements that function primarily as receptors and those that are primarily flood pathways. This allows a difference in the scale of the represented elements. For instance pathway elements mainly include sea defences, dunes and embankments. Receptor elements include urban floodplains and the railway line. Although the pathway elements are in general at a lesser resolution to the receptor elements, their inclusion and representation within the model is easily achieved. Involvement of the stakeholders in building the quasi-2D SPR resulted in the explicit inclusion of the railway line (dotted line and element 'Ra' in Fig. 15) as a distinct receptor element. In addition to its economic importance, the SPR also indicates the potential role of the railway line in flood protection, as well as highlighting the potential impact of a transport disruption by flooding of the railway line. The SPR's participative approach, flexibility and scale-independence are thus demonstrated: these attributes facilitate the inclusion of non-defence elements of different types and to different levels of detail. The SPR captures the varying nature of flood sources and pathways along the estuary. Though most elements are in isolated

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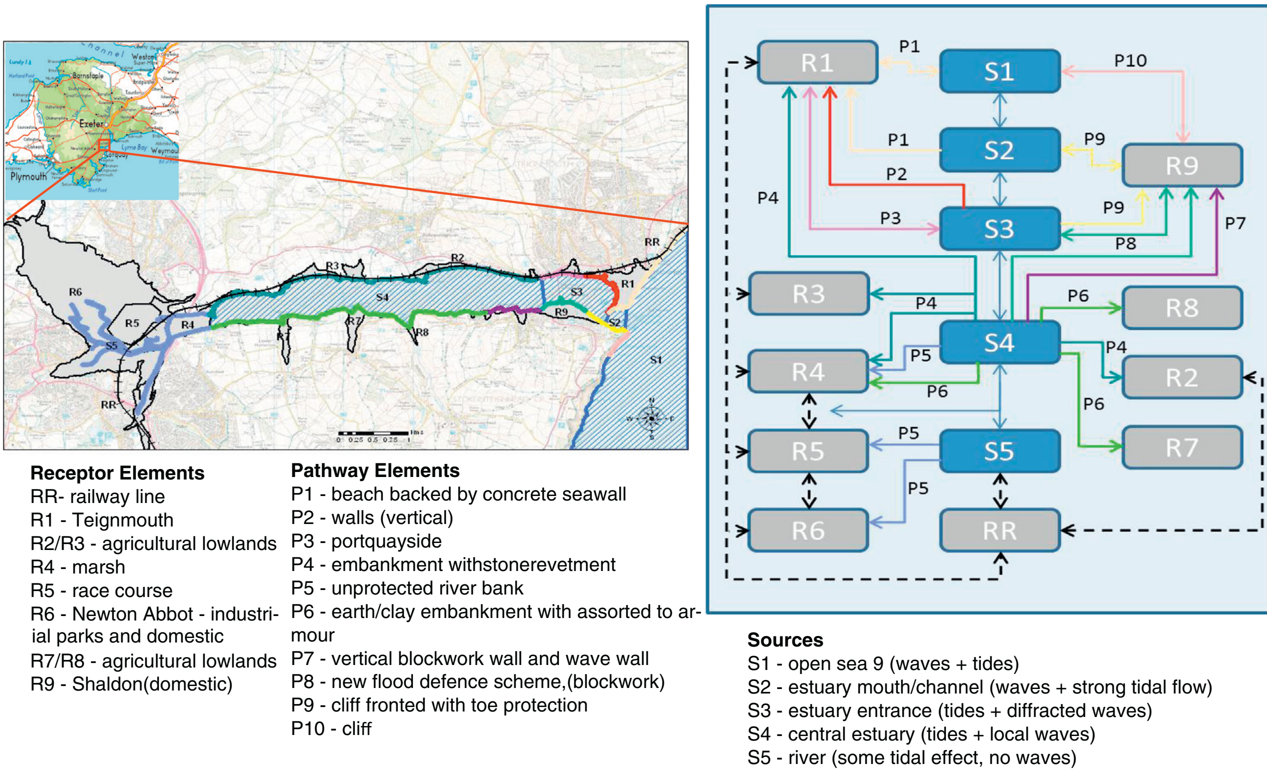

Fig. 15. Map and quasi-2D SPR for the Teign estuary (inset: site location). (Reeve et al., 2012).

flood compartments, the connectivity between elements R4, R5 and R6, and the role of river sources (S5) and estuary sources (S4) are highlighted — this is important as this comprises the urban area of Newton Abbot. Also notable are the elements R1 and R9 which is linked to multiple flood sources: S1 the open coast; S2 the estuary mouth which is exposed to waves and high tidal currents; S3 the more sheltered estuary conditions.

4. Discussion

Quasi-2D SPR applications have provided insights into the key features of coastal floodplains that an integrated flood risk assessment should consider. The model shows promise as the conceptual foundation for the next stages of this work: a probabilistic network model. For it to be practically useful however, evaluations of the conceptual model at all study sites are necessary. In this section, the lessons learnt from model application about the characteristics of each floodplain, as well as the difficulties in quasi-2D SPR model application, its advantages and limitations are discussed in terms of the model objectives listed in Section 3.1. These are summarised in Table 2 at the end of the section. Feedback from all seven sites on model performance with regard to the objectives in Section 3.1 is summarised in Table 3.

4.1. Description of complex coastal floodplains

The Hel Peninsula SPR was found to be most useful in providing a clear picture of the floodplain to local decision-makers and a clear method for information mapping. The model highlights the exposure of all floodplain elements to flooding from two distinct sources, and the vulnerability of all floodplain elements due to the narrow, elongated shape of the peninsula. Due to its relatively high resolution, the model also allows classification and identification of direct and indirect influences between particular floodplain elements. The constructed quasi-2D SPR provides a robust platform for mapping consequences of flooding to floodplain elements. A limitation of this application is the arbitrary floodplain extent for which the model is constructed. The fact that only one SPR is built for the Hel Peninsula however means that assumptions regarding the floodplain extent are not made explicit. This could be improved by building nested SPRs which include the whole peninsula like in the Gironde and Teign estuary cases.

The large-scale Gironde model covers a much larger, naturally limited estuarine floodplain and focuses on a low-resolution description of the floodplain, to identify sensitive regions. Similar to the Hel Peninsula, the estuarine floodplain in the Gironde SPR can be flooded from two directions. However, flooding from the Atlantic Ocean is limited to a single location reflecting existing knowledge on erosion processes in the region. This information mapped on to the large-scale SPR in turn informs the construction of the small-scale Medoc model. The small-scale model has a resolution similar to the Hel Peninsula SPR. However the floodplain description is very different in this model, reflecting essential differences in the way flood risk is managed, and the way in which the floodplain is analysed in these studies. Rather than provide a general classification of floodplain elements by land-use, the small-scale Medoc SPR uses the French zoning regulations to map potential flood pathways against regulatory flood zones. The downscaling from large to small scale model ensures that floodplain extent assumptions are captured by indicating possibility of downstream flooding beyond the considered floodplain extent element 'Medoc floodplain (red zones)' in Fig. 13. The two SPRs also highlight differences in problem-framing at the two scales: the large-scale model identifies the land-use areas that are at risk of flooding due to the failure of a coastal dyke section; the small-scale model details flood pathways in the event of a breach, and therefore does not consider dykes. The breach scenario in the small-scale model is representative of an overall 'do-nothing' scenario where no beach protection or nourishment is carried out along the Atlantic open coast. Though this is an unlikely scenario at present it serves to highlight the vulnerability of the region to a coastal dune breach.

Table 2
Floodplain characteristics, difficulties in SPR model application, and model advantages and limitations for the three pilot sites.

Site	Floodplain characteristics and problem definition	SPR model		
		Difficulties in application	Advantages	Limitations
Hel Peninsula, Poland	A dynamic spit with extensive engineering defences, vulnerable to flooding from two directions; Floodplain extent limited to northern end based on importance of key exposed assets — industry and tourism; Local flood protection requires integrated management of engineered structures and beach nourishment programmes; Floodplain mapping to focus on industry and tourism, road and rail lines, coastal defences, beaches and green-areas	Information on floodplain is distributed across multiple authorities and stakeholders	Model application facilitated dialogue and information exchange between multiple stakeholders; Application process helped users target areas for further data gathering; Constructed model useful for identifying possible flood risk mitigation options for subsequent quantification	Choices of floodplain extent, element classification and level of detail are subjective and require consensus amongst users; The conceptual model is only built for the smaller area, the Peninsula; Conceptual model does not quantify effect of defences and road and railway lines as flood barriers
Gironde estuary, France	Flooding from the estuary with possibility of future localised flooding near the mouth from the Atlantic Ocean via breaching; Two models constructed for floodplain between estuary and Atlantic Ocean — one for the entire estuary, one for the region of possible localised ocean flooding;	Extent of entire floodplain makes detailed mapping for entire estuary difficult and time-consuming; Possibility of future breach near mouth requires indication of potential as well as existing flood routes in this region	Model is easily applied for different extents and scales — larger model with a coarse land-use classification, to contextualise area of localised ocean flooding; Smaller model classifies local floodplain by planning regulations, to map existing and potential flood routes	Though the floodplain extent and land-use classification choices, are illustrated by the models, the assumptions and underlying reasons need to be communicated to the users; Floodplain system models do not quantify likelihoods of specific flood routes
Teign estuary, UK	Estuary consists of multiple, mostly isolated flood compartments, with varying nature of sources from mouth to upstream limit; Flooding in some compartments occurs both from estuary and open coast; Floodplain elements vary widely in terms of size and economic value of exposed assets	Data availability on floodplain topography limited below 5 m contour; Large extent of study site makes detailed mapping of entire estuary time-consuming; Railway line is a critical floodplain element, though much smaller in resolution compared to the floodplain compartments	Model allows mapping of railway line as a key floodplain element, distinct from but linked to the floodplain compartments; Flexible mapping of sources, allows multiple flood sources to be identified based on their physical characteristics (e.g., waves at open coast, changing water levels inside estuary); Mapping process helped identify data and knowledge gaps, to target data-gathering campaigns	Coarse-resolution of mapped elements does not provide much detail on land-use; No quantitative information provided on likelihood of railway line flooding or cost of disruption

The Teign SPR represents a nested model within a larger-scale of the Plymouth Sound to the Exe estuary. Unlike the Gironde estuary where the smaller SPR has connections to non-local elements the highly compartmental nature of the floodplain between the Plymouth Sound and Exe estuary results in localised and isolated SPRs between which no pathways exist. One of the challenges in building the Teign estuary SPR was the definition of the floodplain elements. This was due to the difficulty in obtaining land levels in the 0–5 m range. The model-building process was found to be a useful method of identifying knowledge gaps such as the difficulty in obtaining land level data. Gaps in data on land-levels in the 0–5 m range, and on flood defence pathway elements were identified and strenuous efforts made to collect additional information. The process of model-building and the constructed model are an excellent means of formally capturing existing knowledge about the flood system.

For each of the three case-studies, the SPR provides a unique description of the floodplain. In contrast, a linear or one-dimensional SPR though very effective in communicating the process of flood risk propagation will provide a simplified and rather uniform description of any coastal floodplain to which it is applied. Since the new SPR is spatial or two-dimensional rather than one-dimensional, the constructed model and reflects the characteristics of the site, the assumptions made during model construction, as well as any gaps in data and knowledge.

Table 3
Evaluation of quasi-2D SPR application in study sites with regard to objectives discussed in Section 3.1 ('✓': yes; 'X': no; '○': possible but not considered/achieved in this analysis).

Case-study site	Stakeholders/disciplines involved in SPR application	Feedback: Did the SPR achieve its objectives?			
		Participatory methodology	Capture local knowledge	Rapid description of large, complex coastal floodplains	Easy and consistent application
Medoc region, France	Geologists, geomorphologists; results from a modelling studies and official coastal risk prevention plans were used.	✓	✓	✓	✓
Teign estuary, England	Environment Agency, Teignbridge District Council, local business owners, port & harbour interests	✓	✓	✓	X
Dendermonde, Belgium	Hydraulic engineers	○	○	✓	X
Hafen City, Germany	Hydraulic engineers	○	○	✓	X
Cesenatico, Italy	Hydraulic engineers	○	○	✓	✓
Hel Peninsula, Poland	Maritime Office in Gdynia, local authority, Władysławowo, IBW PAN, IMGW PIB including economics and social sciences	✓	✓	✓	✓
Varna, Bulgaria	Hydraulic engineers, geomorphologists and ecologists	✓	✓	✓	✓

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Table 3, at the end of Section 4, which summarises feedback from all SPR applications, shows that the SPR achieves a satisfactory description of all seven floodplains to which it is applied in the THESEUS project.

4.2. Knowledge capture and participatory methodology

An advantage of the model in all three sites is its usefulness as an integrated and consistent framework for mapping the coastal floodplain. The constructed SPR for each site provides insights into the nature of the questions being asked about floodplain risk, the data available to answer these questions and pinpointing critical information gaps. Importantly, the participatory methodology ensures wide ownership of floodplain understanding and the flood risk problem, improving the level of engagement of diverse stakeholders with the rest of the flood risk study. A chief limitation of this process is the subjectivity involved in the choice of resolution, representation styles, the floodplain extents assumed and the floodplain elements described. The subjectivity of the approach however is viewed as part of the problem-framing exercise. The advantage of this approach is that any implicit assumptions are highlighted in the constructed quasi-2D SPR. For instance, in the larger Gironde estuary model, all floodplain elements are classified by their dominant land-use. The smaller Medoc model uses a different element classification in mapping the Medoc floodplain to answer a different question — the role of floodplain components as pathways, relative to their existing zonation as per French planning regulations.

The quasi-2D SPR also emphasises the duality of an element's status – i.e., flood pathway and flood receptor – thus, this distinction in floodplain element functionality does not limit floodplain characterisation. For instance, flood protection in the Hel Peninsula is a combination of engineered defences and beach nourishment programmes. In this context, the beaches are flood pathways to the rest of the system. However, the beaches are also of high importance to tourism, and therefore also qualify in their own right as receptors of flood damage.

The extent of detail of the quasi-2D SPR is determined by the data, knowledge and time available and the extent of stakeholder participation. Since the mapped information is made explicit by the model, any gaps in knowledge are filled in an iterative process of model construction. The resulting conceptual model of the floodplain state is therefore commensurate with the level of detail of the rest of the flood risk assessment. Table 3 highlights the strong relationship between knowledge capture and participatory methodology for SPR applications. In four of the seven sites, a participatory methodology was not possible due to time constraints and the SPRs were built solely by hydraulic engineers using existing data on flood inundation extents, sources and pathways. This resulted in floodplain descriptions that were hydraulically complete, but lacking in terms of an integrated, multi-disciplinary approach and therefore represent incomplete knowledge capture.

4.3. Ease of application and model limitations

A chief limitation of the quasi-2D SPR and approach is the subjectivity involved in the assumptions and model construction. However as discussed in the sections above, this subjectivity is usually a reflection of the differences in site characteristics, problem-framing processes and data availability. Most of the effort and time in model-building is associated with the collection of data for the land-use maps and organising stakeholder participation for the iterative process of model construction. The average construction time of the 2D SPRs across the seven sites was under one week. While the model can be built by an individual with minimal available data on elevations and land-use this is not ideal and is generally reflected in an incomplete floodplain description. However, the approach allows users to rapidly recognise key challenges in characterising their sites such as data availability or system size and complexity, before application of detailed numerical models. The conceptual description of these challenges is an essential step to inform the inputs to and choice of further models that assess flood inundation (e.g. Jamieson et al., 2012) and flood damages (e.g., Burzel et al., 2012).

This paper emphasises the usefulness of developing a robust conceptual understanding of the state of the coastal floodplain and treating it as a complex system before taking management decisions. The SPR is limited to describing the state of the coastal floodplain at a given moment in time, although the diagrams can be easily and quickly modified to update the description of floodplain state. Thus, while they do not provide a dynamic description of the floodplain, the models can represent multiple snapshots representing changes to floodplain state over time if so desired.

Site applications summarised in Table 3 show difficult and/or inconsistent application of the SPR model for the Teign, Scheldt and Elbe estuarine sites. For the Teign estuary, this is a reflection of the highly compartmental nature of the floodplain and the lack of information on elevations between 0 and 5 m. The other two sites – the Scheldt and Elbe estuaries – are characterised by a large quantity of existing information on inundation and flood risk. Achieving a clear and concise conceptual description of these floodplains is therefore in some respects more difficult since this requires concise distillation of the questions being asked and the required level of detail and classification methodology required to answer these questions. For instance, the SPR model for the Hafen City area of the Elbe estuary, discussed in Monbaliu et al. (in review), could either describe the entire Hafen City floodplain, or focus just on the flood evacuation pathways to inform flood warning and evacuation models, or other questions that might be posed.

The quasi-2D SPRs still lack quantification of flood risk probabilities and consequences. Quantification of the information mapped by conceptual model application is required for its integration within larger flood risk studies (e.g., Oumeraci et al., 2012; THESEUS Consortium, 2009). Work is currently on-going on a tool for quantifying flood probabilities and their propagation across the floodplain pathways identified by the conceptual SPR models.

5. Conclusions and further work

This paper synthesises current conceptual treatment of coastal floodplains, and describes the development and application of a recent conceptual systems model, the quasi-2D SPR, as a conceptual foundation for quantitative integrated risk assessments of coastal floodplain systems. The three key take-home messages from this paper are summarised below, followed by a brief discussion of on-going work on the quantitative extension, to be presented in a follow-on paper.

5.1. Integrated coastal flood risk assessments require a robust, integrative conceptual model

The conventional model for describing the state of the coastal floodplain is the linear SPR model. This is often nested within larger scale conceptual frameworks such as the DPSIR for a more complete picture of the influence of and feedback between external elements and the coastal floodplain. The conventional SPR approach does not provide a comprehensive description of the coastal floodplain — rather, it describes in simple terms the analysis process that the risk assessment follows. While its simplicity is one of its key strengths, the SPR can become a tool for tokenistic consensus-building amongst different stakeholders. Combining the SPR model with the concept of system diagrams to produce a quasi-2D SPR achieves a more robust description of the coastal floodplain emphasising the duality of floodplain elements as both pathways and receptors of flood risk, while maintaining the logic of the source–pathway–receptor approach to flood risk assessment. In this paper, the quasi-2D SPR is developed, applied and evaluated as the conceptual foundation of subsequent quantitative assessments.

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5.2. The quasi-2D SPR is a robust conceptual model whose application provides key insights into the characteristics of coastal floodplain systems

The quasi-2D SPR provides insights into the complexity and characteristics of coastal floodplain systems that the quantitative assessments will need to capture. Model construction is a flexible and participative exercise involving a wide range of stakeholders and scientists in an iterative process. The model also facilitates the development of strong, shared understanding of the coastal floodplain. When dealing with extensive floodplains, the model can be applied in a structured manner at different scales to help inform the downscaling process during the flood risk assessment. Important lessons regarding the individual characteristics of coastal floodplains systems can be learnt through application of the quasi-2D SPR. Model application also helps clarify the problem-framing process and is useful in capturing existing knowledge and identifying critical information gaps. The model provides a framework for "expert analyses" and a powerful means of incorporating non-quantitative expert knowledge about the floodplain.

A limitation of the model is the subjectivity involved in model application, specifically with regard to the data used to build it, the floodplain element definitions, and the extent of stakeholder participation. However this subjectivity is seen as essential as it ensures that the model can be built commensurate to the amount of data and time available. Moreover, these choices and limitations are explicitly reflected by the resulting conceptual model of the coastal floodplain. The process of model construction is universal and equally applicable to all sites, though the resultant model is distinct to the diverse characteristics of each coastal floodplain.

5.3. The quasi-2D SPR is potentially a useful tool for coastal flooding management

The quasi-2D SPR is potentially useful for coastal flooding management. For example, in France, the current flood risk prevention approach delineates flooding hazard and defines the associated prevention measures according to the level of threat (Risk Prevention Plans, PPR; Deboudt, 2010). This hazard assessment is frequently conducted using a detailed flood model of well-defined centennial or historical events. In contrast, the SPR approach might be useful as a preliminary assessment of the potential weaknesses in the flood defence system and associated flood routes. A second potential utility of the quasi-2D SPR is its ability to generate rapid hypothetical scenarios. As part of the adaptation strategy in France, regional and local authorities must assess territorial vulnerability and take appropriate adaptation measures. This requires the generation of multiple scenarios of possible changes to the floodplain state and assessment of the relevance of different adaptation options (e.g., Hallegatte, 2009; Lempert and Schlesinger, 2000). Since detailed modelling is often too expensive for use in high-level scoping studies, and since uncertainties on future coastal hazards are large (e.g. Yates et al., 2011), simpler methods such as multi-criteria approaches (Le Cozannet et al., 2013) or the SPR framework could prove useful.

A key limitation of the model is that it does not, on its own, identify the critical areas of the mapped floodplain system. A quantitative representation of the quasi-2D SPR model is being developed to identify critical system components. The aim of the quantitative model is to provide integrated probabilistic risk assessments for the breadth of the floodplain system, for rapid appraisal of flood risk pathways across uncertain inputs. For this, a Bayesian Networks approach is being applied to a) quantify the states of floodplain elements as receptors of flood risk; b) assess the role of floodplain elements as pathways of flood risk propagation; and c) identify and measure existing/emergent flood pathways in response to changing inputs.

Bayesian NETWORKS refer to a probabilistic systems simulation approach that uses a diagram describing the system and the principles of Bayesian probability theory to model the propagation of defined probabilities across the system Pearl, 2011; Spiegelhalter et al., 1993. They are widely used for developing understanding of complex systems where qualitative and quantitative data and knowledge are uncertain, incomplete and/or spread across disparate elements (Catenacci and Giupponi, 2013; Kelly et al., 2013).

The quantitative model will assess floodplain elements as sources, pathways and receptors of flooding, based on the system diagrams of the quasi-2D SPR conceptual model. For instance, source elements of the quasi-2D SPR will provide the inputs to the model, and describe the probability distribution of water levels or wave heights at a certain location. The model uses these distributions to assess the likelihood of inundation and/or overtopping of coastal defences, inundation and run-up on beaches, and the subsequent flood state of inland floodplain elements. Preliminary work on the case-study sites shows that the quantitative model can be built and run for a local-scale floodplain in a matter of days. The quantitative model will be a powerful tool for rapid scoping of the floodplain system, to quantify and identify specific floodplain elements that act as weak links with regard to flood propagation and are key factors in determining downstream flood extents. This information can in turn inform more detailed quantitative assessments of the floodplain in, for example, a decision support system that investigates multiple flood risk adaptation and mitigation options (THESEUS Consortium, 2009), or an integrated flood risk study that assesses the probabilities and consequences of flood events (Oumeraci et al., 2012). The 2D SPR models are currently being built and applied in European coastal floodplains. This concept could be explored more widely, for example, in sites along the world's coasts as well as fluvial floodplains.

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A holistic model for coastal flooding using system diagrams and the Source-Pathway-Receptor (SPR) concept

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Abstract. Coastal flooding is a problem of increasing relevance in low-lying coastal regions worldwide. In addition to the anticipated increase in likelihood and magnitude of coastal floods due to climate change, there is rapid growth in coastal assets and infrastructure. Sustainable and integrated coastal flood management over large areas and varying coastline types cannot be simply treated as local combinations of flood defences and floodplains. Rather, a system level analysis of floodplains is required to structure the problem as a first step before applying quantitative models. In this paper such a model is developed using system diagrams and the Source-Pathway-Receptor (SPR) concept, to structure our understanding of large and complex coastal flood systems. A graphical systems model is proposed for the assessment of coastal flood systems with regard to individual elements and their topological relationships. Two examples are discussed – a unidirectional model for a large-scale flood system, and a multi-directional model for a smaller-scale system, both based on the Western Scheldt estuary. The models help to develop a comprehensive understanding of system elements and their relationships and provide a holistic overview of the coastal flood system. The approach shows that a system level analysis of floodplains is more effective than simple topographic maps when conveying complex information. The models are shown to be useful as an apriori approach for making the assumptions about flood mechanisms explicit and for informing inputs to numerical models.

1 Introduction

Coastal floods from extreme events are without doubt among the costliest natural disasters worldwide (Kron, 2008). Further, coastal zones are becoming more risky as the probabilities and consequences of these flood events increase due to climate change and development pressures. Therefore, analysis of floods in these regions is essential in order to understand risks and minimise losses. Several regions today adopt risk-based approaches to designing coastal protection by analysing the probabilities and consequences of flood events. To understand these probabilities and consequences, coastal managers and decision-makers use a variety of flood maps based on numerical models of flood events (de Moel, 2009; EXCIMAP, 2007).

These models and maps improve our understanding of the hydraulics of flood events and help reduce losses during extreme flood events through efficient flood risk reduction strategies. However, widespread damage still occurs repeatedly despite excellent forecasts and numerical models being available. Events such as Storm Xynthia in France (Kolen, 2010), the July 2007 floods in the UK (Pitt, 2008) and Hurricane Katrina in the US (Seed et al., 2008), though well-forecasted and modelled, caused considerable damage in their respective regions, and revealed shortcomings in our understanding of coastal flood systems. These shortcomings have more to do with the application of numerical and quantitative models than with the models themselves.

While numerical flood models can be applied with great detail and at very fine spatial resolutions, these are often too expensive in terms of data requirements and computational time for use in large and complex coastal flood systems. Also, the nature of these flood systems poses several

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challenges in ensuring that application of these models is based on a comprehensive understanding of the system. This paper aims to address these issues by proposing a systems level analysis of coastal floodplain behaviour.

2 Challenges in understanding coastal flood systems

2.1 Introduction

A coastal flood system, in the context of this paper, is defined as a geographical region comprising all natural and human related elements potentially affected by a defined flood event. There are several challenges in developing a comprehensive understanding of a complex coastal flood system, including the size of the system, the number of components, including different land uses, and administrative and political boundaries. At present flood risk studies rely almost entirely upon numerical flood models for their analyses of the coastal flood system. However, considerations of financial and computational expense make it difficult to obtain and use accurate data or detailed numerical models at large scales. Added to this are the dangers of missing out key inputs and features that may result in an incomplete definition of the coastal system within numerical models.

2.2 Size and complexity

Hurricane Katrina in 2005 in New Orleans, USA is one of the costliest coastal flood disasters in history (Seed et al., 2008). Though bigger than expected and prepared for, the event provided several key lessons for flood risk management. Due to the size and complexity of the New Orleans coastal defence system as well as the relevant organisations, there was a lack of overview on the state of flood defences prior to the event. This led to weaknesses and maintenance gaps in some dyke sections being overlooked that aggravated flooding in the region (Seed et al., 2008). A similar lack of overview on emergency response measures and flood defences led to aggravation of damage during the July 2007 floods in England (Pitt, 2008) and Storm Xynthia in France in 2010 (Kolen, 2010). A methodology formalising knowledge about the flood system, state, importance and relevant organisational structure would have helped reduce the aggravation of flood damage in these instances. This information would also allow better representation of gaps and weak links within numerical models of the flood system.

2.3 Unexpected pathways and unnatural boundaries

Such a methodology for the formalisation of flood system knowledge will also help identify the existence of potential, unexpected flood pathways that could aggravate flood damage. This issue was brought to the fore during Storm Xynthia in 2010 where development contrary to spatial planning laws and a lack of knowledge of potential flood routes within the system caused authorities and inhabitants to be taken by surprise (Kolen, 2010). Additionally, flood maps and models are often constrained by administrative delineations that do not recognise the full extent of the natural flood system, especially where the systems cross political boundaries. The existence and location of flood routes in urban regions are of particular importance in numerical models, and such information may be missed in low resolution models. The challenge here is to capture simply, yet effectively, the natural flood system in its entirety with key information on all potential flood routes. A formalised understanding of the full extent of the system will also be invaluable when applying models to regions bounded by administrative and political boundaries rather than natural flood boundaries.

2.4 Diverse land-use types and inter-dependencies

Coastal flood systems typically consist of a large number of land-use types and an equal variety of stake-holders and experts. Providing a platform for experts from diverse fields to arrive at a shared understanding of the managed flood system is a difficult task. This is further complicated by inter-dependencies between the flood system elements. For instance, natural coastal habitats such as mangroves and saltmarshes provide protection during flood events, but these are themselves often affected by flood events; and a change in their state during one storm will affect the flood risk of linked areas during subsequent events. Capturing these inter-dependencies across the flood system and quantifying the effects on flood risk due to changes in the states of particular elements are significant challenges. While many models take key relationships between system elements into account, the process is often static and becomes difficult for larger systems. A simplified model of the topological relationships will allow users to understand effects on the system as particular elements change, or as new information about these elements is obtained.

2.5 Summary of challenges

The size and complexity of coastal flood systems means that there are several challenges associated with gaining a comprehensive understanding of these systems. An inexpensive but rigorous and comprehensive model of the coastal flood system is essential not just for understanding these systems but also for planning and designing flood risk reduction measures. In order to overcome the challenges described, such a model should also be able to integrate important information on different types of elements across the system and provide an overview of the relevant topological relationships and inter-dependencies between these elements. Ultimately, this model should be able to inform subsequent numerical models so as to provide a complete picture of all relevant inputs, elements and features within the system being modelled.

3 Current practice in coastal flood risk studies

3.1 Conceptual descriptions of coastal flooding

A popular conceptual model for the description of coastal flooding is the Source-Pathway-Receptor (SPR) concept (Holdgate, 1979). Placed within broader frameworks such as the Driver-Pressure-State-Impact-Response (DPSIR), the SPR allows specific descriptions of the state of coastal flood defence pathways (Evans et al., 2004). The SPR concept has its origins in environmental engineering to describe the flow of environmental pollutants from a source, through different pathways to potential receptors (Holdgate, 1979). It was subsequently adopted for coastal flooding by the UK Environment Agency (H R Wallingford, 2002) to describe the propagation of a flood from a source through flood defences (pathways) to the floodplain beyond (receptors) (Fig. 1).

Coastal flood risk studies generally analyse the physical characteristics of flooding in terms of two components: (a) the hydraulic loading and failure behaviour of structural and non-structural coastal flood defences, and; (b) the hydraulic propagation of flood waters into the landward floodplain (Safecoast, 2008). Coastal flood defences prevent or reduce the entry of coastal flood water into the system. The extent of the floodplain is then dictated by the quantity of water let in by the defence system and local topography.

The pathways of flooding in such an application are limited to coastal defence systems, with every other element in the system being considered a receptor. This does not allow the analysis or description of non-defence system elements or their topological relationships. Therefore, though effective for the analyses of coastal defence systems, this approach does not allow flood risk reduction strategies to address the challenges in large coastal systems (described in Sect. 2).

Recent flood risk studies recognise the coastal floodplain as being a coastal flood system, with inter-linked and interdependent elements. In the UK, the RASP study (Sayers et al., 2002) and the Foresight report on Future Flooding (Evans et al., 2004) recognised the influence of inter-linked elements within the flood system. For instance, these studies consider the role of non-defence elements such as channel vegetation and land-use such as urban habitats in modifying flood event probabilities. The Foresight study used the SPR to describe the role of non-defence elements of the flood system. Subsequent descriptions of the coastal flood system have all been based on a similar concept with minor variations (e.g. Bakewell and Luff, 2008; FLOODSite Consortium, 2009a, b; North Carolina Division of Emergency Management, 2009). Though non-defence elements are considered in these studies, non-local scale system features and relationships relevant to flood management – such as drainage systems or natural habitats potentially acting as flood sinks, were not captured effectively. Further, at a regional to national scale, detailed numerical analysis of the role of individual elements is not practical. It is difficult to capture the topological complexity of a flood system and integrate different element and land-use types within flood models. The Foresight report identified key research priorities for coastal flood systems. These include (a) a framework for integrated modelling of different elements within the flood system and (b) the need for a tool that captures the interactions of system elements, especially at the broad scale, to inform decision and policy makers (Evans et al., 2004).

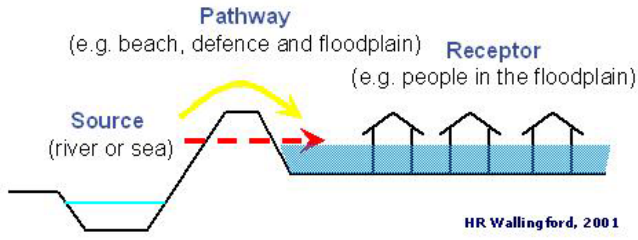

Fig. 1. The Source-Pathway-Receptor (SPR) model in flooding analysis (H R Wallingford, 2002, obtained from www.floodsite.net, © H R Wallingford, 2001).

3.2 Systems models for coastal flooding

Geographical flood maps, while very useful in conveying specific information to particular users, are not well-suited for describing complex systems and topological relationships between elements. A tool or framework, to address the research priorities described, will need to convey large amounts of complex information to users and experts from diverse fields. System diagrams are a popular and effective means of conveying topological relationships and feedbacks between elements in various fields such as electricity and transport infrastructure. A widely known use of a topological system map is the London Underground map. This map provides a diagram of the functional relationships of the underground railway system, despite not conveying scale, depth and distance travelled. Such topological maps can be very useful in communicating complex information at the right level of abstraction (Kramer, 2007).

The Environment Agency (2009) suggested a systems model to effectively describe and analyse large-scale geomorphological systems consisting of several elements with complex interactions. This form of conceptualisation allows the easy identification of key features and relationships. Importantly, being scale-independent the systems model captures the influence of important elements at non-local scales. The model also helps formalise our understanding of the system and removes the black box nature of existing models (EA, 2009). In the field of coastal flooding, fault tree analyses have been conducted on specific coastal flood defences (e.g. de Boer et al., 2007). However, no such model exists for an entire coastal flood system to date.

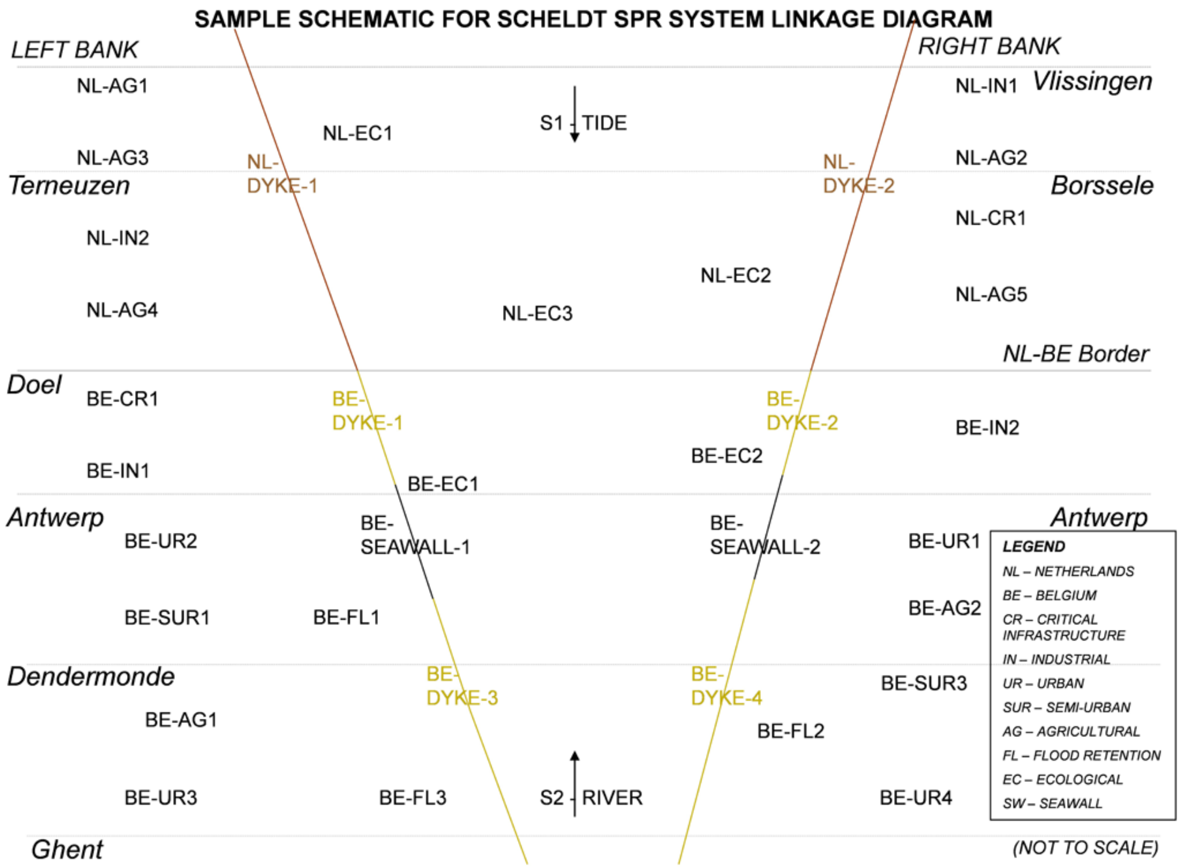

Fig. 2. Simplified stretched schematic of the Western Scheldt showing the considered flood system (100 yr flood + 3 m, planar water level, no defences), the elements within the flood system including assumed defence sections, political boundaries and the (two) sources of flooding (based on data from Google Earth) (based on steps 1 and 2 of Methodology in Sect. 4.2).

4 The a priori systems model

4.1 Introduction

Here, we describe the building of a systems model for coastal flood systems, based on the principles of the RASP (Sayers et al., 2002), Foresight (Evans et al., 2004) and coastal geomorphology (EA, 2009) studies. The SPR approach is combined with the concept of system diagrams to better recognise key system features and topological relationships between elements. Hence, a more holistic understanding of the flood system is achieved, prior to analysis of these sites with numerical models. The authors intend that this model be used prior to numerical models, in order to inform users of the state, constituent elements and inter-dependencies of the coastal flood system being modelled. It will be applied to sites currently being evaluated under the EU THESEUS project (www.theseusproject.eu). THESEUS is a Europe-wide project that aims to integrate analyses of the engineering, ecological and socioeconomic aspects of coastal flood system management for better solutions to the problems of climate change and sea level rise.

4.2 Methodology

The combination of SPR with system diagrams is a powerful way of collating a comprehensive description of the state of the flood system, its elements and their relationships. The initial focus is on identifying the receptors and building up a network of pathways. A key principle in this approach is the recognition that the definitions of "pathways" and "receptors" are relative, rather than fixed as in earlier applications. Thus, all components of a system may simultaneously function as pathways to "downstream" receptors and as receptors in their own right.

The aim of the systems model is to allow event-specific analyses of the coastal flood system. To ensure that no event-specific analysis is in danger of missing out potential sources, pathways or receptors, the model is developed iteratively, with the first iteration performed for the most extreme event considered. This ensures that any analysis starts with the largest considered system extent. Subsequent analyses of the system for lesser events will derive their system extents from the largest possible extent obtained in the first iteration. The

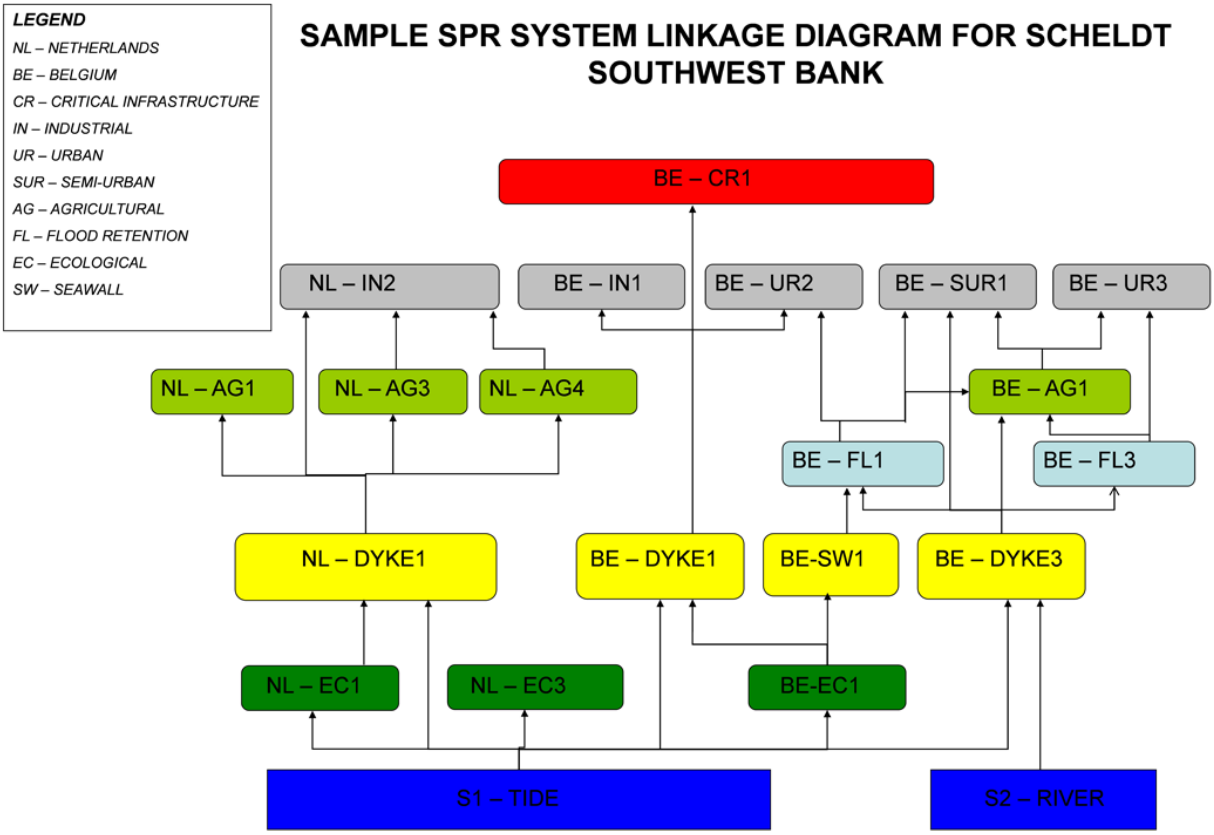

Fig. 3. Systems model for the large-scale flood system (southwest bank of the Western Scheldt), based on the schematic shown in Fig. 2. The sources are indicated as S1 and S2, and the system elements are labelled based on their land-use classification, as shown in Fig. 2 (based on steps 3 and 4 of Methodology in Sect. 4.2).

generic methodology for the first iteration development of the system model is described below.

Step 1: The boundaries of the coastal flood system are first decided using a planar water level model for the most extreme water level being considered. This is done under the assumption of a worst-case scenario where complete failure (or absence) of engineered defences is assumed. This assumption will indicate the full extent of the natural flood system and ensure that all system elements are included in subsequent analyses.

Step 2: Once the natural system extent has been delineated, all elements within the flood system, including flood defences, are mapped as unique entities classified based on land-use. This may be done manually on a map or using a GIS-based software. Individual elements may be of different sizes, since the model is intended to be scale-independent. This allows flexible selection of elements within the system that may be of particular importance to flooding, such as engineered flood defences, flood defences in urban buildings, natural habitat sinks or other such non-local scale features. Since this classification is done after application of the planar water level model, it has no influence on the extent of the system. This classification based on land-use provides a platform for further event-specific analyses of the consequences to specific receptors. Potential effects of changes to land-use within the system during and between flood events may also be analysed. Figures 2 and 4 (discussed in Sects. 4.3 and 4.4, respectively) provide examples of this step.

Step 3: The next step is to define the relationships between the identified elements. At this stage, a link is identified between any two elements if the elements share a geographical boundary. Links between engineered flood defences and the rest of the system are also identified on the same basis. Flood compartments created by these defences can therefore be studied as part of the bigger natural flood system, rather than as isolated sub-systems. The elements and links are then schematised, and a systems map is drawn that maintains as much spatial representation as is practical. The move from a geographical map to a systems map allows easy, quick and comprehensive analyses of the topological relationships between different elements regardless of their location or size. Figures 3 and 5 (discussed in Sects. 4.3 and 4.4., respectively) give examples of this step.

Step 4: Once the complete system diagram is built, the sources of flooding are identified on all boundaries and, if necessary, within the system boundaries. These sources are

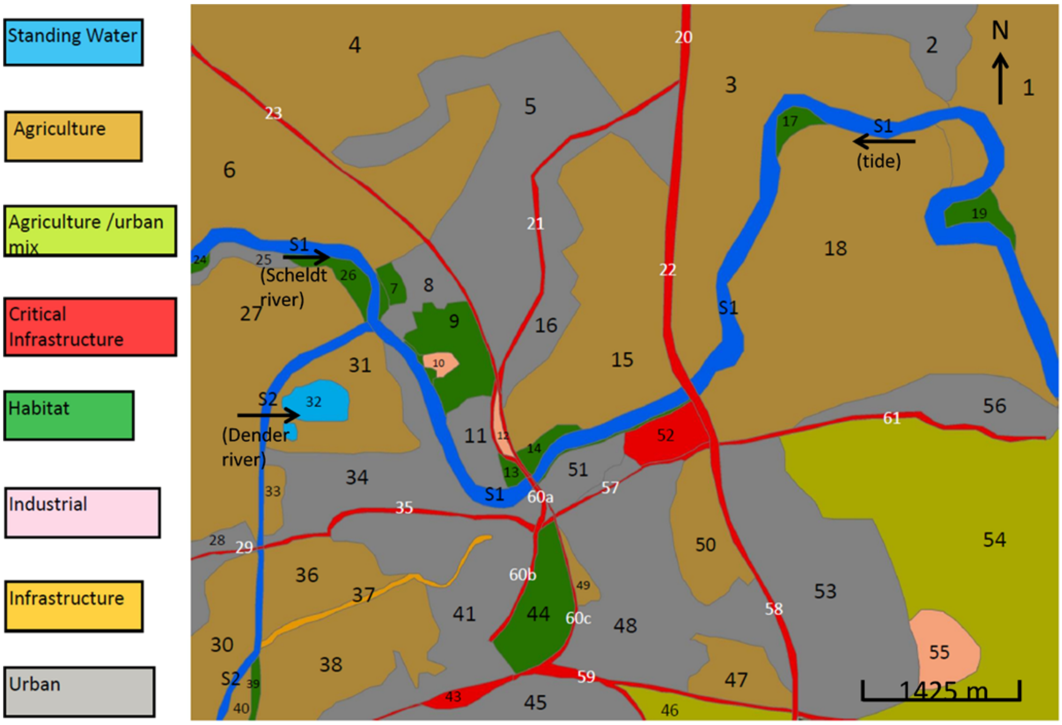

Fig. 4. Dendermonde flood system map for the maximum considered flood extent (100 yr flood + 3 m, planar water level, no defences) with numbered elements classified by land-use (Area A – flood system north of S1; Area B – flood system between S1 and S2; Area C – flood system south of S1, east of S2) (based on data from Google Earth). The regions collectively correspond to element "BE–UR3" in Fig. 3 (based on steps 1 and 2 of Methodology in Sect. 4.2).

also schematised and all links between them and directly connected system elements are identified.

In this way a complete systems map of the natural coastal flood system is obtained, with all the elements under consideration identified. Their relationships regarding possible flood routes, all possible sources of flooding and their directions and points of entry are illustrated. A lesser flood event may result in a modification of system extent and element links depending on the relative flood depth for that event. Though not performed in this paper, this modification can be achieved later with flood data, and/or numerical models and form the basis of further flood risk analyses. The ordered progression of systems analysis from the most extreme events to lesser flood events ensures that key receptors and flood pathways are not missed out during flood risk analyses.

To illustrate the approach, two examples of the systems model are presented here: (1) a unidirectional representation of a regional-scale flood system across two countries; and (2) a multi-directional representation of a small-scale flood system within the region of the first model. The system extent in both cases was decided using a planar water level corresponding to the maximum considered water level (a 100-yr flood plus a freeboard of 3 m to allow for extreme increase in water levels).

4.3 Large-scale systems model (the Western Scheldt)

A systems model was built for the Western Scheldt estuary in Europe. The estuary is 350 km long and flows through Belgium and the Netherlands. The tidal influence reaches the city of Ghent in Belgium. The estuary also experiences river flooding in combination with high tides at upstream locations. Several urban, semi-urban, industrial and agricultural regions are present on either bank in both countries, and these are protected by dikes and seawalls. The estuary and its banks also hold a number of protected natural habitats that are in conflict with human activity (Bouma et al., 2005). Hence, the Scheldt estuary is a complex and interesting flood system and case study.

The systems model for the Scheldt is built using the methodology described in Sect. 4.1. For this study, the flooding on either bank of the Scheldt is considered to be independent. A systems model is built for the entire length of the southwest bank of the estuary. The area is classified into geographical elements based on the predominant land-use. Linear sections of defence elements, differentiated on the basis of element type and design levels, are assumed for the purposes of illustration. Two sources of flooding are considered: high tides and high river runoff.

Figure 2 shows the schematic of the Scheldt used here. This schematic is built based on steps 1 and 2 of the

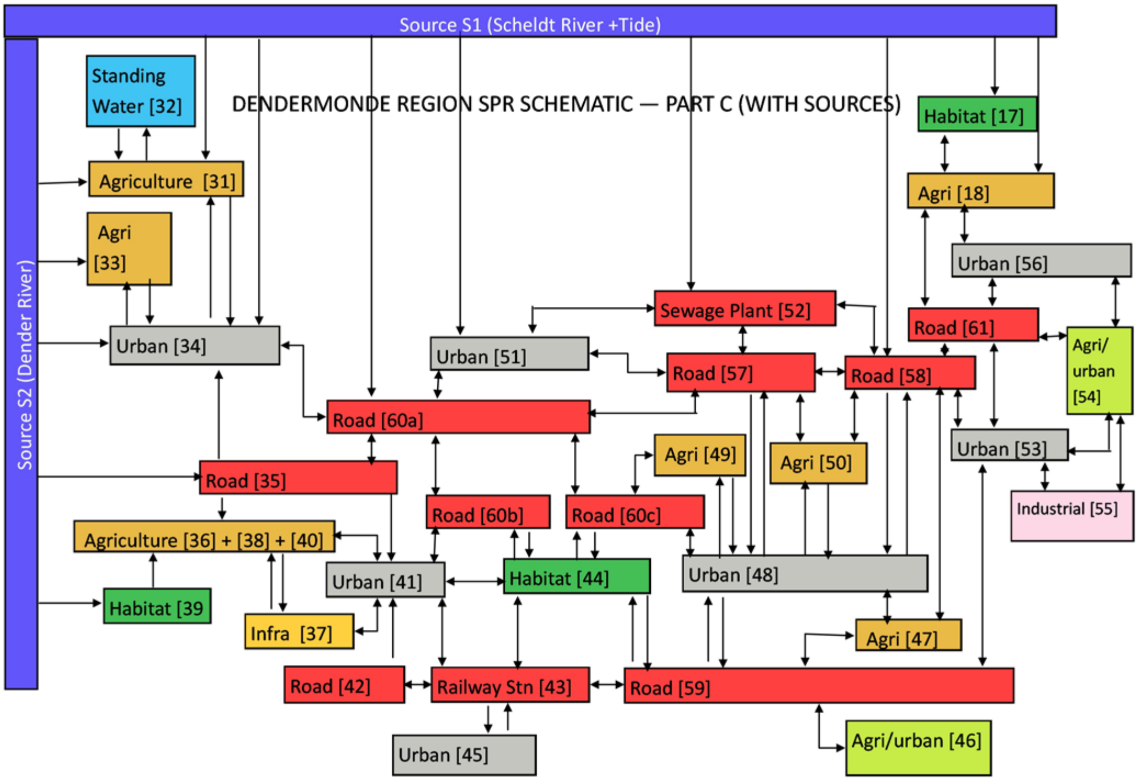

Fig. 5. Systems model for the small-scale flood system (Area C of the Dendermonde flood system shown in Fig. 4). The elements and sources for Area C are represented as per the flood system map in Fig. 4 (based on steps 3 and 4 of Methodology in Sect. 4.2).

methodology described in Sect. 4.2. Since both sources enter the flood system from the river, an elongated shape is used to approximate the river basin. Figure 3, built using the rules outlined in steps 3 and 4 of the methodology, shows the system SPR diagram for the elements on the right side of the bank of the Scheldt (going upstream). Though the diagram is built independent of administrative boundaries, the elements are given suffixes "NL" or "BE" to indicate their political regions.

The system diagram in Fig. 3 allows a rapid broad-scale assessment of this large-scale flood system. The diagram makes explicit the considered system extent, system elements and element relationships. Relationships between specific defence elements and urban regions, such as between elements "BE Dyke1" and "BE SW1" and the city of Antwerp are easily identified. These relationships will not be as obvious on a flood map, especially when the defence elements and the urban regions are at considerably different scales. The model also captures the relative roles of elements as pathways as well as receptors. In the map in Fig. 3, the habitat region of "BE EC1", defence element "BE Dyke1" and critical infrastructure, "BE CR1" are all potential receptors of flood-induced change in their own right. Additionally, there is a link between natural habitat "BE EC1" and critical infrastructure element "BE CR1" through defence element "BE Dyke1". Thus, the habitat and defence elements become pathways when the receptor is the critical infrastructure. This illustrates the fact that a change in state of the habitat will have an effect on the infrastructure element. Such links between spatially disjoint elements are easily identified with this systems model. In this manner, specific weak links may be pinpointed for more detailed studies. The systems map is therefore useful in prioritising further investigations, while making sure that the entire system is captured and understood at all stages of the analysis process. As another example, Fig. 3 highlights the vulnerability of elements connected to defence element "BE Dyke3" to a combination of tidal and riverine flood sources. These include the urban region of Dendermonde, labelled "BE UR3". The combination of sources at this point indicates this area as one where more in-depth investigation would be beneficial. Hence, this area is the subject of the second, smaller-scale systems model.

The large-scale systems model may be used by coastal authorities and managers in both the countries to arrive at a common understanding of the shared flood system, by understanding the relationships between elements on either side of the border. Coastal authorities or concerned stake-holders for specific receptors can use the map as a rapid assessment of the topological links between their receptor of interest and other system elements. This will facilitate integrated policy and decision-making regarding flood zoning and protection measures. Such a map of large-scale systems can also be used to identify critical and important pathways within the system, and provide a rational framework for prioritising further research needs.

4.4 Small-scale systems model (of Dendermonde)

The multi-directional SPR system model permits greater detail and spatial representation. The procedure for building the model is the same as in the previous case. Once the system extents are decided for the worst-case scenario, the Dendermonde flood system is divided into three broad compartments where flooding is assumed to occur independently. This is done based on the nature and location of the sources and the local geomorphology. As in the first example, elements in each compartment are categorised by their predominant land-use. Due to the finer scale and multi-directional nature of the sources, a greater degree of spatial accuracy is maintained during the schematisation.

Figure 4 shows a map with the flood system divided into three compartments based on the geomorphology and classified based on land-use. This figure is built using the rules described in steps 1 and 2 of the methodology described in Sect. 4.2. Figure 5, based on steps 3 and 4 of the described methodology, shows the systems diagram for Area C of the flood system, situated south of the main estuary.

The systems diagram in Fig. 5 allows a quick and comprehensive a priori analysis of the Dendermonde flood system. Since the defences are assumed to fail, the full natural extent of the flood system is made clear. The model makes clear the possibility, however small, that the railway station, "[43]" may be flooded not just from the north or the west, but from other directions as well by flood routes through other system elements. It thus provides a comprehensive platform for analysing the range of flood routes within complex systems. All system elements are presented on the same systems map, making it easy to identify relationships between habitat elements and surrounding urban elements. For instance, habitat element "[44]", if designed as a flood retention region, could mitigate flood risk to the station and surrounding road links. Similarly, agricultural and standing water elements "[32]" and "[31]" may be used to mitigate flood risk to urban element "[34]". Such systems analyses can help to focus the efficiency of the subsequent application of numerical models for flood risk studies. The SPR network potentially draws out detailed, element-specific questions of interest concerning the given flood system that encourage a better model design and application.

4.5 Discussion

In both case studies, the systems model is effective in providing complex information that will be difficult to convey on a simple flood map. It serves to inform users of the assumptions and considerations being made in subsequent numerical models. It is observed from the two case studies that progression to a multi-directional model at smaller scales is necessary to obtain a complete representation of the flood system – similar to the increase in feature representation in numerical models with increasing resolution. This is mainly due to the finer resolution of the sources and elements, necessitating the representation of multi-directional sources and element links. However, since this systems model is scale-independent, it is possible to aggregate different elements or ignore certain links for a more simplified model. Thus, the user can choose only to represent the key elements and links of interest for the given analysis. The main advantage of doing this in the systems model, rather than in numerical models, is that the assumptions made in the process of aggregating elements or ignoring links becomes explicit and can easily be corrected or modified if necessary. It is therefore useful as an a priori model in the flood modelling process.

5 Conclusions

Despite the availability of excellent forecasting and numerical flood models, there remain gaps in our understanding of the coastal flood system, and hence in our applications of these models. However, the size, complexity and diversity of these systems pose considerable challenges in gaining a comprehensive understanding of flood system elements and their relationships. The detail that such studies will require makes it impractical to rely solely on numerical models. In this paper, an a priori systems model for coastal flood systems is developed based on the concepts of SPR and system diagrams. The model is capable of providing complex information about the system and element relationships in a robust and effective manner. It is also a powerful means of making key explicit assumptions and considerations about the system, providing users a comprehensive understanding of their flood system. The systems model is not meant to replace flood maps or fully quantitative numerical models; instead, it is intended to be used alongside these, to ensure that a comprehensive understanding of the flood system before quantitative modelling.

The formalisation of the model building process with a generic rule-based algorithm is being done at present. When finished, this will allow the model to be applied to any type of coastal system at any scale or level of detail. In this paper the model is applied to coastal flood systems at two scales. It is expected to be most useful in large and complex coastal systems where detailed numerical models are expensive and data for calibration and validation scarce. The model provides a structured and integrated overview of both flood systems, avoiding compartmentalisation of system elements into artificial sub-units. Since all the elements are mapped onto the same platform, along with the relevant relationships, the model is very useful in developing a common understanding of the systems amongst experts from different fields. Importantly, this understanding can be achieved prior to numerical modelling. This allows the formulation of element-specific questions about flood risks, impacts and management strategies. Appropriate numerical models may then be applied to explore the resulting questions.

The systems model, by developing the key topological relationships between elements, also provides an excellent foundation for analysing changes in flood risk across the system, due to changes in particular elements. Further work on this aspect of the model will attempt to quantify the uncertainties associated with different weak links within a system. These results, validated by results from numerical flood models, will be used to map the sensitivity of the system to different elements and pathways. Finally, the model offers great potential for identification of critical components and analyses of system failure pathways, all of which will be explored in later stages of this study.

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