Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

The SPR systems model as a conceptual foundation for rapid integrated risk appraisals: Lessons from Europe

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ARTICLE INFO

Article history:

Received 2 June 2013

Received in revised form 22 October 2013

Accepted 29 October 2013

Available online xxxx

Keywords:

Coastal

Flood risk

Integrated

Conceptual model

SPR

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 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 m³.

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 in 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 km². 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).

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

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).

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 bidirectional flooding using existing information. This informs the

Please cite this article as: Narayan, S., et al., The SPR systems model as a conceptual foundation for rapid integrated risk appraisals: Lessons from Europe, *Coast. Eng.* (2013), <http://dx.doi.org/10.1016/j.coastaleng.2013.10.021>

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.

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.)

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

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; 'O': 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	O	O	✓	X
Hafen City, Germany	Hydraulic engineers	O	O	✓	X
Cesenatico, Italy	Hydraulic engineers	O	O	✓	✓
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	✓	✓	✓	✓

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.

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.

Acknowledgements

The support of the European Commission through the project “Innovative Technologies for safer European coasts in a changing climate” (THESEUS), Contract 244104, FP7.2009-1, www.theseusproject.eu, is gratefully acknowledged. The authors are very grateful to the two anonymous reviewers whose patience and comments have been invaluable in strengthening this paper.

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