Investigating the Source – Pathway – Receptor – Consequence Framework for Coastal Flood System Analyses

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Introduction

Coastal floods account for a large proportion of the damage to life and property due to natural disasters world-wide. Out of the 15 greatest natural disasters in the world in terms of monetary losses between 2004 and 2008, 14 were coastal (Kron 2008). However, despite the enormity of a particular flood event, people often return to a flood-prone area after a disaster (Cigler 2007; Parker 1995). This necessitates a need for pro-active management of coastal flood systems. A coastal flood system may be thought of as a geographic unit comprising all natural and human elements potentially affected by coastal floods.

Though hard flood defences remain the primary choice for flood protection in many places, the importance of holistic management of coastal flood systems in limiting the consequences of coastal disasters is increasingly being recognised (Thorne et al., 2007 pp 4). However the complexity and size of coastal flood systems, the diverse nature of their sub-systems and the dynamic nature of their interactions makes this a daunting task. Rapid advances have been made in coastal flood modelling and management in attempts to address this challenge (de Moel et al., 2009). However, there is little understanding of how the elements of a coastal flood system interact with and influence one another, in terms of the flood propagation process, or the consequences of a flood event. A review of current flood system studies shows that most studies fall under two categories. These are (1) broad-scale studies (e.g., Kristensen 2004; Penning-Rowsell et al., 2005; Thorne et al., 2007) that consider the state of the system in relation to external drivers, pressures and responses or (2) detailed analyses that focus exclusively on particular parts of the system such as coastal defences or a natural habitat (e.g., Apel et al., 2006; Harvey et al., 2009; Natural England 2007).

System models that fall between these two ends of the spectrum – namely, models that provide an integrated overview of the engineered and natural elements of the flood system and their interactions, are increasingly being recognised as a necessary part of pro-active and strategic flood risk management plans (e.g., Hunt 2002; Pottier et al., 2005; Sayers et al., 2002; Thorne et al., 2007). However, isolated analyses of various sub-systems have been the norm until recently, reflecting administrative fragmentation (Pitt 2008; Parson et al., 2003). The apparent lack of commonality in flood risk analyses in the past has lead to repeated, avoidable failures with severe consequences such as those witnessed during Hurricane Katrina in 2005, and more recently, Cyclone Xynthia in Europe in 2010 (e.g., Seed et al., 2008; Kolen et al., 2010). Therefore, there is a need for a strong, flexible and consistent model that will help map the relative importance and roles of engineered and natural elements within coastal flood systems and facilitate effective integrated risk management policies.

The Source – Pathway – Receptor – Consequence (SPRC) model has been adopted in recent times in coastal flooding in attempts to integrate the different aspects of coastal flood systems. However, a review of the available literature suggests that the use of the model is often poorly defined and unclear, resulting in an ongoing failure to achieve integration of flood system analyses. This paper reviews current flood mapping practices with regard to where and how a conceptual model like the SPRC can prove useful. The manner of implementation of the SPRC model in coastal flood risk assessments is analysed and suggestions are made using a case-study for strengthening the model and placing it at the heart of flood risk analyses to help fill gaps in current understanding of the coastal flood system.

Flood Mapping Practices

Flood mapping has been carried out for many years and various purposes by governments and private institutions around the world. Several recent flood mapping studies have recognised the need for integration of the different elements of a flood system to achieve long-term flood risk reduction and efficient disaster management, and to facilitate effective environment-oriented flood risk reduction policies (e.g., Dawson et al., 2007; Pitt 2008; Thorne et al., 2007; Schmidt-Thomé 2006). Based on existing practices in Europe, flood maps in general may be distinguished as two types: (1) flood event maps that contain information on the probability and magnitude of a flood event and (2) flood risk maps that contain information about the consequences of particular flood events (de Moel et al., 2009). Due to the wide variety of land-use types, consequence calculation methods, objectives and stake-holders, different countries and regions typically have very different flood risk maps. Flood event maps however, follow a general methodology similar to the one outlined in Figure 1, with minor variations between studies, depending on their purpose and the institutions involved with flood mapping.

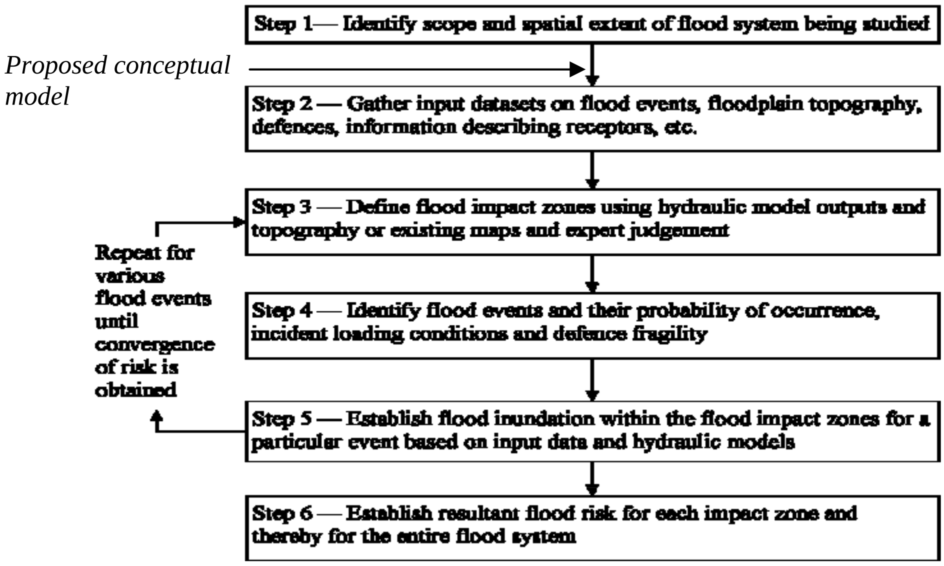

Figure 1: General steps involved in flood risk mapping based on FLOODSite Consortium (2009); DEFRA/EA (2004); de Moel et al., (2009)

While most flood event maps are placed within the context of a broader conceptual framework, it is seen from Figure 1 that the general methodology for flood event mapping does not explicitly include a conceptual model for the physical state of the flood system. The absence of an explicit model may result in inconsistencies in the manner in which the flood system is modelled and makes the collation of information collected from various sources in Step 2 a difficult task. In addition, the absence of a strong conceptual model may result in the exclusion of effects on the overall flood risk, of changes to elements within the flood system. For instance, it is widely recognised that the effects of climate change may include dynamic changes to natural and engineered elements that can have significant knock-on effects on nearby elements with regard to flood propagation and flood risk (e.g., Nicholls et al., 2007; Thorne et al., 2007). Despite this, few flood event maps consider the effects of such changes on future flood events (de Moel et al., 2009). Since the conceptual model used in a study will have a bearing on the nature and scope of its outputs, the inclusion of a conceptual model as a separate step after Step 1 of the methodology will greatly help reduce inconsistencies in the mapping process, provide information on system dynamics and facilitate effective integration of the information gathered in Step 2.

Another important issue in flood risk mapping is that of scale and the inclusion of cross-scale effects. For instance, the development of a port on a coast with extensive wetlands (regional scale change) may affect the wetland distribution, which in turn may affect flood risk in neighbouring towns (local scale effect). While flood event maps that focus on the physical effects of a flood event tend to be applied at local or regional scales (e.g., Horritt & Bates 2002; Gouldby et al., 2008), flood risk maps, that look at the consequences of a flood, are generally prepared at regional to national scales (e.g., FLOODSite Consortium 2009; Thorne et al., 2007). This division in scale can result in key local features within the physical system being overlooked in flood risk maps, especially with regard to their effect on the risk for a particular flood system. A clear conceptual model promotes a system–level understanding of coastal flood systems and provides an overview of temporal and cross-scale changes in flood risk.

Finally, a conceptual model of the state of the coastal flood system is a key step in the comprehension of a large and complex coastal system that comprises many different elements. It facilitates understanding of the system in terms of recognising elements such as sections of coastal defence structures or critical infrastructure that are important with regard to the consequences of a flood event. It also serves as a tool for communication across administrative and institutional boundaries about the aspects of the system that need to be considered in flood management and planning.

It is in an attempt to address the shortcomings in current flood mapping practices and to build a comprehensive model for the state of the flood system that the SPRC conceptual model has been adopted in coastal flooding studies.

The Source – Pathway – Receptor – Consequence Model

Background

The Source – Pathway – Receptor – Consequence (SPRC) model is a common conceptual model in coastal flooding that facilitates integrated flood system analyses by providing a realistic representation of the physical processes of flooding (Thorne et al., 2007). It has been widely adopted in coastal flooding studies in the UK, from its origins in environmental pollution following its use in the Foresight: Future Flooding report in 2004 (Evans et al., 2004). The model is also being used in coastal flooding studies in Europe (FLOODSite Consortium 2009; TU Dresden 2007) and in the USA (North Carolina Division of Emergency Management – Office of Geospatial and Technology Management 2009).

The SPRC model has been in use for more than two decades in the field of environmental pollution, in different forms, to evaluate risks arising from leakage of toxic pollutants. The first detailed definition found in literature is of the ‘Source – Pathway – Target’ model in Holdgate (1979). It has since been used in a variety of environmental risk assessments from tracing the fate of shotgun pellet pollutants (Sneddon et al., 2009) to classifying the effects of offshore wind farms on their environment (Scottish Government 2010). The UK Environment Agency described the use of the Source – Pathway – Receptor (SPR) approach as being fundamental to good practice in risk assessments for landfill sites (Environment Agency 2004).

SPRC in Coastal Flooding

The main premise of the SPRC model in coastal flooding is that the propagation of a flood event can be schematized in terms of source(s) for the event, receptor(s) and pathway(s) by which the event reaches the receptor(s) (see Figure 2). The ‘consequence’ term facilitates evaluation of different types of impacts, positive or negative, of a particular event on different types of receptors, both human and natural.

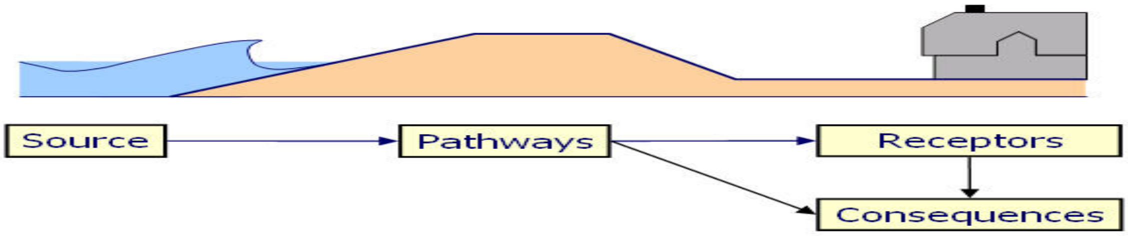

Figure 2: Simplified representation of the SPRC conceptual model for coastal flooding (TU Dresden 2007)

However, despite being cited extensively in coastal flood studies (and flood studies in general), there seems to be little explanation regarding its exact manner of implementation. Compared to other studies that use the SPRC model (e.g., Sayers & Meadowcroft 2005; Reeder et al., 2004; Shrestha 2008) the national-scale Foresight: Future Flooding assessment of the UK (Thorne et al., 2007) provides a comprehensive description of the manner in which the SPRC model has been used in its flood system analyses. Many studies on coastal flooding published after the Foresight report (e.g., Bakewell & Luff 2008; FLOODSite Consortium 2009; North Carolina Division of Emergency Management – Office of Geospatial and Technology Management 2009) use the concept as described therein. The Foresight study however considers a simplified, linear version of the SPRC model that, though useful at a national scale, may overlook several important issues such as element dynamics and the existence of multiple pathways to receptors within the flood system that are relevant to more detailed studies. This gives rise to difficulties in implementing it as a conceptual model for dynamic flood systems with complex, multiple inter-linkages. It is felt that the under-utilisation of the SPRC model is systemic in coastal flooding and strengthening the model to tap its full potential will greatly benefit coastal flood risk studies.

SPRC Implementation and Case – Study

Development of the SPRC Model

The SPRC model in recent applications is not well enough defined to serve as an effective conceptual model for integrated flood systems. However, the model can be developed to create a comprehensive and useful model of the flood system state without unduly sacrificing ease of understanding. The ongoing EU project ‘THESEUS: Innovative Coastal Technologies for Safer European Coasts in a Changing Climate’ (www.theseusproject.eu) aims to address both the human and ecological consequences of flood events across Europe is using the SPRC model as the basis for integrating these aspects in terms of coastal flood management while providing a system-level overview of the flood propagation process (THESEUS Consortium 2009).

In the example shown in this paper, a system linkage diagram is built, starting from the sources, through the various pathways and ultimately to the intended receptors. The main advantage of this approach is that any element on the system linkage diagram may be picked out by the user as a receptor thereby automatically designating the role of ‘pathway’ to all elements linking it to the sources. Hence, the definition of pathways and receptors becomes relative, with everything between a receptor and source being a pathway. This will help different users focus on different elements, For instance, in nature conservation, habitats might be regarded as a receptor, while for emergency planners, they are a pathway to people and their assets. This system diagram affords an excellent overview of the various elements and linkages that have been recognised in the study and as such, constitutes an effective and intuitive conceptual model.

Example Implementation in Great Yarmouth, UK

The SPRC system linkage model is applied to Great Yarmouth on the east coast of England. Great Yarmouth is an important regional town and tourist destination, situated between two rivers and the coast with a wide variety of infrastructure, engineering and natural elements. As such, the Great Yarmouth region offers an illustrative example of a site that can benefit greatly from a comprehensive and integrated conceptual model of the physical flood system.

The model is applied to Great Yarmouth following the methodology described below. The methodology is split into two broad stages – analysis of the Source – Pathway – Receptor (SPR) relationships that characterise the state of the physical flood system, followed by an evaluation of the Consequences (C) of a particular flood event. The conceptual model developed in this example focuses on the physical system state and analysis of the SPR relationships within the system. This is most effective when undertaken for the maximum flood extent being modelled without considering internal topographical variations within the boundary of the study. This approach makes it easy to apply the model in the absence of detailed topographical data or advanced hydraulic models.

The site boundaries are defined based on the flood extent of a current 1:100 year flood + 3m in order to account for future sea–level rise. Using standard national (in this case Ordnance Survey) maps broad-scale land-use receptors are identified as polygons on a GIS software as shown in Figure 4, with each receptor given a unique number reference. Coastal management infrastructure is included as a receptor, ‘Management’ with each type of hard or soft defence being assigned a unique reference. Hard infrastructure such as seawalls and dykes are shown as generally linear features as illustrated in Figure 4 and soft management such as beach replenishment schemes areas, as indicated in Figure 5. Supplementary material such as habitat type, construction material and land use are included as polygon attributes within the GIS software.

Four main sources of flooding are identified for this site: S1 from the open sea, S2 from the downstream confluence of the two tidally-influenced rivers, S3 from River Yare and S4 from River Bure. The site is then divided into three areas A, B and C, based on the general location of the different sources (see Figure 4). A schematic SPR diagram is then built to represent the various elements within the flood system, by considering an individual element as a potential receptor, and identifying for that receptor, all elements through which it may flood. This process is repeated for all the elements identified within the study site. This process offers a succinct illustration of the manner in which a flood may propagate through the system regardless of topography within the boundary flood extent. Since some areas may be flooded by more than one source, the directionality of flood propagation is important. Finally, the specific points at which each source can enter the system are identified. A schematic SPR diagram for Area A is shown in Figure 6 similar diagrams for Areas B and C may be constructed. The SPR diagram will form the basis for subsequent event-based topographical analyses and analyses of consequences.

The conceptual flood system model presented here, based on the SPRC model, provides a strong and robust means of presenting information on the manner of flood propagation through a system as well as the way in which changes to one element may affect the flooding of linked elements. The model thus offers an easy and effective way to qualitatively evaluate the effect of the responses of the flood system to external changes, whether driven by management or climate change factors. Finally, this model presents a simple and effective means of collating and presenting existing knowledge on the different disparate aspects and elements of the physical flood system to the relevant stake-holders. Since the model can be built to any level of detail depending on the data available, the consistency in methodology will ensure that the model provides useful information to the end users at each level.

Conclusions and Further Work

Flood hazard and flood risk mapping, though highly advanced, tend to focus on isolated analyses of elements within the flood system at specific scales and do not consider cross-scale and temporal dynamics between various natural and engineered sub-systems and the defence infrastructure protecting them. Though flood hazard and risk mapping are being increasingly implemented world-wide, flood systems still continue to fail for a variety of reasons, though a lot of the damage can be minimised through effective, integrated flood risk management plans. Policy-makers (e.g., Pitt 2008), managers (e.g., Thorne et al., 2007) and engineers (e.g., Gouldby et al., 2008) are recognising the apparent lack of commonality and the incompleteness of flood mapping practices in this regard. There is therefore an urgent need to develop a dynamic, evolving, rigorous assessment framework for flood risk mapping.

The SPR system model schematic shown in Figure 6 addresses these challenges to consistency and integration in coastal flood system studies and provides a flexible and powerful platform for more detailed assessments of the flood system. Firstly, the model illustrates the complexity of the system being considered. It makes it possible to pick out even at the conceptual stage, sections of coastal defence that may be of particular importance. The schematic identifies and highlights the role of natural habitats in coastal defence and makes it easier to study flood propagation across administrative boundaries. The level of detail of the schematic is representative of the scale of the study, and can be refined or degraded depending on the requirements of the user. This allows for easy and intuitive cross-scale analyses of a particular flood system. Also, this model can easily be developed to include further information on individual elements, such as their vulnerabilities and relative importance, the uncertainties in associated parameters, as well as the effects they may have on linked elements. As part of the THESEUS project, the SPRC system model is being applied in the case study sites and evaluated in the context of decision support for flood risk management. The model will include information on system dynamics, propagation of uncertainty, defence prioritisation, feedback effects of elemental changes and communication of spatial variability in risk during flood events.

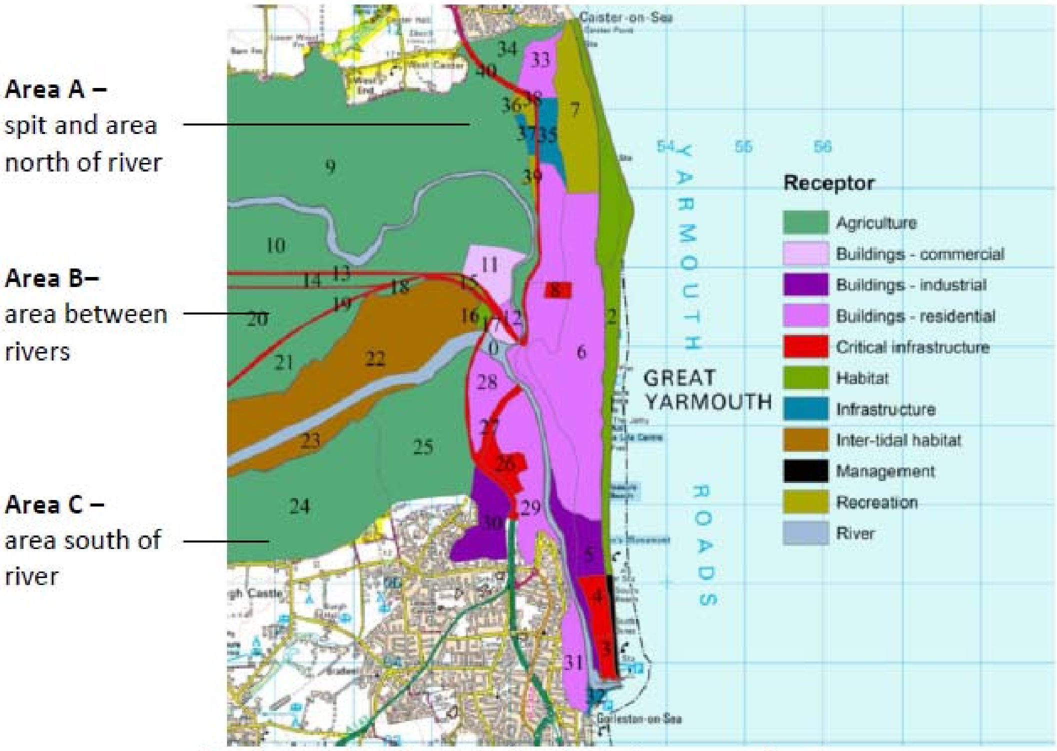

Figure 3: Map of Great Yarmouth study site indicating various receptors and the three compartments for the schematic diagrams based on the sources

Figure 4: Hard management features in the Yarmouth case-study site

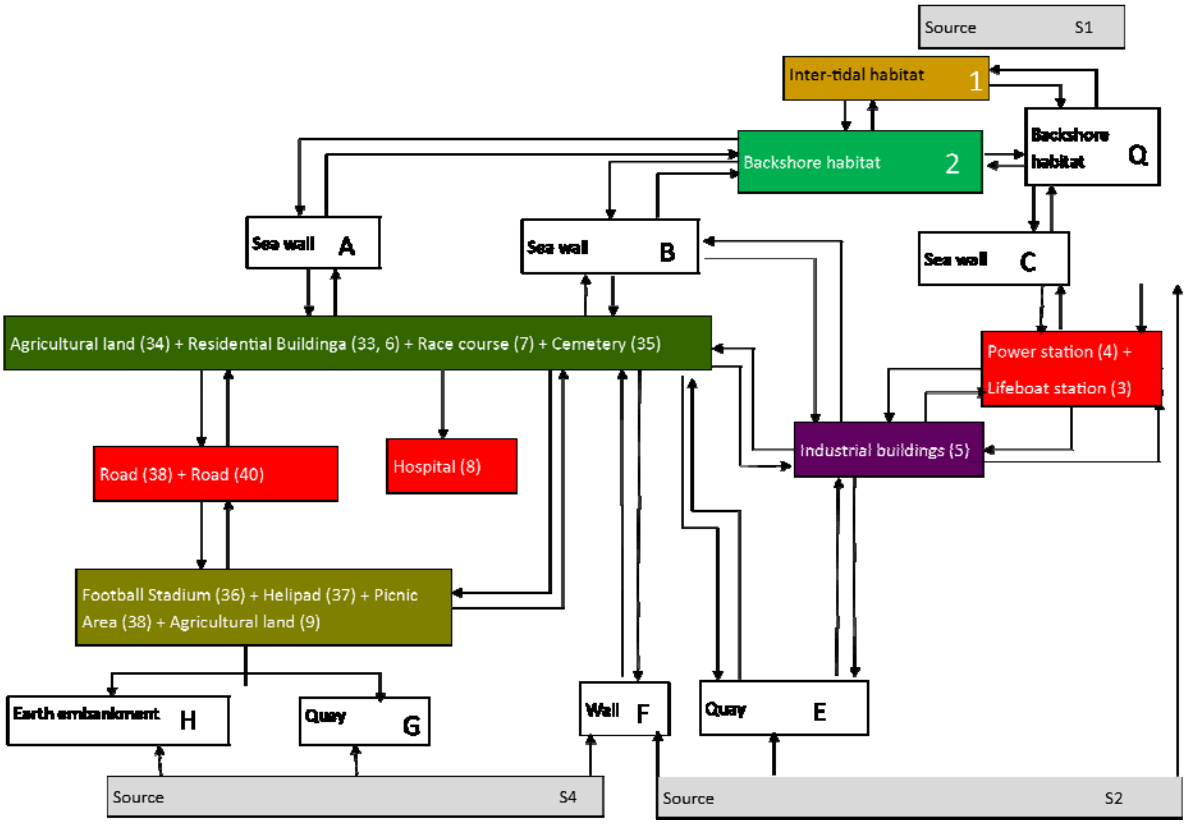

Figure 5: Example schematic SPR diagram for Area A of the Yarmouth case-study site with the sources, pathways and receptors indicated. Unique references have been assigned to receptor classifications (numbers) and hard defence (letters) as indicated in Figures 4 and 5 respectively

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