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The Integration of Coastal Flooding into an ArcFLOOD Data Model

by

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MARINE
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Abstract

The Integration of Coastal Flooding Data into an ArcFLOOD Data Model

Alison Heidi Nock

With the impact of global climate change, the speedy, intelligent and accessible dissemination of coastal flood predictions from a number of modelling tools at a range of temporal and spatial scales becomes increasingly important for policy decision makers. This thesis provides a novel approach to integrate the coastal flood data into an ArcFLOOD data model to improve the analysis, assessment and mitigation of the potential flood risk in coastal zones. This novel methodology has improved the accessibility, dissemination and visualisation of coastal flood risk. The results were condensed into spatial information flows, data model schematic diagrams and XML schema for end-user extension, customisation and spatial analysis. More importantly, software developers with these applications can now develop rich internet applications with little knowledge of numerical flood modelling systems. Specifically, this work has developed a coastal flooding geodatabase based upon the amalgamation, reconditioning and analysis of numerical flood modelling.

In this research, a distinct lack of Geographic Information Systems (GIS) data modelling for coastal flooding prediction was identified in the literature. A schema was developed to provide the linkage between numerical flood modelling, flood risk assessment and information technology (IT) by extending the ESRI ArcGIS Marine Data Model (MDM) to include coastal flooding. The results of a linked hybrid hydrodynamic-

morphological numerical flood model were used to define the time-series representation of a coastal flood in the schema.

The results generated from GIS spatial analyses have improved the interpretation of numerical flood modelling output by effectively mapping the flood risk in the study site, with an improved definition according to the time-series duration of a flood. The improved results include flood water depth at a point and flood water increase which equates to the difference in significant wave height for each time step of coastal flooding. The flood risk mapping provided has indicated the potential risk to infrastructure and property and depicted the failure of flood defence structures. In the wider context, the results have been provided to allow knowledge transfer to a range of coastal flooding end-users.

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Author’s Declaration

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award without prior agreement of the Graduate Committee.

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Presentations:

School of Geography, 2007-2009, Oral Presentations

Institute of Marine Studies, 2009. Oral Presentation

Plymouth Postgraduate Symposium 2008. Oral Presentation

NERC-Proudman Oceanographic Laboratory- Oral Presentations, 2007-2009

Conferences Attended:

Geoweb Vancouver, Canada, 2009

Coast GIS 2008, Santander

Geoweb Vancouver, Canada, 2008

Littoral Venice Italy, 2008

Flood Risk from Extreme Events (FREE) Conference, University of Reading, 2007

Chapter 1

Introduction

1.1 The Research Context

This study has identified a distinct lack of Geographic Information Systems (GIS) data modelling for use in coastal flooding prediction which encompasses the fields of numerical flood modelling, flood risk assessments, information technology (IT). As part of this research a data model has been developed for coastal flood risk analysis which will underpin the development of future flood risk applications. New prediction results are generated which has improved the scientific output provided from numerical flood modelling and improved flood risk mapping. The model will enable the integration of the diverse volumes of coastal flooding data in a bespoke, open geospatial-compliant geodatabase.

This research was undertaken as part of the Coastal Flooding by Extreme Events (COFEE) project, funded by the Natural Environment Research Council (NERC) under FREE (Flood Risk from Extreme Events) programme to predict flooding over a wide range of timescales. The COFEE project involved a range of stakeholders from the University of Plymouth, the National Oceanography Centre (formerly Proudman Oceanographic Laboratory), the British Oceanographic Data Centre, the University of Liverpool, Edge Hill University, and Sefton Council.

The project used Sefton coast located in north west of England as a study site, to understand the response of the coastline to extreme events, the interactions between the physical processes in the eastern Irish Sea and the coastal morphology, and to examine the rate and extent of coastal flooding attributable to changes in mean sea level and extreme events due to global climate change predictions (Williams et al., 2007), as well as the effects on human settlements. The study was in line with the NERC's new strategy, entitled “The Next Generation of Science”, which is to provide the scientific expertise to address key environmental science themes including global climate change and natural hazards satisfying governmental policy (Natural Environment Research Council, 2008).

Within the COFEE project a series of linked numerical models were developed, calibrated and validated against extensive historical, real-time and recent surveys at the site, to simulate the morphological impact of observed storm events along the shoreline and the coastal flooding which propagates onto the shoreline (Williams et al., 2007; Brown et al., 2010; Williams et al., 2011). The modelling system translates the offshore and nearshore metocean conditions such as waves, tides and storm surges during storm events.

One of the main goals of the COFEE project was the development of a GIS platform; this was a requirement for two reasons:

a. To harmonise the disparate data defining tidal/surge water levels, offshore and near-shore waves, beach sediments, bathymetry and topography results; and
b. To combine modelling results in a GIS to produce distinct analysis (Williams et al., 2011).

Once developed the GIS was used to investigate the following broad aims (c.f Williams et al., 2007):

a. What were the areas where future extreme floods will have greater/lower impact?
b. The production of coastal flood risk maps for present and future extreme event scenarios.

It is within this context that the data model developed in this research was proposed to the COFEE stakeholders and end-user group. This model provides a novel method to integrate numerical flood modelling with GIS, produce improved coastal flooding results and allow knowledge transfer to the wider flood risk management end-user community.

1.1.1 The Scientific Context

Extreme coastal flooding events are attributable to global climate change, events of this type that occur close to human settlements and infrastructure are likely to have a significant impact on human activity. It is estimated that almost two-thirds of the world's population and half of the world's cities are exposed to the threat of coastal flooding (UN Atlas of Oceans, 2006). This problem may be exacerbated in the future by global sea level rise and by an increase in the frequency and magnitude of severe storm events.

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC 2007) suggests that climatic hazards will increase in Europe in the future. If IPCC sea level rise predictions are correct, by 2080 an increasing percentage of coastal populations will be threatened by flooding. In the longer-term, sea level rise may include the possible loss of some coastal communities. Current climate models predict the probability of extreme winters may increase fivefold by 2100 (Purvis et al., 2008). Storm tracks are highly likely to move in the vicinity of the United Kingdom (UK), increasing the probability of tidal surge events (Purvis et al., 2008). Any shift in the storm tracks in winter over the North Atlantic produces windstorms and heavy rain due to increased cyclonic activity (IPCC, 2007). These effects will fuel storm surges, when combined with low pressure systems, sea level rise, topography and spring tides could cause severe coastal flooding in areas of the UK (Lowe and Gregory, 2005; Wang et al., 2007). Recently, the UK coastlines have experienced rising sea levels and frequent storms with subsequent coastal flooding to communities. These incidents provide examples of the potential severity of extreme events. The summer 2007 floods in England and Wales-A hydrological appraisal" document summarised this recent fluvial flooding event as "remarkable in extent and severity for a summer event" with estimated insurance claims approaching £3 billion (Marsh and Hannaford, 2007). In March 2008, strong gale force winds combined with spring high tides resulted in coastal flooding along western areas of the UK stretching from southern England to northern Scotland with further billions of pounds in damage.

Previous historic natural disasters such as the North Sea storm surge of 1953 have demonstrated the devastating impact of coastal flooding in the UK and the coastal regions of the Netherlands, Belgium and Germany. During this event severe flooding occurred across low-lying East Anglia and the Thames Estuary claiming over 307 lives; destroying 24,000 homes; and inundating 100,000 hectares of land (Met Office, 2013). Failure of sea defences occurred owing to the unusual combination of high waves, a spring tide, and sea levels attributable to a storm surge of approximately 3 m produced extreme event conditions in the study site (Wolf and Flather, 2005).

1.1.2 Governmental Policy Context

It is estimated that over 5 million people and 2 million properties are at risk of general flooding in the UK (Purvis, 2008). Flood and coastal risk management expenditure was budgeted at £800 million (Environment Agency, 2009). Almost £132 billion worth of assets are at risk of coastal flooding in (Hardaker and Collier, 2013). The cost of flooding could rise between £25 billion to £27 billion by 2080 (Bennet, 2014; Environment Agency, 2013a). To maintain existing flood protection to 2035, spending on asset maintenance and construction would have to increase to over a £1 billion a year, to incur savings to the economy of £180 billion over the next 100 years emphasising the economic and societal impact of coastal flooding (Bennet, 2014).

The challenges faced at the policy-making level are to effectively manage flood risk to reduce the likelihood of flooding and its impacts on land and society. The Environment Agency's most urgent responsibility in the UK is to manage flooding issues. It is the statutory obligation of the Environment Agency to undertake flood management, flood risk assessments and flood mapping to produce effective and timely warning systems for emergency preparedness based on science (Hardaker and Collier, 2013). This thesis supports the pivotal Pitt Review post-flooding report which identifies that the integration of science and engineering is crucial to the prediction of flooding in the UK (Evans et al., 2008). The UK Met Office (Met Office, 2006) believes that the mission of flood risk management is to adopt a wider perspective of coordinated flood risk across the coastal catchment which includes oceans, coastal estuaries and surrounding hinterlands and continues to work closely with other agencies to provide the real-time meteorological data into the COFEE project.

1.2 Research Rationale

The research justification lies within the distinct areas of GIS data modelling, numerical flood modelling and information technology (IT) advances. Its' future use is important to these specific areas. These are explained in the following key points:

a. GIS data modelling does not extend to coastal flooding in the GIS field. In this thesis, it is believed that data modelling is vital to the development of flood applications and the provision of targeted flood risk information to policy-makers interested in making better decisions. Flood risk assessment approaches currently do not use GIS data modelling to logically categorise and classify flood prediction results. This has been identified as a gap in knowledge and science. Through the data model, flooding predictions science are translated in a format for rapid visualisation thereby, allowing faster access and dissemination of crucial flood predictions. Although standardised formats exist, most are ineffective to visualise hydrodynamic-morphological output due to the representation of timeseries data.

b. Numerical flood modelling as developed in hydrodynamic-morphological ensemble or coupled-systems lacks GIS structure. There is no generic framework to facilitate interoperability with GIS systems. Intensive data pre-processing and manipulation are required to transform flood risk predictions to a format which is understood by end-users. This thesis undertakes the pre-processing necessary to develop the flow of useful data from numerical modelling to the data model. This linkage is essential to coastal flooding end-users who are actively seeking improved flood mitigation and disaster preparedness planning. By developing this process, future users of scientific output can rapidly access the desired results through ArcFLOOD's structured framework eliminating the need to reinvent the process and rapidly generating usable predictions. This standardised format enables flexible extension in GIS by future software developers. With ready access to generic flood model output, science can better inform policy-makers impending coastal flooding events.

c. Current trends in IT require linkages to weather specific scientific model data which are only accessible through organised structured data frameworks or data models. The future of flood risk assessments are leaning towards the use and further development of prediction data by the commercial and insurance sectors in partnership with leading climatic research institutions to provide bespoke science solutions.

Based upon the above justification, it is proposed that the data structuring of coastal flooding predictions can provide better informed decisions to government agencies, policy makers and end-users. Within Europe, the fragmentation in the European Union (EU) policies has been identified as a serious obstacle to optimising knowledge and experience in coastal research reinforcing a weakness in the communication of issues such as coastal flooding between scientists and policy-makers (Littoral Venice, 2008). There is a need for the coherent collection and analysis of coastal and marine monitoring data and advanced data modelling to increase the understanding of the complex interactions in coastal-marine systems.

It is proposed that the methodology presented in this research is pivotal as it is seen that policy-makers depend on the scientific community to provide answers to impending climate change issues. Policy requires simplified versions of science which scientists finding challenging to provide considering issues of misuse and interpretation (Wright, 2013). As a result, difficulties exist in communicating challenging climate change issues such as coastal flooding predictions.

In addition, the capability of the data model to widen its scope with varying flood modelling systems is important to the sustainability of flood risk management. Consequently, allowing end-users a capability to utilise effectively complex scientific model output as technology changes numerical modelling techniques, is a progression in flooding and GIS science. Scientists lacking in site-specific knowledge can gain a better understanding of coastal management issues through the innovative use of data models, whilst policy-makers decisions can be based on coastal flooding predictions. The data model allows scientists to benefit from advances in GIS and information technology (IT) and subsequently satisfy key government aims (Evans et al., 2008).

1.3 Aims and Objectives

The purpose of this study is to develop a data model which will assist with the presentation and interpretation of generic flood model output to non-technical end-users since, it is likely that flood modelling will continue to advance in the near future. Specifically, this work aims to develop a coastal flooding geodatabase based upon the amalgamation, reconditioning and analysis of numerical modelling. The data model framework will allow the dissemination of coastal flooding predictions to end-users.

The research aims to consult with end-users to define the required outputs of the analysis. End-users are categorised as technical and non-technical (Williams et al., 2007). Technical end-users are typically engineers and modellers who are likely to undertake future modelling work and contribute to the data model from the Environment Agency (EA) and the National Oceanography Centre (NOC). Non-technical end-users are identified as practitioners, decision makers and policy makers who would use the results of this research but require less technical details of the modelling, such as the tide-surge interactions from the deep water propagated onshore to the beach and into the main river channel in the study area.

1.3.2 Aims

The overarching aim of this study is to define the GIS requirements of this research with technical end-users and non-technical end-users so as to allow exchange of information to these related flood management practitioners. These would be undertaken with end-user workshops and individual meetings. The gathering of end-user requirements is necessary for the building of the geodatabase and the analysis provided in the data model. The usefulness of the flood risk maps will be assessed as an aid to mitigate flood impacts and define future coastal defence needs (Williams et al., 2007). The specific aims include:

a. The building of a geodatabase which allows the harmonisation of disparate oceanographic and coastal flooding datasets necessary for the simulation and continual updating of real-time flooding parameters using ArcFLOOD. This geodatabase is easily uploaded, extended and further customised by future software developers and end-users. The existence of a generic database structure for coastal flooding is undocumented.

b. The integration of numerical modelling from hydrodynamic-morphological flood prediction models and GIS to analyse potential flood risk imposed by coastal flooding in the study site of the River Alt, Sefton coast, north west, England, UK. Ease and flexibility for the prototyping of future software applications on contemporary desktop and internet platforms is enabled through the use of the ArcFLOOD data model to develop customised coastal flooding applications.

1.3.3 Specific Objectives

The specific technical objectives of this study include:

1. The extension of the ESRI ArcGIS Marine Data Model (MDM) to a bespoke ArcFLOOD data model by incorporating the complex coastal flooding relationships, behaviours and rules within a GIS flooding geodatabase is the primary objective. ArcFLOOD is represented in spatial information flows, data model schematic diagrams, and Extensible Markup Language (XML) in an ESRI GIS platform.
2. To extract and convert to ESRI ArcGIS format an extensive database of historical and contemporary coastal/hydrodynamic field data from National Oceanographic Data Centre simulation models of the eastern Irish Sea. The research incorporates two hundred years of data collection and a rich data archive of contemporary data sources.
3. To build the bespoke ArcFLOOD data model based on the end-user requirements and a developed coastal flooding geodatabase. To assist this process with bespoke process models developed in this research. ArcFLOOD

was built by extending the ESRI ArcMarine data model (MDM) (Wright et al., 2007).

4. To categorise ArcFLOOD with the varied processes that are important to flood propagation in structured analysis data schema diagram from which a definition of the spatial location and extent of a coastal flood is documented.
5. To specifically represent within the ArcFLOOD data model the results of the Liverpool Bay model. The Liverpool Bay model is a hybrid numerical flood model based upon hydrodynamic-morphological flood prediction. It comprised the Proudman Oceanographic Coastal Modelling System (POLCOMS) coupled with Waves and the General Ocean Turbulence models (WAM-GOTM) to define the metocean conditions of storm events (Brown et al., 2010a; Brown et al., 2010b). This was further coupled with XBeach to provide the simulation of coastal flooding in the study site (Williams et al., 2011). The XBeach model (www.xbeach.org) is a community-based open source extensively validated numerical model which was predominantly developed to assess the natural response of sandy coasts to storms and hurricanes (Roelvink et al., 2009; Van Thiel de Vries., 2009).
6. To analyse the results to provide improved time series analysis based on tide-surge interactions of a predicted coastal flood and to represent these results in GIS flood risk mapping visualisations for dissemination to end-user groups. The improved results included:
   a. time (t),
   b. floodwater depth (z_s),
   c. significant wave height (h_h),
   d. x-velocity component)(u) and y-velocity component (v),

e. Flood water depth for a given flood point (z_{change});

f. Flood water level increase h_{change} (difference in z_s flood water levels between timesteps which equates to the difference in significant wave height (h_h)).

1.4 Research Methodology

The methodology is outlined using a flow chart which details the logical steps taken during the research (Figure 1.1). Throughout the research GIS data processing was important to all stages of the process. The methodology is explained in stages of work undertaken starting at the requirements gathering phase and ending at the end-user applicability:

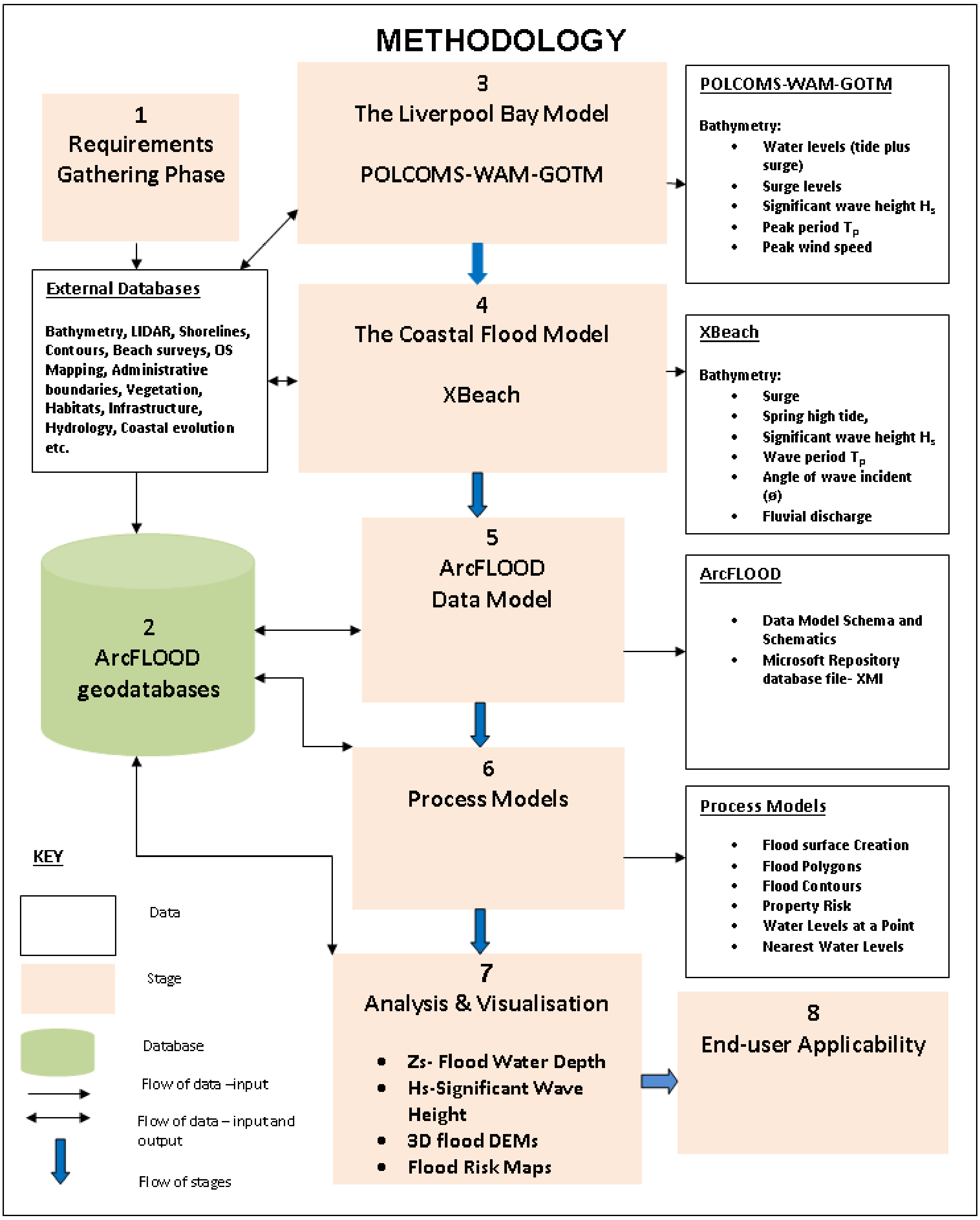


Figure 1.1: Research methodology followed to build an ArcFLOOD data model based on end-user requirements and consultation; the development of a coastal flooding geodatabase by integrating numerical modelling from hydrodynamic-morphological coastal flood models in time series analysis in a GIS; the design an ArcFLOOD data model by categorising within ArcFLOOD the varied coastal flooding processes in a structured analysis data schema diagram; and the analysis and visualisation of potential flood risk in a GIS to identify flood risk and end-user applicability in the study site of the River Alt, Sefton coast, north west, England, UK.

1. The tailoring of end-user requirements is important to the overall aims and objectives of the COFEE project to involve end-user needs. The gathering of requirements from end-users were useful in assisting the definition of the proposed GIS analysis; allowed the amalgamation of diverse datasets into a bespoke coastal flooding geodatabase; identified the flow of data from numerical modelling into the ArcFLOOD data model design; and provided generic needs for the mapping and visualisation of flood risk. In Figure 1.1, stage 1 illustrates the requirements gathering phase undertaken with end-users from Sefton Council, National Oceanographic Centre and the British Oceanographic Data Centre. The requirements were gathered from a series of individual meetings, site visits, workshops and presentations within the COFEE partnership.
2. In this process, the data relevant to the design of the ArcFLOOD data model was initially collected from the Liverpool Bay model. Bathymetry, topography, coastal and beach survey data were amalgamated for conversion into an ArcGIS geodatabase. The majority of the datasets required conversion into the ArcGIS format to create a central repository for coastal flooding data which is accessible to end-users. The geodatabase development stage is seen in Figure 1.1 stage 2.
3. The numerical modelling of the Liverpool Bay model (POLCOMS-WAM-GOTM) involved the pre-processing and post-processing of bathymetry to run the hydrodynamic simulation as seen in Figure 1.1 stage 3. The bathymetry essential to the running of the numerical modelling was improved in ESRI ArcGIS software with datasets at the coastal boundary of the model. These included Light Detection and Ranging (LIDAR) and beach survey data obtained

from post-storm surveys. ESRI ArcGIS techniques were used to create an improved dataset to commence numerical modelling. Throughout the research, the results of the Liverpool Bay model were improved with more accurate beach survey and LIDAR data. The results of the final numerical modelling was imported into ESRI ArcGIS and processed as input into the coastal flood model (XBeach).

4. The results of the Liverpool Bay model simulation of a coastal flood was converted into XBeach and the data resampled for improved accuracy with additional flood defence detail as in Figure 1.1 stage 4. XBeach is unable to immediately use data from the Liverpool Bay model and as a result, GIS processing was essential in the numerical modelling. For the simulation of coastal flooding in XBeach, the final results were exported in binary formats and reprogrammed in XBeach to produce an output file of time series coastal flooding results.
5. Data model design for the ArcFLOOD data model comprises a conceptual, physical and logical design which is outlined in Chapter 4 and seen in Figure 1.1 stage 5. The initial process involves tailoring the end-user requirements into specific analysis to be modelled in the ESRI ArcGIS data model schema. The data model was developed by loading the ESRI ArcGIS ArcMarine data model; amending the model by re-using relevant data structures; and extending the model with new analysis flows to achieve the time series representation of a coastal flood. The model was designed to rapidly export improved coastal flooding spatial analysis to end-users.
6. Development of process models in ESRI ArcGIS provided software utilities which automated the generation of spatial analyses results (Figure 1.1 stage 6).

As datasets were cumbersome and labour intensive, the process models aided performance in GIS processing.

7. GIS analysis technique was incorporated to produce flood risk information and mapping which satisfied end-user needs (Figure 1.1 stage 7). This was heavily dependent on corroborating ArcFLOOD results with the XBeach results to validate the data model design. Flood risk visualisation methods were explored.
8. This final stage was a discussion of the applicability of the data model to end-user needs outlining any advances made in the research and the practical rationale for end-user usage (Figure 1.1 stage 8).

1.5 Structure of the Thesis

The summary structure and content of each chapter are provided to achieve the aims and objectives of the thesis. Chapter 1 provides the research context, the research rationale, aims, objectives, methodology and summary structure of the chapters. Chapter 2 provides the literature review of the role of data models. Chapter 3 gives documented evidence of the study site hydrodynamics and coastal morphology. Chapter 4 presents the buildings of the ArcFLOOD data model. The end-user spatial analyses which were derived to perform GIS flood risk assessments arising out of the numerical flood modelling are presented in Chapter 5 and Chapter 6 provides the main discussion of the practical use of ArcFLOOD, including a proof of concept coastal flood visualiser prototype tool was developed for Sefton Council as a benchmark for emergency preparedness. Finally Chapter 7 gives the summary, discussions and conclusions derived from the research.

Chapter 2

Importance of GIS Data Modelling

2.1 Introduction

Data models allow the efficient acquisition, aggregation, storage, analysis and dissemination of improved coastal flooding information to end-users. The data model framework is necessary for a range of numerical flood modelling and Information Technology (IT) advances. Although, open data standards are available, few platforms exist to enable coastal flooding modelling output to be disseminated and visualised in GIS. There also exists a lack of methodologies to facilitate the synthesis of coastal flooding predictions; its mapping and visualisation in end-user software. Specifically, no data model exists which identifies the broad range of coastal flooding information, rules, and behaviours; and optimises the use of these datasets in GIS spatial querying.

It is proposed that a coastal flooding data model is important to scientists and decision-makers who increasingly need to integrate information from multiple disparate and third party sources; extract predictions in a format to be spatially analysed in GIS; and produce information which are ready for visualisation. In addition, a further advantage of data models is that the effort spent in documenting coastal flooding allows the rapid use of flood risk predictions by GIS software programmers and end-users.

2.1.1 GIS Data Modelling

The first section of this chapter proposes that data models are essential to coastal flooding. A discussion of the fundamentals of the proposed data model is presented. Evidence of the use of data models in coastal flooding and marine applications is provided. The role of GIS data modelling is discussed with reference to the absence of coastal flooding GIS data models, examining the foundations of the ArcMarine data model; and the evidence of the use of coastal flooding and related marine data models. The section is divided into the following sub-sections:

a. An ArcMarine data model which includes the following ordered phases:
    i. A conceptual phase
    ii. A logical phase
    iii. A physical phase
b. Evidence of the data model in related coastal flooding and marine applications which are further sub-divided into three sub-sections:
    i. The Marine Institute of Ireland ArcMarine data model
    ii. ArcHydro data model
    iii. Sediment budget and coastal evolution studies

2.1.2 Numerical Modelling

The second section of this chapter provides a review of the role of GIS in numerical modelling by identifying which flood modelling systems have GIS decision support systems and access to data model frameworks as a justification for the research ; and presents a review of relevant coastal flood models based on hydrodynamic-morphological modelling, which use GIS functionality. Numerical modelling is discussed with reference to the importance of data modelling to provide a knowledge base for coastal flooding prediction systems.

2.1.3 Information Technology (IT) advances

The third section of the chapter provides a review of the current information technology advances (IT) in which data modelling plays a significant role. A discussion of how the use of data exchanges standards is likely to influence the use of coastal flooding data is provided to strengthen the research motivations.

2.2 GIS Data Modelling

This research has importantly identified the absence of GIS data modelling within the complex area of numerical modelling and Geographic Information Systems (GIS). Currently, data models are seen to represent the formalised abstraction of real world processes implemented in computer systems to classify and determine specific rules and behaviours (Wright et al., 2007). The GIS data model is an integrating mechanism which facilitates synthesis of data at a local, national and global level (Breman et al., 2002). This thesis promotes the data model as the essential link which allows the identification and analysis of coastal flood risk information from a range of sources to be disseminated across the internet. Within this research, the GIS data model allows generic numerical flood modelling to access and share common coastal flooding and related marine data, thereby, fulfilling a definite gap in the knowledge of coastal flooding.

By attempting to represent a broad range of coastal flooding and related marine data types, processes and behaviours within a GIS, it is believed that data model design is the best approach to developing marine-related GIS software applications (Bartlett, 2000). This novel approach adopted here forms the basis upon which GIS software developers can program numerical model flooding results with GIS functions. This allows a dual approach to future flood applications where GIS analytical capabilities are embedded in future coastal flooding models; and conversely, coastal flooding models are executed from within GIS systems.

In GIS, data models are a description of the rules by which data is defined, organized, queried, and updated within an information system (ESRI, 2014a). Traditionally, it is known that GIS data models accurately represent the spatial location and extent of dynamic entities, behaviours and attributes within a GIS (Wright et al., 2007 and Lord-Castillo, 2009). Data models consistently and correctly predict the behaviour of real world phenomena and are therefore essential to any GIS application. They provide a conceptual organization of a database upon which software developers can develop coastal flooding software applications, whilst incorporating the full advantages of GIS functionality (Wright et al., 2007).

Data models are known to allow the update, maintenance and derivation of new information products from a variety of data sources and by a wide range of users through its extensible, flexible and adaptable approach (ESRI, 2014b). The advantage of representing a broad range of coastal data types and processes makes this approach appropriate to developing coastal flood applications requiring the integration of disparate datasets and modelling results from the established marine data model classification (Bartlett, 2000; Breman; 2002). A thematic approach is the first step in identifying the basic elements of flooding data. As rudimentary as this concept is the elements of coastal flooding have not been documented in data models. GIS software developers have limited knowledge from which to begin to develop these applications.

Longhorn (2007) describes the need for data models through a general lack of standardisation in datasets and difficulties in combining datasets for spatial analyses which is an identifiable problem with coastal flooding data. The use of GIS is generally limited by disparate infrastructures, data standards, and a resulting lack of interoperable systems (Bartlett, 2000; Wright et al., 2007). It is seen in this thesis that the performance of data processing is optimised through the hierarchical data structure of the data model enabling improved dissemination to end-users. Prior to the ArcFLOOD data model, coastal flooding end-users have no means to exchange and disseminate flooding predictions arising out of numerical modelling. Currently, no such data model framework exists in the flooding sector which allows the exchange of information from scientists to end-users.

The evidence of data modelling is seen in mainstream GIS. The ArcMarine data model was designed specifically for the marine data (Wright et al., 2007). In this research, ArcFLOOD is derived by reusing the initial design of the MDM and redesigning the data model schema with coastal flooding elements and features. In this way, ArcFLOOD inherits the common marine elements and framework and ensures its interoperability with GIS, whilst, appropriately documenting coastal flooding.

In addition, technological advances have also improved the computational capacity, compatibility and functionality of GIS, thereby improving flood analysis in data models. One such advance is the ability to integrate diverse volumes of coastal flooding datasets in an open geospatial format compliant geodatabase in GIS. Improved definitions of the relationships which exist amongst entities are outlined in data models. In the broader sense, they assist with the manipulation of the spatial-temporal properties of data.

Lastly, it is indicated that the broad challenges which marine practitioners encounter when attempting to integrate data include (Wright et al., 2007):

a. The multi-dimensional and dynamic nature of the oceans is difficult to understand and represent in data formats. For example, the timeseries presentation of data from numerical modelling which the data model analyses to produce improved results;
b. The spatial-temporal character of shorelines and coastal processes which are adequately visualised in GIS and not available in numerical models for coastal flooding;
c. The undefined ocean-coastal zone boundaries and inherent mapping of data in these zones only achieved through GIS systems mapping;
d. The need for spatial data structures that vary in position and time to be integrated with time series coastal flooding analysis to provide newer versions of flood risk information to current data available;
e. And, the lack of conceptual data models for marine objects and phenomena which allows its understanding to policy makers and end-users.

These challenges accurately reflect the GIS issues encountered in the prediction of coastal flooding and a defined gap in data modelling in this field. In the subsequent section, the ArcMarine data model is provided as a standardised marine and coastal data model in GIS. A review of the current knowledge in the GIS field is given and examples of implementations of the ArcMarine data model and related data models are provided.

2.2.1 The ArcMarine Data Model

At present, the ArcMarine data model is the only model which has attempted to represent a broad range of marine and coastal data types representing the dynamic nature of the oceans, shorelines and coastal processes in GIS (Wright et al., 2007; Longhorn, 2007). This data model provides a GIS description of coastal flooding in computer schema code (extensible mark-up language (XML)). Using this approach, ArcFLOOD outlines the flow of generic coastal and marine data which have been identified as important to developing marine GIS applications. The schematic representation of the description and manipulation of a data is represented in data flow diagrams in a hierarchical structure using a relational database. The inter-relationships between data are organised highlighting the relationships which exist in spatial data tables. In this method, the relationship between the feature and its descriptive attribute table is specified in a data model which further sub-categorises data according to an entity's relationship to other entities. The resultant data model schematic is a simplification of such relationships which allows a database management system (DBMS) to query the produced analysis based on the identification of all elements in a data model.

The features encoded in the MDM represent points, lines and area data which are commonly mapped in marine GIS applications. Other complex data such as interpolated marine rasters, meshes and grids which require 3D representation are included in the data model. The data model most importantly, provides spatial representation for interconnecting datasets with their corresponding rules and relationships (ESRI, 2014b). In addition, data models sub-categorisation and classification also assist with streamlining the spatial flows of data for improved spatial analyses. A systematic, consistent and comprehensive approach to data management is embodied in data models.

Data are represented in an analysis diagram which identifies thematic groups and object classes found in each group according to standard data model design templates. The hierarchical structure used represents generic features to various user groups. The strength of this data model is the facility for end-users to re-customise according to changing needs. These may include mapping in schematic representations of features in the ocean; amalgamation of data in the marine environment; and the identification of the processes in schematic code which produce spatial analysis.

In Figure 2.1, the MDM is shown to represent the common marine data types in a high level hierarchical structure (Breman et al., 2002). This principle extends to coastal flooding whereby an extended data ArcFLOOD model defines the broadest categories of flood risk information. Future end-users can modify a data model to include any bespoke application. The data model is seen as an evolving and adaptive framework designed for refinement (Wright at al., 2007). This diagram shows the entity definitions of the common marine points, lines, area, time series, animations and mesh (volumetric) features taken from case studies of the seabed. An end-user can choose any number of entity definitions to explain a system, phenomena or process and interconnect relationships to devise new analysis. Further to the data model identification of common data types, an ordered three-stage process is used to develop a data model design in GIS comprising: conceptual, logical and physical phases.

2.2.1.1 The conceptual phase

The conceptual phase of data modelling involves the definition of the overall scope and content of the model by identifying all common and essential objects in the coastal flooding domain. These are identified in a data requirements gathering phase with stakeholders and end-users. A geodatabase is developed and populated with data specific to that data model. Once the requirements have been gathered, an analysis diagram is produced which identifies the data into specific coastal flooding thematic groups and defines object classes for each thematic group. For example, the ArcMarine common marine data types will be extended to include coastal flooding data types, coastal flooding data types, subgroups and spatial relationships (as seen in Figure 2.1). The main outputs of the conceptual phase are an analysis diagram.

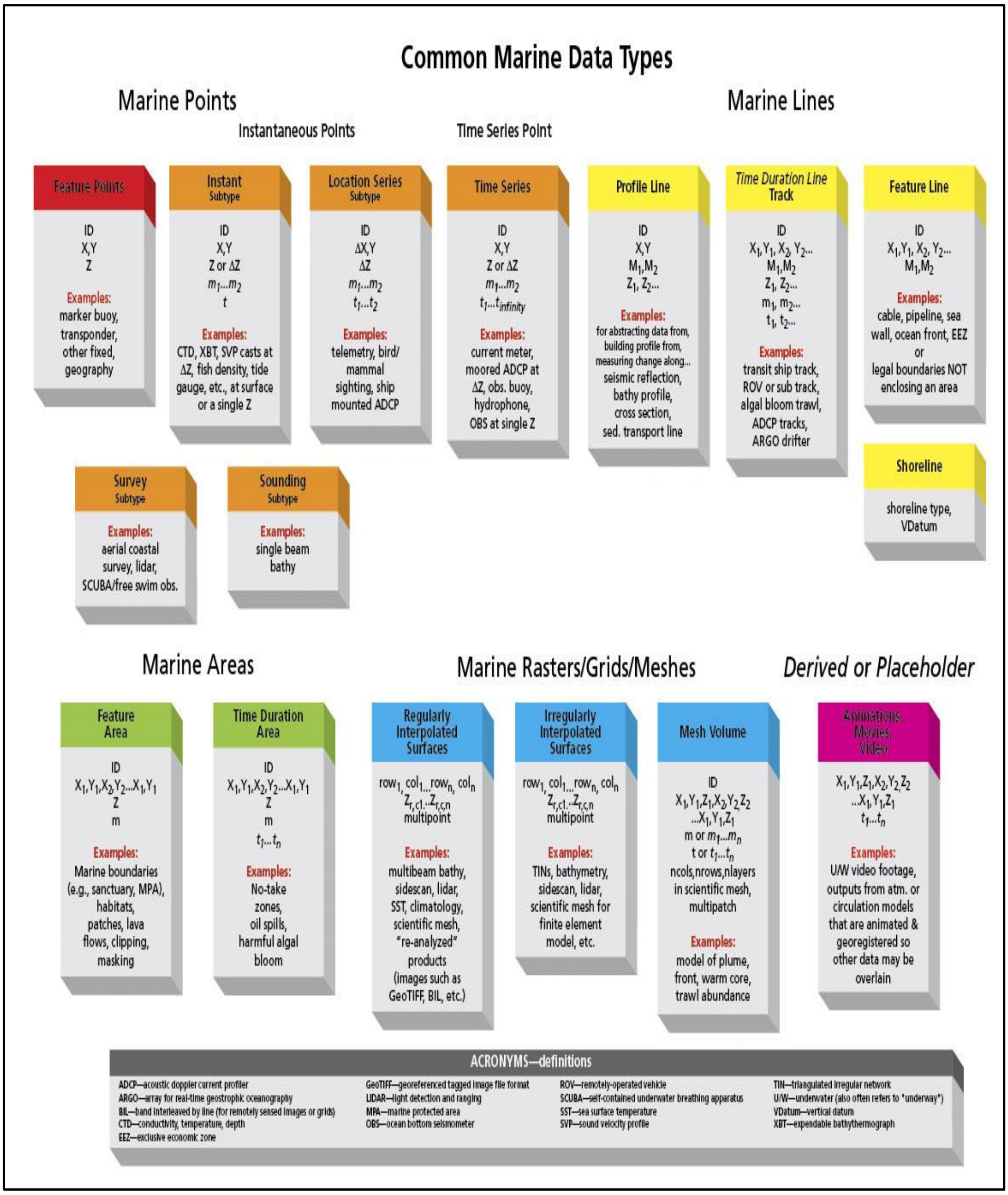


Figure 2.1: The MDM common data types diagram showing the conceptual framework for the data model. Note the red headings list specific instruments, vehicles, real-world features or products. Italic headings are abstract features classes whilst other headings are feature classes or subtypes. Lowercase 'm" denotes a measurement in the field. Uppercase "M" denotes a GIS geometry measure. Time is represented as lower case "t" (Wright et al., 2007a). Permission to reproduce this image has been granted by Professor Dawn Wright of Oregon State University.

In the overall MDM analysis diagram, an example of a marine vessel is given where several cruises can contain zero or many tracks through the CruiseHasTracks relationship class, which uses the CruiseID attribute in both tables. In reality, Cruise (a vessels journey) can have multiple tracks. In Figure 2.2 a survey is defined as a collection of points, where each point has a depth which is uniquely identified by the TrackID in the SurveyInfo table. In addition, each unique survey point (SurveyID) can have multiple depths. A SurveyID can have a one-to-many relationship (1: m) with a TrackID. At each depth, there exist many measuring devices; measuring one or more variables over time in a Time Duration Point table for instance. The analysis diagram allows the propagation of the above relationships throughout a database to be encoded in a data models. This relationship is represented in a unique way in a data model by using unique identifiers or primary keys to allow relationships to be perpetuated in a database. This process is extended to coastal flooding data in this research.

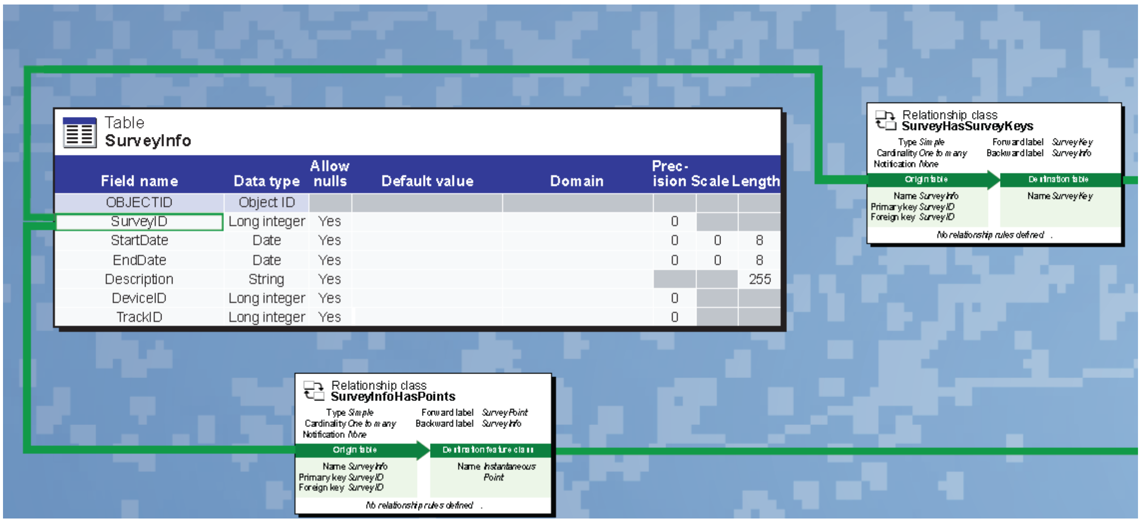


Figure 2.2: An analysis diagram from the MDM showing the spatial representation of a line feature called Track in the ArcMarine data model poster (Wright et al., 2007). Permission to reproduce this image has been granted by Professor Dawn Wright of Oregon State University.

2.2.1.2 The logical phase

Upon completion of the data model design in analysis diagrams, the second stage of the data modelling process is the logical phase. The logical phase involves three steps: migrating existing databases to a geodatabase using ArcGIS tools; creating a schema for the geodatabase design based on loading the existing ArcMarine schema as the initial template; and building the new geodatabase.

2.2.1.3 The physical phase

In this stage, the physical model phase schemas are exported to an intermediate format and loaded as a data model to be used by software developers. The data model design approach includes the development of schema (software) code in unified modelling language (UML). UML diagrams and a database repository for extension by future developers in an extensible mark-up language interchange template (XMI) or a geodatabase repository. The loading of these information technology artefacts within ESRI Inc. ArcGIS desktop software allows its use and further extensibility in a software development environment. Using the ArcGIS computer-aided software engineering (CASE) tools, a schema is generated upon which further data model designs are developed. This is the identifiable sole process of data model design in GIS whereby a new geodatabase is created which needs to be repopulated with bespoke data upon which extension is possible for any new field of study. An end-user or software developer with limited knowledge on coastal flooding can develop analyses based on the schema designs.

The ArcMarine development team has highlighted that the MDM is challenged to represent the multiple dimensionalities of oceans and coasts in position and time (Wright et al., 2007b). In this research, the data model specifically has represented the timeseries nature of predicted flood simulations from the coastal flood numerical modelling. Within the UK climatology field, it is noted that a major hurdle to climate modelling is the dissemination of the capture and modelling of the complex marine environment as no systems exist to accurately represent phenomena (Met Office, 2006). ArcFLOOD allows the representation of coastal flooding within the wider context of the MDM.

It is also seen that specific organisational benefits arise from using the MDM which includes the reduction in software development time for future end-users by developing a detailed schema for coastal flooding; improved data quality standards to ensure consistency in data specifications; improved access to spatial databases through the integration of a diverse data; and dissemination to a wider audience of results which are generally limited to view in numerical modelling systems (Hennessey et al., 2006). Within the GIS domain, data models are seen to promote a uniform approach to developing software applications; provide a powerful research tool upon which future analysis is based; and enable improved information sharing and exchange (Wright et al., 2007 and Lord-Castillo, 2007).

2.2.2 Evidence of MDM Coastal and Marine Applications

The extensibility of the MDM is indicated in the range of global applications demonstrating its use in this section. Few applications of the MDM are documented in Wright et al. (2007a). The implementation of the ArcMarine data model varies from coral reef monitoring in the National Park Service, Hawaii; sea turtle and commercial fisheries applications by Duke University- National Oceanographic Administration Association (NOAA); sea level rise in the Mississippi Delta and Louisiana continental shelf by the Florida International Science Center for Coastal and Watershed Studies; and mapping of sea floor for subsidence and sea level rise by the United States Geological Survey (USGS) (Wright et al., 2007b).

Andrews and Ackerman (2004) produced geological seafloor mapping using the MDM to synthesise survey data collected at sea. Studies by Wilson and Gesch (2004) in the Mississippi River Delta and the Louisiana continental shelf basin gathered data on subsidence and sea-level rise using the MDM to develop a sedimentary and environmental database for researchers, planners and coastal managers. The data model was used to produce an efficient query and retrieval mechanism. The range of data collected in the geodatabase included sediment cores, seismic-reflection profiles, bathymetry, side-scan sonar, tide-gauge data, sediment data and satellite imagery. The geodatabase was built based upon the MDM feature classes and object classes. In this case study, it was important to generate point data at varying depths over time based on the modelling of disparate data types.

2.2.2.1 The Marine Institute of Ireland MDM

The Marine Institute of Ireland MDM has been used to model the temporal dimension by implementing the timeseries measurement aspects of the data model design (Miller, 2005). End-users are provided with a logical means of accessing time-series data for spatial query and visualisation. This is particularly relevant to the implementation of timeseries coastal flooding simulations which allows querying at a particular location in time in 3D and 4D. The Marine Institute of Ireland's (MRI) implementation was initially implemented to resolve significant organisational data management problems for its two hundred and twenty million acres of marine estate. Data management problems included loss of integrity in datasets non-integrated diverse data sources; and an inability to provide spatial information (Hennessey et al., 2006). These issues were resolved by the implementation of a marine data repository developed from an MDM geodatabase. The relevance of this implementation of the MDM is the development of time-varying data arising out of the improved spatial querying capabilities of the MDM. The MRI adopted the common marine data types as seen in Figure 2.3.

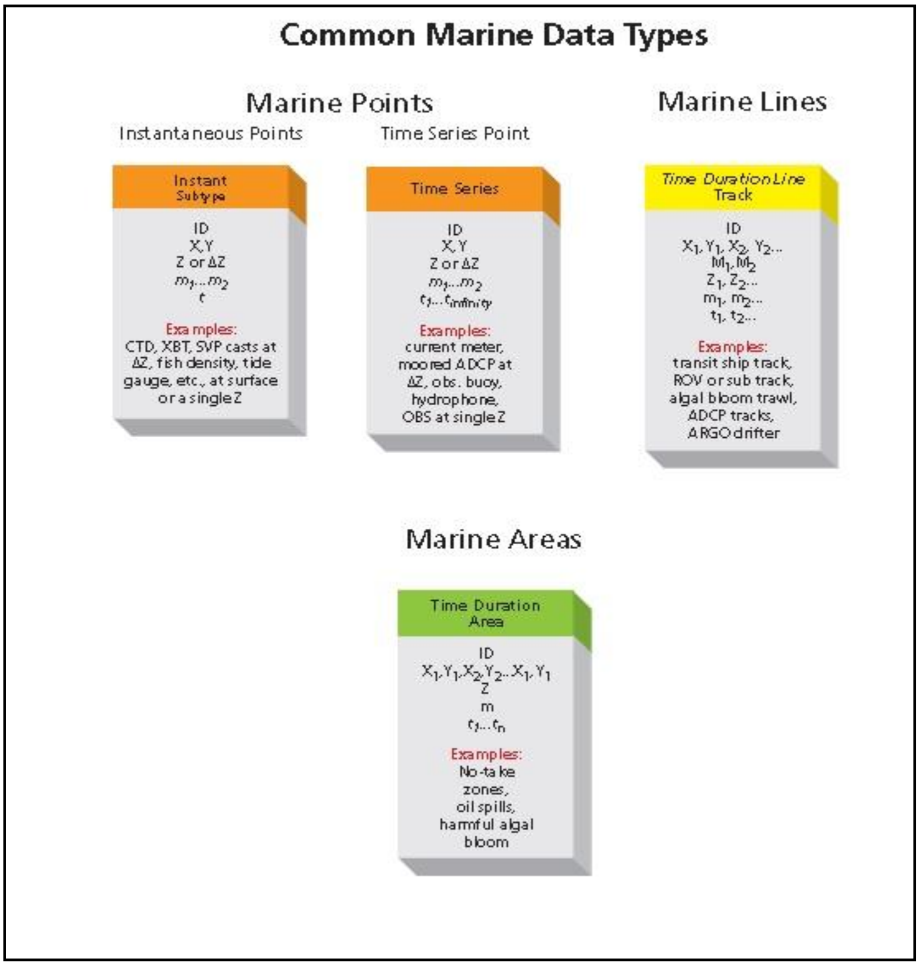


Figure 2.3: The common marine data features of the MDM adopted in the Marine Institute of Ireland for points, lines and areas developed as part of a conceptual framework for the data model to map the sea floor under the intercontinental shelf for benthic habitat mapping and biological sampling. The headings in italics are abstract feature classes in ArcMarine. All other headings are feature classes or subtypes of feature classes. Lowercase “m” denotes a measurement in the field; uppercase “M” is a GIS geometry measure; and “t” is time (Wright et al., 2007a). Permission to reproduce this image has been granted by Professor Dawn Wright of Oregon State University.

However, for time-varying studies the InstantaneousPoint and TimeSeriesPoint feature classes were the only MDM feature classes adopted specifically to store survey data with multiple depths relevant to its software applications. InstantaneousPoint is used to store the locations of its research vessel underway data for instance. It is defined according to its x- and y-coordinates in space with time stamp, t, and four subtypes available for this feature (Instant, Sounding, Survey and LocationSeries). TimeSeriesPoint feature data is used to represent offshore weather buoy, nutrient monitoring, and coastal temperature probe locations. The TimeSeriesPoint feature class is a subclass of the main data model MeasurementPoint. Both the InstantaneousPoint and TimeSeriesPoint feature classes are linked through ActivityID in the Activity table to the MRI data model business tables and feature classes as seen in Figure 2.4.

The TimeSeriesPoint data is linked to the MRI data model as seen in Figure 2.5. TimeSeriesPoint is linked to parameters of wave height, temperature, and wind speed and wind direction. These parameters are further categorised in the table according to a TSInterval field which defines values of time ranging from minutes to hours. This data model is important to show how the InstantaneousPoint feature class is linked to a Measurement featureclass which is spatially located in time and varies in depth as seen in Figure 2.6. The data model relationships allow collected CTD cast parameters which is an oceanographic instrument used to determine the temperature, conductivity and depth of the ocean. It is important to note that the integration of these relationships can be achieved only through data modelling and the spatial-querying of GIS.

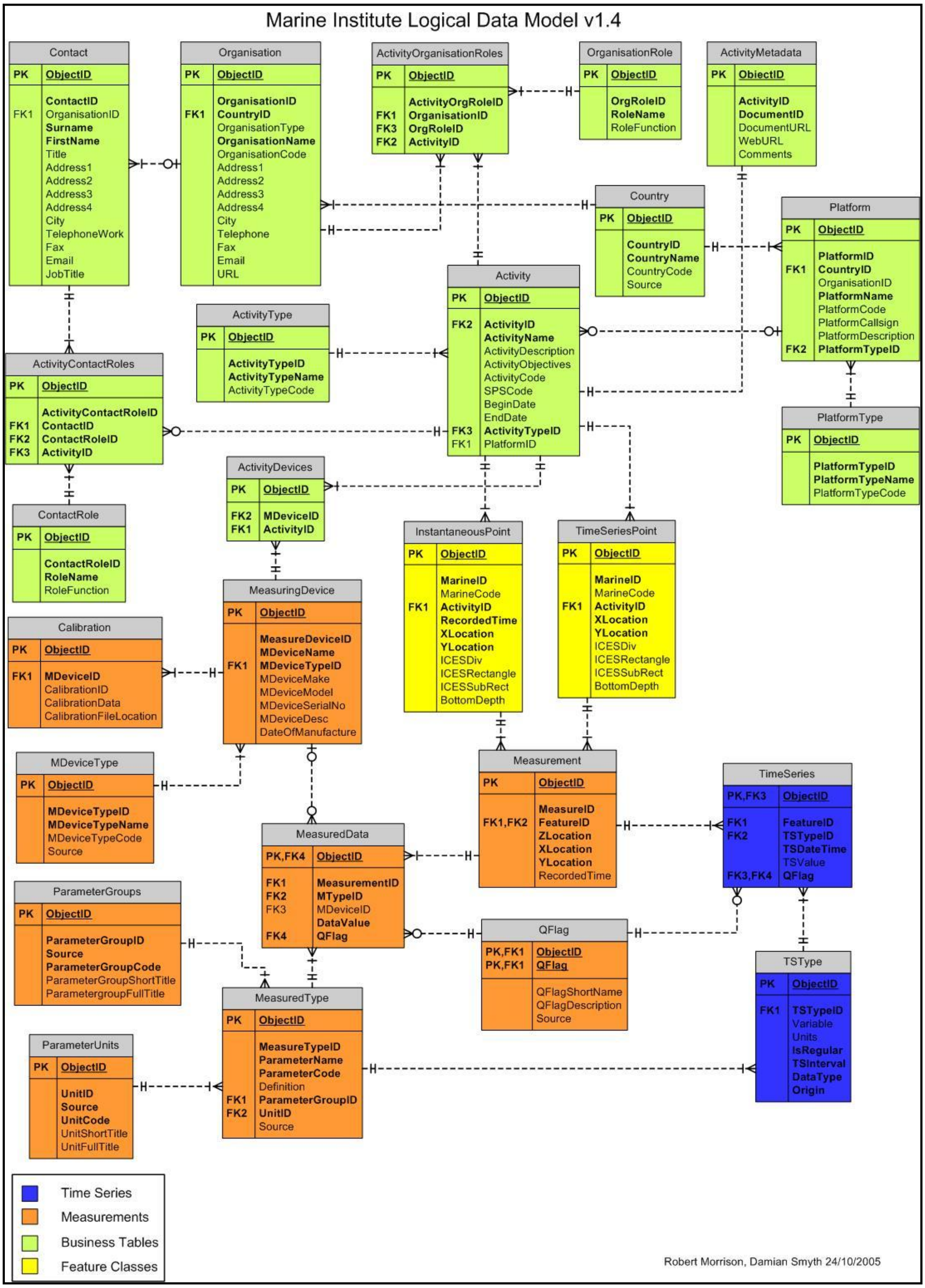


Figure 2.4: Marine Institute of Ireland ArcMarine Data Model implemented with core ArcMarine feature classes for time-series marine seabed features. The InstantaneousPoint and TimeSeriesPoint are the only elements of the MDM included. © Marine Institute, Ireland (Wright et al., 2007a). Permission to reproduce this image has been granted by Professor Dawn Wright of Oregon State University.

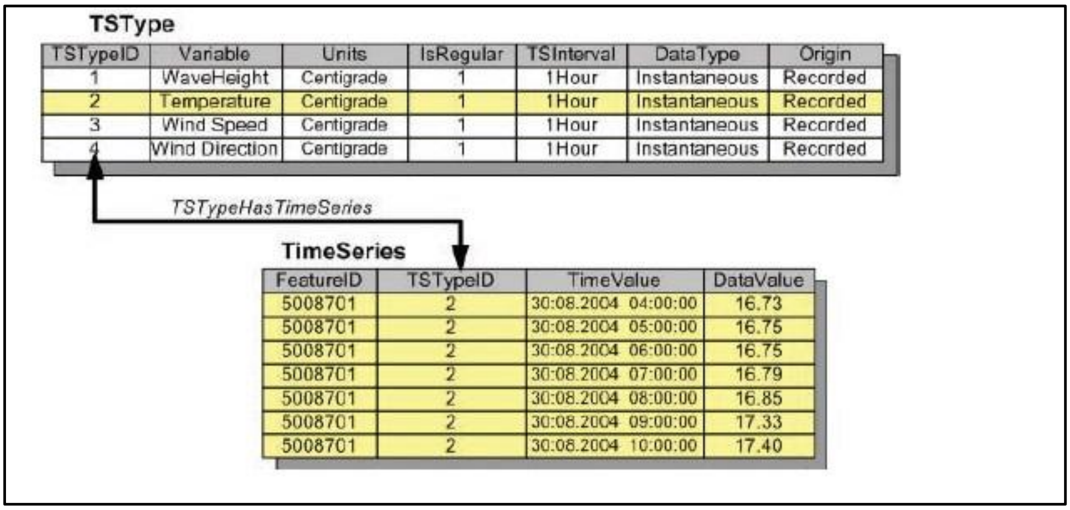


Figure 2.5: The Marine Institute of Ireland’s MDM structure comprising the relationships between the TSType and the TimeSeries tables through the TSTypeID (Wright et al., 2007a). Permission to reproduce this image has been granted by Professor Dawn Wright of Oregon State University.

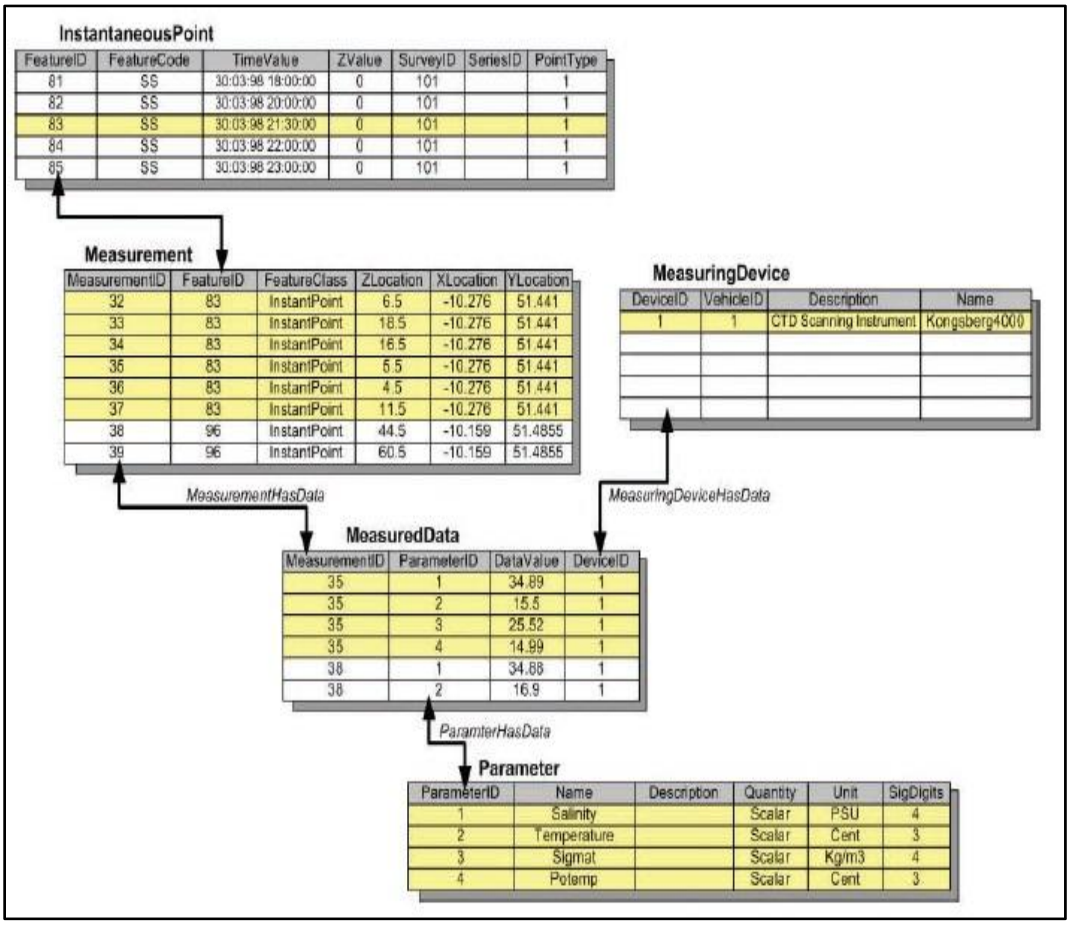


Figure 2.6: Marine Institute of Ireland´s storage of time-series InstantaneousPoint and Measurement through MeasureID, FeatureID, DeviceID and ParameterID (Wright et al., 2007a). Permission to reproduce this image has been granted by Professor Dawn Wright of Oregon State University.

2.2.2.2. DHL Water and Environment Temporal Analyst Tool

Through the use of an MDM, analyses were further developed in ESRI Inc. ArcGIS using the DHI Water & environment temporal analyst tool. The tool enabled the importation of time series data from a variety of sources for mapping; and the identification in GIS of the measurements of a TimeSeriesPoint as seen in Figure 2.7. It is seen here that the time series measurements are related to a depth location through the Measurement table (Figure 2.6). The MeasurementID is linked to the FeatureID in the TimeSeries table to provide a query for temperature data which responds with corresponding feature locations with the specified temperature.

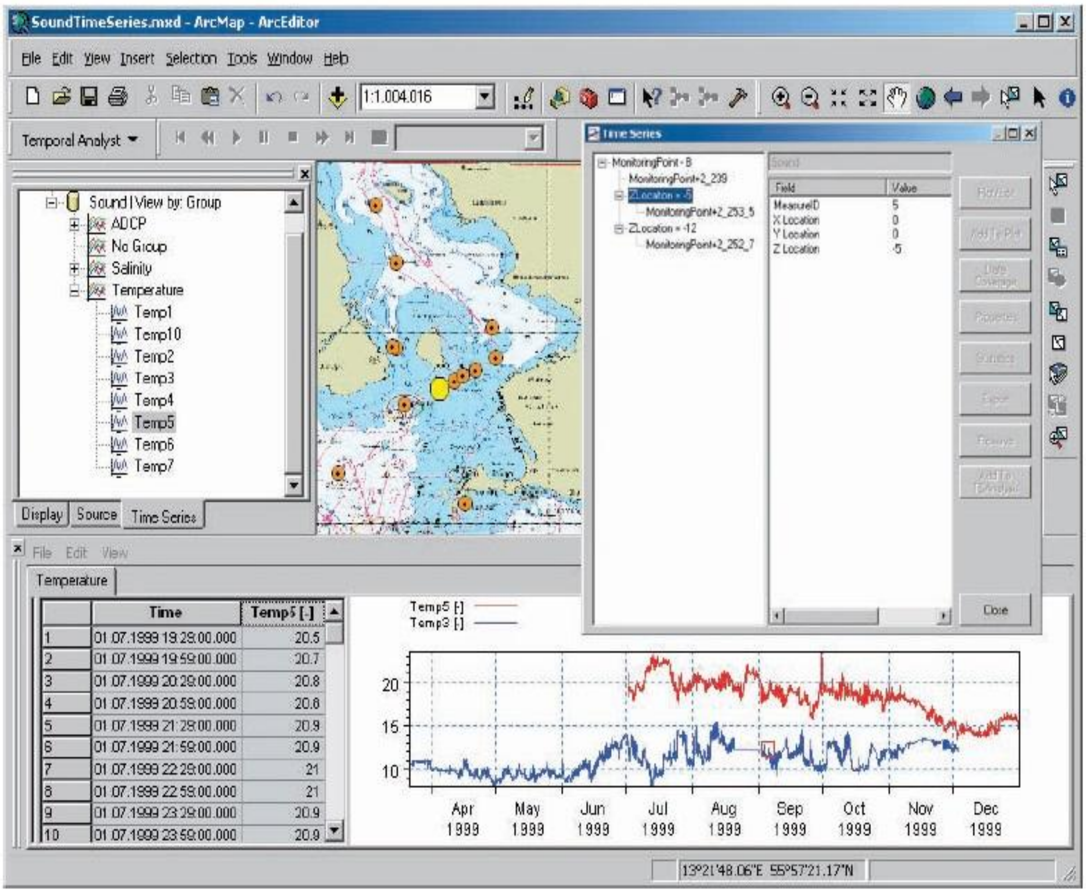


Figure 2.7: The implementation of the DHI Temporal Analyst extension in ESRI Inc. ArcGIS to allow end-users to view and query time series data associated with the measurements of a TimeSeries point (Wright et al., 2007a). Permission to reproduce this image has been granted by Professor Dawn Wright of Oregon State University.

2.2.2.3. The ArcHydro Data Model

The ArcMarine data model TimeSeries classes are also implemented in the ESRI Inc. ArcHydro data model (Arctur and Zeiler, 2004; Maidment et al., 2002; Wright et al., 2007a). Within this implementation of the MDM time-stamped data is propagated throughout the geodatabase for hydrological modelling in watershed areas and geospatial water resource information (Maidment, 2004). Originally, ArcHydro was developed by the US GIS and Water Resources Consortium of data providers and users and the Center of Research in Water Resources at the University of Texas. ArcHydro describes the geographic-hydrologic relationships in a data model. ArcHydro is able to link these features in a hydrologic landscape to time series information on water resources (Maidment, 2004). The City of San Antonio, Texas implemented studies to understand the impacts of actions such as land use changes on flooding, groundwater and water supply. However, the basic ArcHydro data model does not model riverine flooding. Specifically, this model uses the structure for TimeSeries point data in its ESRI Inc. ArcHydro data model (Wright et al., 2007a).

Whiteaker et al. (2006) developed an integrated watershed modelling system for flood information using a riverine flood simulation system and the ArcHydro data model. An overview of the system used, is illustrated in Figure 2.8. The diagram shows the connectivity of ArcHydro with engineering models. An ensemble suite of data models was developed for ArcHydro to model the hydrological-fluvial environment to produce flood inundation mapping. ArcHydro is populated with relevant data from the watershed databases. Engineering numerical modelling systems such as HEC-HMS and HEC-RAS access the data from the ArcHydro data schemas to provide flooding analyses. Similarities which exist within this research are the use of specific process models which define similar workflows for processing flood related data. These process models are automated software code which is bundled together in ArcGIS to generate results. ESRI ArcHydro was not considered due to its watershed emphasis. ArcMarine has provided a more accurate delineation of the coastal-marine domain. However, this approach consolidates the view proposed in this research to use numerical modelling integrated with data modelling to achieve the desired coastal flooding predictions.

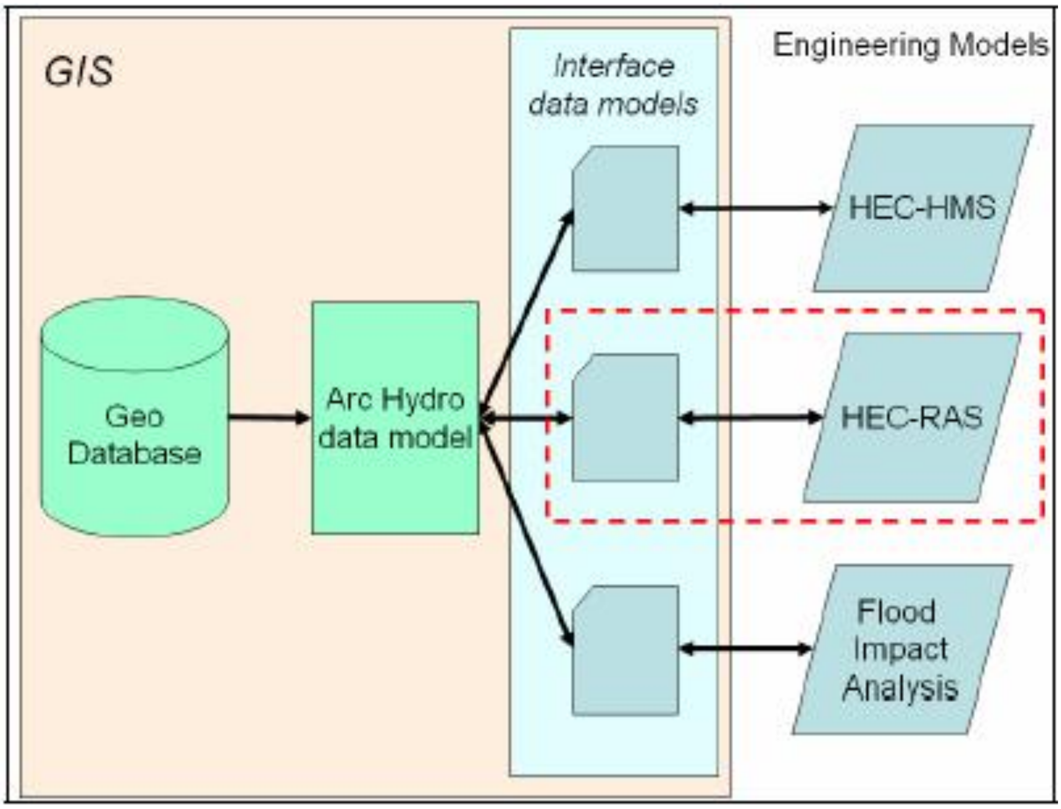


Figure 2.8: The spatial Integration of ArcHydro with hydrological-riverine engineering models to predict flood risk information at watershed areas (Whiteaker et al., 2006). Permission to reproduce this image has been granted by the American Society of Civil Engineers.

2.2.2.4 Sediment budget and coastline evolution studies

The ArcMarine data model is currently used in related studies on the analysis of the nearshore and coastal shoreline. Case studies are found in DHI Water & Environment (Denmark) to determine historical coastal evolution, measurements of bathymetry for cross-shore profiles and the simulation of sediment transport rates with numerical models. The MDM is used to model data in MIKE Marine GIS and DHI LITPACK software to investigate the morphological impact of coastal processes on the coastline. LITPACK, numerical model to simulate coastal evolution is used with MIKE Marine GIS to manage, analyse and visualise sediment budget and coastal evolution studies.

ArcMarine has been extended with additional feature classes, object classes and relationship classes to achieve the analysis provided in MIKE Marine GIS. The studies have been shown to adopt the definition of timeseries data for wave climates and sediment budgets in Figure 2.9 (Wright et al., 2007a). This linkage with ArcMarine for sediment transport and coastline evolution validates using the approach used in this thesis for coastal flooding. Timeseries data is represented as data in a measurement table which as attribution in two parameter tables TimeSeriesPoints and TSType (see Figure 2.9).

This application of the MDM has allowed the development of GIS software to perform calculations of wave climate according to wave direction, wave period and wave height; transfers wave climate from deep sea point to near shore points; and view waves from a 2D model without generating flooding. The GIS software also provides calculations on sediment transport along transects. A function is provided to import one-dimensional (1D) data into a survey transect for the generation of sediment transport profiles. The shoreline evolution data model provides input on local wave conditions and sediment properties into other sediment transport systems such as LITPACK to simulate littoral drift along the coastline (Wright et al., 2007a). The sediment transport ArcGIS application is seen in Figure 2.10. It is used to simulate littoral drift along the coastline. The figure shows the MDM demonstrates the concept of how data models improve analysis from numerical modelling by providing analysis on the annual net transport of sand which is important to determine shoreline evolution and sediment drift (Wright et al., 2007a). In addition, the commercial product MIKE FLOOD by DHI software simulates in a riverine environment flood inundation modelling in 2D. However, it is important to note that a coastal flooding data model has not been documented for this software.

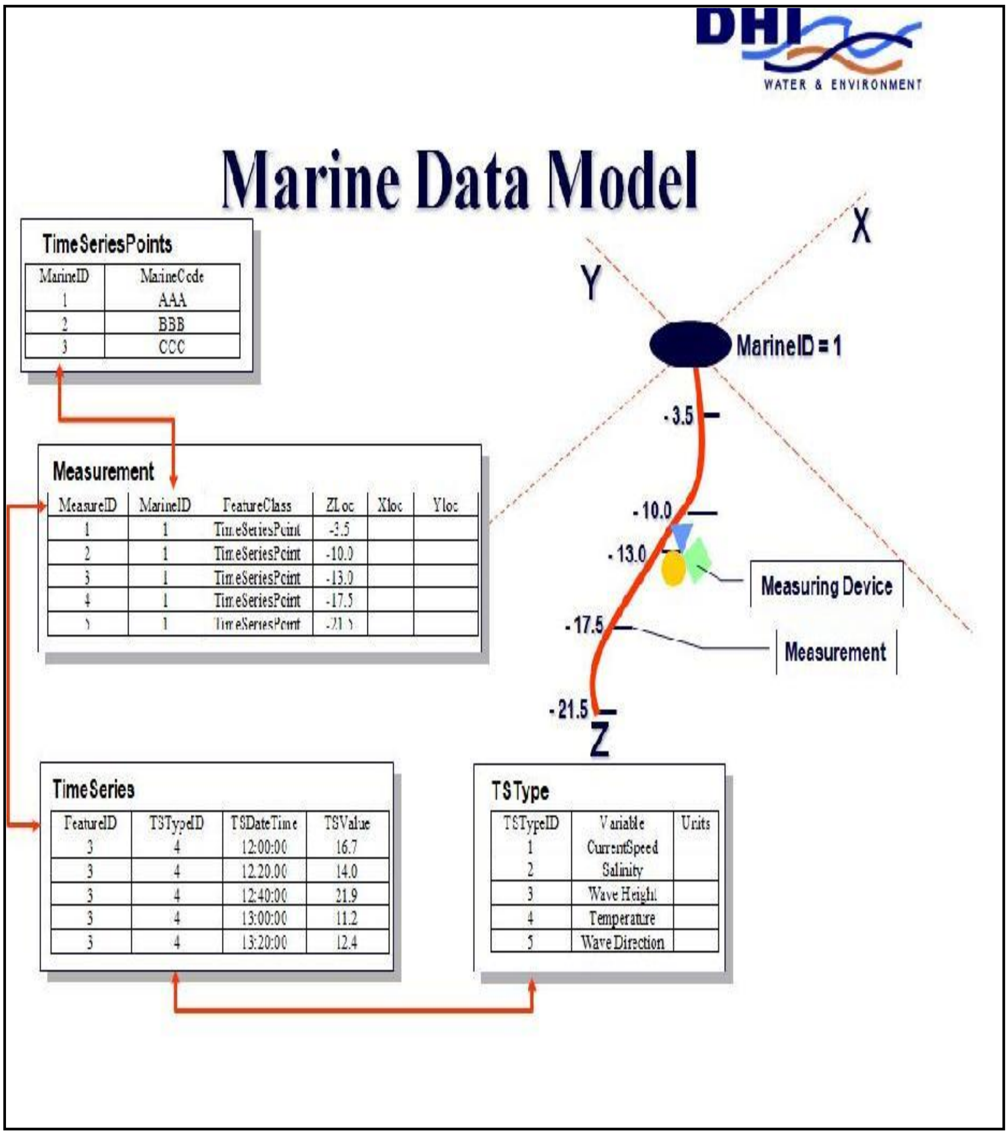


Figure 2.9: DHI Water and Environment, ArcMarine Data Model diagram showing component XML schematisation of the MDM TimeSeries feature classes linked to wave characteristics in a TSType table using TSTypeID measured at a point in time (Wright et al., 2007a). Permission to reproduce this image has been granted by Professor Dawn Wright of Oregon State University.

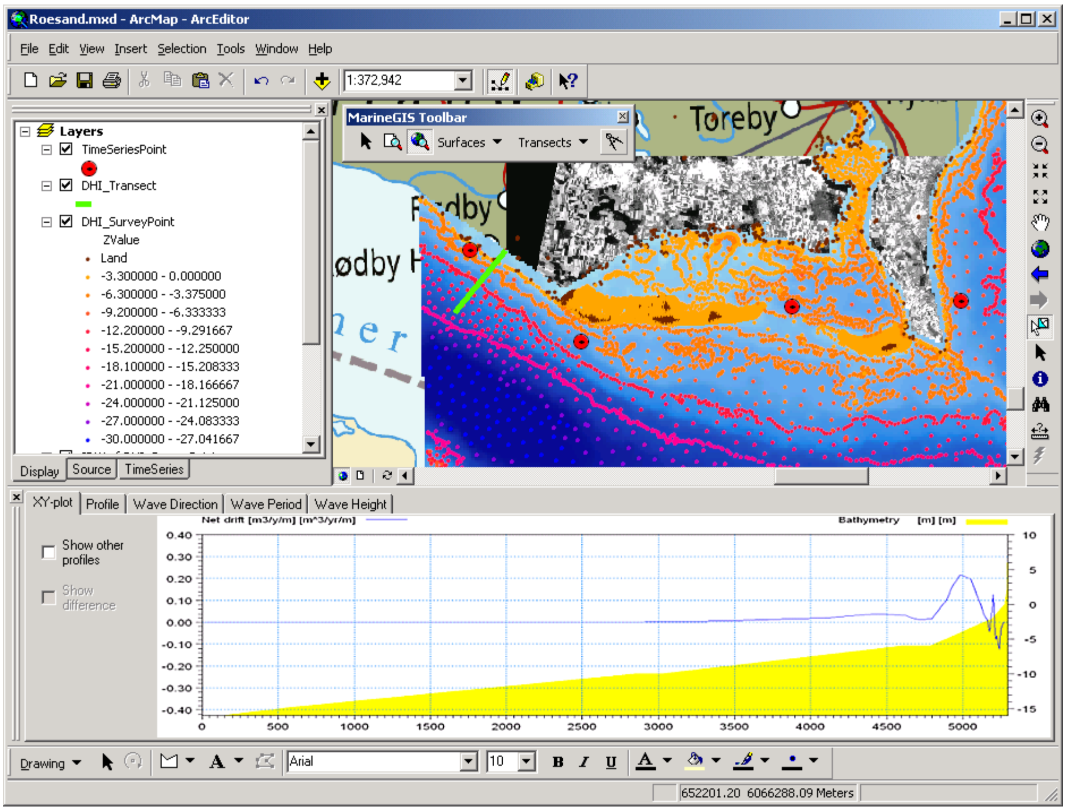


Figure 2.10: Sediment transport ArcGIS application based on the MDM data structure which allows mapping of TimeSeriesPoint and SurveyPoint to predict wave characteristics along the coast influence on sediments (Wright et al., 2007a). Permission to reproduce this image has been granted by Professor Dawn Wright of Oregon State University.

2.3 Numerical Flood Modelling

Numerical flood modelling which focuses on representation of physical processes, in general lacks the capability to be interoperable with GIS and the current generation of smart-mobile information technology (IT) platforms. This problem is significant as it restricts the compliance of numerical flood modelling with international open GIS standards and the most fundamental ability to exchange and disseminate crucial model predictions. Numerical flood modelling exists primarily in complex programming languages and formats whose major deficiency is its inability to interoperate in heterogeneous, autonomous and distributed computing environments such as in GIS and internet mapping. Notwithstanding, its non-existence, there still exist an identified lack of structured methodologies to extract the pertinent coastal flooding information from flood modelling simulations and predictions as found in data models. This review will seek to discuss the modelling systems which are commonly used in coastal flooding and illustrate the lack of data standards, and data exchange functionality to justify the importance of data modelling.

A second argument for data models is the critical delivery of timely information at a range of spatial-temporal scales found in GIS systems. Furthermore, advances in technology demand more innovative systems to disseminate coastal flooding predictions to a range of non-technical end-users. Without the data model structure, numerical flood modelling is limited in use and understanding as it’s unable to share valuable predictions. The data model is significant, as it allows the capability to advance the quantification of flood risk according to spatial-temporal analysis not found in numerical modelling.

To support this argument, the data model will allow the exchange of flood risk information to end-users. The UK flood consortiums agree that the future of flood modelling lies with the design of new models and solution algorithms which emanate from advances in rich spatial data sources (FLOODsite, 2007). Specifically, the re-insurance sector prescribes the use of models to address the lack of high resolution risk information for the underwriting of coastal flooding natural disasters (Munich RE, 2012).

The following sub-sections will discuss the most appropriate coastal flooding models based on the linking of hydrodynamics and morphology. In the second sub-section, the role of data modelling is explained in terms of numerical flood models which use GIS decision support systems (DSS). DSS typically are enhanced by data model design. Without the data model design, decision support systems analysis results are not clearly understood by users. Data models provide that essential role by improving decision support systems through its hierarchical structure. The section will also present the main properties of numerical flood modelling systems which are applicable to coastal flooding prediction.

The hydrodynamic component of numerical flood modelling uses sea level rise scenarios combined with oceanographic models to simulate coastal flooding. The prediction of water levels and flood inundation extent remain the most critical factors in assessing coastal flood risk arising from meteorological and associated sea-surface conditions such as tide, storm surges winds and waves; the quality and durability of flood defence systems; and the possibility of failure of sea defences during storms (Dawson et al, 2007).

The prediction of water levels by interpolation across grids in one-dimension (1D), two-dimensions (2D) and three-dimensions (3D) remain pivotal. These complex systems provide approximations of a flood wave based on the computations from topographic or bathymetric surfaces such as digital elevation models (DEM). Water depths are calculated by subtracting the ground elevation from the water level surface generated. For instance 2D flood inundation models simulate water flow over a water level surface in two directions (2D). Models which are 1D and 2D coupled can provide simulations through 1D water flow channels but the floodplain flow is simulated in 2D (FLOODsite, 2007). These models provide a level of accuracy for complex topographies which have a varying resolution from the floodplain flow. For a 3D flood inundation model the water flow is predicted in three directions where the third dimension is vertical height or depth as in a water column. It has been noted that they are suitable for environments where it is important to maintain an interaction between the flow of the main channel and the floodplain (FLOODsite, 2007).

The most appropriate choice of model for coastal flooding in shallow seas and estuaries remains the 2D horizontal solutions of the Shallow Water equations (Jakobsen and Madsen, 2004; Battjes and Gerritsen, 2002). Bates et al (2005) recognised the need for simplified 2D models which represented the hydrodynamics of a coastal flood at reduced computational costs. These systems process accurate high-resolution topographic data such as airborne laser altimetry Light Detection and Ranging (LIDAR) and bathymetric datasets for the oceans. Typical two-dimensional numerical hydrodynamic model solutions present significant costs when used at regional scales. The 2D model uses the Saint-Venant shallow water equations which produce acceptable results for floodplain hydraulics, assuming that 2d flow over inundated plains is a slow and shallow phenomenon (FLOODsite, 2007). It is indicated that uncertainties over topography and boundary roughness specifications influences model results more than the use of simplified mathematical descriptions (Bates and De Roo, 2000). The most commonly used flood inundation numerical models in the UK and their descriptions are included in a comparison of flood inundation models in Appendix A, Table A.1 (Pender, 2006; FLOODsite, 2007). Though not a specific area of research in this thesis, an outline of the flood inundation models used in coastal flooding are highlighted for reference in the following sections.

2.3.1 POLCOMS-WAM-GOTM Model

Within this research the specific numerical modelling used is the hybrid Liverpool Bay model which comprises the POL Coastal Ocean Modelling System; the Wave model; and the General Ocean Turbulence model (POLCOMS-WAM-GOTM). This model is usually run on a large spatial scale, and provides necessary hydrodynamic conditions required for any subsequent finer gird model simulations.

An extensive database of historical and contemporary offshore data from the NOC provides the coastal Irish Sea dataset for the (POLCOMS-WAM-GOTM) system which defines metocean conditions of storm events (Williams et al., 2011). A three dimensional (3D) model is used to integrate (near) real-time measurements with coupled models to produce results for tide-surge interactions (Holt and James, 2001). WAM is a third generation spectral Wave Model (WAM) (Brown et. al., 2010b) coupled with GOTM to provide 1D water column predictions (Howarth et al., 2008; Holt and James, 2001). The combined modelling includes tide, surge, and wave-current interaction in the Irish Sea on a 1.85 km grid. The model captures an externally-generated surge from the mid-Atlantic (Holt and James, 2001). It involves important scientific modelling such as piece-wise parabolic method of advection (PPM); turbulence closure using the general circulation model and a total variation diminishing (TVD) wetting and drying scheme which propagates water back onto the coast from offshore for the North Atlantic Margin shelf seas and the Irish Sea as indicated in Williams et al. (2011).

The broad ranges of models provided by the NOC provide daily forecasts for the deep ocean (Lorenc et al., 1991; Bell et al., 2000). Another component is the Atlantic Margin model (AMM); the Irish Sea Model (IRS); and the Liverpool Bay (LB) models which are all linked together. Conversely, the results are used by the Met Office to update the forecasts of the shelf seas and seasonal prediction.

Tidal elevations, currents and wave data are produced by POLCOMS. The model is also known to provide daily forecasts of sea shelf metocean conditions. However, to model the changes in the coastline, Liverpool Bay and the Dee, Ribble and Mersey estuaries, the model was expanded with WAM, making it suitable to predict coastal flooding. The output data includes meteorology and river flows such as currents, temperature, salinity and sediment transport (Williams et al., 2011).

2.3.2 XBeach

The XBeach model (www.xbeach.org) is regarded as a community-based open source extensively validated numerical model which was predominantly developed to assess the natural response of sandy coasts to storms and hurricanes and simulate coastal flooding (Roelvink et al., 2009; Van Thiel de Vries., 2009; Williams et al., 2012). At present XBeach makes limited use of GIS for flood prediction. It has been used to test storm thresholds for morphological change along the Sefton Coast (Esteves and Williams, 2009; Williams et al., 2012). In comparison to the other similar models, XBeach is believed to provide better modelling of sea defences and early warning indications of extreme events providing improved flood mitigation (Williams et al., 2012). XBeach is the most appropriate model not only for its applicability of the study area mentioned above but for the modelling of the offshore boundary wave and flow conditions from the eastern Irish Sea onto the coast. In addition, XBeach propagates a flood onto land due to its long wave propagation and long wave run-up and rundown on a plane sloping beach without friction.

XBeach has been previously used on the Morphological Impacts and Coastal Risks induced by Extreme Storm Events (MICORE) project. MICORE aimed to develop and demonstrate online tools to predict the morphological impact of marine storm events for civil protection mitigation strategies using GIS overlay function tools. The post-storm morphology modelling of the Sefton Coast provided XBeach dune erosion storm impacts on dune frontages using the generic XBeach parameter settings based on previous studies which examined the sensitivity of these parameters (Williams et al., 2011). In these studies, the investigations of both 1D oblique wave alongshore current and single 2D XBeach models were compared to observe the spatial differences in coastal responses to storms. It was found that by the recent 1D oblique wave simulated and removed eroded sediment than the 2D model. 1D model runs were faster and provided closer agreements between the measured and predicted post-storm profiles. In this study the model responses of six storms from POLCOMS-WAM were examined individually in XBeach using hydrodynamic data and beach profile data from a series of historical storms (between 2002-2008). The studies indicated that XBeach scenarios predicted coastal flooding routes with reasonable and good assessment of storm impacts in response to elevated sea levels and more severe storm parameters (Williams et al., 2011).

It was noted that the model excluded groundwater effects due to a lack of data on beach and dune groundwater profile data and dune sediment moisture content above the water table. The studies found that XBeach overestimated dune erosion due to an underestimation of soil strength and groundwater interactions at the time of high water as previously modelled (Williams et al., 2012). It was recommended that future studies may involve the gathering of field information on groundwater and the physical sediment spatial grain size to be included in XBeach.

In this thesis, XBeach is the model chosen to propagate a coastal flood based upon its easy integration of hydrodynamic forcing and coastal erosion effects on sandy dune beaches such as the Sefton Coast. It is the most appropriate numerical flood simulation model with its' coastal morphological emphasis. The reprogramming of XBeach and its open source environment allows model output to be exchanged with GIS systems reinforcing its compatibility with technological data exchange advances.

2.3.3 Two-Dimensional Fluvial Flood Model

A predominant UK model is the hybrid LISPFLOOD-FP. It is a simplified 2D fluvial hydraulic model developed for the coastal zone which predicts maximum inundation during dynamic events uses GIS integrated with the flood inundation modelling process (Purvis et al., 2008; Brown et al., 2005; Horritz and Bates, 2002). LISFLOOD-FP models sea level rise scenarios used to define water levels at the model boundaries. The model has been used to estimate the probability of future coastal flooding given uncertainty over possible sea level rise using IPCC scenarios (Purvis et al., 2008). Using a method of volume filling, the model captures the downstream propagation of a flood wave and the response of flow to free surface debris (Bates and Roo, 2000). GIS is used to represent a water channel as a single vector or polyline along its centreline. An interpolated floodplain raster grid method is employed to calculate the surface elevation DEM. The channel is interpolated with the DEM to identify cells intersecting in the floodplain grid which have a channel lying beneath them. The model allows that when the channel is filled, water is transferred from the channel to the overlying floodplain grid (Estrela and Quintas, 1994).

Purvis et al., 2008 applied the LISFLOOD-FP model to a 32 km stretch of the UK coast in Somerset, South-West England to produce an ensemble of coastal flooding simulations The impact on flooding for no sea level rise was compared to sea level rise of 0.48 m for 2100 from the IPCC third assessment report (Church et al., 2001). In Figure 2.11 the comparisons of no sea level rise lead to minimal flood damage and overtopping of coastal defences for a 1 in 1 year (A); 1 in 100 year (B); 1 in 200 year high tide events (C); and withstand a 1 in 1000 year high tide event (D) defending Weston Super-Mare and Clevedon from flooding. Minimal flooding was predicted to occur at the mouth of the Gordano Valley between Portishead and Avonmouth with overtopping of fluvial defences and at the Somerset Levels (Figure 2.11). The model predicted the breaching of the River Yeo and Axe for the 1 in 100 year, 1 in 200 year and 1 in 1000 year high tide events affecting grasslands on the River Yeo and arable land which adjoins the River Axe.

The methodology was extended to determine the probability of flooding in each model grid cell over the ensemble was approximated using IPCC sea level rise values of 0.48 m in 2100 (Figure 2.12). The LISFLOOD-FP method allowed the tabulation of the statistics for the total areas of inundated land assuming no sea level rise and 0.48 m of sea level rise for decision makers. The LISFLOOD-FP methodology produced similar mapping of flood water depths for the 0.48 m rise in sea level for the various recurrence event intervals.

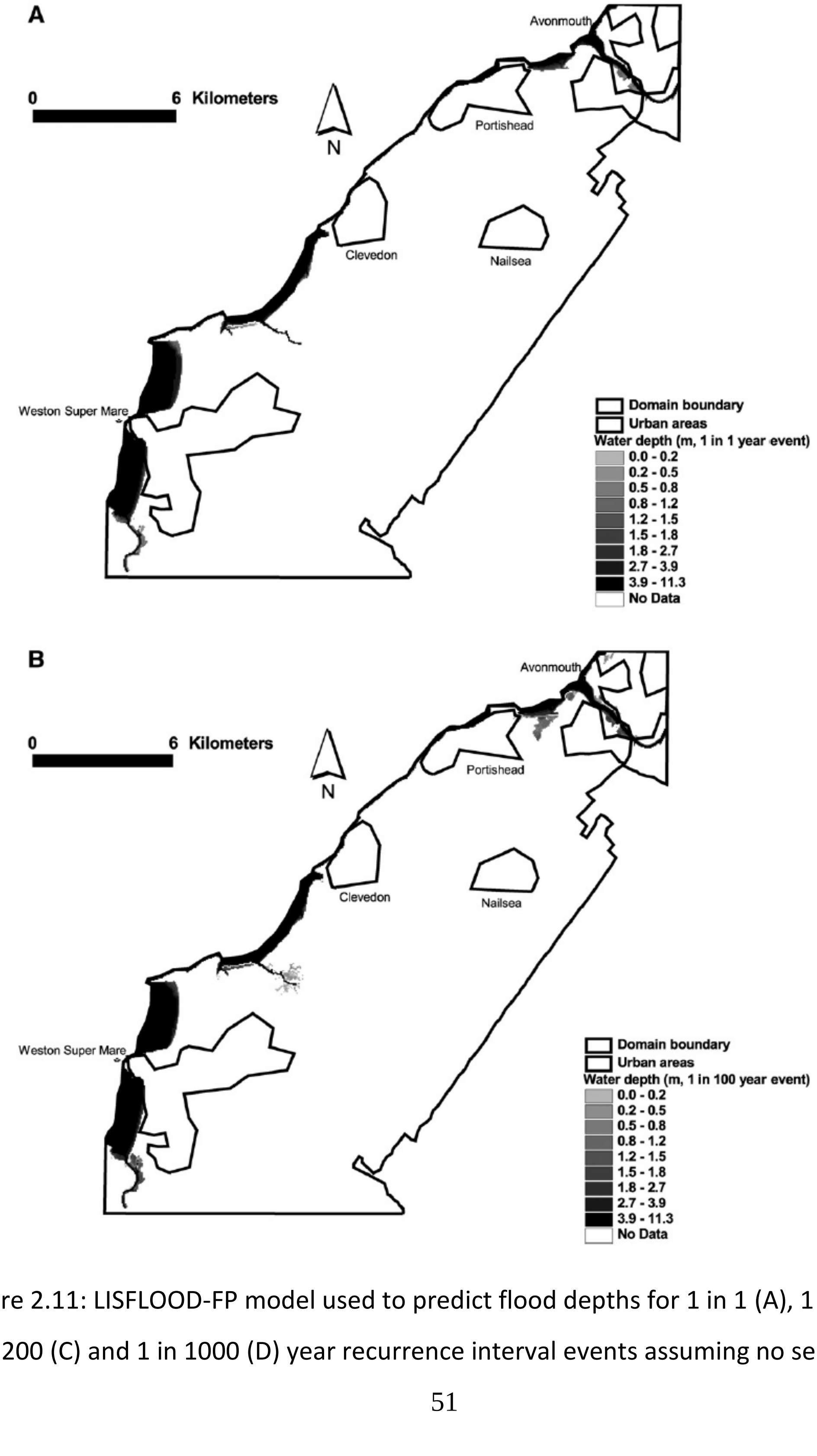


Figure 2.11: LISFLOOD-FP model used to predict flood depths for 1 in 1 (A), 1 in 100 (B), 1 in 200 (C) and 1 in 1000 (D) year recurrence interval events assuming no sea level rise

using a 50 m flooding DEM map for the catchment area derived from a 2m spatial LIDAR grid supplemented with survey data (Purvis et al., 2008). Permission to reproduce this image has been granted by Elsevier.

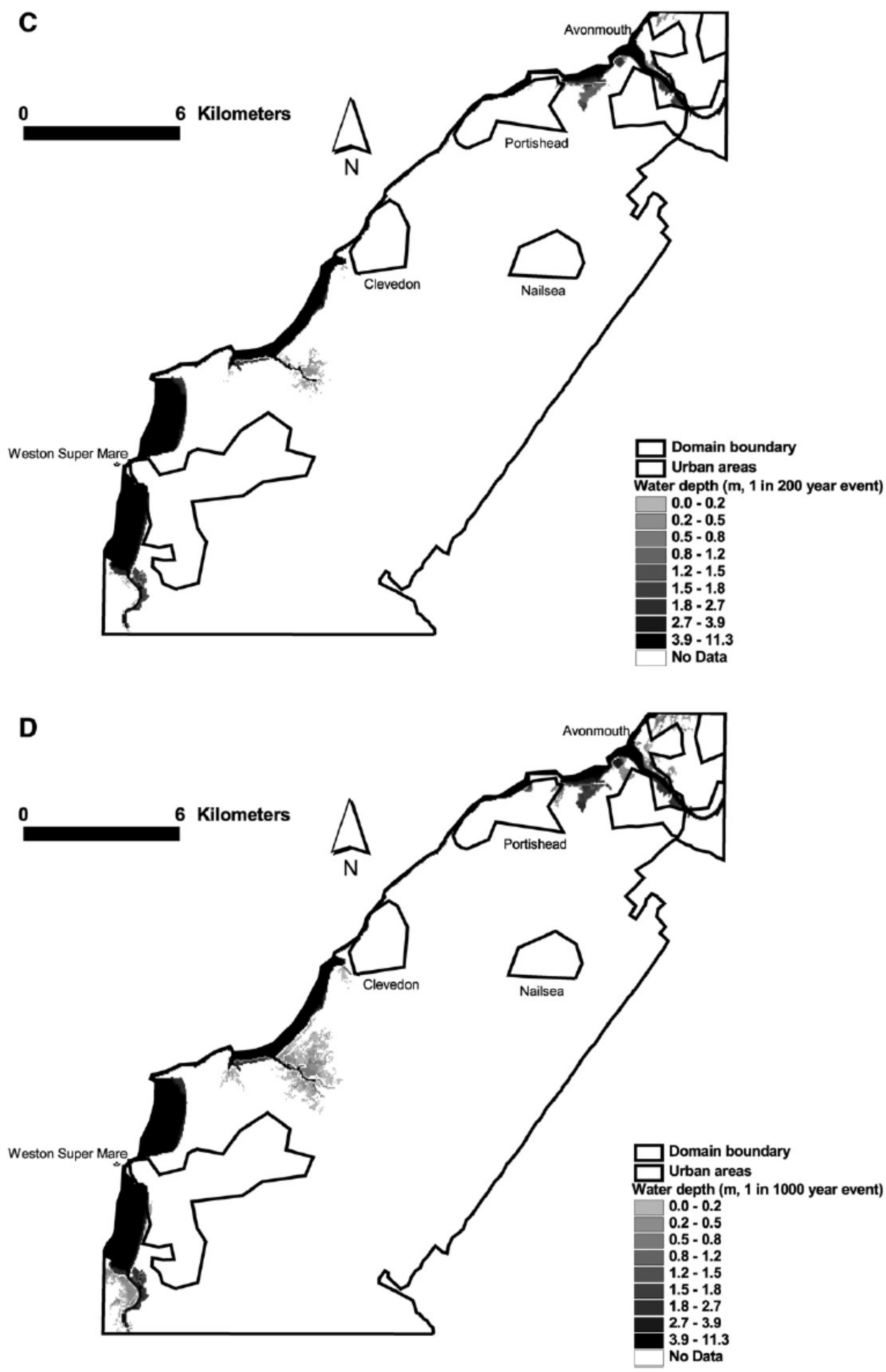


Figure 2.11 Continued

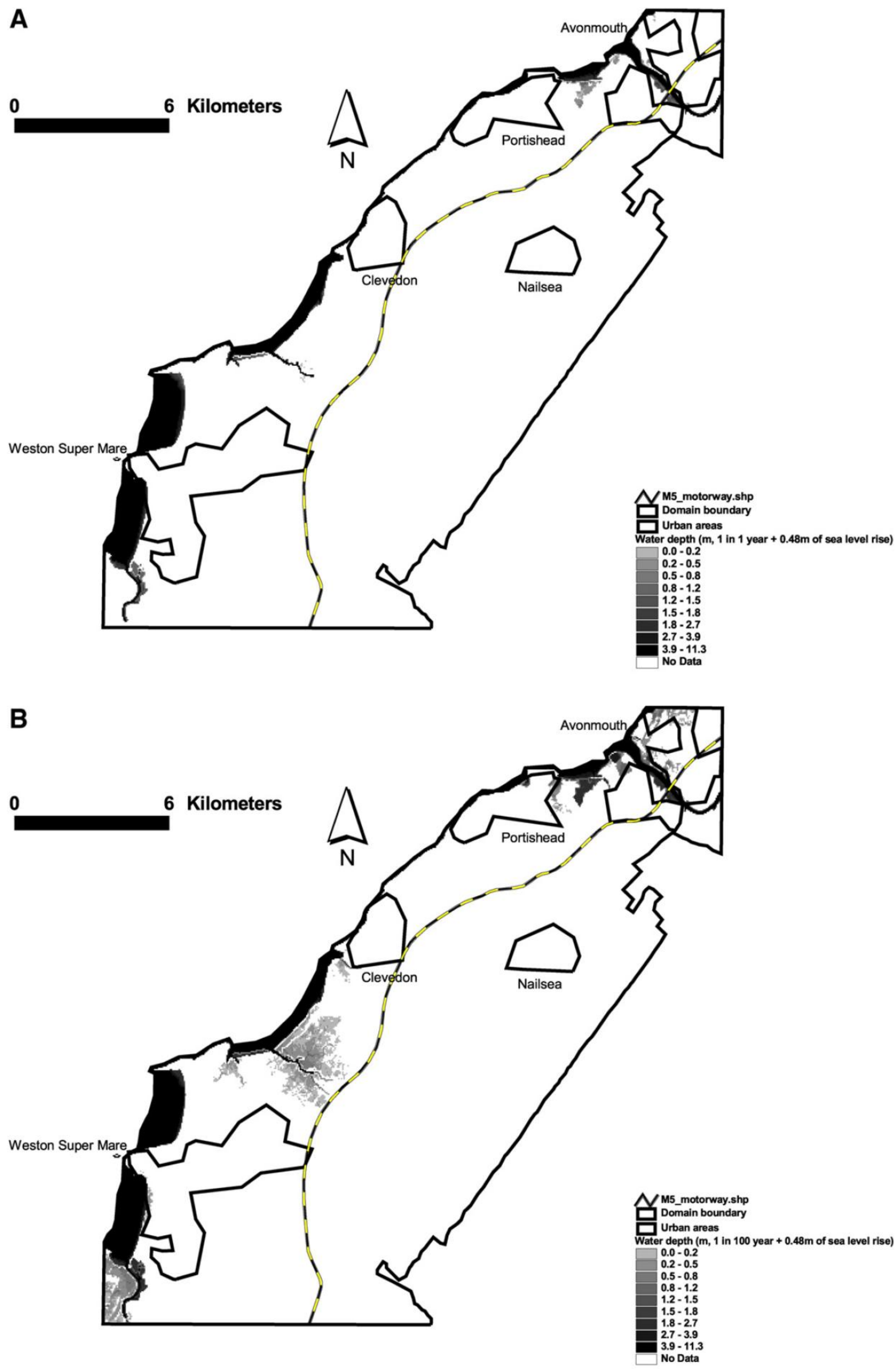


Figure 2.12: LISFLOOD-FP model used to predict flood depths for 1 in 1 (A), 1 in 100 (B), 1 in 200 (C) and 1 in 1000 (D) year recurrence interval events assuming a sea level rise of 0.48 m using a 50 m flooding DEM map for the catchment area derived from a 2m

spatial LIDAR grid supplemented with survey data (Purvis et al., 2008). Permission to reproduce this image has been granted by Elsevier.

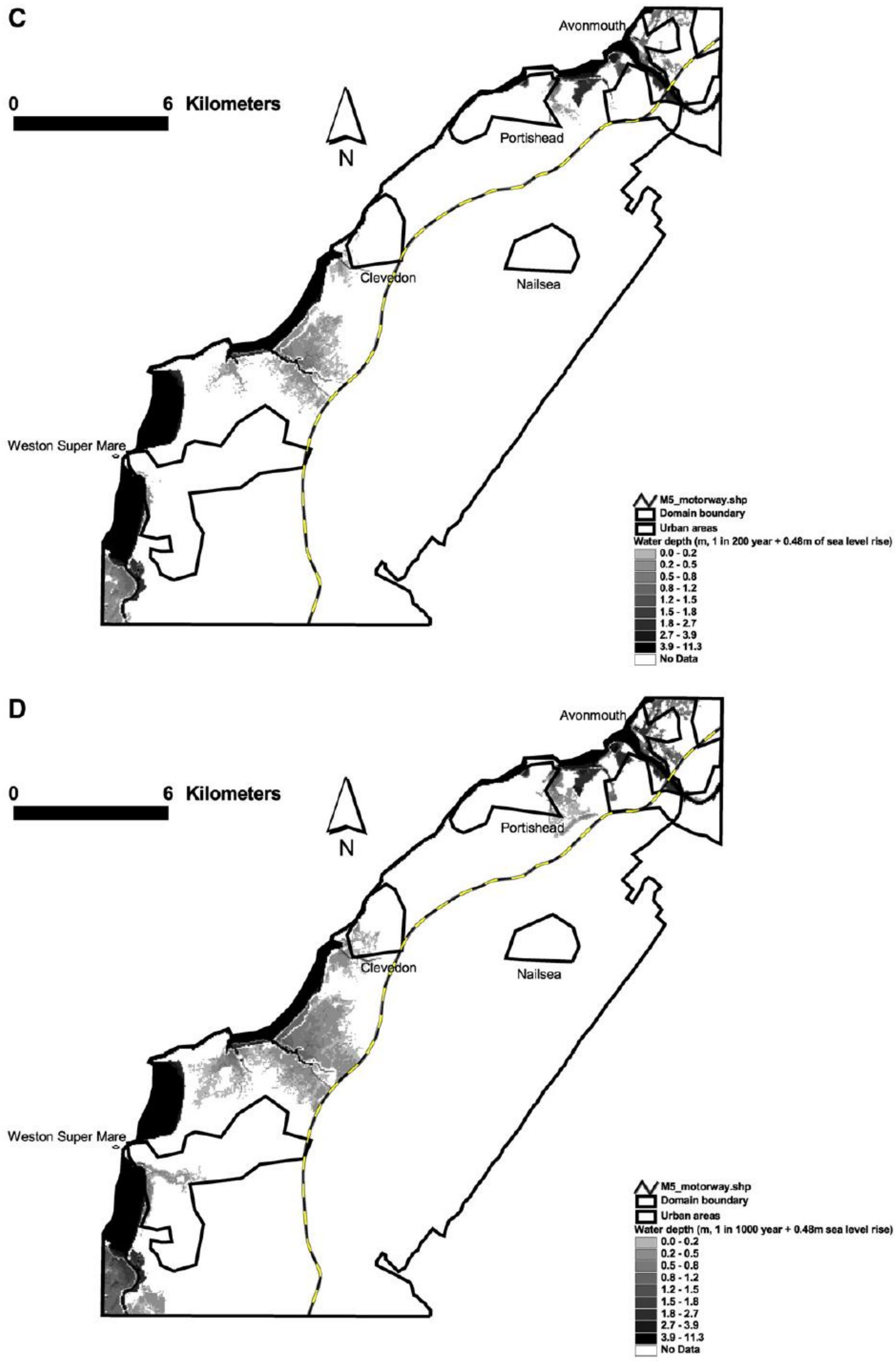


Figure 2.12 Continued

Within this model floodwaters expand using the DEM across the Somerset Levels to the M5 motorway embankment without taking into account the culverts and bridges which traverse the motorway. The deficiency in the mapping of this model is the inability to determine the precise extent of flooding locations in the town centre locations. These methods can be improved by using GIS mapping. Further details on the comparison of flood inundation models can be found in Pender et al., 2006 and FLOODsite, 2007.

2.3.4 Dynamic Domain Defining Method (DDM)

The Central Research Laboratory, Hitachi Ltd. Japan has developed flood simulation software called Dynamic Domain Defining Method (DDM). It is based on GIS software called DioVista. The software was used for a study based on 2D shallow water equations and the model results have been compared with a recent flooding event in 2004 at Fukui City, Japan, caused by 50 m of levee failure resulting in the flooding of 220 hectares of urban areas for 6 hours. The dynamic DDM automatically defines its calculation area to reduce computational time which is different from other models which inputs the calculation area in advance of the simulation. The model method automatically expands or shrinks the calculation area to exclude dry cells. The model divides the area into multiple sub-domains to allow faster searching and processing. LIDAR methods were used to create the topographic layer in DioVista. The GIS allows the user to input levee failure points on a 3D map with respect to direction of outflow. The software also integrates water surface and buildings three-dimensionally to estimate damage to property.

2.3.5 MIKE FLOOD

MIKE FLOOD is a hydrodynamic modelling package designed to integrate flood plains, streets, rivers and sewer/storm water (DHI, 2014). MIKE FLOOD uses a GIS graphical user interface. The 1D model can be used to represent flow in channels, simulate hydraulic structures such as culverts, bridges and weirs and the route the flow in longer river reaches. The 2D model can be used to represent overbank flows and accurately model the geometry of floodplain for discharge, storage and attenuation. The model simulates flow splits based on the input topography and removes the need to pre-define flow paths. It also understands the street and pathway networking in urban areas.

Flood maps in MIKE FLOOD can be visualised in 2D and 3D mapping (Figure 2.13). In addition, MIKE FLOOD is an ESRI ArcGIS plug-in and can use the 3D capabilities in ArcGIS. Even more applicable, a plug-in to Google Earth (.dfs2) provides 2D and 3D visualisation online. The major advantage of this system is its open source design used for GIS and internet-based mapping applications. It is believed that MIKE's flexible mesh gridding systems provide a better means of simulating river situations but are lacking in recreating the coastal processes and hydrodynamics which would compromise sea defences (Williams et al., 2011).

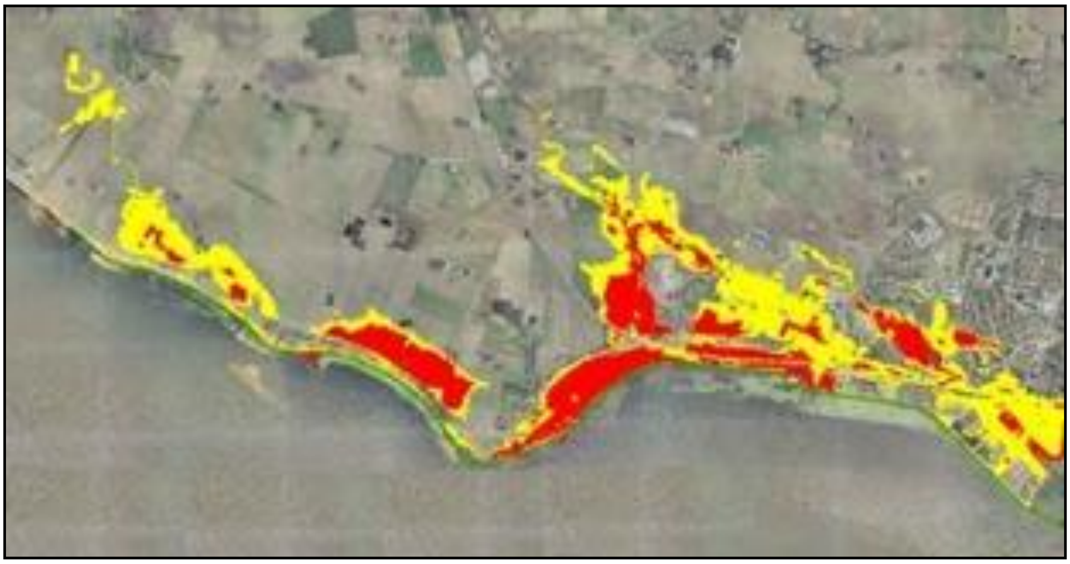


Figure 2.13: Flooding for a storm surge event with 50 years recurrence for the present sea level conditions (red) and for the conditions in year 2100 in Trelleborg, Sweden (yellow flooding displayed on aerial imagery in MIKEFLOOD (DHI, 2014). Permission to reproduce this image has been granted by DHI.

2.3.6 TUFLOW

TUFLOW has been developed as a joint research and development project between WBM Pty Ltd and The University of Queensland for estuarine and coastal studies including flood modelling. The system has linkages to GIS to produce risk assessments and 3D visualisation and is the model of choice for the Environment Agency. The system provides 2D and 1D solutions for free-surface flow equations to simulate flooding (Figure 2.14). The solution models hydrodynamics in coastal waters, estuaries, rivers, floodplains and urban drainage networks using complex 2D flow patterns and 1D/2D representation of hydraulic structures. The system is flexible to accommodate 2S/1D dynamic linking and multiple 2D domains. In addition, the system produces rapid and stable wetting and drying for 2D cells allowing hydrodynamic water propagation on land. The model automatically switches from upstream and downstream flow over levees and embankments. The computational engine makes this system efficient at data handling, flexible to change from 1D/2D domains and provide high quality assured output. TUFLOW successfully integrates with other systems such as XP-Software's XP-SWMM 1D engine and GUI, Halcrow's ISIS 1D engine and Environmental Modelling Systems SMS software.

Figure 2.14: TUFLOW Flood Inundation Model of Queensland, Australia showing the predicted flood extent highlighted in light blue. The river channel is outlined in a deeper blue hue (TUFLOW, 2014) has been removed due to Copyright restrictions.

The Environment Agency who is the authority for flood modelling in the UK have used a broad range of 2D flood inundation models (riverine and coastal) which include ANUGA, FloodFlow, TUFLOW, InfoWorks, ISIS2D Mike21 and JFLOW to predict flooding (Environment Agency, 2009a). Currently 1D flood inundation modelling such as HEC-RAS is used to produce the topography necessary for the Flood Map data. TUFLOW 2D is the flood inundation modelling tool generally used to produce a one in two hundred year (1:200) occurrence of flooding by modelling tides and storm surges without sea defences. Within this thesis, it is proposed that a combination of the 2D shallow water equation; wetting and drying effects which propagate coastal flooding inland; and the effective use of GIS inundation mapping and analysis are essential components of numerical flood modelling. XBeach is therefore the chosen numerical flood model used to examine the impacts of coastal flooding in this research satisfying these requirements.

2.4 Flood Modelling with GIS Decision Support Systems (DSS)

A discussion of the flood modelling (numerical models) integrated with GIS will be presented in this section to indicate the use of GIS and the lack of the data model approach. Flood inundation modelling has advanced in step with technological innovations in computing power, more accurate high resolution imagery and powerful GIS functionality (FLOODsite, 2007). However, studies have found that that the full potential of hydrodynamic flood modelling has not been realised due to limitations of integrating model output with existing GIS architectures supporting the use of the data model approach (Zerger and Wealands, 2004).

Current research in coastal flooding integrated with GIS technology has focused on the use of DSS to provide flood risk analysis, flood risk hazard mapping and vulnerability assessments indicating a defined gap in data modelling (Purvis et al., 2008; Kortenhaus and Oumeraci, 2008; Mendoza and Jiminez, 2008). The most recent integration of GIS in coastal flood modelling is provided in the study of coastal erosion in the UK to predict coastal change using bespoke GIS software (Brown et al., 2005; Mokrech et al., 2007; Nicholls et al., 2009).

State-of-the-art hydrodynamic flood models which loosely link with GIS decision support systems (DSS) have been used to predict fluvial flooding with little or no focus on coastal flooding. DSS typically use GIS capabilities to perform spatial queries with a user interface to produce analyses. The models presented here do not produce a data model for coastal or fluvial flooding but use numerical models and GIS database querying to undertake flood risk assessments. These are the closest approximations of data models implemented in flood modelling. A discussion is provided to indicate absence of these systems in coastal flooding

The UK flood consortium has outlined a methodological guide to GIS mapping which uses a decision support tree with semi-qualitative analyses in ESRI ArcGIS to provide flood risk assessments for hazard and vulnerability mapping (FLOODsite, 2007). The high level hierarchical tree in Figure 2.15 develops GIS decision support spatial querying capabilities for hazard and vulnerability assessments in fluvial flooding. The DSS uses GIS spatial union tools to merge hazard data with vulnerability data to produce a flood risk map. This method is adequate to identify GIS tools required for querying and analysis but insufficient to provide an identification of data structures and types outlined in data modelling. The data model is necessary in this structure to document the data and processes required for hazard and vulnerability mapping not available in DSS. As a result, end-users using DSS can identify functions in GIS but are uninformed of the data analysis and relationships which exist amongst entities used to manipulate and generate coastal flooding prediction results. Thereby, data models enhance the decision making capabilities of the DSS to produce targeted coastal flooding results.

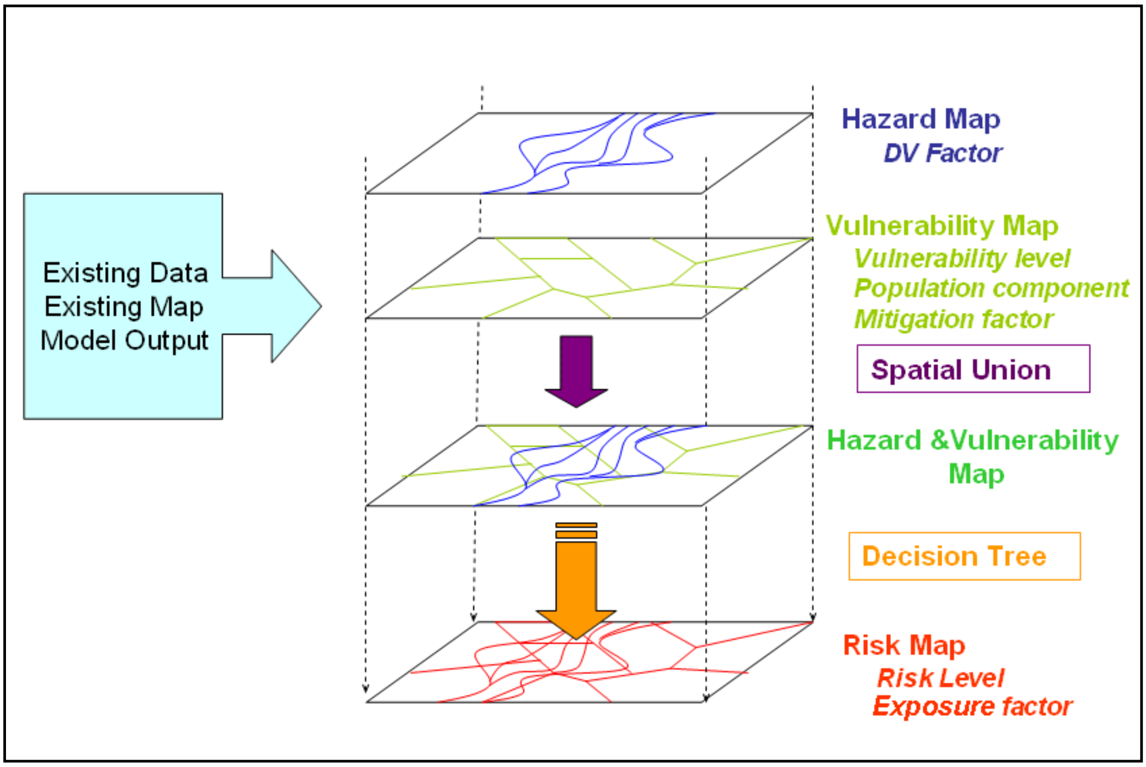


Figure 2.15: A GIS decision support system decision tree conceptual framework for hazard and vulnerability mapping of flood risk (FLOODsite, 2007). Permission to reproduce this image has been granted by FLOODsite.

Levy et al. (2005) produced flood DSS architecture for flood disaster management and planning in the Yangtze River valley, China using the HEC-RAS numerical model implementing GIS coupling with numerical modelling (see Figure 2.16). The DSS developed comprised: a flood database, flood modelling functions and a graphical user interface (GUI). The flood database comprised meteorological, hydro-geologic, administrative and socio-economic datasets with real-time access to river monitoring data. Schematically, the interconnecting mechanisms of flood disaster management and planning were outlined in the DSS framework (Figure 2.16) which allowed the analysis of time series data through the amalgamation of a flood database of geospatially relevant datasets. Damage functions were provided based on depth values from the numerical flood modelling.

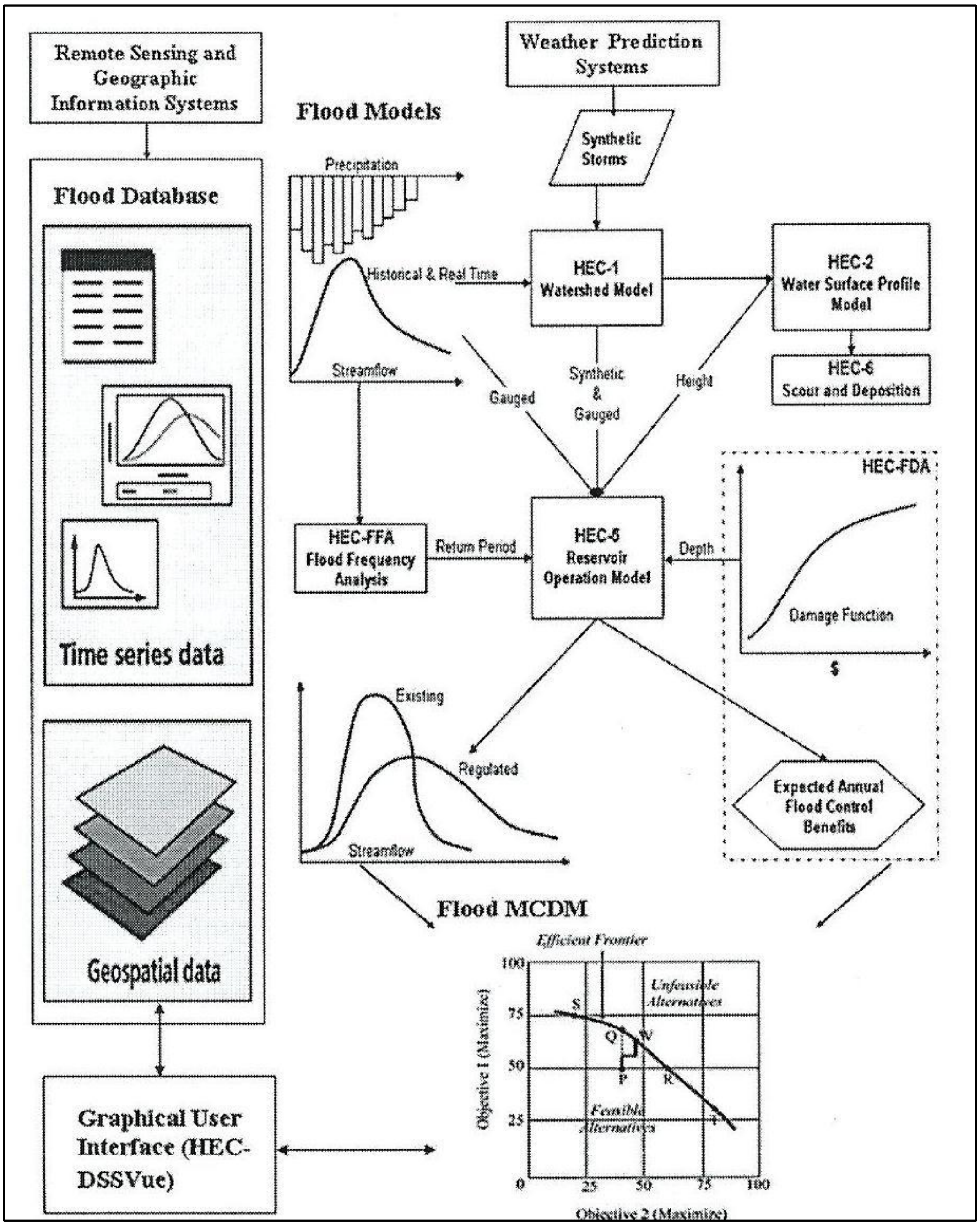


Figure 2.16: Decision Support System Architecture for flood disaster management and planning in the Yangtze River valley, China showing the DSS which comprised a HEC-RAS numerical model, a flood database, flood modelling functions and a graphical user interface for geospatial and time- series mapping (Levy et al., 2005). Permission to reproduce this image has been granted by Taylor & Francis.

This DSS has included flood modelling functions such rainfall-run-off simulations and discharge levels using HEC-1 (flood hydrograph package) developed by the US Army Corps of Engineers Hydrologic Engineering Centre (HEC). The GIS provided information on flood magnitudes and associated frequencies. A flood multiple-criteria decision making (MCDM) model was developed to encode flood decisions based on Saaty (2008). However, this framework represented the broad activities and processes with no consideration to the core relationships, rules and behaviours which exist amongst the data types. Any potential flood user is unaware of the relevant information necessary to conduct similar analysis.

In another implementation, Zerger and Wealands (2004) developed a framework for a DSS to link hydrodynamic modelling outputs, GIS and relational database management systems for cyclone events (see Figure 2.17). The generic framework was designed for common database standards, structured query language (SQL) and open database connectivity (ODBC) to provide rapid access to time-series flood information. ArcGIS techniques were used for DEM's/bathymetric model generation; database integration to represent surface roughness; parameterise flood models; and automatically delineate watershed and stream networks. The framework was designed to work with the Australian Bureau of Meteorology Maximum Envelopes of Water (MEOWS) storm surge model and the TUFLOW 2D hydrodynamic model.

Zerger and Wealands (2004) further extended the model to produce 432 raster inundation surfaces for a 72 hour event analysed at 10 minute intervals. The approach used numerical flood modelling and provided improved analysis through a decision support system. Microsoft Access and Oracle databases were used to provide the database support in ESRI ArcGIS mapping demonstrating a similar concept but a definite lack in data modelling. These examples re-emphasise that the integration of GIS and numerical modelling to date have not included the detailed data modelling approach that will allow a clearer understanding of the natural disaster whether it be a coastal flood or a cyclone. Furthermore, the analysis focused on hazard mapping and vulnerability assessments.

The most advanced use of GIS for coastal studies in seen in the two-dimensional (2D) coastal simulator model developed by the Tyndall Centre for Climate Change Research (Mokrech et al., 2007. The model links a series of nested models within a nested spatial framework using ESRI ArcGIS as a graphical user interface to allow a range of spatial and non-spatial analyses using 2D and 3D visualisation (Figure 2.17). It is one of the few flood inundation models which has been developed in ESRI GIS desktop software.

The DSS approach was used to develop decision criteria, this model uses the finite element code from the TELEMAC system. It uses a TOMAWAC module for wave action propagation; TELEMAC-2D module for tidal flows and SISOHE module for morphodynamics. Nearshore wave climate provided input to the SCAPE (Soft Cliff and Platform Erosion) model. The SCAPE data were validated against 17 years of historic shoreline data used by the study to simulate 45 potential climate change and coastal management futures. The SCAPE model was integrated with coastal flood risk data. The flood risk assessment was based on the influence of beach volume on sea defence instability to predict the probability of structure failure and breaching. Where breaching and overtopping occurred, the LISFLOOD-FP numerical flood model was used to simulate coastal flooding.

Figure 2.17: The integrated framework for developing the coastal simulator, based on a series of linked climate models within a nested framework at three spatial scales: (i) the global (GCM) scale; (ii) the regional scale and (iii) the Simulator Domain (coastal sub-cell). The models feed into each other and describe a range of relevant processes: sea level, tides, surges, waves, sediment transport and coastal morphology (Mokrech et al., 2007) has been removed due to Copyright restrictions.

The GIS coastal simulator incorporated model-based approaches to apply socio-economic scenarios (Nicholls et al, 2009). An innovative decision-rule agent-based model (ABM) was used to distribute housing data though algorithms that model the interactions between the local and regional levels whilst taking into account varying socio-economic futures consistent with climate change and implications for flood risk management. A GIS allowed users to explore, query and model results using decision support tools to allow 2D analysis and 3D visualisation in ESRI ArcScene/3D Analyst software. Future enhancements to these models included standard time series, 3d visualization of coastal features and uncertainty representation, real time linkages with the ecosystem models (Mokrech et al, 2007). The current model generated cliff recession using probabilistic models. The coastal simulator has been further updated for cliff recession using the ESRI ArcGIS GUI to identify at risk residential properties on a map (Figure 2.18). It provides the most recent benchmark for coastal impacts using GIS in the UK.

Figure 2.18: The Coastal Simulator Graphical User Interface designed to determine the impacts of future cliff recession on the coast in ESRI ArcGIS and identify residential properties (points on map) at risk of cliff erosion (Mokrech et al., 2007). has been removed due to Copyright restrictions has been removed due to Copyright restrictions.

Further to the coastal simulator, the Tyndall Centre for Climate Change developed a probabilistic framework for estimating the risks of coastal erosion and coastal flooding using a coupled system of hydrodynamic, morphological, reliability and socio-economic models implemented under scenarios of climate and socio-economic change (Dawson et al., 2007). A risk-based approach was used to predict coastal behaviour in probabilistic terms combined with assessment of impacts to quantify the expected annual damage. Flood risk was calculated by combining the annual probabilities of flooding with maps of the location of properties in the coastal flood plain (Figure 2.19).

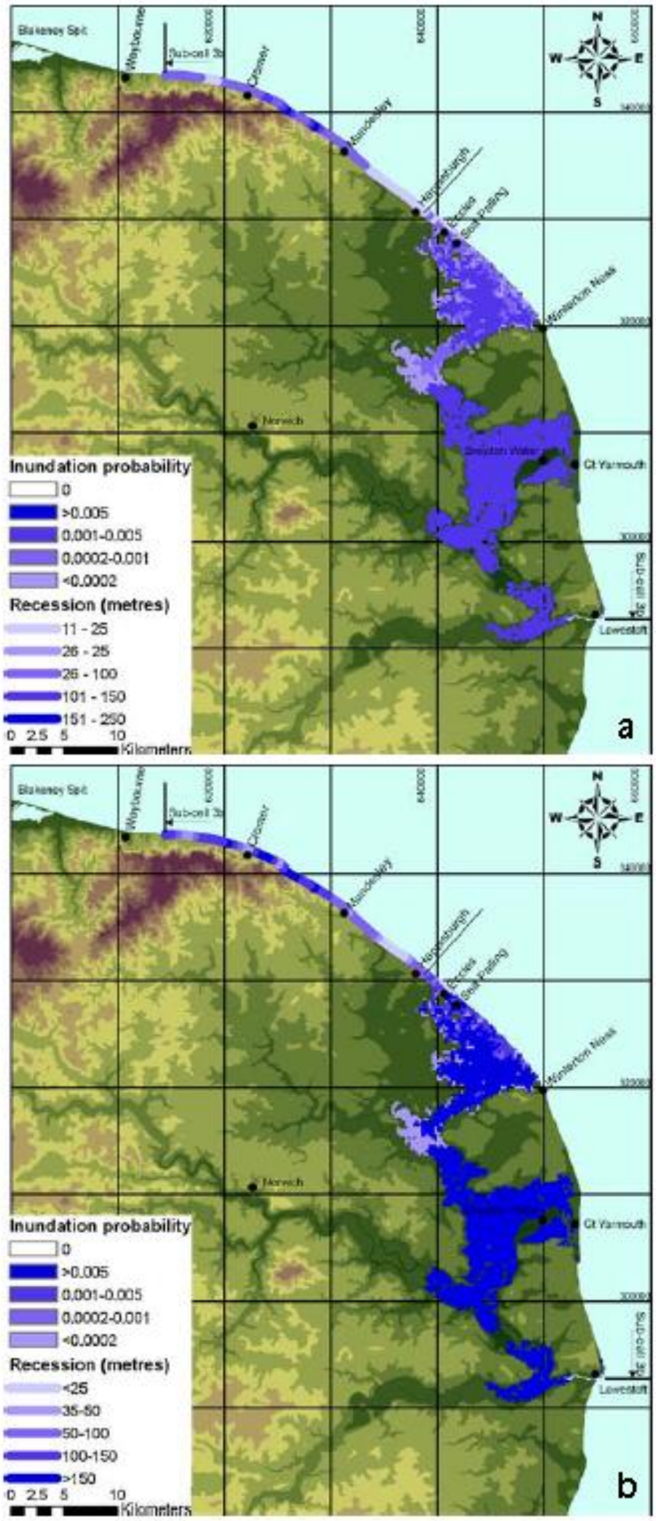


Figure 2.19: The Tyndall Centre for Climate Change map of flood and erosion risks derived from probabilistic risk assessments (Dawson et al., 2009). Permission to reproduce this image has been granted by the authors.

Waves were propagated off the East Anglia coast using TELEMAC (Stansby et al., 2006). The nearshore wave climate data results incorporated hourly time series. Hydrodynamics were generated in a simple model in LISFLOOD-FP to produce a spatial field of water levels from which the DEM was subtracted to give a field of flood depths (Bates and De Roo, 2000) and maximum flood inundation extents (Horritt and Bates, 2001, Bates et al., 2005). The model was validated against the UK extreme 1938 flooding in East Anglia. The maximum flood depth for each model grid cell was extracted from a total of 20,000 runs of the hydrodynamic model and used to evaluate flood damages in the baseline risk calculation. In comparison with analysis improved by GIS data modelling, this hydrodynamic model did not provide more accurate mapping of the flood risk. Flood risk was determined by calculating the annual probability of flooding based on damage and visualised in statistical graphical formats (Figure 2.19).

Probabilistic studies are important analysis tools for flood risk. The Environment Agency's current prototype, the Mapping All Sources (MAST) Tool, uses the principles of joint probability of extreme events to produce GIS flood risk simulation scenarios, vulnerability statistics, and decision support in the MAST tool (DEFRA, 2011). MAST was created to combine data on flooding from different sources such as rivers, sea or surface water. Using flooding information, the tool produces a single map of flooding from varied sources. Figure 2.20 shows a diagrammatic flow of MAST software and data to produce GIS mapping and probabilities. Using a GIS interface, data is mapped collectively using a MAST engine.

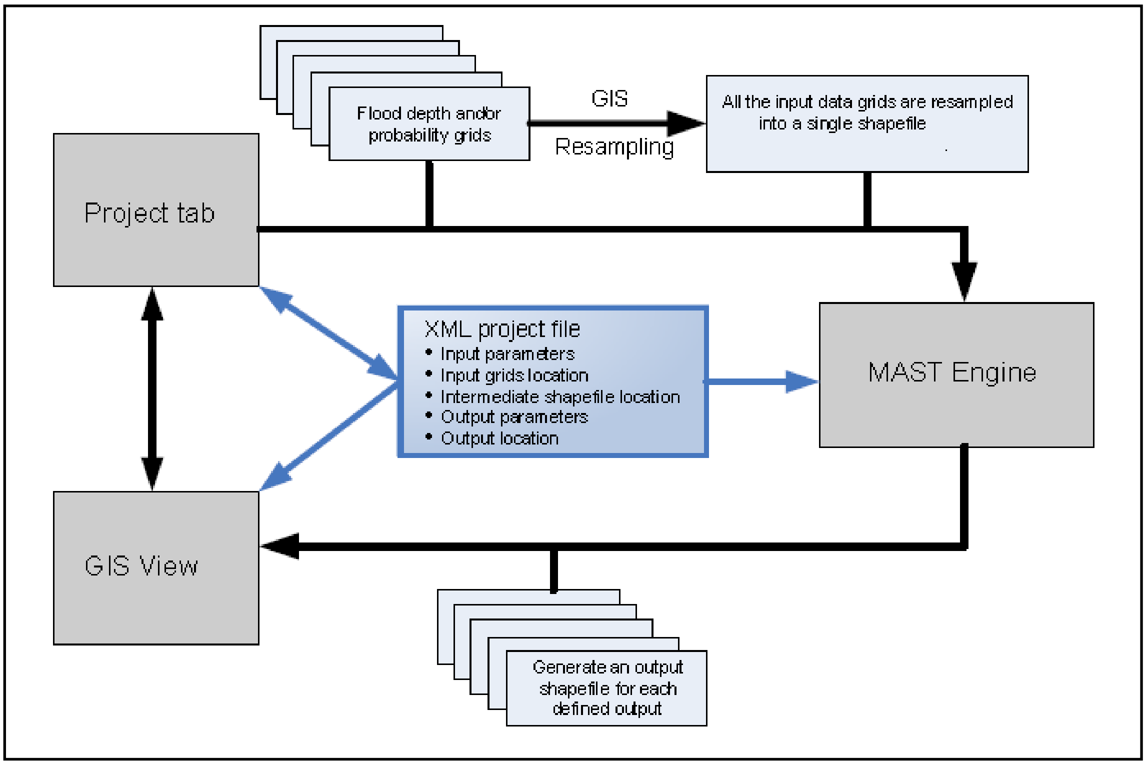
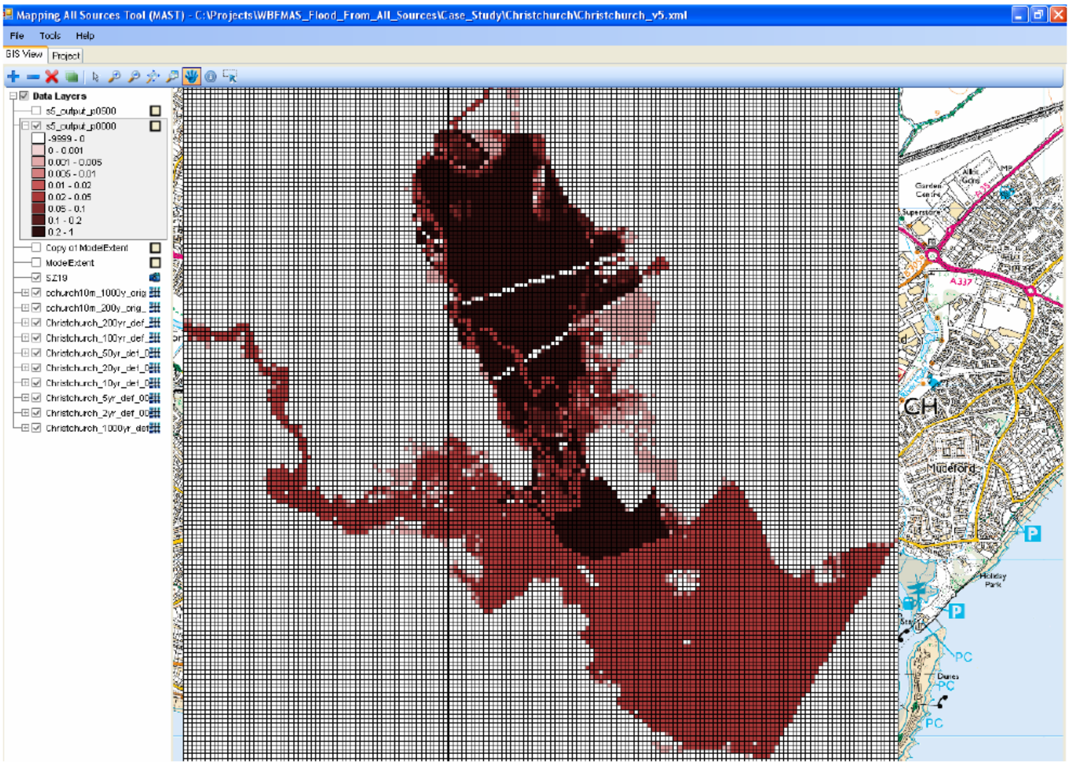


Figure 2.20 Diagrammatic flow of MAST software components and data used to combine flooding data from all sources; and produce GIS mapping (DEFRA, 2011). Permission to reproduce this image has been granted by the Environment Agency.

The MAST GIS interface includes simple GIS functionality to visualise input flood mapping datasets represented either as depth data or flood probability data (Figure 2.20). The MAST engine seen in Figure 2.20 reads the GIS data layers and derives a depth probability curve for flooding. This curve is subsequently combined with other flood sources by the engine to produce a more comprehensive output seen as a GIS View for a simulation scenario (Figure 2.21). The methodology calculates a single measure of combined flood hazard with its corresponding best estimate probability by grid cell. The theory used to determine the combined estimates of probability are described in Hawkes et al. (2005).

Figure 2.21: MAST GIS View of the combined flooding from fluvial, coastal and surface water results to produce a simulation scenario (DEFRA, 2011). Permission to reproduce this image has been granted by the Environment Agency.

The results produced are polygon shapefiles in an ESRI ArcGIS grid with specific probability attributes defining the combined value for each grid cell either as a probability or a depth. The percentage contributions from each single data source at grid cell are provided. The combined best and lower estimates of uncertainty are provided at the grid cell location. In Figure 2.22 the best estimate of probability of a simulation scenario are shown in the MAST interface as an example. The output from MAST also includes percentage contributions from each single data source present at the grid cell location and combined uncertainty upper and lower bound statistics valuable to flood defence mitigation. MAST also determines the probability of failure of assets which contribute to the residual risk on a defended floodplain including raised flood defences such as embankments, weirs, culverts and bridges. The MAST tool delineation of flood risk would be improved by the schematisation of coastal flooding time series data and analysis detailed in a coastal flooding data model.



Best estimate probability

Figure 2.22: Best estimate probability depth grid for a simulation scenario calculated using the MAST tool where individual cells flood risk uncertainties are provided (DEFRA, 2011). Permission to reproduce this image has been granted by the Environment Agency.

It is inconclusive whether the DSS reviewed can adequately integrate and analyse disparate data sources as proposed in the data modelling approach. A definite lack of data models integrated within DSS exists to determine flood risk. Miller et al. (2005) identified several challenges for developing effective decision support systems for flooding which include: interoperability of technologies; accessibility to the Internet and a wide audience; internet security; and data ownership issues which are improved through data modelling. These critical issues are resolved by the ability of data models to integrate and categorise the results of coastal flooding derived from numerical modelling. It is demonstrated that systems which integrate flood models with GIS are well documented but far fewer are used for coastal flood modelling. However, even fewer DSS frameworks which integrate flood model outputs from hydrodynamic models with GIS provide key decision-making support to end-users exist. Moreover, the data model is able to provide the foundation for internet mapping of flood risk to a wider audience supporting its essential role in coastal flood modelling.

2.5 Information Technology (IT) Advances

The rapid information technology (IT) advances in computer based extensible mark-up language (XML) has led to a new generation of data exchange standards in marine and climate GIS. These advances facilitate common standards and provide a strategic foundation for phenomena such as coastal flooding. This section discusses the advances made in data exchange standards which are relevant to coastal flooding. Today, traditional GIS capabilities can be programmed on web applications providing some of the querying and analysis of desktop GIS. As a result of this need for internet mapping and visualisation, technologies such as data exchange standards have emerged which are regarded as the most relevant technology to internet mapping (O'Reilly Media Inc and Pahlka, 2009).

2.5.1 Data Exchange Standards

Geospatial data exchange standards have become important mechanisms for the storage, integration and dissemination of climate change and weather data in GIS.

Data models provide details of how data are queried to undertake spatial analyses, whereas, data exchange standards outline the format and specification of individual datasets for exchange from one system to another. It is proposed that data exchange standards define the generic information about data which allows improved dissemination between numerical modelling systems and GIS. The relevant data exchange standards for marine, coastal, and weather data are provided and their relationship to data models.

Data models are seen as effective tools to promote and enable data standardisation. They provide a framework of spatial data, metadata, and end-users processes for a specific application. The eventual role of a data model is to allow the management of data through the integration of distributed spatial databases for multiple interacting users. Data models assist data exchange standards with the efficient update, sharing and dissemination of data. Data exchange standards use data models to identify which type of data and where data is located in order to facilitate exchange amongst disparate systems.

2.5.1.1 XML Data Exchange Standards

The data model presented in this thesis is schematically coded in Extensible Markup Language format (XML) which is an open standard of exchange on the internet. Most recent information technology applications use XML to enable the database management of cross-disciplinary and faster Database Management Systems (DBMS) querying in GIS. Without XML, GIS data formats cannot be applied on the internet without the language of XML code. XML supports the access of GIS to web services. GIS spatial data interoperability is based on XML of which there are two types: geography markup language (GML) and scalar vector graphics (SVG). Within the ESRI ArcGIS software used to develop data models, the geodatabase content and representation is developed in XML to allow interchange of geospatial information amongst geodatabases and internet mapping. External systems on the internet can access geodatabases through the XML specification (ESRI, 2014c).

2.5.1.2 Marine, Coastal and Weather Data Exchange Standards

In the GIS community, the data exchange standards which are relevant relate directly to the ArcMarine data model. The Network Common Data Form (netCDF) is the standard data model format for array-oriented scientific data specifically multidimensional time series data. Many hydrodynamic models aim to use this format to exchange data with GIS and mapping systems. However, an understanding of the data structure is necessary to further amend netCDF to handle coastal flooding time series data. NetCDF is still an on-going development. GIS software typically imports netCDF array data as animation files and raster layers. NetCDF is widely used for data exchange in GIS by the US agencies the National Atmospheric and Science Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA). Major GIS software companies such as ESRI Inc. foster the netCDF format for scientific data exchange. It is an internationally accepted format used and recognized by the Open Geospatial Consortium (OGC). The Climate and Forecast Interchange Format (CFnetCDF) is in an experimental standard currently undergoing testing. It intends to encode georeferenced binary data and is currently under development to exchange with hydrodynamic systems.

Within the UK, the flood and coastal erosion risk management metadata schemas are a list of information of data stored between the major bodies such as the Environment Agency. It is accepted in this thesis that the ArcFLOOD framework will improve current knowledge to this standard. The Environment Agency, National Flood and Coastal Defence Database (NFCDD) developed with the help of 1Spatial and its' system integration partner Scisys is aimed at data re-engineering using Oracle database models for coastal defence engineering. In addition, the European Union (EU) Inspire Directive Marine Overlays on Topography (MOTIVE) championed the need to develop and test varying standards and methodologies for interoperability. MOTIVE defined generic high level marine feature types or themes and investigated the cost/benefits of harmonised and un-harmonised datasets. The key findings of MOTIVE reinforced the need for consistent data models in the UK (Millard et al., 2006).

2.5.1.3 Climate-change and Weather Data Exchange Standards

In the UK, NERC has been pivotal in developing research on the use of common standards to coordinate GIS activities; provide flood risk management; and transfer flood risk information to knowledge end-users. The Met Office, Hadley Centre for Climate Prediction, the National Oceanographic Centre and the National Centre for Atmospheric Research (NCAR) are the UK bodies responsible for climate-change research. It is found that within these bodies, data models have not been developed or used to provide that essential link to end-user GIS systems. The Met Office Hadley Centre for Climate Prediction uses detailed 3D representations of major components of the climate system in computer models to predict climate change. Their models are collaboratively used, but lack the common spatial data infrastructure provided by data models, upon which they can be more effective for GIS decision making.

The DataGrid (NDG) is a NERC-funded project aimed at oceanographic and atmospheric data archives. Its' goal is to interconnect data held by individual research groups and in archives to create a seamless environment upon which to compare and manipulate data. The NDG uses a vocabulary-server to provide access to a list of standardised terms in the oceanographic sector. It is a metadata system designed as useful input into marine data models. In addition, NERC's British Oceanographic Data Centre (BODC) operates as a data coordination gatekeeper. However, their main aims are to present metadata and not document data models. The proposed data model can be easily integrated into the knowledge base of the BODC.

The European Union (EU) consortium is building a coastal and maritime platform to facilitate improved delivery of services through greater communication of policy. The current knowledge base for coastal matters is called Coastal Wiki and comprises an online coastal portal of articles and metadata. The program aims to integrate and strengthen research in Europe (http://www.coastweb.info). However, there is no current understanding of coastal flooding data indicating a lack of coastal flooding data models in Europe.

The OGC role in emergency response and disaster management has introduced data standards to allow the rapid sharing, integration and application of geospatial information for first responders (OGC, 2014). The OGC is addressing initiatives in climate and weather through working groups in critical technology areas specifically with interoperability between modelling tools using interfaces, encodings and protocols. Their work is focused on developing standards such as the Open GeoSMS standard which is a new tool for user-generated or volunteered geographic information (VGI) and crowdsourcing. It is believed that end-users play an important role in emergency response and disaster management.

The Climate Science Modelling Language (CSML) is an OGC metadata standard for atmospheric and oceanographic data-exchange, specifying seven data feature types for data exchange. These are generic categories of data themes which provide interchange guidelines. Recent NERC programs such as the eScience grid system acts as a scientific data repository for web access for a wide range of information and can benefit from a coastal flooding data model and geodatabase. These examples of metadata reinforce the data modelling approach and indicate a gap in knowledge for integrating data model mechanisms for policy makers and end-users. It also supports the view proposed in this thesis that communication and data sharing amongst end-users depends on open standards (OGC, 2014).

2.6 Summary

This research has identified the absence of GIS data modelling for coastal flooding within the complex areas of numerical modelling and information technology (IT) advances. Although, open data standards are available, there exists a lack of approaches to facilitate the synthesis of coastal flooding predictions; and its mapping and visualisation in end-user software GIS. Data modelling is vital as few platforms exist to extract the pertinent coastal flooding information from flood numerical modelling simulations. Within the UK there is no documented use of this approach within the organizations which undertake river and coastal flood mapping studies such as the Environment Agency. Even though, OGC standards are widely accepted in corporate databases, few tools exist to enable interdisciplinary data to be shared and disseminated through leading visualisation tools on the internet.

The proposed data model is also critical to scientists and decision-makers who increasingly need to integrate information from multiple, disparate and third party sources. The effort spent in documenting coastal flooding, as seen in this thesis, allows the rapid use of coastal flooding information by data analysts and scientists in future applications. Therefore, the data model is adapted in the present research in an attempt to increase knowledge from its analysis of coastal flooding predictions whereby scientists can improve the quality of flooding predictions in further generations of numerical flood modelling. Without the data model structure, numerical flood modelling is limited as it does not enable the sharing of valuable predictions.

The GIS data model allows generic numerical flood modelling to access and share common marine and coastal data fulfilling a definite gap in the knowledge of coastal flooding. This problem is significant as it restricts the compliance of numerical modelling with international open GIS standards and the most fundamental ability to exchange and disseminate crucial model predictions. It is also seen that coastal flooding data models provide structured knowledge and promote information exchange standards for marine, coastal, and weather applications.

Chapter 3

Numerical Flood Modelling in Sefton

3.1 Description of Study Site

The study site Sefton coast is characterised by the largest sand dune system in England and Wales which traverses approximately 16 km and extends 2109 hectares. At their maximum height, the sand dunes extend 4 km inland at Formby Point; and up to 30 m in height, forming a natural flood defence barrier to protect the surrounding low-lying agricultural land and urban settlements (Pye and Blott, 2008). The sand dune system is significant for environmental and recreational purposes. The coastline is fully exposed to the impact of storms from the eastern Irish Sea.

In this location, storms are known to arise out of a combination of extreme tides, strong westerly winds, waves, and storm surges (Lowe et al., 2001; Lowe and Gregory, 2005; Woodworth et al., 2007). In Figure 3.1 the study sites are shown at the River Alt and Formby Point locations. The Sefton coast extends from Southport in the North towards Liverpool in the south. The study site is characterised by fine sandy beaches, tidal flats and salt marshes (Atkinson and Houston, 1993; Sefton Coast Partnership, 2003).

Figure 3.1: Study site map showing specific sites at (A) Formby Point and (B) the River Alt estuary at Hightown. Aerial photography supplied ©Crown copyright by Sefton Council and the insert overview map supplied ©Crown copyright the COFEE project.

In the past, Hightown has been flooded with loss to property and infrastructure where the River Alt acted as a conduit to propagate coastal flood waters inland. XBeach was used to simulate coastal flooding from which ArcFLOOD analysis will define the extent of potential flood risk. In Figures 3.2 the River Alt estuary is shown at low tide in image (A) and the Hightown coastal defences which comprise loose brick flood defences are shown in image (B) illustrating the study site.

Figure 3.2: Sefton study site coastal defences showing low tide at the River Alt estuary (left image (A)) and the Hightown (right image (B) comprised of loose brick on tidal flats and sandy beaches indicated by white arrows on the photographs (right image).

The sand dune system is known to exhibit high sediment mobility and aeolian sand transport during storms producing dune toe and wave undercutting (Parker, 1971; Pye and Blott, 2008). These effects increase the risk of flooding as the dune face slumps and retreats resulting in collapse. It is known that the dunes north of the River Alt have been eroding since 1900 (c.f Williams et al., 2011; Gresswell, 1937, 1953; Parker, 1971; Pye and Neal, 1994; Pye and Blott, 2008). Recent studies within the COFEE project have indicated erosion rates varying between 3.5m to 5 m/year north of Formby Point from 2001 to 2008 (Esteves et al., 2009). Previous studies validate the dune recession rate of 4 to 5 m/yr (Sefton Coast Partnership Annual Report, 2003). Recent XBeach studies reproduced the characteristics of dune erosion for six storms indicating between 2m to 6 m/yr of erosion at Formby Point (c.f Esteves et al., 2010).

In recent years, a managed realignment policy has been put in place to allow the dune system to behave as naturally as possible with limited flood defences. Sefton coastal policy has left the coast undefended due to an established pattern of sediment transport which stabilises the morphology of the coast, providing natural protection. This pattern is known to be a “divergent sediment cell” which exists at Formby point. Eroded beach and dune sediments are transported northwards and southwards at Crosby and Southport respectively, stabilising the coast (c.f Williams et al., 2011; Pye and Neal, 1994; Pye and Blott, 2008. At Southport setback areas accommodate coastal flooding and reduce the impact on flood defences. At the study site locations, one of the major concerns is the planning of adequate coastal defence. This research informs Sefton policy makers on the extent of coastal flooding in the most vulnerable sites at the River Alt and Formby Point.

Flood defences within the study site at the River Alt comprise seawalls, revetments and pumping stations to assist in protecting the urbanised sections of the coast. The sand dunes along Formby Point have been left in its natural state. Further up the coast at Southport, the flood defences are known to be overtopped during storm conditions. At Formby Point and the River Alt, these conditions were simulated in XBeach to determine the effects of erosion, breaching and overtopping. It is known that the current hard sea defences are built to accommodate sea level rises of 4 millimetres (mm) per year without taking into account increased wave heights and tidal surges, therefore reducing their effectiveness to withstand climate change induced flooding (c.f Williams et al., 2011). This site was chosen within the COFEE project due to its potential for dune blow-outs, breaching and overtopping.

3.2 Meteorology of Storms

Storms which affect the Sefton coast are produced by the complex interaction of meteorology, the tidal modulation of water levels, surge level, wave height, wind speed, bathymetry and topography. Studies indicate that in Sefton the external surge from the Atlantic Ocean combines with a locally generated surge to produce an extreme event (Brown and Wolf, 2009). The eastern Irish Sea surges are due to winds from the west and north-west. As a result of this meteorology, storms have produced significant erosion along the coast but few have been recorded which produce coastal flooding. An extreme event which produced disastrous coastal flooding was recorded in 1720 claiming over 6600 acres of land and destroying 157 homes (Atkinson and Houston, 1993). A lack of contemporary data outlining critical bathymetric and topographic responses of storms is peculiar to this site (Williams et al., 2011).

It has been identified that a significant 1/10 year extreme event can produce damaging coastal flooding and erosion along the Sefton coast when surges coincide with spring high tides (Pye and Blott, 2008). The most damaging storms to have affected Sefton, owing to extreme tidal levels elevated by surge occurred in March 2004 and February 2008 (Williams et al., 2011; Pye & Neal, 1994; Pye & Blott, 2008). The prevailing winds were known to be the most influencing factor for coastal flooding (Williams et al., 2011). Other natural forcing factors such as mean sea level, wind/wave, storm surge frequency and sediment supply produce coastal flooding in this location (Pye & Blott, 2008). In addition, the increased frequency of storms acting upon waves alters the rates of coastal erosion and produces coastal flooding (Lozano et al., 2004; Regnauld et al., 1998; Orford et al., 1995). Formby Point is the area most exposed to the winds along the Sefton Coast. Hightown is sheltered from the north westerly winds. The Met Office predicts that the month of January has the highest average wind speeds with winds in November and December indicating that the winter storms are likely to occur from October to March due to the south westerly winds.

Most of the evidence indicates that increases in storm surge activity will produce coastal flooding. Storm surges are temporary increases in sea level, above the tide, caused by low atmospheric pressure and the force of strong winds on the sea surface (Lowe and Gregory, 2005). The water level is increased by the topography and in some instances creates a funnelling effect, when in combination with high tides are dangerous to low-lying coastal areas (Lowe and Gregory, 2005). The actual calculation of a surge can be determined from several methods which include (Woodworth et al., 2007):

a. Difference between predicted and observed water level at any time in the tidal cycle, referred to as the 'surge residual';
b. Difference between the height of predicted high water;
c. Observed tidal height at the time of predicted high water (i.e. the surge residual at predicted high water.

Other metocean information for the eastern Irish Sea at Liverpool included the semi-diurnal tidal regime; mean tidal range of 6.7 m; and a storm surge pattern exceeding 1m across the Irish Sea and NW European continental shelf (Woodworth et al., 2007).

Recent climatologists have predicted that storm tracks are highly likely to move, increasing the surge height and frequency of floods in this location (Purvis et al., 2008). Most models have agreed an increase in storminess due to storm surge frequency and magnitude during the next century (Lowe et al., 2001; Lowe and Gregory, 2005). One crucial prediction to coastal flooding is the increase in sea level of 4 mm/yr in the next 50-80 years expected to threaten the coastline (Purvis et al., 2008). Other studies have indicated that climate change increases the risk of coastal flooding in the UK due to a combination of sea level rise and increased storminess (Lowe and Gregory, 2005).

3.2.1 Storm Conditions in Numerical Flood Modelling

Within COFEE, the identified storm processes included wind, waves, tides and river discharge which interact to influence coastal flooding on the beach and shoreline; and sediment transport along the coast. Specifically, near-shore wave conditions, sea level rise, geology and the availability of sediment have been identified as crucial factors which require further modelling. The semi-diurnal macrotidal regime and mean tidal range of 10m are known to promote erosive activity when coincident with storm surges (Williams et al., 2011). Evidence has shown a link between the highly energetic waves of storm surges and erosion on the coasts (Pye and Blott, 2008). Therefore, it is important to understand how the storm parameters interact generically within the numerical model for this research.

The models were used to produce the rate and extent of coastal flooding based on the complex interactions as seen in Figure 3.3. This diagrams shows a simplified view of the physical interactions in the hydrodynamic-coastal domain which have been studied to simulate coastal flooding in Sefton. It is seen that the rate and extent of coastal flooding is dependent on the natural processes of winds, waves, tides and rivers. The hydrodynamic model controls included the near-shore wave conditions and sea level heights.

The numerical flood modelling of past storm events is defined by these controlled morphological impact data (beach and shoreline; sediment transport; sediment availability; and geology. The morphological impact data was used to define tidal surge water levels in the numerical flood modelling along with accurate bathymetry and topographic coastal data (Williams et al., 2011; Brown et al., 2010, Brown and Wolf, 2009). The processes of erosion and accretion which are responsible for the soaking of the dune toe; wave undercutting; slumping of the dune face, and dune retreat are modelled, resulting in increased flood risk (Pye and Blott, 2008; Pye and Neal, 1994; Gresswell, 1937; Parker, 1971).

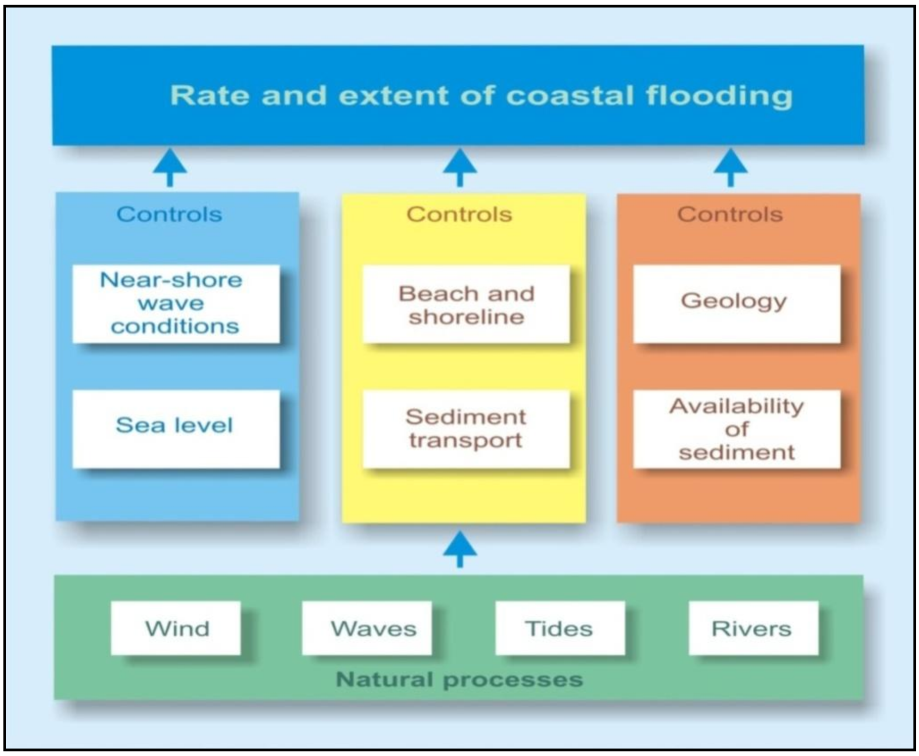


Figure 3.3: The complex physical interactions which produce coastal flooding (Williams et al., 2008). Permission has been granted by the authors.

3.3 Integration of the Liverpool Bay Model and Coastal Flood Model

The numerical flood modelling is defined by integrating the results of the Liverpool Bay model into the coastal flood model as seen in Figure 3.4 methodology of the flow of data. The Liverpool Bay model translates offshore forcing factors (waves, tidal currents and storm surges) into near-shore water elevations and wave conditions (Williams et al., 2008). The coastal flood model uses XBeach model which has been previously known to simulate coastal flooding and examine coastal erosion along this coast (Esteves et al., 2010). It has also been used in a similar study to model gravel barrier profile response to combined waves and tidal forcing in Slapton Sands, UK (Williams et al, 2012).

These specific results arising from this integration were defined in the ArcFLOOD data model to produce improved flood risk information.

The underlying principle in the Liverpool Bay model was that the effect of water levels and waves were considered more important on dune morphology and topography than rising sea level (Brown et al, 2010a; Pye and Blott, 2008). As a result, the integration of tide and surge interaction is critical to coastal flooding. This interaction has not been developed in any of the numerical models discussed in chapter two. Several calibration and validation studies were undertaken to validate the modelling.

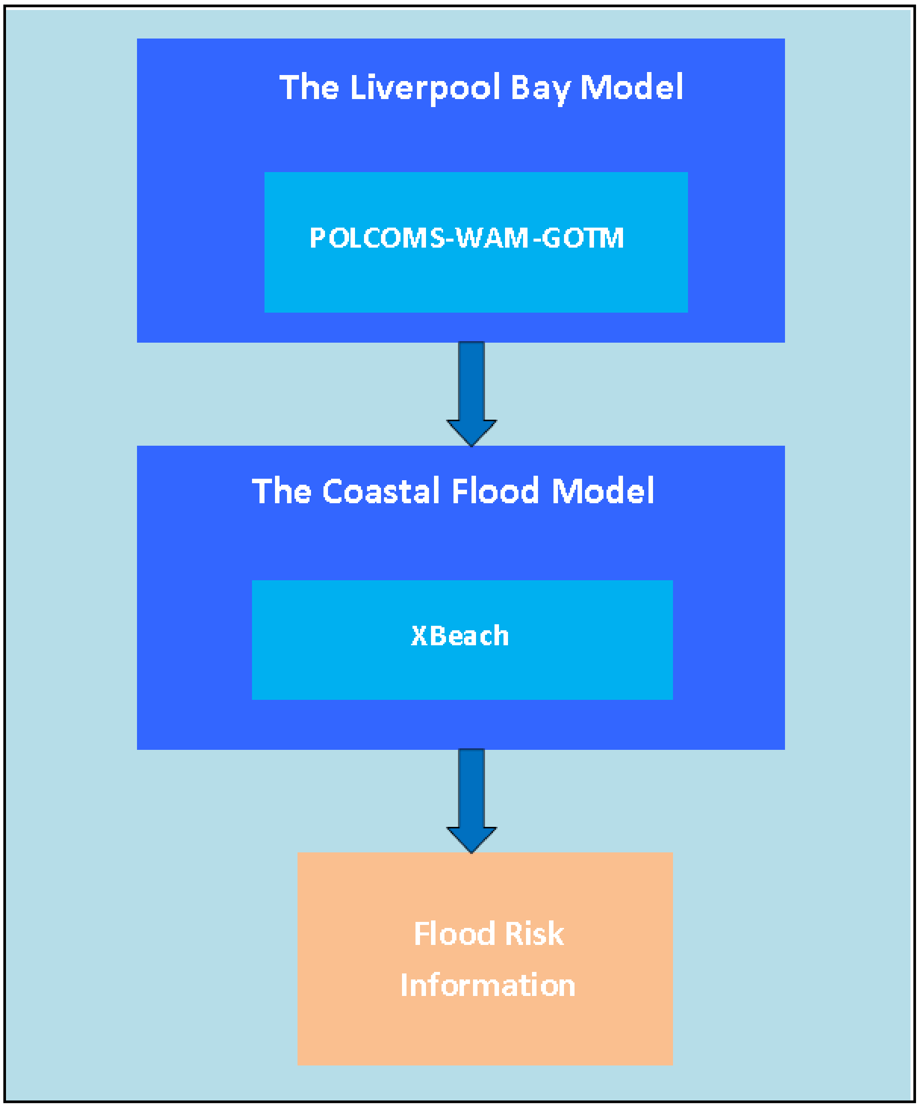


Figure 3.4: Methodology of numerical flood modelling of coastal flooding data using the Liverpool Bay model (POLCOMS-WAM-GOTM) and the coastal flood model (XBeach) to produce flood risk information.

3.3.1 The Liverpool Bay Model

The model was used to characterise storm events in the eastern Irish Sea (Brown et al., 2010a; Brown et al., 2010b). Waves from the northeast Atlantic Sea were simulated. Tide and surge interactions were generated outside the Irish Sea based on meteorological and riverine forcing. The model propagated a "wetting and drying effect" which allowed water to propagate on the coast and recede modifying the bathymetry to reflect the action of storms as seen in Figure 3.5 (Brown and Wolf, 2009). The data covers the area from Southport to Liverpool. The existing coastal defences at Southport, Formby and Crosby are indicated by a range of hard defences and unprotected sand dunes.

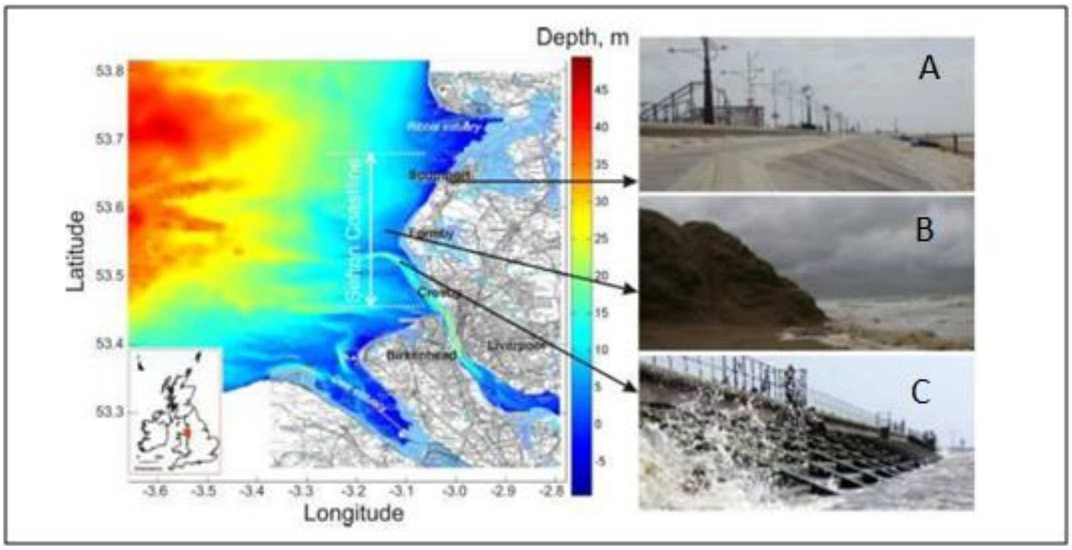


Figure 3.5: The Liverpool Bay Model bathymetry on a Cartesian grid (OS grid) representing depth in metres (M) and showing the range of study sites at Southport (A), Formby (B) and Crosby (C) (Williams et al., 2011). Permission has been granted by the authors.

The validated storm surge events of November 1977 and January 2007 provided consistent water levels across the domain with no under-prediction of significant wave height supporting the accuracy of the Liverpool Bay model (Brown et al., 2010b). The conditions which were simultaneously modelled were the wave's ability to breach sea defences and surface drag caused by wind waves interacting with the sea surface. In this model, the predicted surge for a particular time period and location was defined as the measured water level minus (-) the predicted or modelled tidal elevation.

The results of the modelling included total water level and surge residual results. This has been validated using data obtained from 19 tide gauges and wave measurements from 5 locations in the Irish Sea. Storm surge heights are seen to exceed 2m in

Liverpool Bay (Brown et al., 2010). The bathymetric modelling was revised for the study site with the effects of tide and surge. Only recently had surveyed storm data become available through bathymetric and topography post-storm mapping of the March 31, 2010 storm event (Williams et al., 2011). In addition, an archive of beach and shoreline surveys along with recent beach surveys of January 2008 to March 2010 provided an improved dataset of the shoreline (Esteves et al., 2009; Williams et al., 2011). LIDAR topography on the coast was added to improve missing beach and shoreline data. In comparison with other numerical flood modelling systems, the inclusion of tides, waves and surges significantly improved the modelling of coastal flooding. Permission was granted to use the modelling outputs to develop the data model.

3.3.2 Liverpool Bay Model Extreme Event Hindcast Validation

A further evaluation of the model involved an 11-year (1996-2007) validation (Brown et al. 2010a). The studies provided validated results of offshore conditions derived from hindcast predictions of tide-wave-surge interaction. The hydrodynamic behaviour of a previous storm event on 27th October 2002 was simulated. The model generated the essential wave input conditions; modelled post-storm bathymetry; and shoreline topography for XBeach as indicated in Williams et al. (2011).

In this study it was found that extreme surges reached up to 1.37 m in Liverpool Bay and the largest wave to have occurred in Liverpool Bay reached 5.63 m (Brown et al. (2010a). In addition, tide-surge interaction produced extreme surges up to 2.41 m in Liverpool Bay. The most extreme surge of 2.26 m was recorded during a 27th October 2002 storm event. Higher surge elevations were achieved in this version of the model.

In addition, the studies corroborated that an offshore wave height of 5.05 m is likely to produce coastal flooding when a major wind event occurs close to high water (Williams et al., 2011; Brown et al., 2010a). This indicates that any storm surge occurring within the parameters outlined above will lead to increases in water levels.

The modelling reprocesses bathymetry from the Hydrographic Office with tidal-surge interactions to produce more accurate water levels in the bathymetry to be used as XBeach model input (Williams, 2011). Excluded from the modelling were the processes of surface wind stress, bottom friction and refraction of waves by water levels and currents due to a lack measurement. The results indicated the following important storm surge characteristics (Brown et al., 2010a):

a. The largest high water levels in the past decade occurred at 6.18m above mean tidal level (MTL) at Heysham and 5.64m (above MTL) at Liverpool.
b. The largest surge is most likely to occur during low water levels.
c. Wind is known to produce the highest flood risk at or near high water which consequently increases water levels and overtops sea defences.
d. The threshold limit for sea level rise is 0.7 m.
e. Surge elevation is dependent on wind speed.

Extracted from the modelling are important parameters to define coastal flooding in XBeach modelling (Williams et al., 2011):

a. Maximum water levels (tide plus surge) modelled at Heysham, Liverpool and measured at Formby Point;

b. Measured maximum surge levels at Heysham and Liverpool where the tidal range, at the time of a surge, controls the size of the additional water level on top of the tide which is defined as the value of the surge;
c. Modelled significant wave height and peak period; and
d. Measured peak wind speed.

3.3.3 The Coastal Flood Model Integration

XBeach 1D and 2D models were validated to assess the differences in coastal response to storms; and provide a close match between observed and predicted beach profile data for specific storm events of moderate intensity (Williams et al., 2011). A storm on March 31, 2010 was used to calibrate an actual coastal flooding event. The XBeach modelling was provided in Williams et al. (2010) and Williams et al. (2011) to be used in this thesis to produce the GIS requirements of the COFEE project. The research focused on measuring the dune conditions during the period from January 2008 to March 2010 (Williams et al., 2011). The validation studies included the most contemporary datasets of six storm periods ranging from 2002 to 2008 in the January to March months (Esteves et al., 2010; Williams et al., 2011).

Three test areas were selected to model coastal flooding included: (a) a dune blow out at a location of 1 kilometre (km) north of Formby Point; (b) steep un-vegetated dunes at Formby Point; and (c) a lower region of the vegetated dunes approximately 2 km south of Formby Point. The site chosen as the dune frontage is vulnerable to overtopping and breaching; dissected by a footpath to the beach which provides a possible flood conduit; and the lower section of the dunes protects residential properties. The test areas are provided in the following sections.

3.3.3.1 XBeach 1D modelling at Formby Point: Site A

The XBeach 1D model was used to predict a 1:100 year storm event. Such a storm occurred on the 31 March 2010. The model compared the actual coastal impacts of erosion of an extreme event with the predicted XBeach results providing specific hydrodynamic conditions to the model event (Williams et al., 2011). The model provided good agreement between the measured and predicted beach profile response to the storm event indicating the XBeach 1D model ability to predict the erosion impacts of extreme storms (Williams et al, 2011).

In the simulation of the beach profiles responses to the March 31 2010 storm, oblique waves were modelled to hit the coastline. The model used measured wave and tidal conditions during the peak of the storm activity when the measured mean water level exceeded 4 m ODN (Ordnance Survey Datum). In Figure 3.6, the Digital Elevation Model (DTM) of Formby Point is shown in the XBeach modelling domain comprising topographic LIDAR survey data (2008) and bathymetry (2000-2008). In Figure 3.6, the profile lines P11, P12, P14, P15, P16 and P117 are shown of which P14, P15, P17 and P18 symbolised in red were selected for 1D XBeach storm impact modelling due to the better quality of data at these sites. The profile lines traversed along the crest of the dune ridge to the spring low water mark line. The results were exported as an image from XBeach as it has no capability to export geospatial data. The results of the DTM points are exported in a complex binary file which required further reprogramming to be exported in a GIS format.

From the results, it was determined that the majority of erosion along this coast arose out of wave undercutting of the dune and slumping at a rate of 3-5 m during this storm event which is a good representation of the actual physical conditions (Williams et al., 2011). The results also indicated that Formby Point is satisfactorily resistant to extreme storm conditions. The only discrepancy in the study was a three week delay in monitoring after the actual post-storm event. XBeach storm impacts were run for six other events to determine sediment loss along the coast (Esteves et al., 2009). The results of the study measured 2m to 6 m dune erosion post-storm at various site locations (Williams et al., 2011). The availability of erosion and sediment in XBeach provides a more accurate view for coastal morphology.

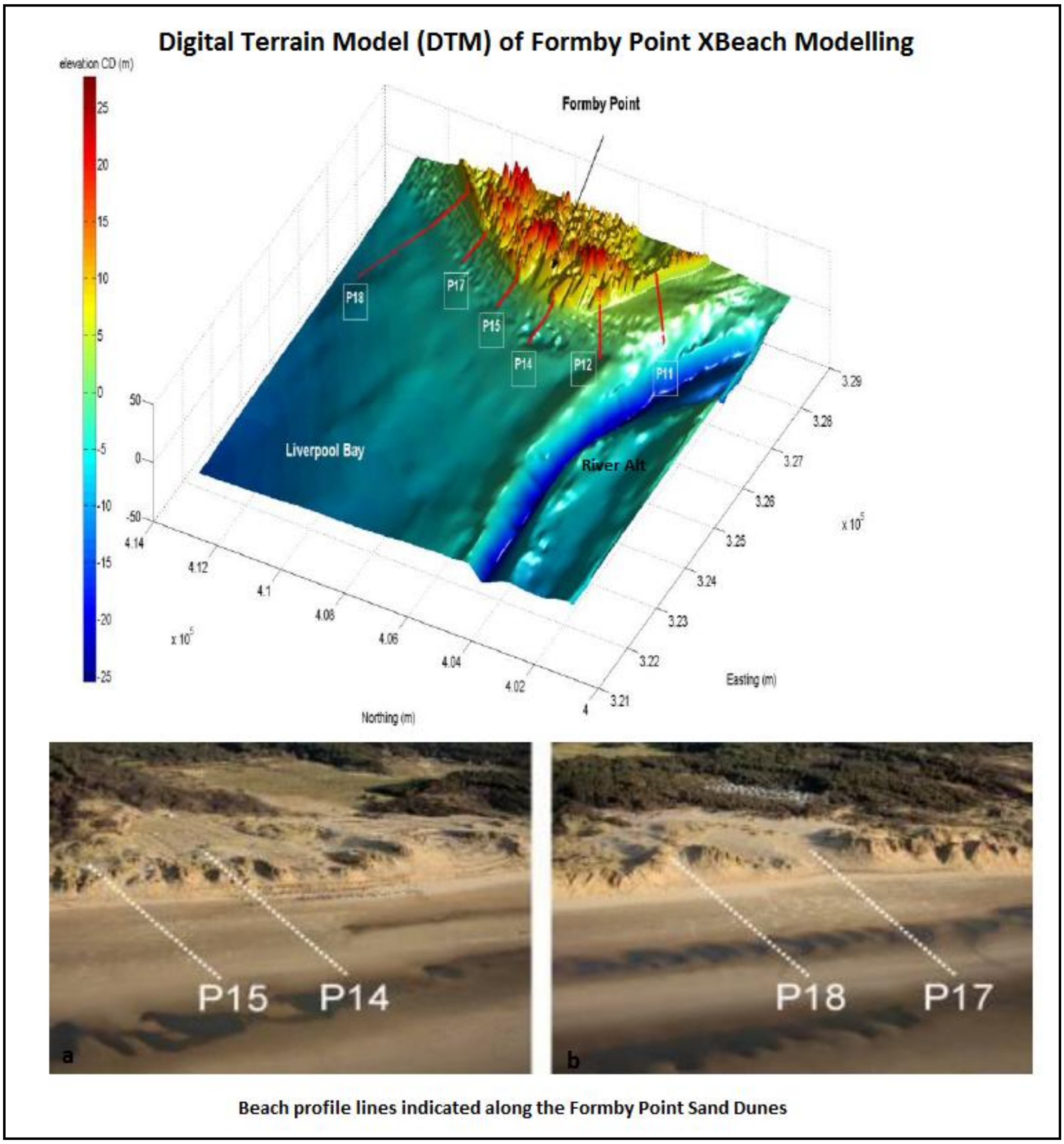


Figure 3.6: DTM of the Formby Point XBeach modelling domain comprising combined LIDAR survey data (2008), University of Plymouth beach survey data (2008) and POLCOMS-WAM-GOTM. The red lines show the Sefton Council beach profile lines P11, P12, P14, P17 and P18 selected for 1D XBeach storm impact modelling. DTM is symbolised according to elevation in metres (m). The photographs (a) and (b) show the location of the profile lines selected along the Formby Point sand dunes (Williams et al., 2011). Permission to reproduce this image has been granted by the authors.

The important parameters within the model which allowed storm simulation included: maximum water levels (tide plus surge); measured surge levels; modelled significant wave height Hs and peak period Tp; and modelled peak wind speed. A total loss of 10 m in dune frontage was measured (Williams et al., 2011). The 1D XBeach modelling used the hydrodynamic parameters seen in Figure 3.7. These show the characteristics of events causing significant erosion or flooding impact for six storm events whose dates are seen in Figure 3.7. The study concluded that 1D XBeach was sufficient to predict storm impacts (Williams et al., 2011).

A. Characteristics of storms causing significant erosion or flooding impact at Formby Point

Date	Max water level[a] (m CD)			Max surge level (m)		H_{m0}[b] (m)	Tp[b] (m)	Peak Wind speed (m/s), Liverpool Bay	Observed Coastal Impact
	Heysham	Liverpool	Formby Point[b]	Heysham	Liverpool				
1	11.35	10.68	10.7	1.28	1.13	3.0	9.2	22.0[b]	Up to 13 m of dune retreat along the entire dune frontage
2	10.85	10.40	10.0	2.08	1.75	5.4	8.9	26.9[b]	Up to 9 m of dune retreat observed along most of the dune frontage
3	10.27	10.27	9.7	0.99	1.08	1.0	8.6	18.9[b]	Up to 9 m of dune retreat observed along most of the dune frontage
4	10.70	10.55	9.9	0.36	1.01	3.3	9.1	17.7[b]	Up to 9 m of dune retreat observed along the entire dune frontage
5	9.93	9.72	9.4	0.51	0.56	1.0	9.5	15.5[b]	Up to 10 m of dune retreat observed along most of the dune frontage. Reduced erosion to the south and at Formby Point.
6	10.81	10.56	10.3	1.66	1.93	2.9	7.9	26.9[b]	Up to 14 m of dune retreat observed along the entire dune frontage.

[a] Tide plus surge; [b] Model results (see Appendix 2)

B. Measures of XBeach model performance for the events above

Date	Brier Skill score				Observed dune retreat	Predicted dune retreat
	P14	P15	P17	P18		
22 Jan to 8 Feb 2002	-	-	-	-	Up to 13m±2m	15m
21 Dec 2004 to 24 Jan 2005	0.46	-	0.52	-	Up to 9m±2m	10m
18 Aug to 22 Sept 2005	0.47	0.51	0.63	-	Up to 9m±2m	14m
22 Sept to12 Oct 2006	-	0.61	0.44	0.34	Up to 9m±2m	6m
10 July to 06 Aug 2007	0.55	0.64	0.48	0.59	Up to 10m±2m	12m
03 Mar to19 Mar 2008	-	-	-	0.43	Up to 14m±2m	18m

Figure 3.7: Characteristics of events causing significant erosion or flooding impact from six storm events in table A: (a) 22 January to 8 February 2002; (b) 21 December 2004 to 24 January 2005; (c) 18 August to 22 September 2005; (d) 22 September to 12 October 2006; (e) 10 July to 06 August 2007; and (f) 03 March to 19 March 2008. Table B shows the measures of XBeach model performance between the observed and predicted dune retreat (Williams et al., 2011). Permission to reproduce this image has been granted by the authors.

3.3.3.2 XBeach 2D modelling at Formby Point: Site B

2D modelling was also undertaken with 1.5 m grid resolution in the hydrodynamic domain to investigate coastal flooding. It was found that coastal flooding along Formby Point represented a localised risk to the recreational caravan park behind the sand dunes (Williams et al., 2011). The simulation indicated a weak point behind the dunes along the steepest part of the dune, which created a blow-out, to provide a possible onshore route for coastal waters inundating prime agricultural land and high valued residential property. At the River Alt study site where the dunes are its lowest elevation, the site was found to be the most vulnerable to extreme events with serious risk to property, infrastructure and human livelihoods at Hightown. The 2D XBeach modelling used the same forcing conditions as the 1D XBeach simulation for March 31, 2010 and parameter settings. The XBeach 2D modelling predictions of coastal flooding are seen Figure 3.8. Coastal flooding was simulated at profile line P17 (Figure 3.7). The numbers at the top of each simulation shows elapsed time from the start of the model run in: 406, 811, 1217 and 1611 seconds (s) respectively (Williams et al., 2011). The coastal flood is seen to breach the dunes, settle and recede.

It is indicated in this simulation that the predicted erosion and accretion amounts varied ± 1.5 m alongshore. Eroded sediment was dumped c. 50 m to 100 m offshore from the dunes in line with the accepted pattern of sediment transport in the area (Pye and Neil, 1994; Pye and Blott, 2008).

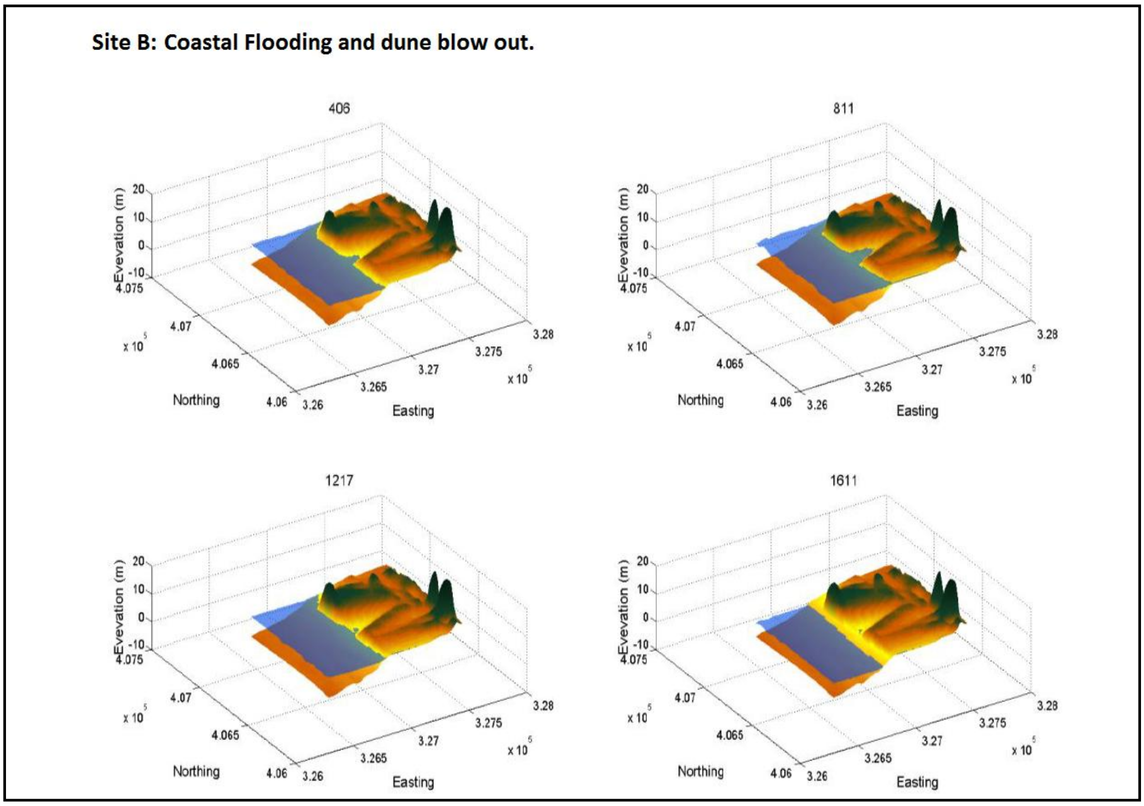


Figure 3.8: Extreme event simulation using 2D XBeach at profile line P17 (Figure 3.7) which shows coastal flooding. The numbers at the top of each simulation shows elapsed time from the start of the model run in: 406, 811, 1217 and 1611 seconds (s) respectively (Williams et al., 2011). Permission to reproduce this image has been granted by the authors.

The erosion occurred at the foot of the dunes on either side of the blow out location. Accretion occurred in front of the dunes. The study found that the inundation was not sufficient to flood the caravan park at the back of the dunes as the flood waters did not spread inland due to the limited time the dune was exposed to water and wave action (Williams et al., 2011). The study concluded that the coast at Formby Point is resilient to the extreme event with limited accretion and erosion varying between c. 2m to 10 m (Williams et al., 2011; Esteves et al., 2010).

3.3.3.3 XBeach 2D modelling at Formby Point: Site C

A 2D extreme event simulation was undertaken to show the inundation behind the dunes (Figure 3.9). The numbers shown at the top of each simulation diagram shows elapsed time from the start of the model run in: 406, 811, 1217 and 1611 seconds (s) respectively (Williams et al., 2011). The results indicated that the dune is sufficient in height and width to resist an extreme event with the parameters mentioned in Figure 3.7. Williams et al. (2011) indicated dune recession in the magnitude of 4 m potentially increasing the vulnerability to future flooding events.

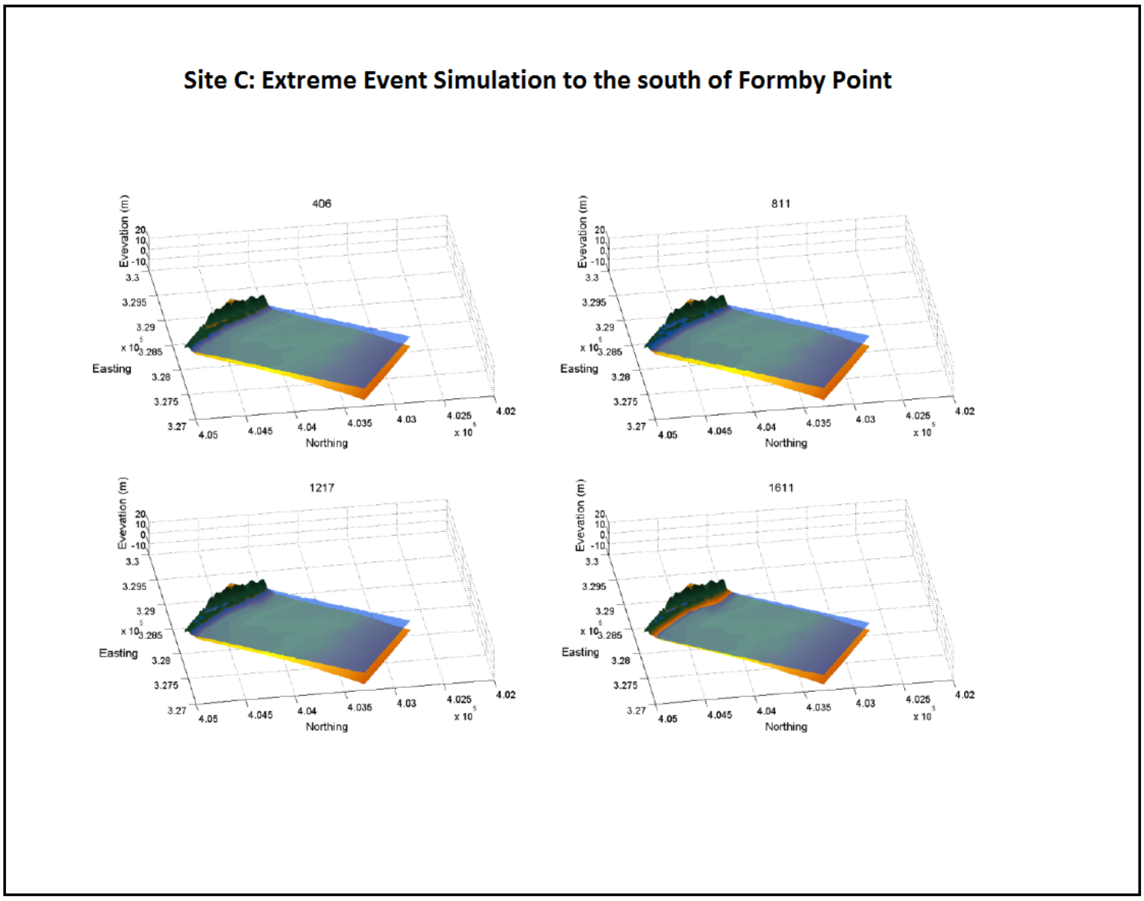


Figure 3.9: 2D Extreme Event simulation to the south of Formby Point showing the inundation of the areas behind the dunes. The numbers shown at the top of each simulation diagram shows elapsed time from the start of the model run in: 406, 811, 1217 and 1611 seconds (s) respectively (Williams et al., 2011). Permission to reproduce this image has been granted by the authors.

3.3.4 XBeach - Coastal Flooding Modelling at the River Alt, Hightown

The coastal flood model is seen to propagate a flood onshore due to long wave propagation onto a plane sloping beach without friction in the 2D wide area modelling of the River Alt (Williams et al., 2011). The modelling provided validated observations of the morphological impact of observed storm events. The outputs of the Liverpool Bay Model were used as inputs in this case. The XBeach input included the most accurate bathymetry of the eastern Irish Sea with water level values which arise out of the combination of mean sea level, tides, surges and wave set-up in this location (Wolf and Brown, 2009; Williams, 2011). Wave set-up is defined as the process of increasing the total water level.

Coastal flooding at the River Alt, Hightown was simulated with the following conditions:

a. An imposed surge of 1.5 m;
b. Spring high tide;
c. Significant wave height H_s = 1.75 m and wave period T_p = 8 seconds (s);
d. An angle of wave incident on coast at an angle (ø) = 270 degrees;
e. Fluvial discharge of the River Alt at > 14 cumecs after a heavy pluvial event or rainfall;
f. The propagation up the river channel from offshore low frequency waves to increase flood water levels.

Within the 2D modelling, a re-calibrated constant gradient was imposed on the river channel from the farthest point inland to the coastal limits, including river discharge from the land and from the seaward side (Williams et al., 2011). A mean flow velocity of 0.75 m/s was set. The resultant DTM of the study site was visualised in XBeach as seen in Figure 3.10.

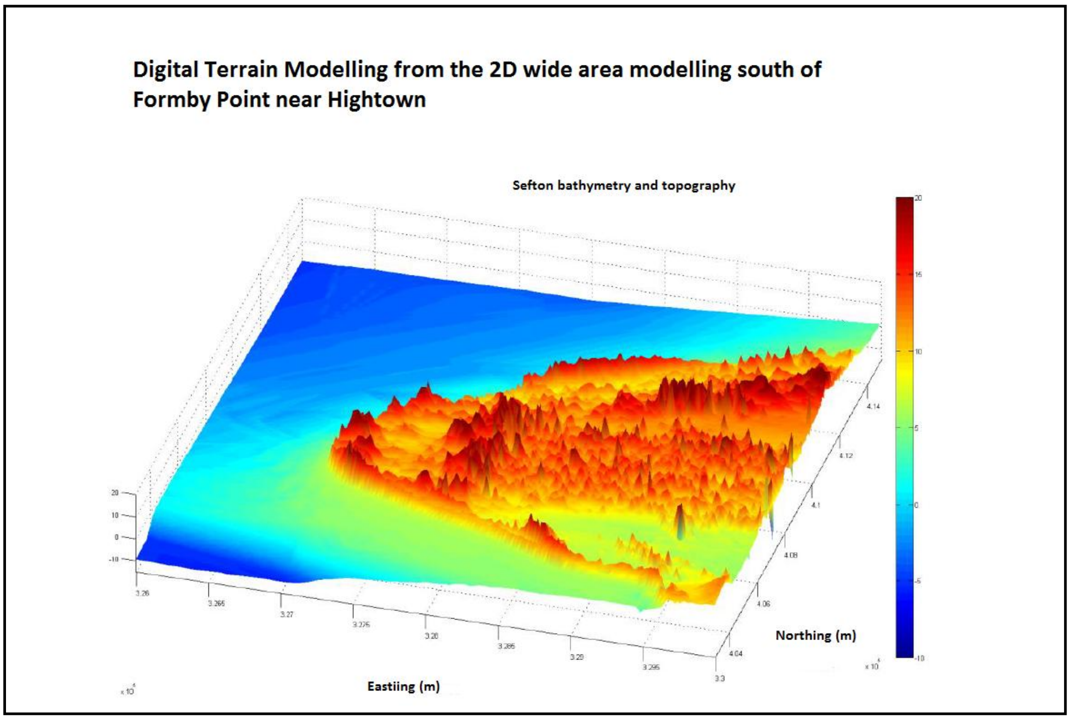


Figure 3.10: The XBeach model of pre-storm bathymetry and topography in the 2D wide-area simulation of the Sefton coastline for the March 13, 2010 extreme event storm 4 km south of Formby Point near Hightown (Williams et al., 2011). Permission to reproduce this image has been granted by the authors.

The modelled XBeach DTM data was resampled by this thesis research in ESRI ArcGIS with a 3m grid resolution to achieve performance in model runs. A bare earth model was created to remove built structures. The river channel and flood embankments were recreated in the dataset with elevations of 2.5 m to describe current river bank topography to assist the work of Williams et al. (2011) and show the importance of GIS to flood modellers. Williams et al. (2011) achieved constant water levels from river discharge one hour before simulating the tide, surge and wave parameters offshore. Within XBeach tidal levels were increased to the maximum spring tide parameter to increase water levels in the River Alt, overtopping flood embankments and flooding residential property in Hightown (Figure 3.11). The numbers above each flood sequence indicated the time elapsed from the start of the model run in hours (Williams et al., 2011).

The study indicated that when a critical level was achieved the river defences (2.5 m embankments) were overtopped. The coastal flood was seen to inundate the River Alt and the area behind the sand dunes and property in Hightown. Flood water depths reached 3m in some locations. Within the XBeach model there was no drainage facility, however, it is seen that the pumping stations up river will reduce the water levels in the event of coastal flooding. The GIS analyses will reproduce these results to verify the accuracy of the data model querying.

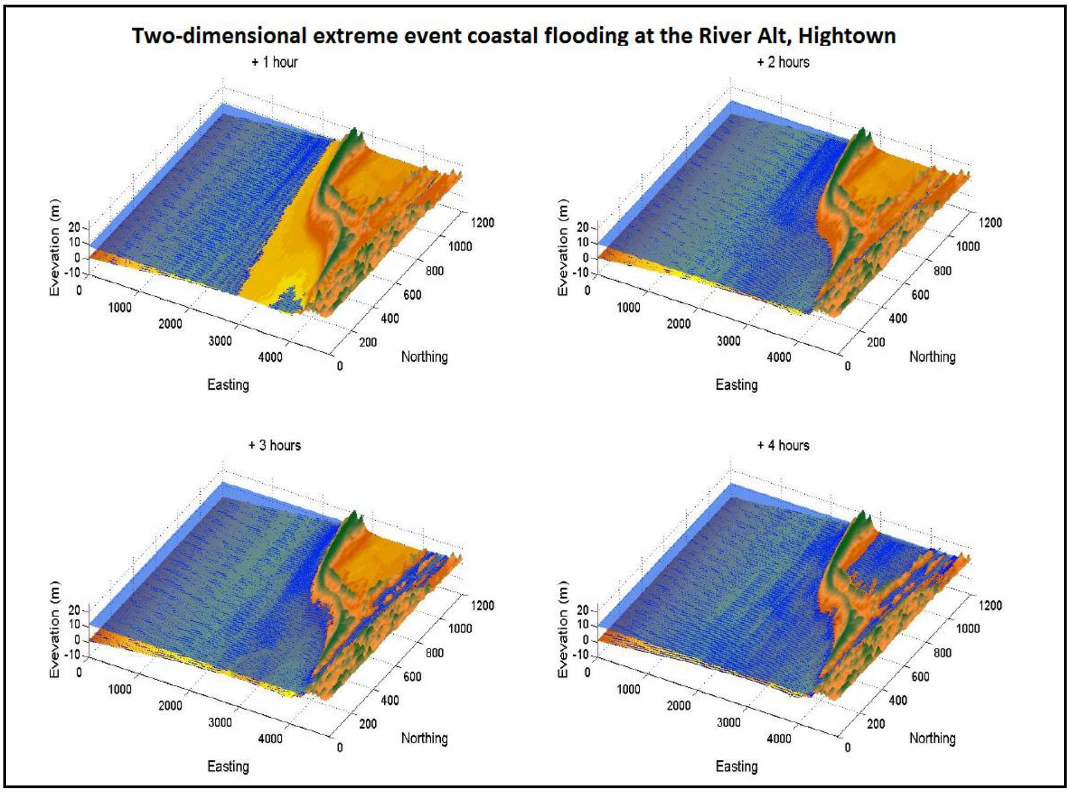


Figure 3.11: 2D Extreme event simulation of a coastal flood on the River Alt, Hightown showing stages of coastal flood due to high tidal levels and flood fluvial discharge. The numbers above each flood sequence indicates the elapsed time from the start of the

model run in hours (Williams et al., 2011). Permission to reproduce this image has been granted by the authors.

3.4 Summary

The integration of tide and surge interaction in the Coastal Flood Model (XBeach) represents a significant advance in numerical modelling (Williams et al., 2011). An improved definition of flood risk is provided according to the morphological response of the coast through erosion, accretion, sediment availability and sediment transport. From the modelling, the critical parameters necessary to produce more accurate bathymetry in XBeach included (Williams et al., 2011):

a. Maximum water levels (tide plus surge) modelled at Heysham, Liverpool and measured at Formby Point;
b. Measured maximum surge levels at Heysham and Liverpool;
c. Modelled significant wave height and peak period; and
d. Measured peak wind speed.

In addition, the definition of a storm surge was defined as the value for the surge residual which is the additional water level on top of the predicted tide due to a storm event to increase water levels and exacerbate coastal flooding. Specifically, the specific parameters which reproduced a coastal flood included:

a. An imposed surge of 1.5 m;
b. Spring high tide;
c. Significant wave height H_s = 1.75 m and wave period T_p = 8 seconds (s);
d. An angle of wave incident on coast at an angle (ø) = 270 degrees;

e. Fluvial discharge of the River Alt at > 14 cumecs after a heavy pluvial event or rainfall; and

f. The propagation up the river channel from offshore low frequency waves to increase flood water levels.

The results from the modelling are used to define flood risk based upon the following:

a. The processing and analysis of the time-series data arising out of XBeach to generate flood risk mapping DTM's.

b. The identification of the vulnerable sites which will be mapped and visualised in GIS.

c. The validation of the maximum flood water depth of 3 m through spatial analyses.

Chapter 4

Building the ArcFLOOD Data Model

4.1 Methodology

The building of the ArcFLOOD data model comprises the following stages identified in the methodology diagram (Figure 4.1):

a. Requirements gathering
b. Data collection and processing
c. Building the geodatabase
d. Process modelling.
e. Building the ArcFLOOD data model

GIS requirements were gathered to tailor the data modelling to the end-user needs (Figure 4.1 Stage 1). A wide range of topographic mapping, bathymetry and coastal data were collected in unprocessed formats requiring extensive processing into coastal flooding geodatabases (Figure 4.1 Stage 2). The Liverpool Bay model data was processed (Figure 4.1 Stage 3) as inputs into the coastal flood model (Figure 4.1 Stage 4). The datasets for both these models were pre-processed in GIS and provided to flood modellers.

The software tools and framework necessary to build the geodatabase and design the data modelling were identified (Figure 4.1 Stage 5). In this approach, the ArcFLOOD data model was built by extending the ESRI ArcMarine Data Model (MDM) (Wright et al., 2007). The schematisation structure of the MDM was initially used to develop ArcFLOOD. However, since the MDM was designed for the marine applications, only certain aspects of the MDM were retained. New data modelling was added based upon the results of the numerical flood model and selected end-user requirements as described previously. The end-user requirements were decomposed into specific queries from which the data products and tools necessary to create these queries were identified.

Tools were identified as process models in ArcGIS. A methodology to create new process tools in ArcGIS to semi-automate the processing of flooding data was identified (Figure 4.1 Stage 6). These process models used the data stored in the coastal flooding geodatabases defined by the data properties (field name, data type, and format) of the ArcFLOOD data model to generate in a semi-automatic batch programs in ESRI ArcGIS software, a range of new datasets derived from analysis. Data was generated for each process model. This particular integration of data allowed the data defined within the data model to be documented according to end-user analyses requirements. Upon the generation of these enhanced datasets using process models, the ArcFLOOD data model was further refined in an iterative process to document data properties.

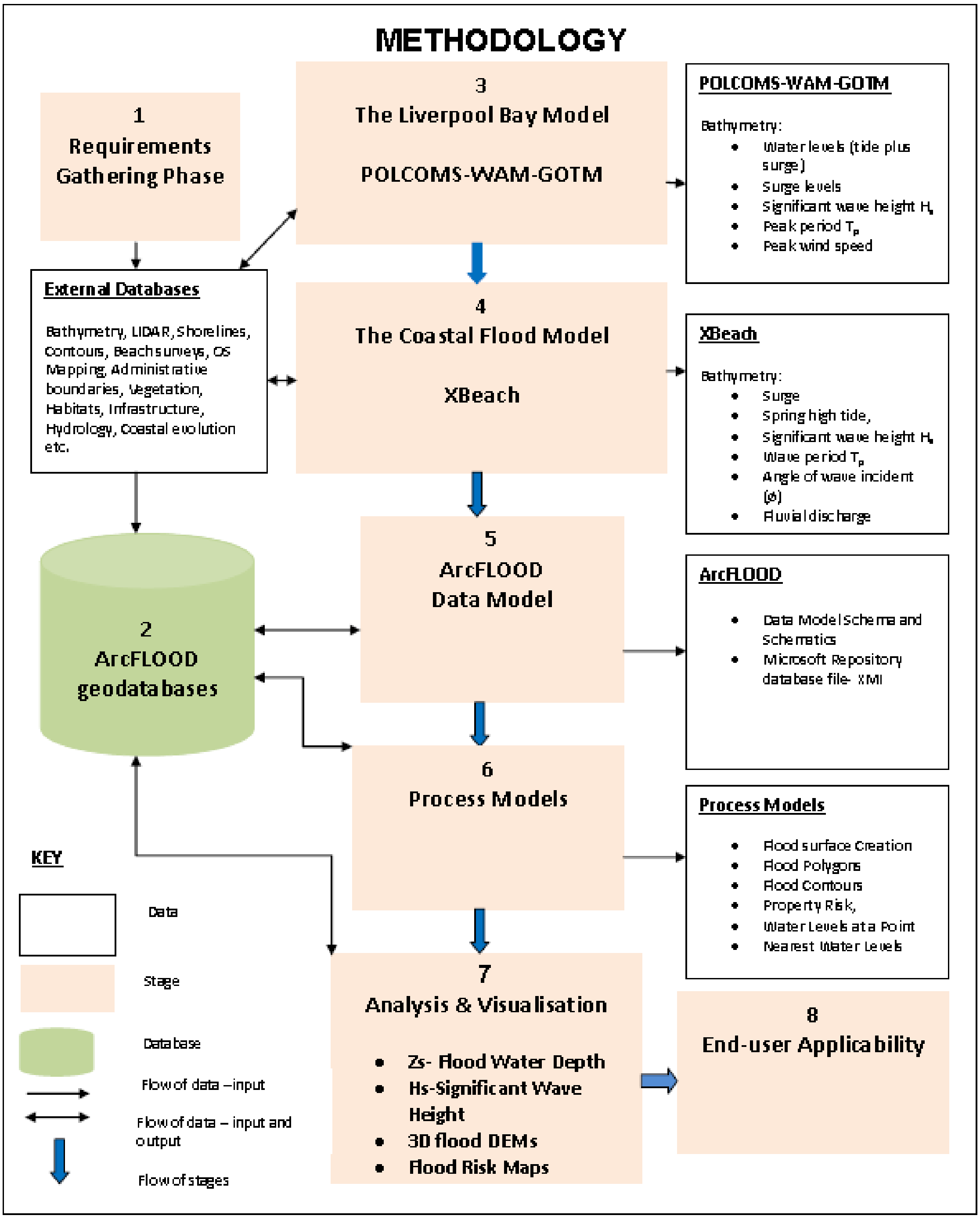


Figure 4.1: Research methodology to build the ArcFLOOD data model and conduct flood risk assessments from the requirements gathering phase; ArcFLOOD geodatabase building; the integration of POLCOMS-WAM_GOTM and XBeach; building the ArcFLOOD data model in ArcGIS; and using process modelling tools in ArcGIS.

4.2 Requirements Gathering

End-users are categorised two specific types, technical and non-technical (Williams et al., 2008). The technical end-users included Sefton Council engineers who may possess knowledge of GIS to manage the flood defences at the coast. The British Oceanographic Data Centre managers with an interest in GIS data modelling and open data standards were also defined as technical end-users. The National Oceanographic Centre scientists who would use the data model to integrate flood modelling into GIS for visualisation; and to improve the flood modelling export of data to GIS were included in this category. A range of non-technical users were defined as decision-makers who need to use the results generated but have little interest in the hydrodynamic flood modelling undertaken such as Sefton Council flood planners.

The requirements which were gathered were extracted and communicated directly from Sefton Council by interviewing members of the flood defence teams and the end-users. During the initial stages of the research, seminars and individual meetings were utilised to interview end-users. Specific seminars were held to inform the end-user group about the proposed research and approval was sought for the research on data modelling. More specifically, within these meetings, the end-user GIS data needs were identified and translated as requirements Table 4.1. It was found that some requirements were not feasibly reproduced in a GIS and therefore, served as requirements for the numerical flood modelling, assisting the overall COFEE project broad aims. In Table 4.2, the scientific requirements were identified from technical end-users. It was determined that these requirements were beyond the scope of a GIS and should be included in the flood modelling.

Table 4.1: Requirements and identification for the GIS and data model

Identified Requirements	**Identified End-User**
Geodatabase access	British Oceanographic Data Centre, National Oceanographic Centre, Sefton Council, University of Plymouth
Data model to aid OGC exchange data standards such as netCDF.	British Oceanographic Data Centre
Flood Risk Mapping	British Oceanographic Data Centre, National Oceanographic Centre, Sefton Council, University of Plymouth
Spatial Query: At what time is a feature point flooded?	National Oceanographic Centre, Sefton Council, University of Plymouth
Spatial Query: Which defences would be overtopped?	National Oceanographic Centre, Sefton Council, University of Plymouth
Spatial Query: What is the water depth at a particular location?	National Oceanographic Centre
Decision Making: For what depths should the flood defences be modified?	National Oceanographic Centre, Sefton Council

Table 4.2: Scientific requirements identification for numerical flood modelling

Science Requirements	**End-Users**
Based on joint probability, what are the minimum conditions of a storm to cause flooding?	University of Plymouth
Which type of storm causes breaching and dune erosion?	University of Plymouth
Given the characteristics of a storm, what is the flood level at this specific point?	University of Plymouth, National Oceanographic Centre
Is it the waves or the water level which causes overtopping?	National Oceanographic Centre
Given values for surge, high water level and wave height, can the GIS predict the flood?	National Oceanographic Centre

During discussions with the end-users relevant requirements were identified which fulfilled the broad aims of this research:

a. To harmonise data in a geodatabase as a useful resource for coastal management in Sefton.
b. To use the GIS to assess the usefulness of the flood risk information provided in terms of defining future coastal defence needs and policy.
c. To provide structures to bridge the gap between the scientific information derived from flood modelling and the provision of targeted GIS predictions to enhance decision making.

d. The analyses provided from this thesis should aid the investigation of what areas will be affected by future extreme floods and its´ impact on settlements.
e. Some knowledge was to be gained from the flood water depth and rate of extent of the flood following an extreme event such as a storm surge.
f. To develop a data framework to promote open standards for coastal flooding which facilitated sharing of coastal flooding data and predictions within the broader national data sharing framework as identified by the British Oceanographic Data Centre.
g. To use GIS to perform spatial analyses, this is non-existent in end-user groups, at Sefton Council. It was identified that current coastal flooding mapping is centred on using MapInfo GIS software to print coastal related data of flood defences and dune surveys to assist their role in the shoreline management process.

The requirements gathering process was successful in convincing end-users that GIS data modelling was important to process and analyse the large volumes of data being collected by end-users at Sefton Council. The primary requirement of non-technical end-users was the development of GIS tools and/or mapping by which flood risk assessments based on the numerical modelling could be provided in a tailored end-user environment i.e. GIS.

4.3 Data Collection and Processing

4.3.1 GIS Software

The chosen GIS platform to undertake data collection, processing, data modelling and analysis was the ESRI ArcGIS desktop software. The ESRI ArcGIS software was the system of choice due to its unique geodatabase development environment and advanced data modelling capabilities present in no other GIS software package.

4.3.2 Data Collection

Based upon the identification of end-user requirements, relevant data was collected from the end-users at Sefton Council in electronic formats, to develop the geodatabase in ESRI ArcGIS. The process of creating a geodatabase was rudimentary as no GIS databases existed, only archives of files stored on computer hard drives primarily in *.txt formats and MapInfo MIF files. The initial process involved investigating the data stored at the Sefton Council; identifying the related shoreline, beach, dune and environmental datasets which may be relevant to future GIS analysis. Discussions with the coastal managers provided beach and dune survey data from their most recent annual monitoring programme. A communications channel was established with the British Oceanographic Data Centre to provide hydrodynamic bathymetry for the Liverpool Bay Model. A relationship was established with Sefton Council to provide aerial imagery of the coast; and the Environment Agency to provide updated LIDAR surveys of the entire Sefton Coast during the lifecycle of the COFEE project.

The datasets which were collected to build flood risk mapping for the Liverpool Bay model and coastal flood model were:

a. Topographic Light Detection and Ranging Data (LIDAR) survey data (2008) from the Environment Agency.
b. Pre-storm and post-storm beach survey data from recent Differential Global Positioning Systems (DGPS) surveys.
c. National Oceanographic Centre bathymetric surveys of Liverpool Bay (2000-2008).
d. Annual beach survey profile lines of the Sefton Council annual monitoring scheme.
e. Ordnance Survey mapping which included 1:250,000 & 1:50,000 raster imagery and OS MasterMap data.

The broad range of data collected and ordered into GIS thematic layers for the data modelling is seen in Table 4.3 GIS thematic layers for ArcFLOOD. The term thematic is used in GIS to order data according to its use.

Table 4.3: GIS Thematic Layers for ArcFLOOD

GIS Data	Thematic Layers
Aerial Imagery	1945, 1961, 1979, 250k, 50k, 1993, 1997 & 1999.
Eastern Irish Sea	NOC Bathymetry
LIDAR	Sefton Coast - June 2007 & 2009.
DEMS	Sefton Coast - June 2007.
Digital Shoreline Analysis	Dune Toe Surveys (2002-2008) & Beach Topographic Surveys 1999-2008.

Beach Surveys	Topographic Surveys 1999-2008, Profile Lines 1999-2008.
Coastal Evolution	Coastline locations, Dune Erosion, Dune Accretion, & Historic Dunes.
Coastal GIS	Coastal defences, Cross-sections, Contours, Sandbanks & Beach barriers.
Infrastructure	Parks, Railways, ROW's, Streets, Roads, Bus paths, Cycle Paths, slip roads etc.
OS Mastermap	Roads, Buildings, Built-up environment & Water.
Sefton GIS	OS Administrative Boundaries.
Vegetation Habitats Surveys	Dunes, Estuaries, Green Beach & Salt Marshes.
XBeach	Flood Model input created from LIDAR.

4.3.3 Data Processing

GIS Mapping was essential to generate Digital Elevation Models (DEM) of the coast and surrounding hinterlands upon which spatial querying in GIS were conducted. The DEMs produced in this research were used in the GIS analysis undertaken by Esteves et al. (2009) and Williams et al. (2011). The process of merging the LIDAR and topographic datasets were cumbersome and comprised the processing of over six million topographic 3D points (*x*-Easting, *y*-Northing and *z*-depth) for the study site as input into XBeach. Standard geoprocessing tools in ArcToolbox were used to merge the datasets.

The XBeach input data for the study site at Formby Point and River Alt estuary was constructed in ArcGIS by merging the following datasets together to create a complete representation of depth and elevation from the coast to the floodplain:

a. Environment Agency topographic LIDAR survey;
b. University of Plymouth beach topographic surveys (2008);
c. National Oceanographic Centre Liverpool Bay bathymetry; and,
d. Sefton Council annual beach profile surveys.

4.3.3.1 Linear Interpolation Methods for DEM creation

LIDAR topographic data was used to create topographic 3D Digital Elevation Models (DEM) in the analysis. LIDAR was supplied by the Environment Agency with a sufficient precision and measurement density of 0.25 metres (m). The beach and coastal post-storm data supplied from the University of Plymouth were measured with DGPS techniques at 0.15 m precision in collection. The DEM were created using linear interpolation of raster imagery techniques commonly used in flood mapping (Brown, 2005; Bates at al., 2005). The eastern Irish Sea bathymetry from the Liverpool Bay model was improved by creating a variable grid with offshore and nearshore accuracies of 3m and 0.15 m resolutions respectively. The amalgamation of LIDAR, bathymetry and survey data provided confidence in the data used to map coastal flooding.

In order to build coastal flooding DEM, standard GIS processing tools in ESRI were used to manage the XBeach model output. Within the DEM produced, the location of each cell or pixel was defined by its row and column numbers. A value of Z_s was assigned to the cell or pixel with a value based on the LIDAR topographic elevation. Within ArcGIS the decision to use the linear interpolation method in ArcGIS spatial analyst tools to create the DEM of sufficient resolution of detail was the method of choice. The techniques which were utilised to generate DEM were the Inverse Distance Weighted (IDW) and the Nearest Neighbour (NN) methods. The use of both IDW and NN provided flexibility in developing DEM for specific mapping analysis. It was found in this thesis that for topographic areas with higher density of population, the IDW provided more detail on the land, whereas the NN was better suited to natural land forms such as the sand dunes and River Alt mapping. As the study site area was small, IDW was chosen to generate DEM. The linear interpolation technique was selected for its capability to define varying levels of accuracy in raster structures.

In ArcGIS, the IDW produced an appropriate 3D surface (DEM) based on the Voronoi (Thiessen) polygon which calculated the proportion of overlap between this new surface and the initial points based on the Delaunay triangulation method to create a DEM. IDW computed the average distance which cannot be greater than the highest or lowest value in the points selected. An output cell size of 0.5 m was indicated which represented the actual ground distance cell for which flood water depths testing is practical. IDW assumed that the local influence of points diminish with distance giving a greater weighting to the points closer to the prediction location than those farther away. The method performed cross-validation and produced RMSE values for the predicted location. It was used to provide regular and irregular grids for analysis. In addition IDW was suitable for dense networks as the study site comprised over 6 million survey points from which to generate a DEM.

The IDW technique was chosen in preference to developing a Triangulated Irregular Network (TIN) which was used to create ridges and valleys in higher elevation data. The Sefton coast is relatively flat in topography. In addition, IDW provided a better resolution to show linear discontinuities such as paths, roads and water bodies. In this method a minimum of six search points and 0.25 m output cell size were chosen to match LIDAR data accuracy in data collection. The NN method calculated a nearest neighbour index based on the average distance from each feature to its nearest adjacent feature for about twelve points. The method was suitable to comparing different features in the same fixed study area. It was expressed as an index based on the ratio of the observed mean distance to the expected mean distance. If the index was less than 1, the pattern exhibited clustering; and greater than 1 dispersion which resolved DEM features differently from the IDW. Both methods were suitable but the IDW was selected for its ability to handle dense LIDAR data and provide a more accurate DEM based on fewer interpolated points.

Comparisons were undertaken in both methods using the XBeach River Alt simulation data where after 1.5 hours of flood the interpolated grids from the NN and IDW were both consistent with ground features. Using the NN method of linear interpolation of a flood DEM at a specified point in Hightown an interpolated flood water depth of 19.549 m was achieved (Figure 4.2). The IDW method of linear interpolation of a flood DEM at the same point returned a consistent value 19.549 m, although resolving more detail in the DEM than the NN method (Figure 4.3). In Figure 4.4, the IDW linear interpolations were used with a very fine resolution of 0.25 m and a reduced number of six search points difference in Z_s producing a value of 18.358 m.

Another reason accounting for the change in value given more accurate parameters was the inclusion of a flood defence barrier whose points were inserted in the DEM file at the mouth of the river based upon suggestions by XBeach modellers. The stretched symbolisation used to colourise the raster grid improved on the pixel resolution of flooding points. Upon close inspection it was found that the values of flood water depth differed with the flood defence barriers. In future studies, validation studies are required to determine the accuracies of the various methods.

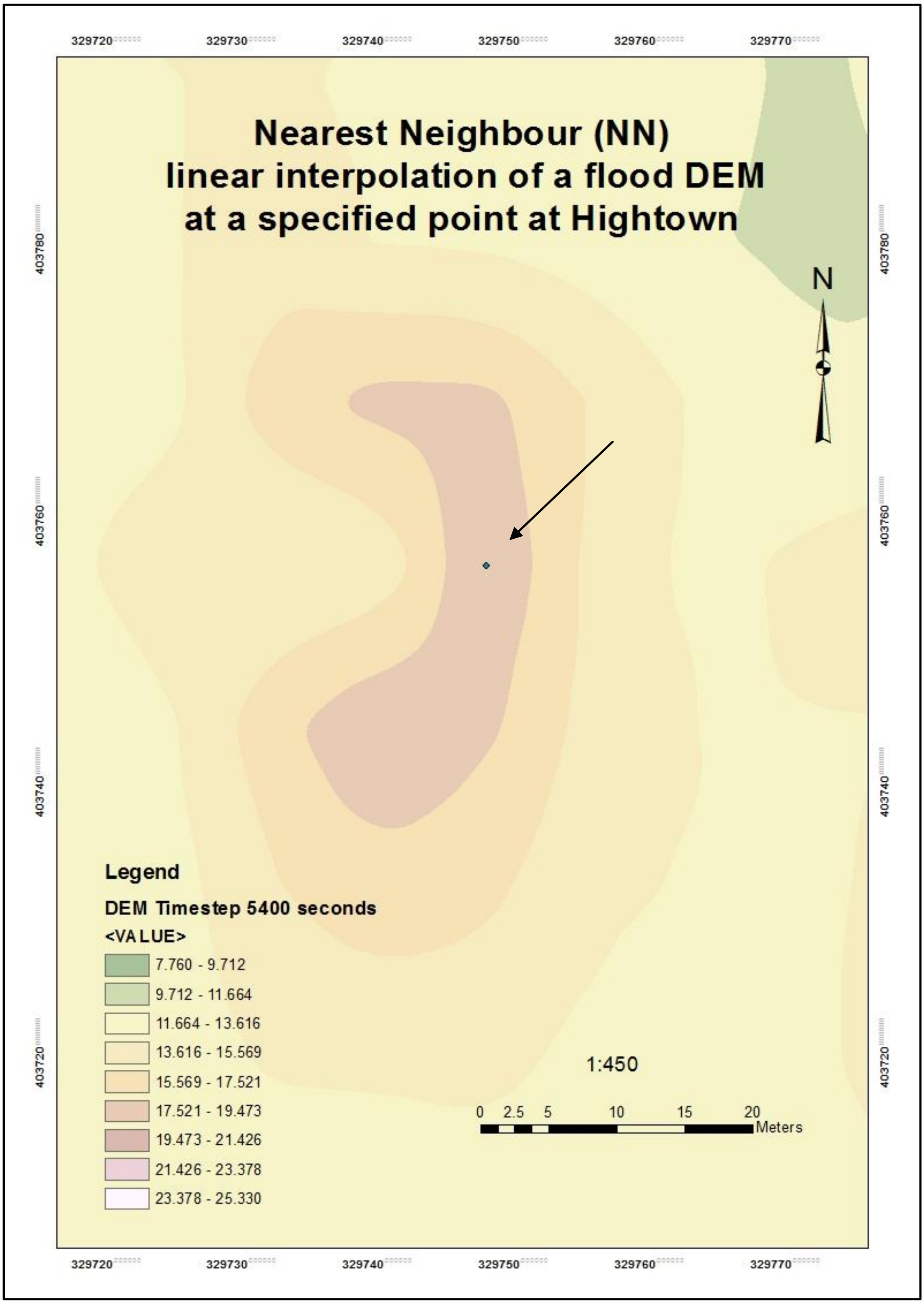


Figure 4.2: Nearest neighbour (NN) linear interpolation of a flood DEM at a specified point in Hightown indicating an interpolated flood water depth of 19.549 m.

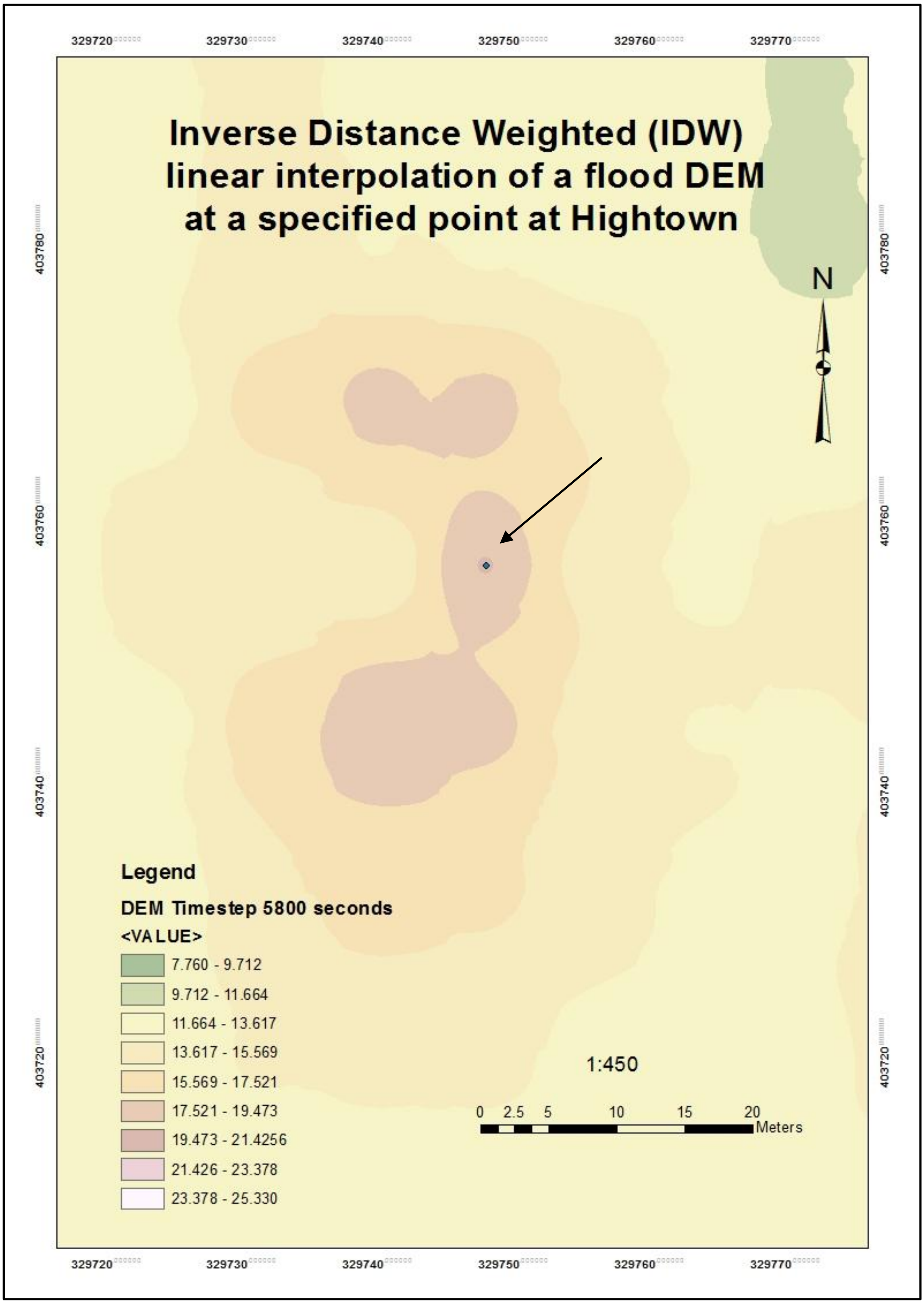


Figure 4.3: Inverse distance weighted (IDW) linear interpolation of a flood DEM at a specified point in Hightown indicating an interpolated flood water depth of 19.549 m.

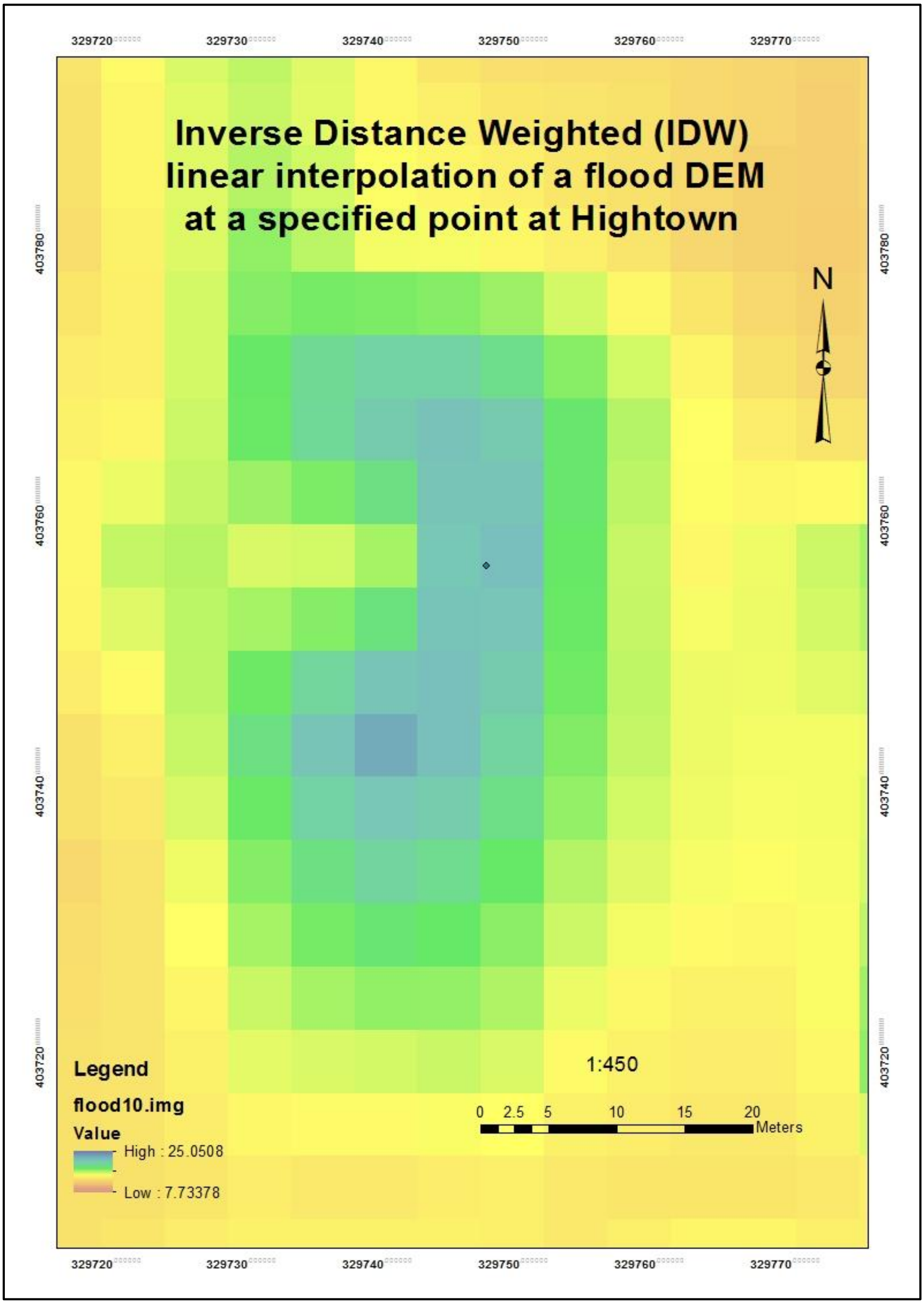


Figure 4.4: Inverse distance weighted (IDW) linear interpolation of a flood DEM at a specified point in Hightown indicating an interpolated flood water depth of 18.358 m showing a greater resolution of pixels.

4.3.3.2 POLCOMS-WAM-GOTM Results Processing

The modelling was reprocessed with beach profile survey data to provide a more accurate dataset for hindcast simulation data for coastal flooding in standard ASCII format. These processing of these datasets in ESRI ArcGIS produced DEM which was re-exported into ASCII format to be used in the Liverpool Bay model to produce enhanced bathymetry with tide and surge interactions. The precision of the data was improved offshore in ESRI ArcGIS by creating a variable grid with offshore and nearshore accuracies, 3 m and 0.15 m respectively.

During the months, the data processing was augmented with updated LIDAR (2009); recent beach surveys; cross-sectional profile data at Formby Point and the River Alt; and flood embankment data to improve the dataset for the coastal flood model. The most recent LIDAR survey (2007) at that time provided the best topography of the River Alt. In Figure 4.5, the Liverpool Bay model enhanced bathymetry with tide and surge interactions is shown (Brown et al., 2010b). The tide and surge interactions allowed wetting, drying and recession of water of the coast from the waters of the eastern Irish Sea, exhibiting the natural behaviour of the sea.

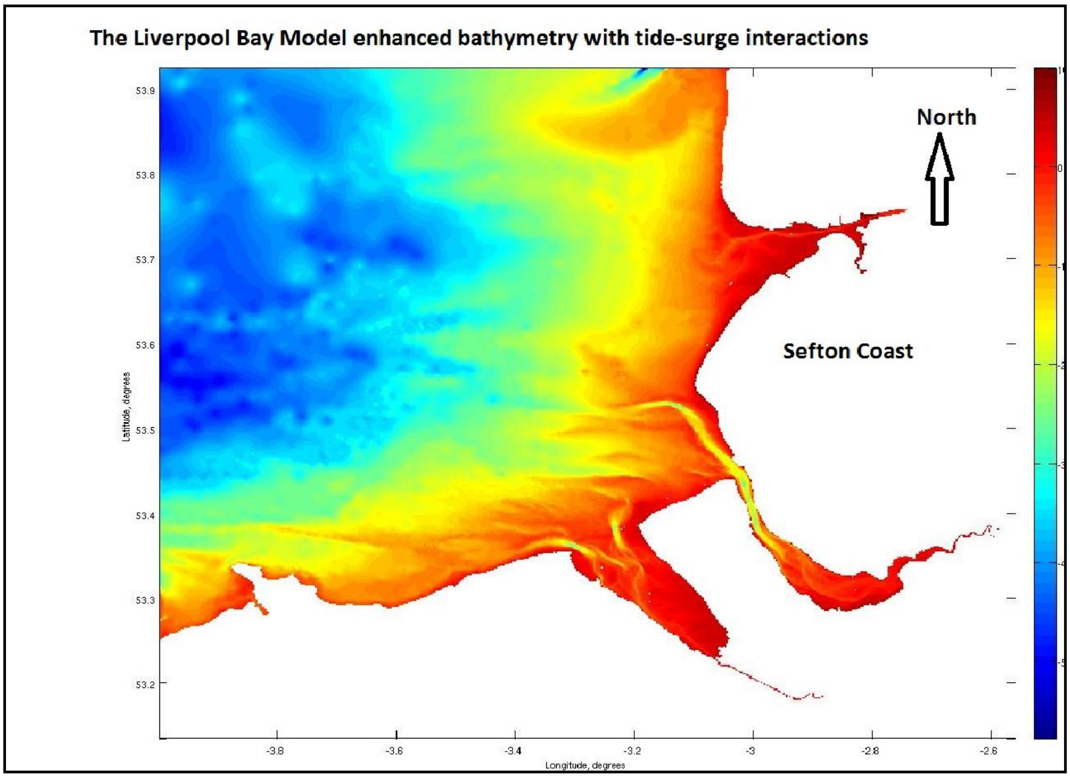


Figure 4.5: Bathymetric data simulated for the eastern Irish Sea with a wetting and drying effect allowing the coastal waters to recede (Brown and Wolf, 2009).

4.3.3.3 XBeach Results Processing

The bathymetry of the eastern Irish Sea was resampled in ESRI ArcGIS to 3m grid size in order to achieve satisfactory performance in the XBeach model runs. A bare earth model was created to remove built structures. The river channel and flood embankments or levees were recreated in the dataset with elevations of 2.5 m to describe current river bank topography as the LIDAR data was unable to detect any real-world flood defences. It should be noted that the LIDAR data measured the height of the river surface at the time of flight-data collection which provided inaccuracies in the dataset along with flow regulation structures in the site. There also existed no survey information on the depth of the River Alt channel to improve the accuracy of XBeach processing.

The topographic datasets were improved to 0.15 m accuracy based on the recent beach and coastal surveys provided. An updated DEM was generated and merged with the 3m precision bathymetry. The grid extended 1.5 km along the coast. The accuracy of the most recent LIDAR (2009) supplied by the Environment Agency was 0.25m. Due to the limitations on desktop processing in XBeach, the propagation of the flood was focused on the River Alt estuary and the lower reaches of the Formby sand dune system. With server processing, a wider study area could have been undertaken. The final dataset used in XBeach was supplied in an x-easting, y-northing, and z-vertical height in British National Grid (BNG) coordinates. The XBeach model set up location data domain is illustrated in Figure 4.6 (personal communication Alison Heidi Nock and Williams et al., 2011) model set-up showing the GIS datasets within the model. These datasets included recent beach profiles along the coast. However, the modelling was undertaken in three sections as discussed previously.

In addition XBeach parameters recreated a calibrated constant gradient on the river channel from sources at the sea and upstream. A mean flow velocity of 0.75 m/s was set in the XBeach model. ArcFLOOD analysis will prove a 1.5 m increase in water levels in these locations. An enhanced 2D extreme event storm impact was simulated in 4 phases where the river flows down the channel at the origin and discharges at the coast due to high tidal level and fluvial discharge (Figure 4.7) (Williams et al., 2011). The diagram shows time elapsed from the start of the model runs. The delivery of results in XBeach was delayed until the model could be recalibrated for a live storm event. The 31 March 2010 storm provided the data necessary to predict storm impacts on dune frontage. Pre-storm and post-storm surveys were used in the calibration of the dune frontage (Williams et al., 2011).

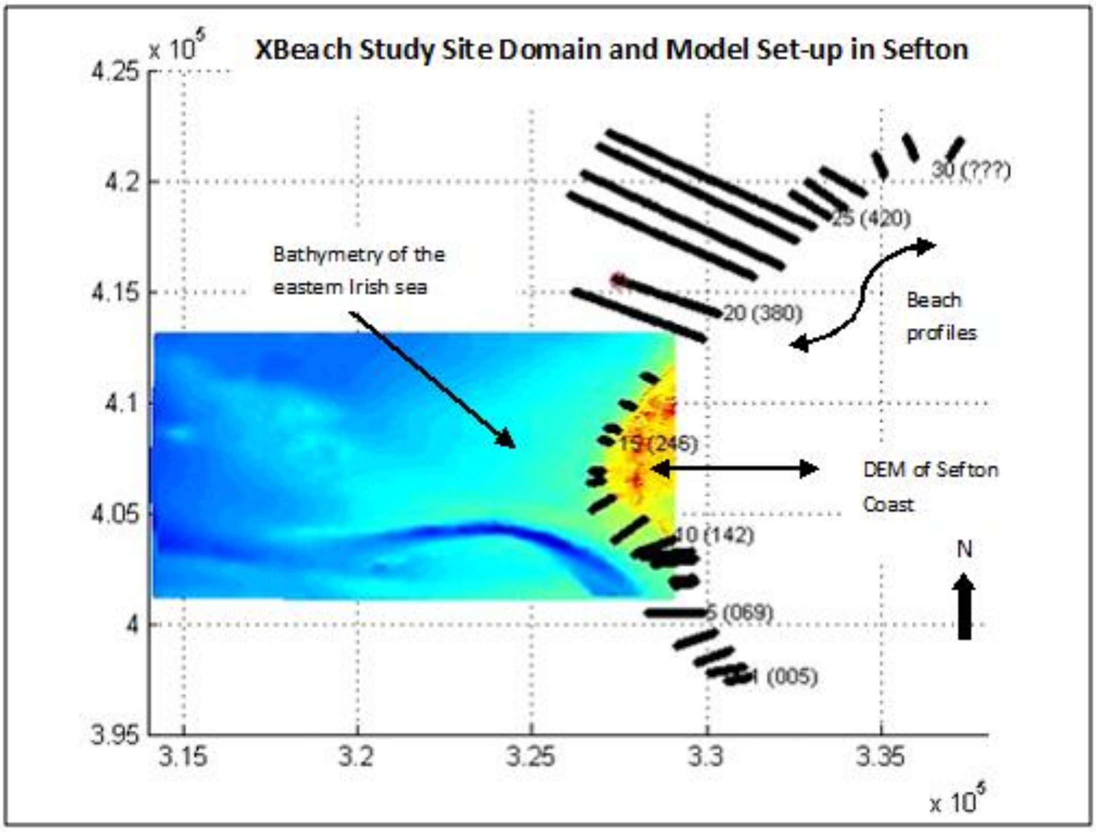


Figure 4.6: XBeach location data domain and model set-up for the Sefton study site showing beach profile data, bathymetry and DEM.

Data was reprogrammed in XBeach utilising Matlab code to export to a compatible ESRI format such as a text (*.txt). This was partially due to the complex nature of binary array flood data with multiple dimensions and the limited data exchange standards built into XBeach open source code. The results of XBeach were initially output in a binary netCDF file, the standard format for timeseries data in GIS. However, netCDF was unable to adequately export the time series simulations from XBeach and visualise flooding sequences in ESRI ArcGIS.

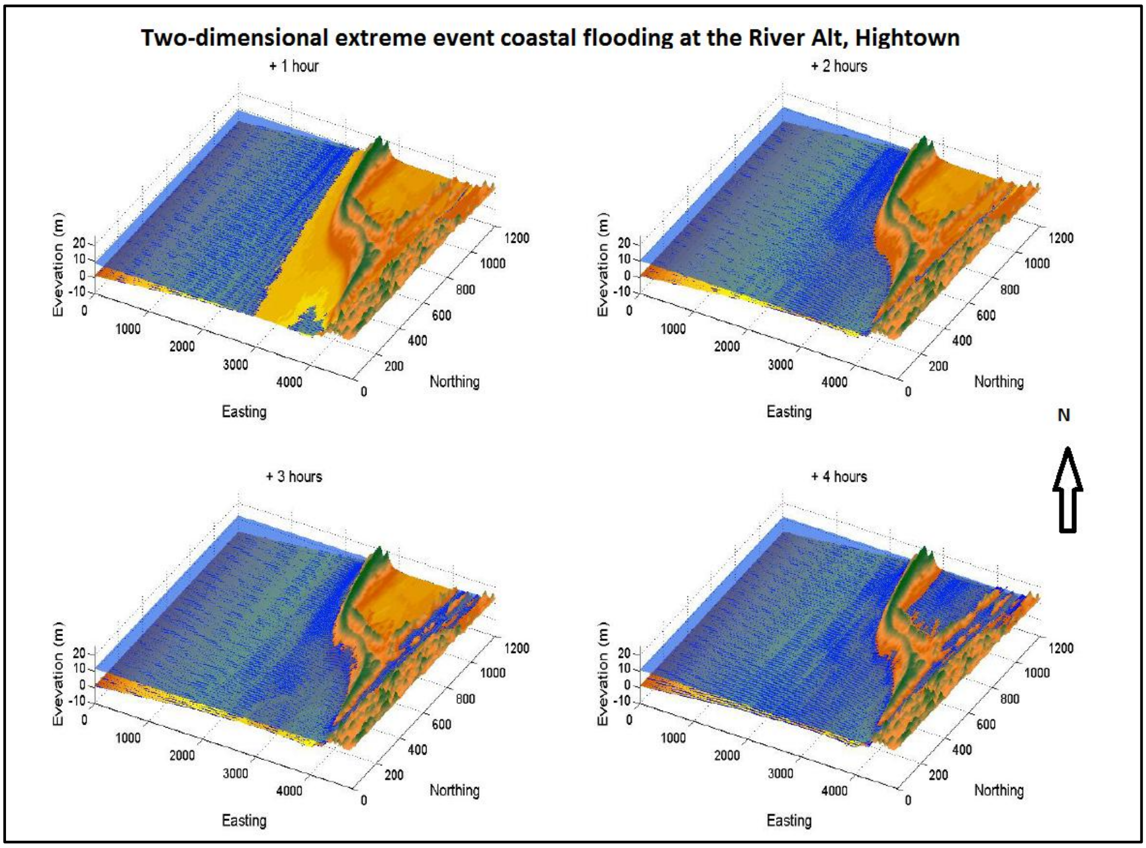
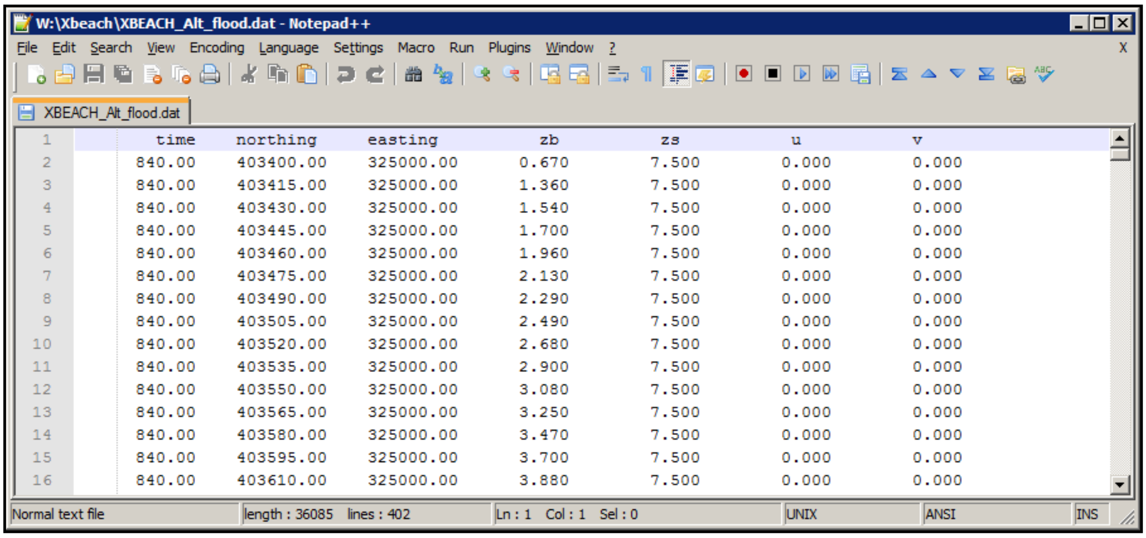


Figure 4.7: XBeach two-dimensional (2D) simulation of extreme event coastal flooding due to high tidal level and fluvial discharge on the River Alt at hourly timescales of 1, 2, 3 and 4 hours.

POLCOMS-WAM-XBeach modelling results stored data in ASCII/Binary formats. The decision was made to reprogram XBeach to convert numerical flood modelling results into a *.DAT format to provide much more accurate data and flexibility of use of timestep point data. However it was found that the *.DAT file format was not interoperable with GIS and required further conversions. The flood model output provided in the .DAT format was loaded into Notepad and exported as a .csv or .txt file to be edited in Microsoft Excel. The Microsoft Excel text to column function use was necessary to prepare the data as a table file to be used in GIS with headings and column fields. Although these processes were simple, they are not standardised and outlined in any flood data processing manual. Therefore, If flood modellers are to use flood model output in GIS, it is recommended that it is the responsibility of numerical flood modellers to export flood model output into OGC standard formats. In addition, it was possible that the inability of netCDF to visualise the time series results was due to the lack of headings and a standardised tabular format in XBeach. The data processing has indicated a deficiency in flood modelling systems to integrate its data into GIS through import and export routines.

Finally the data was prepared in an ASCII text (*.txt) format as seen in Figure 4.8 showing the XBeach results produced in an ArcGIS table. The global XBeach flood model output variables which were included in the data modelling were:

i. Z_s -surface flood water depth of the predicted flood level;
ii. H_s-significant wave height which also represents height of the maximum wave height above the sea surface elevation;
iii. u -velocity in the x-direction- speed of wave;
iv. v -velocity in the y-direction- speed of wave.



time	northing	easting	zb	zs	u	v
840.00	403400.00	325000.00	0.670	7.500	0.000	0.000
840.00	403415.00	325000.00	1.360	7.500	0.000	0.000
840.00	403430.00	325000.00	1.540	7.500	0.000	0.000
840.00	403445.00	325000.00	1.700	7.500	0.000	0.000
840.00	403460.00	325000.00	1.960	7.500	0.000	0.000
840.00	403475.00	325000.00	2.130	7.500	0.000	0.000
840.00	403490.00	325000.00	2.290	7.500	0.000	0.000
840.00	403505.00	325000.00	2.490	7.500	0.000	0.000
840.00	403520.00	325000.00	2.680	7.500	0.000	0.000
840.00	403535.00	325000.00	2.900	7.500	0.000	0.000
840.00	403550.00	325000.00	3.080	7.500	0.000	0.000
840.00	403565.00	325000.00	3.250	7.500	0.000	0.000
840.00	403580.00	325000.00	3.470	7.500	0.000	0.000
840.00	403595.00	325000.00	3.700	7.500	0.000	0.000
840.00	403610.00	325000.00	3.880	7.500	0.000	0.000

Figure 4.8: XBeach results produced with new fields for flood water depth (Zs); U-velocity (u); Y-velocity (v); and significant wave height (Hs).

4.3.3.4 Time Series Processing

The basis of the processing was the manipulation of the time series flood model output in a new table **Timesteptotal**. Within this table, a point file of flooding points was x, y, z integer fields was used to represent the location of a point using the unique identifier **OBJECTID**. **OBJECTID** was defined as a field in XBeach modelling results tables (**XBeachinput**) to spatially enable flooding data in a GIS geodatabase. Due to the processing limitations of XBeach, the model experienced a performance limit and crashed in the export routine from GIS. The output provided 1.5 hours of flooding (6000 seconds) simulation which was enough to provide end-user analyses. In addition, the processing of coastal flooding from XBeach was essential as the existing standard netCDF also failed to visualise the model output 3D sequences in ArcGIS. The timestep processing was decomposed into eleven (11) stages of flooding from zero seconds to six thousand seconds (0 to 6000 s) and was converted using the following processes:

a. Importing tool: The text file was imported into ESRI ArcGIS and reconverted to an ESRI spatial dataset in the geodatabase. The dataset was then mapped and symbolised in GIS.
b. Spatial Query Builder tool: A simple SQL query was embedded in the timestep data to represent the total flood model run from XBeach and to generate individual timesteps from this layer for t=1,n:
    a. The query "**SELECT from timesteps_total** model run **WHERE TimeID = 1, n;**" where n is the value of the timestep.
c. Exporting tool: The resulting query was then exported as new file **Timestep** which is a spatial layer in ArcGIS.
d. Create Table command: The create table command was used to export 11 time layers for the 11 stages of flood from t = 0 to t = 6000 seconds.

e. **Query Builder Tool:** Used a new query to output a spatial point file of timesteps using the TimeSeries table.

f. A **"Select by Attribute" query** where **timestepID** was set to the row value, re-populated and exported as a table. This query was inbuilt in the data to assist the extraction of the flooding sequences or timesteps. Once the data was exported as a table file in ESRI ArcGIS, the file was then re-exported as a spatial point file to allow the mapping of time sequence points.

g. This was commonly performed by re-plotting the easting and northing; and by setting the spatial referencing system in a GIS. A visual programming tool was created to automate this procedure using model builder. Total Timestep Layer was the time-series output from Matlab which was reconverted to a usable format in ArcGIS. Definitions of field type, length, precision, scale, and number format were inbuilt into the ArcFLOOD data model.

h. Query Builder Tool: was used to export individual timestep sequences. A query was inbuilt in the Timestep file to select from the **totaltimestepsimulation** file, the individual sequences (Figure 4.6) which shows the tabular representation of the timestep layer data. Timesteps were created for the stages of flood. **SELECT from timesteps_total, WHERE TimeID = 1, n;** where n was the value of the timestep**,** and **TimeID** uniquely identified the time intervals in seconds (s) from t= 1, n where, n = 0, 600, 1200, 1800, 2400, 3000, 3600, 4200, 4800, 5400, and 6000 seconds (s).

i. The export function was used in ESRI ArcGIS: to export individual timestep layers

j. **Create DEMs:** Using the IDW spatial interpolation tools in ESRI Spatial Analyst extension, the individual time series DEMs were generated to use in the analysis. The NNM (Figure 4.9) and IDW (Figure 4.10) were both used to create DEMs based upon the **Z_s** and **H_s** parameters of **flood water depth** and **significant wave height**. Triangulated Irregular Network (TIN) models were developed using linear interpolation methods to provide best estimates of Z_s and H_s, however, TIN models were found to provide less than sufficient detail due to the uniform cell size rather than user-defined cell sizes such as NNM or IDW which improve accuracies. These techniques to reclassify the DEM proved sufficient for analysis and appropriate for flood visualisations.

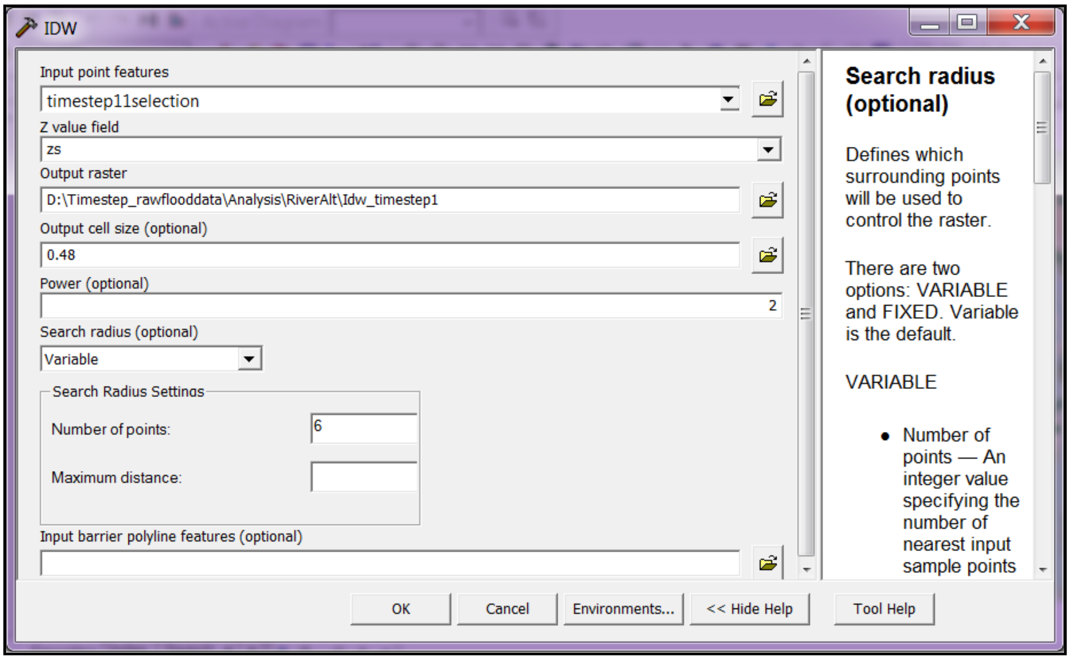


Figure 4.9: Creating XBeach DEM's using attributes z_s and h_h parameters within the DEM using the Inverse Distance weighting (IDW) method of interpolation of points.

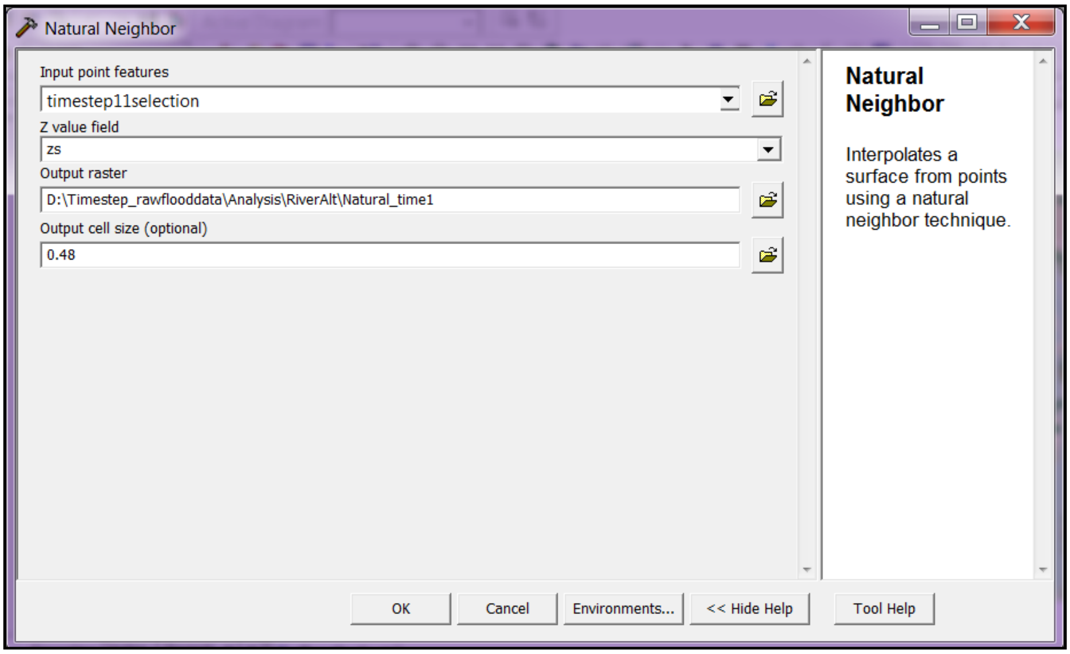


Figure 4.10: Creating XBeach DEM's using attributes zs and h_h parameters within the DEM using the natural neighbour method of interpolation of points.

A programmer would be able to follow these steps to automate the representation of time series data in ESRI ArcGIS as the knowledge of the processes and data content have been provided in this research. With the data processed in ESRI ArcGIS, the geodatabase for ArcFLOOD was built.

Finally, the data is further conditioned in ESRI ArcGIS for the data model design. Within the ArcFLOOD data model, each flooding point was defined as having a unique identifier **OBJECTID** and defined by flooding results $\mathbf{z_s}$ and $\mathbf{h_h}$, water depth and significant wave height measurements respectively (Figure 4.11). In Figure 4.11, the XBeach timestep layer feature class properties were defined in the flooding tables. In addition the properties of **u** (x-velocity) and **v** (y-velocity) were also included. The eleven timesteps of flood or ten stages of flooding were merged into the **Timesteptotalsimulation table**.

In order to prepare this table for the data modelling, a one-to-many (1: m) relationship with **Timestep** was created in feature class properties of the table which allowed this unique relationship to be propagated throughout the geodatabase. **Timestep** unique identifier **TimeID** was defined as double integer used to link all flooding tables within the ArcFLOOD data model. **TimeID** represented the specified time interval of flood. In the data model, the **TimestepTotalSimulation** table was used to compute the actual flood water depth.

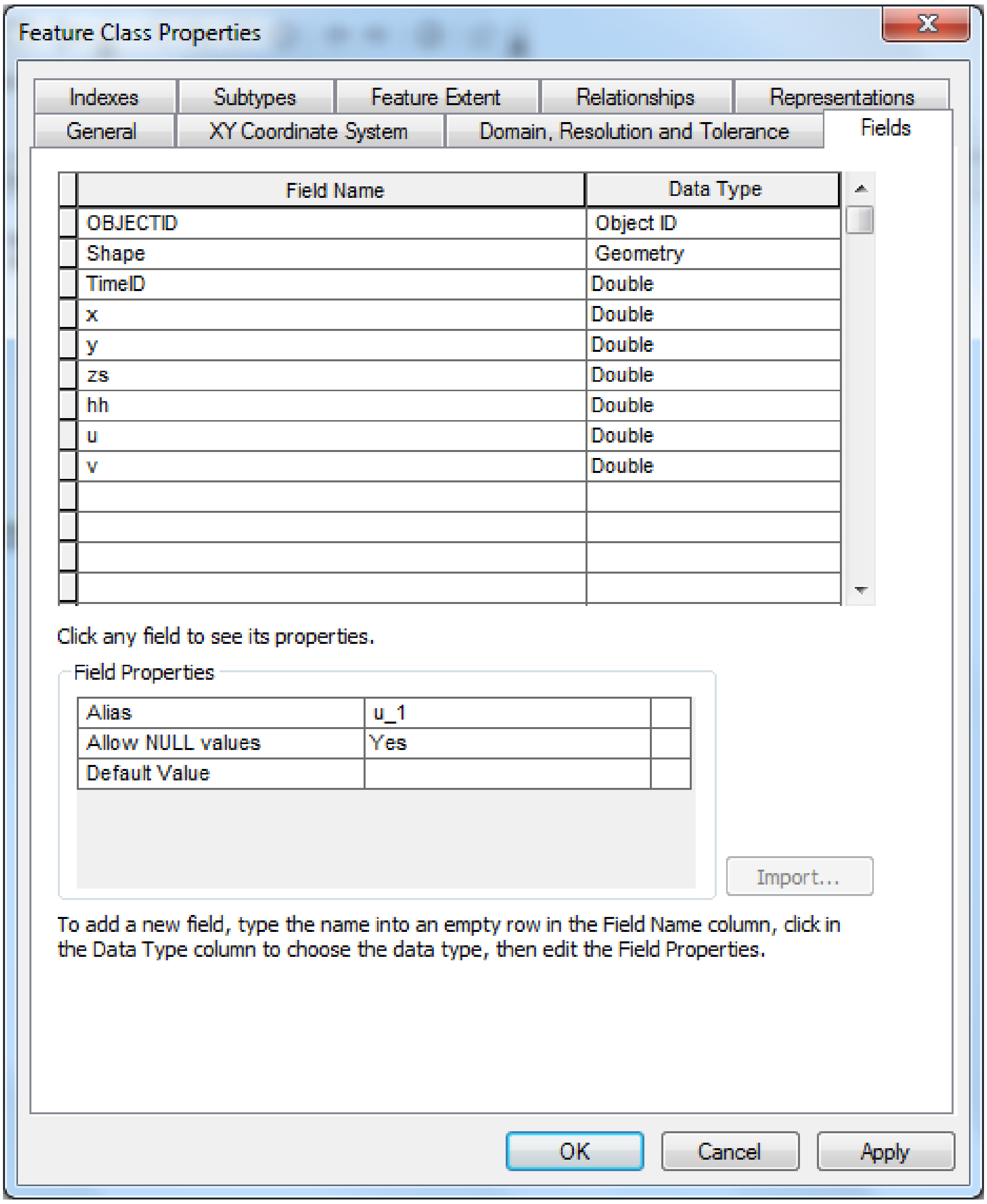


Figure 4.11: XBeach timestep layer with an attribute TimeID in ESRI ArcGIS table layer properties defined with x-coordinate, y-coordinate, z_s, h_h, u and v parameters.

4.4 Building the Geodatabase

Within the COFEE project, the end-users should maintain the geodatabases developed in this research. The details of the geodatabase design process were further explained in Appendix B.5.

4.4.1 Geodatabase Concepts

The building of the ArcFLOOD geodatabase required technical GIS knowledge of relational database management systems (DBMS). The specific geodatabase in ESRI ArcGIS designed was a multi-tier application architecture found in other advanced DBMS applications such as Oracle, Informix and SQL server. The architecture used was the object-relational model. Within the geodatabase, objects existed in rows in DBMS tables. The behaviour defined in a table was developed as application logic and is separate from storage of data. The application logic was used for querying which supported GIS objects such as feature classes, raster datasets, topologies, networks and numerous spatial processing techniques in GIS software.

The datasets were converted into an ESRI ArcGIS format using a combination of tools including MapInfo, ESRI ArcGIS and FME Safe Software to convert from primarily text format (*.txt) and MapInfo (MID) formats to an ESRI geodatabase. The FME Safe software tools can be freely downloaded from the internet to provide conversions into GIS from MapInfo. The MapInfo datasets from Sefton Council were converted using a MapInfo format (MID) to MapInfo interchange format (MIF) conversion and then were imported into ESRI ArcGIS through the ArcCatalog software. ArcCatalog was used to create a coastal flooding geodatabase and files were imported into the geodatabase.

Several geodatabases were created within one geodatabase to categorise the types of data collected.

The basis of the geodatabase is that tables and attributes types identified in the thematic structure of Table 4.1 were imported into an empty personal geodatabase in ESRI ArcGIS, ArcCatalog. See Appendix B1.1 for instructions on how to create a geodatabase. The geodatabase was used for storage initially, to house all COFEE project data. Subsequently, the geodatabases were copied and refined to store the data defined in the data model; embed the data modelling relationships; and embed structured querying language (SQL) queries within the data. These were the essential data processing steps to create, modify, load and export data for processing flooding queries.

4.4.2 Geodatabase Storage

Two geodatabases were created. One for storing the coastal flooding data amalgamated for the COFEE project and the other for developing the ArcFLOOD data model. In Appendix B.2.1 the folder directories show the ArcFLOODcore.mdb geodatabase created and populated with feature datasets. In Appendix B.2.2 the raster catalogues were created. Feature datasets were used to store points, lines and polygons. Raster catalogues were used to store imagery from aerial photography and LIDAR grids. This geodatabase was used as DBMS storage throughout the research.

In the geodatabase feature classes were stored as tables which possessed information or attributes about the data and shape files which described the geometry of the feature (point, line and polygon). SQL queries can access both tables and geometry in a GIS.

Numerical modelling lacks the ability to spatially produce the geometry of features; hence, it is limited to tabular output. The geodatabases comprised two types of tables for each individual feature class: dataset tables and system tables. Dataset tables were used to manage data and process querying. System tables were used to maintain the geodatabase schema changes; specify dataset definitions, rules and relationships; and manage metadata to implement geodatabase properties, data validation rules and behaviours. Two separate versions of the storage geodatabase were created as a working copy and backup. The initial version was eventually replaced with the repopulated and modelled ArcFLOOD geodatabase.

4.4.3 Geodatabase XML

ESRI ArcGIS openly publishes and maintains the geodatabase schema and content as an XML specification. XML allowed the interchange of geospatial information to and from a geodatabase. As a result, external applications can receive ArcGIS XML data streams for internet mapping. Using ESRI ArcGIS tools, the XML documents were automatically created in the system tables which included: a **Workspace** document, a **RecordSet** document, and a **Data Changes** document. It is important to mention this characteristic to potential end-users as software developers are provided with a choice of schema definitions.

4.5 Process Models for Coastal Flooding

Before the data was modelled in ArcFLOOD, process models were created which would automate the flow of data and provide flood risk datasets to be used in analyses (Appendix B.6). The approach used in the ArcHydro modelling of flooding was adopted in order to develop process models to produce flood coastal flood risk data (Andrews and Ackerman, 1999; Whittaker et al., 2006). This enabled faster customisation of the flood risk data output descriptions.

The ESRI ArcGIS model builder tool was used to derive process flows in specific flooding toolkits. These flooding toolkits housed flood risk process models for coastal flooding (Appendix B.6). The process models developed semi-automated the generation of coastal flooding results (Appendices B.6.1 to B.6.9). The process models created flooding polygons and DEM from which analysis were derived. The primary data used in the process model was the XBeach model output time series data. The automation processes included: the process of creating flooding polygons from point files containing x, y, z where x-is the x-coordinate (easting); y is the y-coordinate (Northing) and z- is the z-coordinate (depth or elevation).

Only through this approach can the full advantages of GIS processing for query, manipulation and analyses be achieved. The alternative is reprogramming in Visual Basic (VB) or Python software languages. The process model reused VB code designed to execute generic geoprocessing functions. Having a thorough knowledge of GIS geoprocessing functions is necessary to process time series data from XBeach into GIS and to rapidly produce flood risk datasets.

In addition, the use of the raster geoprocessing tools in ESRI Model Builder allowed the automation of timesteps or the 11 phases of flooding from XBeach. The complex process to generate flood DEMs were improved from the automation provided in process models which ensured consistency in the tabular data. The logical workflow created in process models aids the future rapid prototyping of software applications by its re-usability.

Subsequently, coastal flooding process models were created using Boolean and algebraic calculations to generate flood polygons from the XBeach results. The DEM were interpolated with z_s and h_h by either using NN or IDW techniques which were user-defined. These rasterised DEM were converted to editable tables for spatial analysis. Using a minus raster function, the pre-flood and post-flood DEM were subtracted to obtain the flood increase rasters for each timestep. These datasets were converted to flood polygons by using a Boolean function which selects depth grid values to indicate coastal flooding. These results were converted to flooding polygons. A Zonal statistical analysis tool was used to attach flood water depths to rasterised roads and property data enabling these layers to be interrogated through spatial analyses.

The process models developed to automate the above mentioned calculations included (Appendix B.6.1 to B.6.9):

a. **Create Flood DEM** (CreateFloodDEM) which created flood raster surfaces from XBeach data or LIDAR data (Appendix B.6.1).

b. **Create Flood Polygon** (CreateFloodPolygons) which automated the create flood polygons from post-flooding timestep data process (Appendix B..6.2).
c. **Create Flood contours of water depth** (CreateFloodContours) (Appendix B.6.3).
d. **Dissolve Flooding Zones** (DissolveFloodedZone) (Appendix B.6.4).
e. **Post-flooding property query** (CalCHangeFloodWaterLevel) performed comparisons of pre-flood and post-flood water levels and relative increase in water level at a point (Appendix B.6.5).
f. **Find the water level at this point** (FloodLevelChangeDiffTimesteps) for a particular timestep of flood simulation (Appendix B.6.6).
g. **Find the water level which is nearest to a feature and buffer the zone** (BufferPropertyMap) returned all water levels in a user defined zone in an attribute table. The process model examined water depth levels per timestep at building features and can be adapted to river polygon data (Appendix B.6.7).
h. **Find the water level flooding a building or property** (FloodFootprintBuildings). The tool attached flood water depths to a feature in the flood hazard zone producing the floodwater depth for that feature at a particular timestep as a tabular file and raster file (Appendix B.6.8).
i. **Find the change in flood level between timesteps** (FloodLevelChangeDiffTimesteps) which was necessary to determine rates of change of flooding and satisfied a COFEE requirement. These values were also useful to calculate the surge level or the height of the additional water level on top of the tide (Appendix B.6.9).

4.6 Building the ArcFLOOD Data Model

The object-relational hierarchical data modelling approach developed over many years has been used to provide a flexible framework to manipulate dynamic objects in the real-world (Hernandez, 2013; Cabot, 2008; Lightstone et al., 2007; Date, 2000; Codd, 1974). It was the fundamental technique to data modelling in this thesis. This approach was appropriate for requirements transference which provided end-users with immediate access to data (Lenz, 2013). In this approach an entity's procedures was combined with its data in a hierarchical tree like structure. Within the structure, objects were identified and defined by specific relevant classes to describe the objects detail. A most important property of the data modelling approach was the propagation of inheritance within the hierarchical structure where higher objects inherit the spatial relationships of lower objects throughout the data model. The most important advantage of this data model approach used was its unique extensibility which allowed improvements as changes arose in the data modelling. The ArcGIS Geodatabase Diagrammer tool Microsoft Visio components were used to edit, visualise and export the analysis diagrams produced. The extension of the MDM was initiated with the loading of the MDM data model (Wright et al., 2007).

Before the physical creation of the data model the elements of the MDM which were to be retained were determined. The table properties of these were noted and matched with the table properties of the new data which were to be linked with the MDM data model data. Once the geodatabase schema was extracted from ArcGIS geodatabase diagrammer, the process was not reversible which meant it was no longer possible to amend the table properties such data and field names. If and when amendments were to be made, the data model was recreated.

An iterative process was used to develop and refine the structure and content of the data model until a finalised version was achieved. The elements of the MDM which were retained included **FeaturePoint**, **SurveyPoint** and **MESH** definitions for future 4D analyses. It was found that the MDM fields did not match the time series outputs from flood modelling and therefore a decision was made to maintain the above elements. It was found in this thesis that the MDM descriptions of marine data were not entirely appropriate representations for coastal flooding entities. Therefore, the bespoke ArcFLOOD data model was developed by reusing some components of the MDM. In addition, the ESRI ArcHydro fluvial flooding data model suitability for incorporation was limited to the process model development of data.

When data modelling, the generic DBMS rules which were incorporated into building ArcFLOOD included:

a. A background in GIS and DBMS were essential to developing data models.
b. The relational model used separated data into interrelated tables which contained rows and columns.
c. The tables were pre-identified in an initial design based on evaluating end-user requirements to determine which datasets in the geodatabase was necessary.
d. Table references were created with foreign keys or unique identifiers to interconnect the tables using the foreign keys as primary keys throughout the structure. **ObjectID**, **TimeID** and **FeatureID** were the most important primary keys. They allowed cross-referencing of data which was critical. Spatial entities were encoded in ArcFLOOD with foreign keys to reduce duplication errors in records.

e. Each record in the data model relational database conformed to a specific element of a schema with a fixed number of fields (rows and columns) each specifying data type, descriptions and relationships between entities in the data model. The data field properties were defined to allow inheritance of data flows from other tables.
f. A process of normalisation was used to decompose large tables such as the timeseries tables into smaller interrelated tables to improve the performance of spatial querying. This was important to create time series DEM's to represent coastal flooding at various stages of the flood.
g. The principles of database design such as dependency, association, generalisation and realisation were applied to maintain consistency in techniques.
h. The data model aimed to simplify the process model outputs which created coastal flooding analyses.
i. The identification of data flows and relationships from the process models created formed the key linkages in the data modelling.
j. Information such as scale ranges and spatial relationships were identified to describe a flood.

4.7 ArcFLOOD Data Modelling Phases

The data modelling process was undertaken in the following ordered design phases:

a. Conceptual phase
b. Logical phase
c. Physical phase

4.7.1 Conceptual Phase

The conceptual phase involved the design of the data model analysis diagrams. The ArcFLOOD data model was organised into three components represented in diagrammatic schema:

a. Coastal Flood Data Model(Appendices C.2.1 and D.1);
b. River and Estuarine Data Model (Appendices C.2.2 and D.2);
c. Mesh Data Model (Appendices C.2.3 and D.3).

The data model schemas were presented in an Adobe Reader (pdf) poster format using the Microsoft Visio software to design the diagrammatic schema (Appendix D.1).

This stage was critical as once the model was completed and exported from Geodatabase Diagrammer, the changes were irreversible. Any change in the data content must be redesigned in a new schema model. Several drafts of the data model and schema were prepared before the finalised model was exported as a geodatabase and schema from ArcGIS. Extensive preparation work was necessary to construct an initial design based upon the data which exists in the geodatabases; and end-user requirements. From this point, it was necessary to consider which elements of the MDM were reusable. The elements of the MDM which were retained included **SurveyPoint**; **FeaturePoint** used to represent the time series flooding data**.** The **MESH** data model was included due to its future importance in mapping four (4D) and five (5D) applications. The majority of the MDM was unsuitable to coastal flooding.

The conceptual phase involved the following main steps to design a data model:

a. The derivation of a complete list of essential data from the Liverpool Bay Model and Coastal Flood Model. The core dataset was the time series data.

b. The design of process models to semi-automate the design of the flow of data throughout the data model. These process models satisfied end-user requirements: flood water depth at a particular location and flood water depth change between different timestep simulations.
c. Creation of a geodatabase as file storage for existing data and developing process models to create new datasets from this geodatabase.
d. Development of a schematic representation using ArcGIS geodatabase diagrammer and Microsoft Visio tools by using the identifying following pre-requisite steps:
    i. Any possible differences between the ArcFLOOD schema and the data to be added;
    ii. The feature classes are to be included;
    iii. The attributes of each data set;
    iv. The relationships between the data.
    v. The key fields in your features datasets and attribute tables.
e. Extracting the finalised schema from ArcGIS in an extract schema wizard; and exporting the finalised coastal flooding geodatabase into ArcCatalog.
f. Examining the contents of ArcFLOOD to ensure that field properties match original requirements.

Within Appendices C.2 additional information on data modelling can be found. Appendices C.1.1 to C.1.2 provide details on developing ArcFLOOD geodatabases. Appendices C.1.3 provides geodatabase development in an ArcMap project detail. The technical instructions on how MDM schema was applied to the geodatabase in ArcCatalog are provided in Appendices C.1.4 and C.1.5. The use of the schematic wizard generator in ArcCatalog was required to create the data model design diagrams.

4.7.2 Logical Model

The logical model phase involved producing schema for the ArcFLOOD geodatabase as an XML templateArcFLOODcore.xml and ArcFLOODcore.vsd. The data model schemas were generated using ESRI ArcCatalog schematic tools which were the mechanism by which any end-user can recreate the geodatabase and repopulate with data using the loading schema tools in ArcCatalog. Schema diagrams were created in Microsoft Visio (*.vs) format and exported as Adobe *.pdf formats for publishing. The final ArcFLOOD data model was converted to an XML Metadata Interchange (XMI) format which was a tabular structure for the schema to facilitate loading of the data model into other relational data servers such as Microsoft Access, Oracle, Informix or Couchbase for example.

4.7.3 Physical Model

In this phase the schemas were exported into a Microsoft Repository or an XMI file from which any programmer can load the data model. End-users can begin to load geodatabase time series data and additional data into the tables to populate the data model. In this way, the model is further extended by end-users. Appendix C.1.5 gives additional information on how to apply the ArcFLOOD schema to a personalised geodatabase in ArcCatalog.

4.8 Description of the ArcFLOOD Data Model

The new elements of the ArcFLOOD data model are described below. This detail is not found in the MDM and incorporates the extension of the MDM into a bespoke ArcFLOOD data model.

4.8.1 Coastal Flood Data Model

The detailed diagrammatic design of the coastal flood data model is found in Appendices C.2.1 and D.1. The following were the relationships defined in the data model:

a. T**imesteptotalsimulation** was an array of simulation sequences, with a one-to-many (1: m) relationship with **Timestep**. **Timestep** unique identifier **TimeID** was a double integer used to link all flooding tables within the ArcFLOOD data model. **TimeID** exist from t= 0 to t = n where **n** was the number of seconds. This table was used to compute the flood water depth.

b. The **TimestepTotalSimulation** tables were exported in ArcGIS to produce a **FloodingPoint** table which was linked to the original MDM as a **FeaturePoint** representation. This process demonstrated reusability of the MDM's **SurveyPoint** and **FeaturePoint**. This definition provided the flood water depth at a point.

c. The individual **Timesteps** tables which defined a particular time of flooding or stage of flooding was linked to a **FloodZone** raster DEM from which **FloodPolygons** were produced. **FloodPolygons** were used to produce **TimeDurationArea** shapefiles which represent the flooding polygons at particular times. The **FloodZone** shapefiles were used to generate a table **BuildingsCompareTimesteps table to** statistics to calculate the changes in Z_s,

H_h. This definition provided the flood water depth change at a particular time.

d. Between timesteps or two stages of flood the **Floodchangetable** was created. **FloodZones** were defined with a one-to-one (1:1) relationship with the **FloodBuildingPoint**.

e. **FloodBuildingPoint** was merged with the property building data in **FloodZones (raster flood DEMs)** to produce **BuildingFloodZone** and **Property** spatial datasets. **FloodZones** were also linked to **FloodContours** table to allow end-users to query buildings with water levels (**BuildingWaterLevels**). The **BuildingsWaterLevels** table were generated from Ordnance Survey OS MasterMap data utilising the unique identifier **TOID**. The TOID was useful to merge with national UK datasets.

f. A statistical query was performed on the **Selectionhightownfloodlevels** to produce individual flood level points for building locations linked to FeaturePoint in the MDM.

g. Another query defined in the data model was the **Timestep** relationship between Timestep and the TotalDepth_Z lookup table. A one-to-one (1:1) relationship existed with **TimeID** and SignificantWaveHeight using the **OBJECTID**. This table was linked to another lookup table **Floodingthreshold**s for flood modellers to update their information and feedback into the modelling results with updated GIS data.

4.8.2 River and Estuarine Data Model

The river and estuarine flooding data model included the riverine component which was important to give an overall definition of flooding linked with coastal flooding. The complete **River Estuarine Data Model** is found in Appendices C.2.2 and D.2. The yellow container in the schematic drawing is the coastal flood model which is shown to be linked to the River and Estuarine data model (Appendix D.2). The areas which are not highlighted in yellow are the new elements extended to river and estuarine querying.

The data were provided by the **FloodZones** raster DEM spatial dataset which produced a **FloodPolygons** spatial dataset from which **FloodContours** created for mapping detail. The **FloodPolygons** spatial dataset was converted to timestepped areas of flood in the **TimeDurationArea** spatial dataset for mapping. The **FloodZones** (raster DEM) table was merged with a **River** rasterised file which determined the change in flooding between timesteps (**FloodChangeTable**) for features such as buildings, rivers and roads. The results were exported as a **RiverPoints** where the flood water level was attached to the River. The same was performed with buildings and roads. These operations allowed the River Alt to be populated with flood water levels upon interrogation in a GIS.

4.8.3 Mesh Data Model

The mesh data model was the only MDM schema included wholly into ArcFLOOD as a link for future multi-dimensional analysis in four dimensions (4D) and five dimensions (5D) as seen in Appendix D.3. No analysis was undertaken using the MESH data model due to a lack of data in the u and v values provided from XBeach results. The **MeshPoint**, which is an interpolated flood point, can be linked to timestep tables from the time series array XBeach data to identify the water level value at a point in mesh. In this data model, the spatial dataset **Timestep** was introduced to create a link through **OBJECTID** to MeshPoint allowing **TimeID** to be propagated to the MDM. The data model has a one-to-one (1:1) relationship between the **MeshPoint** and the **Meshtotaltimesteps** table. The MDM has identified measurement tables, parameters and relationship classes.

4.9 Implementation

The analyses presented in Chapter 5 will determine the extent of coastal flooding based on specific time durations of a flood sequence. The data model has allowed the calculation of **flood water depth = FloodLevel** for a given flood point. The **flood water level change h_h** (difference in Z_s flood water levels between timesteps) equates to the difference in significant wave height between timesteps ($h_{h\ (t=6000s)} - h_{h\ (t=0s)}$). These statistics are calculated from the **Floodchangetable**. The approach undertaken in chapter 5 is to use ArcFLOOD to perform end-user analyses relevant to Sefton Council. Flood risk mapping will be produced to verify the improved flooding calculations developed in the data model. The parameters which were incorporated into the ArcFLOOD data modelling to be used in the analysis in Chapter 5 included:

a. z_s-surface flood water depth;
b. h_h- significant wave height which was used to compute the actual flood water depth;
c. **u** (x-velocity in the x-axis direction);
d. **v** (v-velocity in the y-axis direction.

These results were achieved by manipulating the time series data for the flood simulation found in the **TimestepTotalSimulation** table which housed all the flood model output from XBeach processed in a GIS format. The methods to embed

ArcFLOOD schema into coastal flooding data can be found in the technical instructions: Appendix C.1 for guide to data modelling; Appendix C.1.4 for Loading ArcFLOOD and applying your data to the schema; and Appendix C.1.5 for Applying an ArcFLOOD schema to your datasets by importing the XMI file created for ArcFLOOD and importing ArcFLOOD into each dataset.

Chapter 5

End-User Spatial Analyses

5.1 Introduction

This chapter presents end-user spatial analyses which have improved flood risk assessment arising out of the numerical modelling in the study site at the River Alt, Hightown. Two calculations have been analysed to produce new definitions of coastal flooding which included **flood water depth at a point in time (z_s)** and **flood water level increase between timesteps (h_h)** for any particular location in the study site. These new calculations have been derived solely through GIS data modelling of time series numerical modelling results. In addition, flood risk mapping has fulfilled the need for flood mapping arising out of numerical modelling of predictions.

As previously indicated in Chapter 4, process models have generated the prerequisite data for the ArcFLOOD geodatabases in the GIS data structure and format necessary for spatial querying. The process models guided the processing and the manipulation of the GIS data loading from the ArcFLOOD geodatabase (Appendices B.2 and B.3). The technical instructions used are provided in Appendix B.4 (geodatabase properties; Appendix B.5 (model builder building); Appendix B.6 (process models for coastal flooding and Appendix C (guide to data modelling).

The derived flood risk mapping have identified vulnerable locations and improved the content of the predictions to decision-makers. These spatial analyses included:

a. The rasterisation of map features to attach flood water levels to urban settlement data such as buildings.
b. Predictive flood risk mapping for flood water increase.
c. Flood extent analysis.
d. High and low flood risk-hotspot mapping.
e. Flood water depth at a point in time analysis.

5.2 Spatial Analyses

The spatial analyses techniques used involved rasterisation and linear interpolation which linked coastal flooding predictions to urban settlement layers such as OS MasterMap buildings, road and river layers to enhance end-user analyses in the study site area. The spatial processing of the DEM surfaces from the **timesteptotalsimulation** table in the data model in Chapter 4 produced DEMs to represent predictions from the onset of the flood to 1.5 hours of inundation, where **TimeID** = 0, 600, 1200, 1800, 2400, 3000, 3600, 4200, 4800, 5400 and 6000 seconds of simulated flood based on the validated actual storm event in XBeach of 31 March, 2010. A simple SQL query is specified in the data table to extract individual DEM for each timestep based on a specific **TimeID**. The DEM values Z_s and H_s in the predictions contribute to the rate and extent of flooding calculation which is the Z_s divided by u and v components respectively in both x and y directions.

5.2.1 The Rasterisation of Map Features

Linear interpolation methods were used to add flood water depths from the predicted flood DEM in a particular timestep simulation to the urban settlement layers buildings, roads and rivers. These values were critical to the determination of the extent and size of flooding during a simulation and its effects on infrastructure such as property, roads and buildings. A complete dataset of flooding were produced for the buildings, road and river layers which allowed flexible analysis in any time sequence. The resolution of the rasterised features were 0.25 m. Without this predictive analysis, the attachment of flood water depth can only be achieved through post-flood surveys.

The rasterisation of map features such as the River Alt estuary, roads and buildings were undertaken in ArcGIS using the spatial analyst linear interpolation IDW tool which allowed these feature layers to be interpolated with a flooding value approximating the weighted average distance between six flooding points. The feature layers were interpolated with the values of the DEM at TimeID = 6000 seconds. The features were then attributed in a resulting table with flood water depths at a point in time enabling the end-user to identify flooding for these features of interest on the map. Process models **postfloodingproperty** (Appendix B.6.5) and **floodlfootprint** (Appendix B.6.8) were used to assist end-users automation of the data production. In Figure 5.1 the rasterisation of urban settlement data in a pre-flooding impact stage is shown. These technqiues allowed the identification of natural and man-made features by location and flood water depth values, not possible in current numerical flood modelling systems.

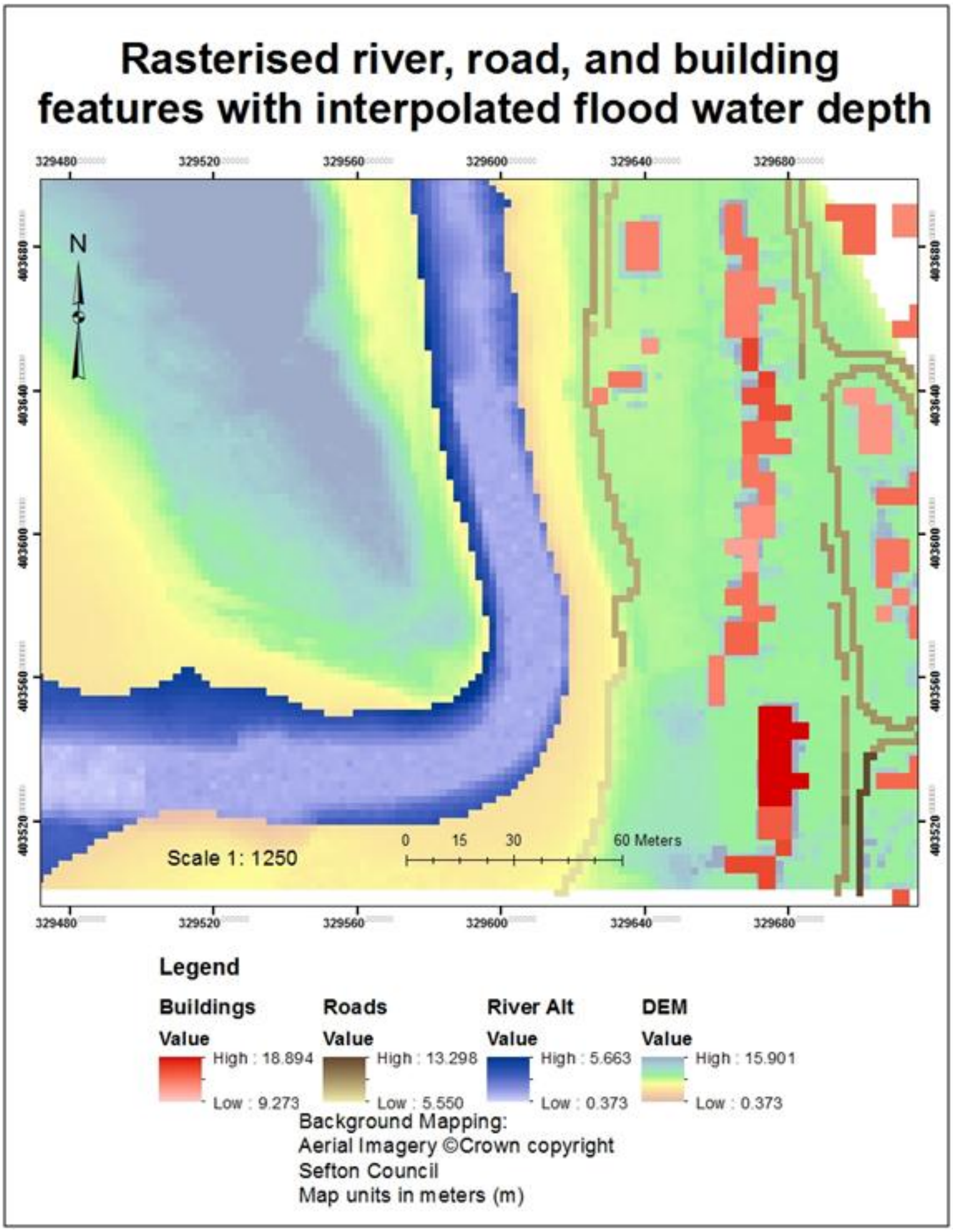


Figure 5.1: Rasterised river, road and buildings features interpolated with flood water depth as spatial grid DEM.

5.2.2 Predictive Flood Risk Mapping

The ArcGIS map algebra tools for raster data allowed the manipulation and comparison of tabular data from pre-flooding and post-flooding DEM. The flood water depth was predicted for an extreme event flood of 3m at the study site. The relative change in water depth $\mathbf{z_s}$ **and** $\mathbf{h_h}$ in the **FloodingPoint** table (Appendix C.1 ArcFLOOD-Coastal Flood Data Model), were manipulated by subtracting the pre-flooding DEM and post-flooding DEM to find the differences in value for **TimeID** to be 6000s (Figure 5.2). A field $\mathbf{z_{s\,change}}$ is extracted using the *minus function* in ArcGIS to show an increase in flood water levels (Figure 5.2) indicating the increase between $\mathbf{z_s}$ and $\mathbf{z_{s\,change}}$ and $\mathbf{h_h}$ and $\mathbf{h_{schange}}$. Average statistics were run to indicate that the average flood increase for **TimeID** = 6000s was for z_s (flood water depth) was 0.752 m and H_h(significant wave height- additional water level on top of the tide) was 0.750 m. These calculations in the table can be applied to any **TimeID**.

Attributes of t0t6000

OID	TimeID	x	zs	Hs	u_1	v	X_1	Y_1	ZS_1	HH_1	U_12	V_1	zsChange	HsChange
0	0	327692	7.408	2.178	0	0	327692	403468	9.302	4.072226	-0.324767	0	1.894	1.894226
1	0	327700	7.408	2.128	0	0	327700	403468	9.303	4.022032	-0.316219	0	1.895	1.894032
2	0	327708	7.408	2.078	0	0	327708	403468	9.307	3.976015	-0.282793	0	1.899	1.898015
3	0	327716	7.408	2.038	0	0	327716	403468	9.312	3.941096	-0.224563	0	1.904	1.903096
4	0	327724	7.408	1.988	0	0	327724	403468	9.318	3.897218	-0.15309	0	1.91	1.909218
5	0	327732	7.408	1.948	0	0	327732	403468	9.324	3.863043	-0.074326	0	1.916	1.915043
6	0	327740	7.408	1.908	0	0	327740	403468	9.33	3.828303	0.007485	0	1.922	1.920303
7	0	327748	7.408	1.858	0	0	327748	403468	9.335	3.783985	0.087171	0	1.927	1.925985
8	0	327756	7.408	1.818	0	0	327756	403468	9.339	3.747975	0.160443	0	1.931	1.929975
9	0	327764	7.408	1.768	0	0	327764	403468	9.343	3.701595	0.226248	0	1.935	1.933595
10	0	327772	7.408	1.718	0	0	327772	403468	9.346	3.654693	0.283974	0	1.938	1.936693
11	0	327780	7.408	1.678	0	0	327780	403468	9.348	3.616938	0.333975	0	1.94	1.938938
12	0	327788	7.408	1.628	0	0	327788	403468	9.35	3.56913	0.376308	0	1.942	1.94113
13	0	327796	7.408	1.588	0	0	327796	403468	9.351	3.530385	0.411216	0	1.943	1.942385
14	0	327804	7.408	1.538	0	0	327804	403468	9.352	3.481627	0.43892	0	1.944	1.943627
15	0	327812	7.408	1.498	0	0	327812	403468	9.352	3.442011	0.459478	0	1.944	1.944011

Record: 0 Show: All Selected Records (0 out of 27440 Selected) Options

Figure 5.2: FloodingPoint table showing the change z_s and h_h in metres between t = 0 and t= 6000s.

Both levels are fairly similar indicating a consistent increase based on two different parameters. Due to the lack of simulation data from XBeach for a model-run of 4 hours a comparison at the final flood level could not be determined. With 4 hours of flooding data simulated, the total flood water level could be linked to the predicted surge level. This result was achieved using simple analysis in ArcGIS. The value of 3m is the imposed extreme event surge in the coastal flood model (XBeach) which was produced after 4 hours of flooding and validated for the March 31 2010 storm event (Williams et al., 2011).

A simple SQL querying was performed on the flooding table in the ArcFLOOD geodatabase to calculate the predicted flood increase where $\mathbf{z_s}$ was increased by 1, 2 and 3 m in the FloodingPoint table. The query returns the actual flood water increase between timesteps and populates a field in the table with this calculation. This field was represented as t = 0 m water level i.e. not flooded. A subsequent SQL query performed an addition of 1, 2, and 3 m flood water level increase and populated new fields within the table **where** $\mathbf{h_h = z_s + 1}$**,** where n= 1 to 3. This basic process is also used by the Environment Agency to apply any flood water depth to return the corresponding flooding in the absence of validated numerical modelling. IDW raster interpolations were generated for the rise in $\mathbf{z_s}$ values. In Figure 5.3, the predicted flood water depth increase (h_{hDiff}) was defined for 1, 2, and 3 m and highlighted in a light blue column in the table which is the default ArcGIS selection colour when new results are returned.

A further spatial function allows the export of the table as flood polygons for spatial mapping. The Environment Agency provides flooding polygons from this similar conversion technique in ArcGIS. The technique used in this analysis exported flood mapping polygons from the tables by using the process model **CreateFloodPolygon** (Appendix B.6.3). This process model compared the input of the **TimeID = 0 seconds** and **TimeID = 6000 seconds** DEM using the *raster calculator less than function* in the *map algebra tool* in ArcGIS. The *less than function* tool compares two rasters and assigns a value of 1 or 0 where one raster is less than the other based on flood water depth. It is a function used to create a DEM based on the difference in the z_s value. The resultant raster grid was converted to flood polygons of specific flood water depth not achievable in numerical flood modelling systems. This method has been validated in the hydrological modelling of fluvial flooding to generate flood polygons using the ArcHydro data model (Whiteaker et al., 2006).

Attributes of predictedfloodlevelincrease

OBJECTID *	TimeID	x	zs	hh	u_1	v	X_1	Y_1	ZS_1	HH_1
1	0	327692	7.408	2.178	0	0	327692	403468	9.302	4.072226
2	0	327700	7.408	2.128	0	0	327700	403468	9.303	4.022032
3	0	327708	7.408	2.078	0	0	327708	403468	9.307	3.976015
4	0	327716	7.408	2.038	0	0	327716	403468	9.312	3.941096
5	0	327724	7.408	1.988	0	0	327724	403468	9.318	3.897218
6	0	327732	7.408	1.948	0	0	327732	403468	9.324	3.863043
7	0	327740	7.408	1.908	0	0	327740	403468	9.33	3.828303
8	0	327748	7.408	1.858	0	0	327748	403468	9.335	3.783985
9	0	327756	7.408	1.818	0	0	327756	403468	9.339	3.747975
10	0	327764	7.408	1.768	0	0	327764	403468	9.343	3.701595
11	0	327772	7.408	1.718	0	0	327772	403468	9.346	3.654693
12	0	327780	7.408	1.678	0	0	327780	403468	9.348	3.616938
13	0	327788	7.408	1.628	0	0	327788	403468	9.35	3.56913
14	0	327796	7.408	1.588	0	0	327796	403468	9.351	3.530385
15	0	327804	7.408	1.538	0	0	327804	403468	9.352	3.481627
16	0	327812	7.408	1.498	0	0	327812	403468	9.352	3.442011

Record: 0 Show: All Selected Records (0 out of *2000 Selected)

HH_1	U_12	V_1	zsdiff	hhdiff	Hpozs3m	hypzs1m	hypzs2m	Shape *
4.072226	-0.324767	0	1.894	1.894226	10.802	8.408	9.408	Point
4.022032	-0.316219	0	1.895	1.894032	10.803	8.408	9.408	Point
3.976015	-0.282793	0	1.899	1.898015	10.807	8.408	9.408	Point
3.941096	-0.224563	0	1.904	1.903096	10.812	8.408	9.408	Point
3.897218	-0.15309	0	1.91	1.909218	10.818	8.408	9.408	Point
3.863043	-0.074326	0	1.916	1.915043	10.824	8.408	9.408	Point
3.828303	0.007485	0	1.922	1.920303	10.83	8.408	9.408	Point
3.783985	0.087171	0	1.927	1.925985	10.835	8.408	9.408	Point
3.747975	0.160443	0	1.931	1.929975	10.839	8.408	9.408	Point
3.701595	0.226248	0	1.935	1.933595	10.843	8.408	9.408	Point
3.654693	0.283974	0	1.938	1.936693	10.846	8.408	9.408	Point
3.616938	0.333975	0	1.94	1.938938	10.848	8.408	9.408	Point
3.56913	0.376308	0	1.942	1.94113	10.85	8.408	9.408	Point
3.530385	0.411216	0	1.943	1.942385	10.851	8.408	9.408	Point
3.481627	0.43892	0	1.944	1.943627	10.852	8.408	9.408	Point
3.442011	0.459478	0	1.944	1.944011	10.852	8.408	9.408	Point

0 Selected) Options

Figure 5.3: Predicted flood increases 1, 2, and 3 m are shown in the fields highlighted in blue for h_{hDiff}.

The resulting query produced the inundated areas as seen in Figure 5.4. The flood polygons were extracted and symbolised using a RBG (red, green and blue) colour model in ArcGIS with corresponding values 0, 38 and 115. For end-user dissemination flooding polygons extracted from the DEM were shown overlaid with buildings, roads and river layers to indicate the threat to urban settlements and an a more accurate identification of flooding in GIS based on the influence of coastal morphology, built structures and topography.

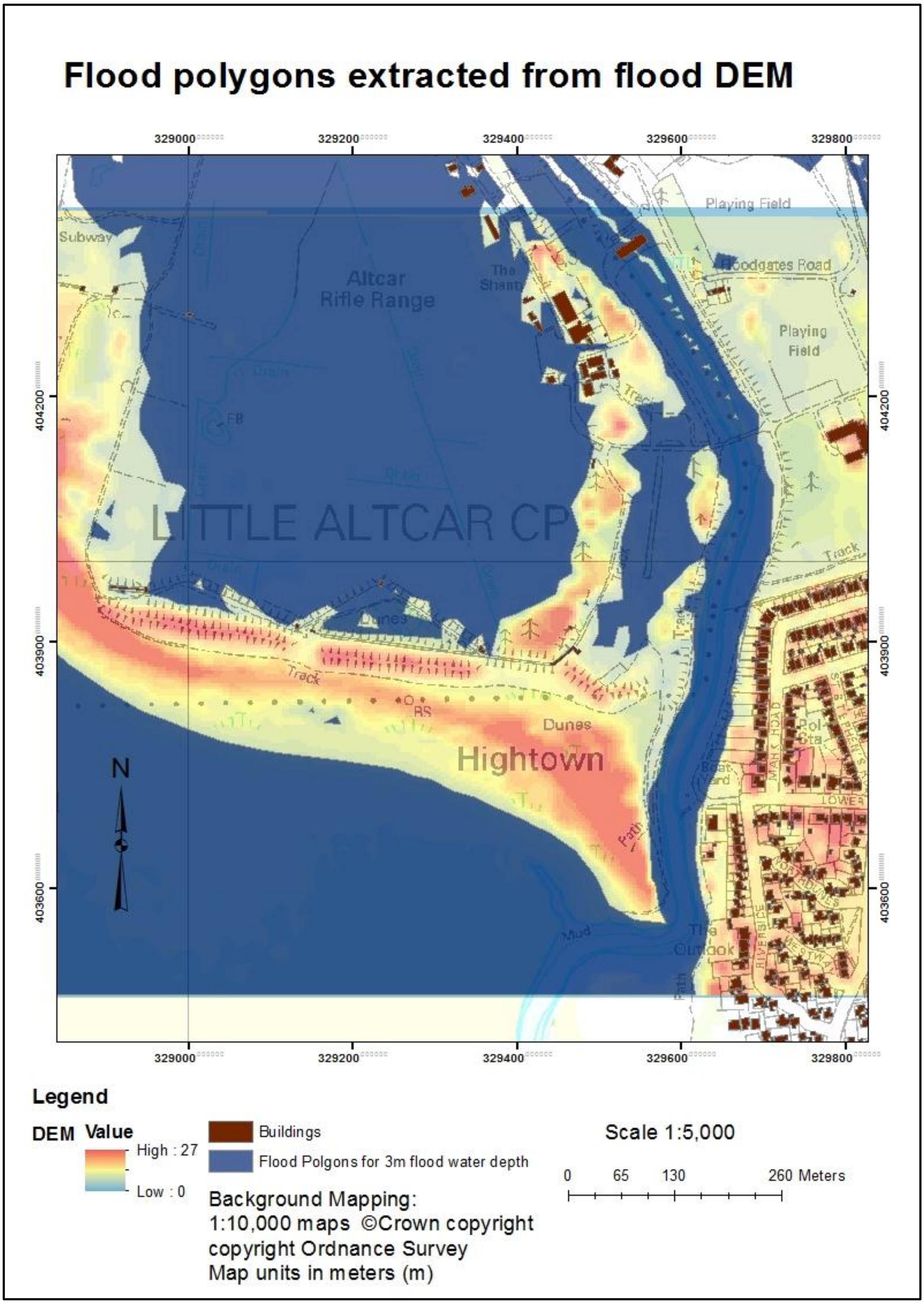


Figure 5.4: Flood polygons for a 3m flood water depth extracted from the spatial DEM and mapped in the study site domain with urban settlement rasterised buildings generated at t = 4 hours. The River Alt overflows its banks onto the Little Altcar Rifle range, training camp, Hightown boatyard, and coastal path.

Future developments in reprogramming XBeach and server side DBMS should address this issue in further model-runs to provide a complete dataset for GIS analyses. The 3m increase depicted below shows the inundation to the flood pumping stations at Hightown. It depicted a scenario of approximately 3m flood rise which corresponds to 4 hours of flooding as predicted by XBeach. These were depicted as flood polygons on the map. It must be mentioned that flood risk mapping has not been standardised in symbology and are typically end-user defined.

5.2.3 Flood Extent Analysis

Further analysis was derived to determine the actual flood extent which defined a flood path after 1.5 hours of flooding (Figure 5.5). ArcGIS spatial analyst tools *less than minus function* in the *map algebra tool*, returned accurately all the flooding points that had increased for that timestep interval where the value was greater than 1 in binary language. An *intersect function* was used to extract the relevant flood points from the landscape. The extracted flood at 1.5 hours was exported as a flood polygon using the **CreateFloodPolygon** process model (Appendix B.6.2). The results extent was mapped showing the water level rising in the eastern Irish Sea above the tide. The legend in Figure 5.5 shows the flood water increases over the normal value of the tide. The data was further symbolised in ArcGIS to give a probable indication of the high risk areas which experienced flooding by creating a new DEM from the flood path (Figure 5.5).

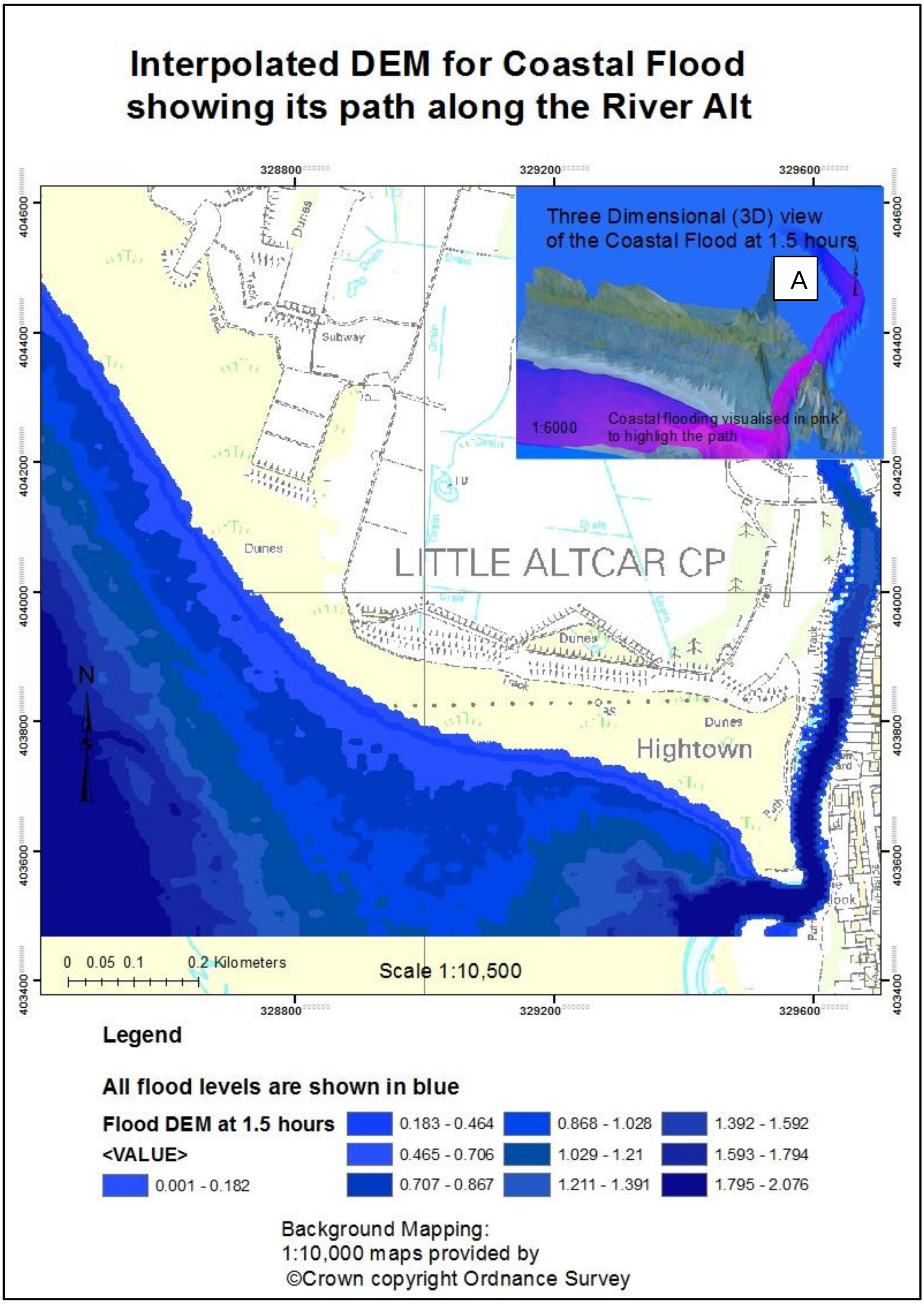


Figure 5.5: Interpolated DEM for coastal flood showing its path along the River Alt after 1.5 hours of flooding. The insert shows the 3D visualisation of the impending coastal flooding after 1.5 hours.

The colours of the flood were represented in graduated shades of dark blue to purple were used to illustrate the varying flood water levels with topography. The HSV (Hue, Saturation and Value) colour model was used as the data was rendered through classification. The corresponding HSV values ranged from (240, 94 and 57) to (193, 100, and 84) to allow symbolisation of the simulated coastal flooding. The map insert A shows the 3D visualisation of the flood in ArcGIS ArcScene as it approaches the mouth of the River Alt from the eastern Irish Sea. The varying colours of pink to purple were symbolised using the colour model HSV (284, 97 and 93) to (76, 0 and 115) to solely exaggerate the increased flood water depth of 3 m moving in 3D along the River Alt.

The extent of the flood path was also shaped by the topography of landscape including the River Alt channel which was used as a *cookie-cutter mask* to extract the areas in which elevation had remained unchanged, removing all the areas where there were flood increases.

5.2.4 High and Low Flood Risk- Hotspot Mapping

The cluster and outlier spatial analysis technique used the spatial analyst tools to generate clusters of extreme high and low statistical flood mapping referred to as hotspot mapping. Cluster values based on low and high flood risk were returned. The method has been proven to provide 95 per cent confidence level for over 30 features in GIS. This technique identified statistically significant low values of flooding in the sand dune area based on the Z_s value. The technique produced a point file of low and high values which were interpolated with IDW to re-create a DEM of flood risk mapping.

In Figure 5.6 the hotspot mapping of flooding in the study site domain was shown indicating that the blue areas correspond to the high flood risk zones and the yellow areas to the low flood risk zones. All other colours corresponded to the low risk flood zones which were cross-referenced with contours and aerial imagery to verify the dry areas as higher ground in the sand dunes. The colour was symbolised using a RBG (red, green and blue) colour model in ArcGIS with corresponding values 0, 112 and 255 to represent the flooded areas. A differing shade was used solely to contrast with the DEM.

These results indicated a high likelihood that the low levels of the sand dunes can be breached in a most extreme storm event. It also indicated the most resistant sand dune locations which are useful as decision making tool. However, the techniques did not produce an estimate of coastal flooding. This technique demonstrates the scope of GIS spatial analyses.

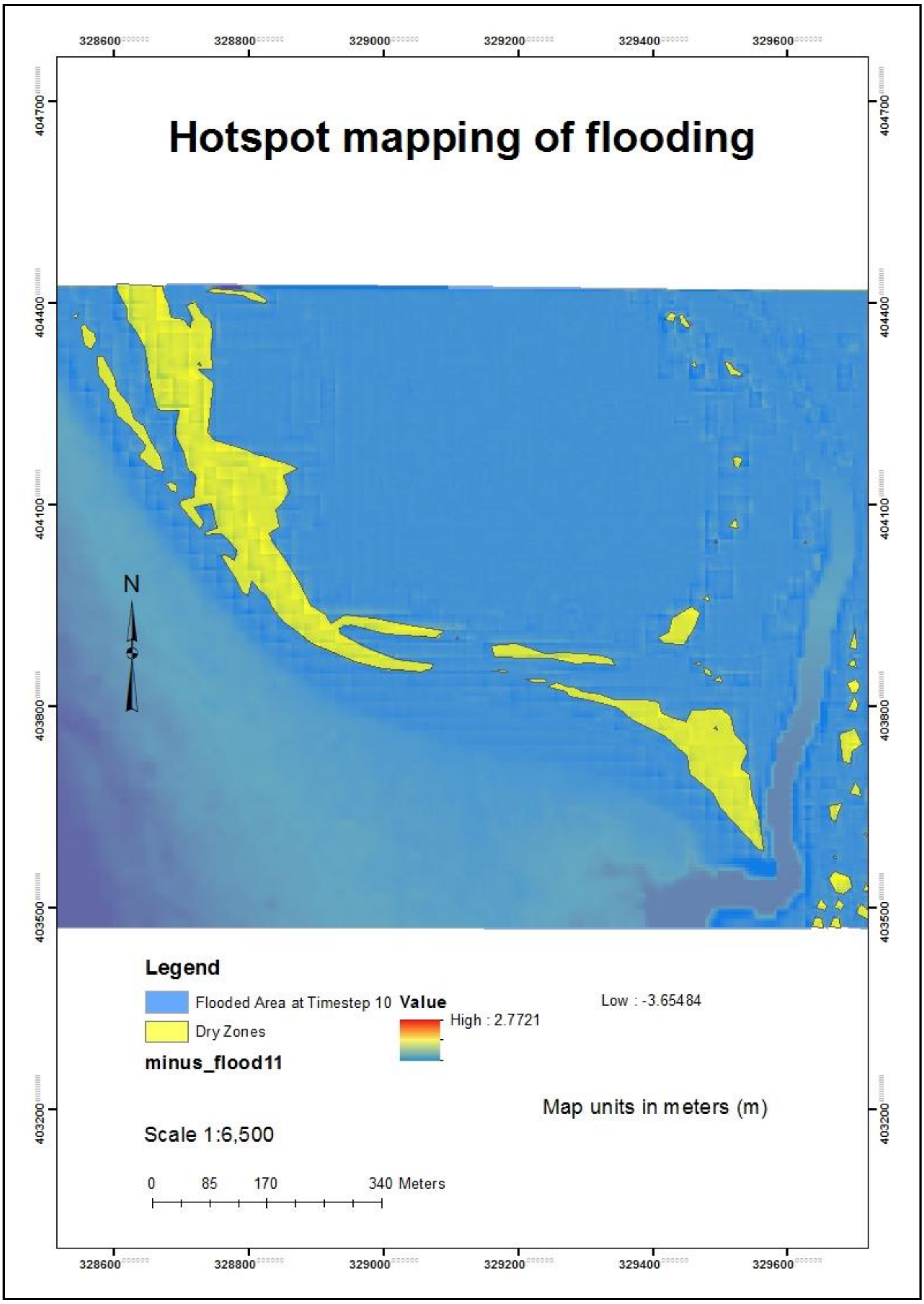


Figure 5.6: Hotspot mapping of flooding in the study site domain is shown indicating that the blue areas correspond to the high flood risk zones and the yellow areas to the low flood risk zones.

5.2.5 Time Varying Flood Water Depth

The process model **CalCHangeFloodWaterLevel** (Appendix B.6.6) provided the calculations to produce the change in flood water depth at a building between varying **TimeID**. The calculations to determine the flood water depth at a point were computed from the **totaltimestepsimulation** and **FloodingPoint** tables. Rasterised buildings and property were merged with the post-flooding grids. In addition, the **FloodLevelChangeDiffTimesteps** process models (Appendix B.6.9) also produced flood levels at a point and a resultant flood change table. The resultant map of relative change in flood water depth at the River Alt based on these calculations was indicated in Figure 5.7 with a table insert showing the minimum and maximum flood levels between timesteps of the selected locations on the map with their pre-flood and post-flood values showing an average of above 2 m rise in water levels for this timestep around the Hightown Marina, the Sefton Coastal path and B-roads. Further analyses can be undertaken using probabilistic methods found in the MAST tools to determine the statistical variations of the water levels (Environment Agency, 2011). The River Alt was depicted using a RBG (red, green and blue) colour model in ArcGIS with corresponding values (0, 38 and 115) in ArcGIS. A blue algorithmic colour ramp was used in the stretched colour renderer in ArcGIS to symbolise the DEM.

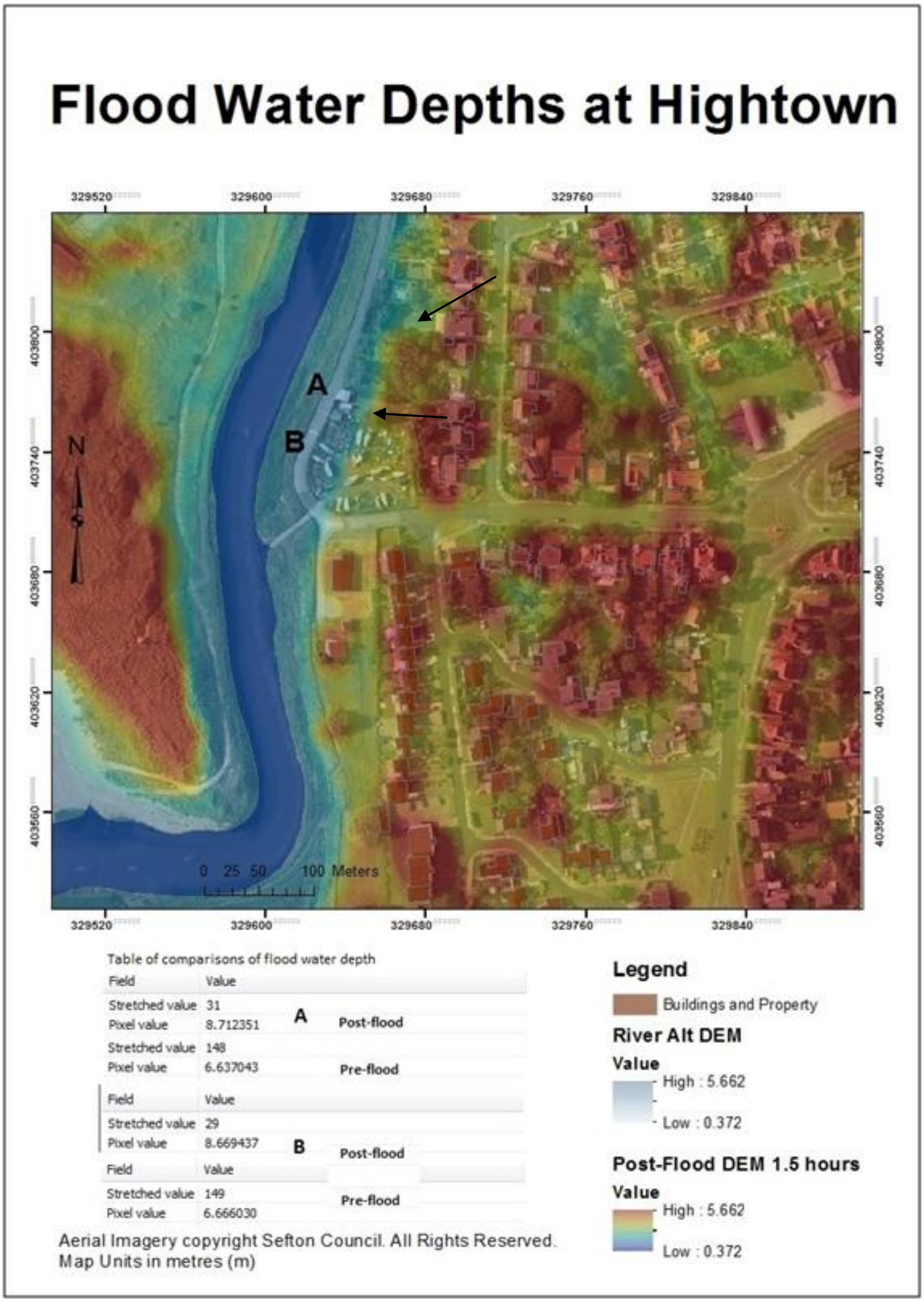


Table of comparisons of flood water depth

Field	Value		
Stretched value	31	A	Post-flood
Pixel value	8.712351		
Stretched value	148		Pre-flood
Pixel value	6.637043		
Field	Value		
Stretched value	29	B	Post-flood
Pixel value	8.669437		
Field	Value		
Stretched value	149		Pre-flood
Pixel value	6.666030		

Figure 5.7: Flood water depths at flood prone buildings, public pathways and roads calculation.

To improve this analysis for flood risk assessments, the **BufferProperty_Map** (Appendix B.6.7) and **FloodFootprintBuildings** (Appendix B.6.8) process models generated the datasets to produce flood risk mapping. By joining the buffer table with the flood change table and the buffer distance polygon, a corresponding table of pre-flood and post-flood heights were produced. This allowed the identification of the flood water depth at a point in time and relative increase in flood water depth. The buffer analysis in GIS returned the maximum flood depth at any point on the map based on a user specified extent chosen in a GIS. It was found that the flood depth values varied significantly across the study site showing coincidence with topography and the inability to predict trends without probabilistic testing.

5.3 Analysis of Coastal Flooding Results

In the past Hightown has been affected by coastal flooding exposing some property and infrastructure to damage. No loss of life attributable to coastal flooding has been known during the last century. The area is protected with flood defences including flood gates and embankments which have protected the coast and human lives. In previous storm events it has been noted that tidal elevations soak the dune toes exposing the dunes to coastal wave action (Pye and Blott, 2006). In the study site, the River Alt acts as conduit to spread the flood inundation inland.

The results provided by XBeach show that coastal flooding inundated the Altcar Rifle Range and surrounding land behind the dunes with minimal impact on the dune frontage. It was found that the present dunes can withstand the current simulation with some local inundation. It has been noted that slumping of the dunes has been simulated at Formby and Hightown. The Sefton Coastal footpath was also inundated with some B-roads being affected providing other possible routes to spread the waters inland into the Altcar Training camp and flood gates (Williams et al., 2011). No simulations were done to spread the water further inland. Flood risk maps were produced to indicate the flood waters moving up the River Alt and overflowing the embankments and flood gates along its path.

The mapping produced in this research has processed the results of the XBeach time series predictions to provide more intelligent mapping designed for spatial querying in GIS. Ordnance Survey mapping were used to provide the background data to give a location context and link predicted flood risk to infrastructure, land types and buildings. In the GIS, the analyses have embedded flood water depths into these features through spatial raster interpolation techniques. These spatial analyses techniques are generally undertaken by end-users and not provided by the Environment Agency.

The flood risk mapping presented provided an indication of the vulnerability of these locations to the potential rise in 1m, 2m, and 3m flooding. The maps indicated the sites which were most likely to experience an extreme event coastal flood. The locations which were most at risk were identified as Hightown homes and marina at high risk of a 1, 2 and 3 m flood increase (Figure 5.8); Altcar Training Camp, Ranger Centre and Pump House at high risk of a 1 m, 2 m and 3 m flood increase (Figure 5.9); and the Hightown Flood Gates at high risk of a 2 m and 3 m flood increase (Figure 5.10). The flooded areas DEM were represented using a classified colour ramp in ArcGIS and an HSV colour model with corresponding flooding defined as 239, 100 and 38.

Within the study site, these flood risk maps indicated the most vulnerable locations to include: Hightown marina; the Sefton coastal path; B-roads along the River Alt; the flood pumping station and gates which were breached; the Altcar training camp and Altcar rifle range; and the land behind the sand dunes at Hightown. It was seen that after a 1m increase in flood water depth the locations inundated the Hightown marina (Figure 5.9); the Altcar training camp, rifle and pumping stations (Figure 5.9). After 2 and 3 m increase in flood levels the locations which were most at risk were the Sefton coastal path and residential areas of Hightown bounded by the River Alt embankments. The coastal flood waters were also seen to infringe the B roads near the embankments disrupting transportation and access. It is important to mention here that the flood risk DEM's incorporated the main flood defence barrier located at the mouth of the River Alt and the embankments of the River Alt in the GIS dataset which were pre-processed for XBeach simulations.

Using the predicted GIS vulnerability mapping, end-users have a visualisation of coastal flooding which allows the interrogation of a flooding surface flood risk to identify at risk urban settlement layers such as buildings and roads. Cross-referencing the imagery from the XBeach River Alt simulation shows a positive correlation with the generated results of the spatial analyses of a 3m extreme event coastal flood.

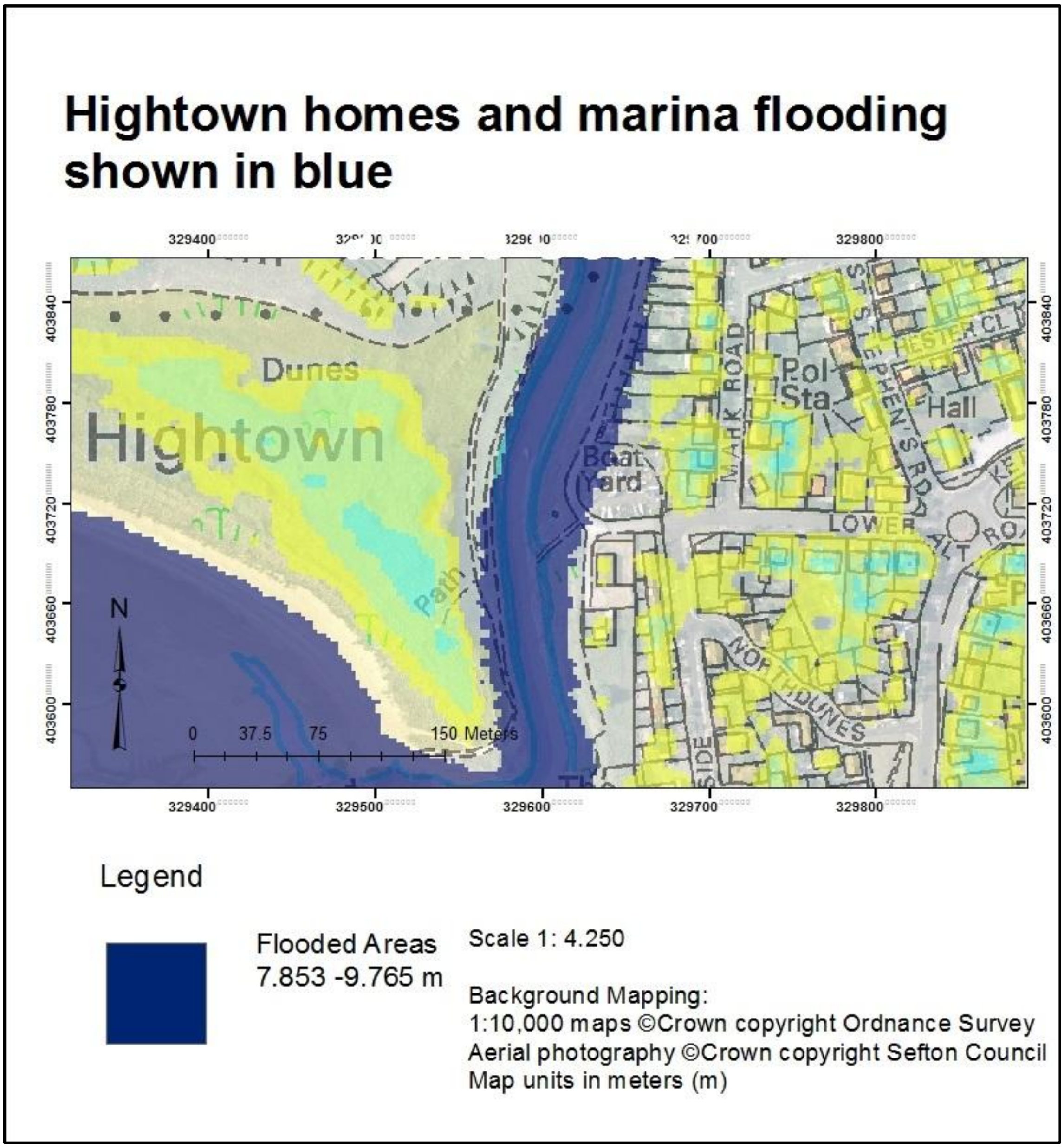


Figure 5.8: Hightown homes and marina at high risk of a 1, 2 and 3 m flood increase.

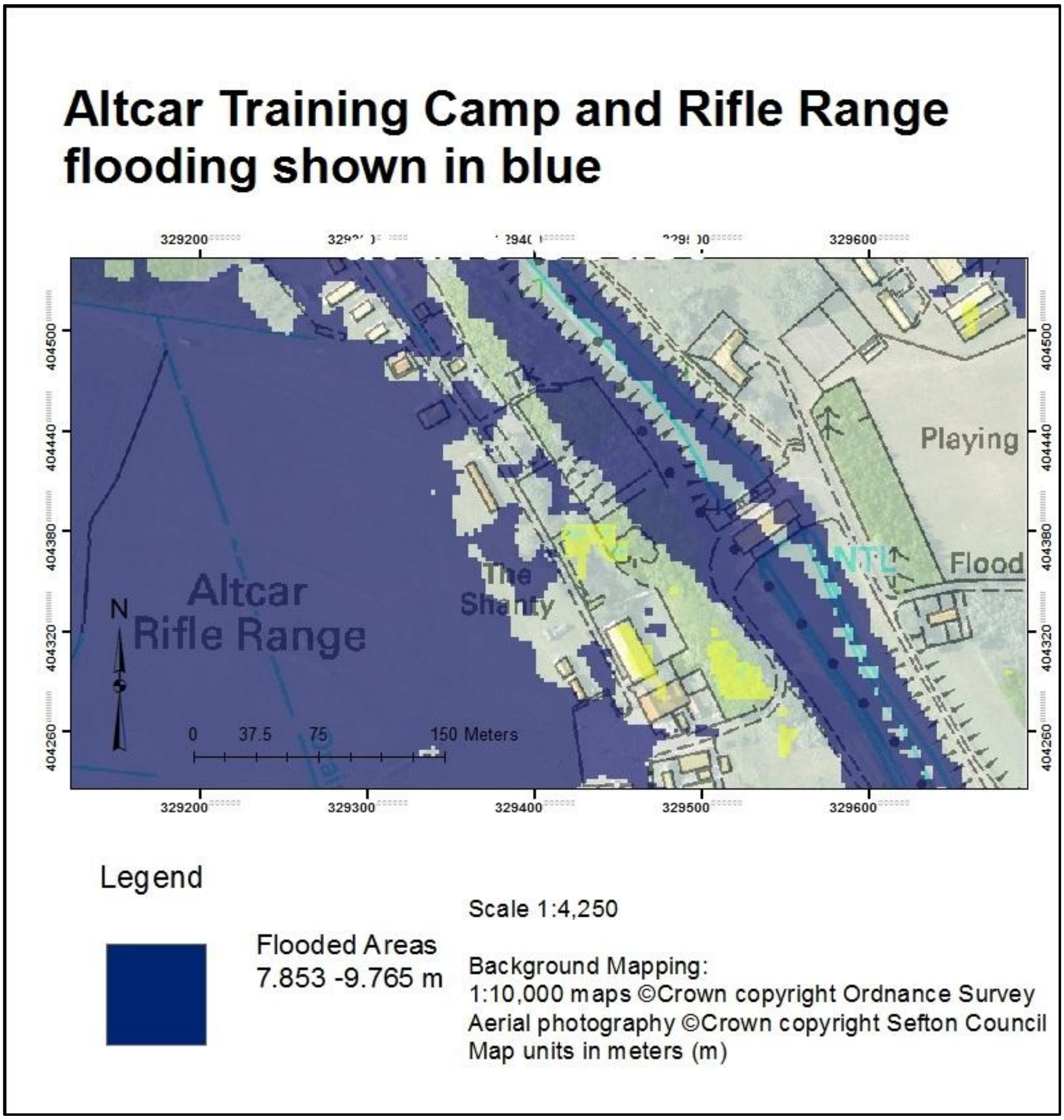


Figure 5.9: Altcar Training Camp, Ranger Centre and Pump House at high risk of a 1 m, 2 m and 3 m flood increase.

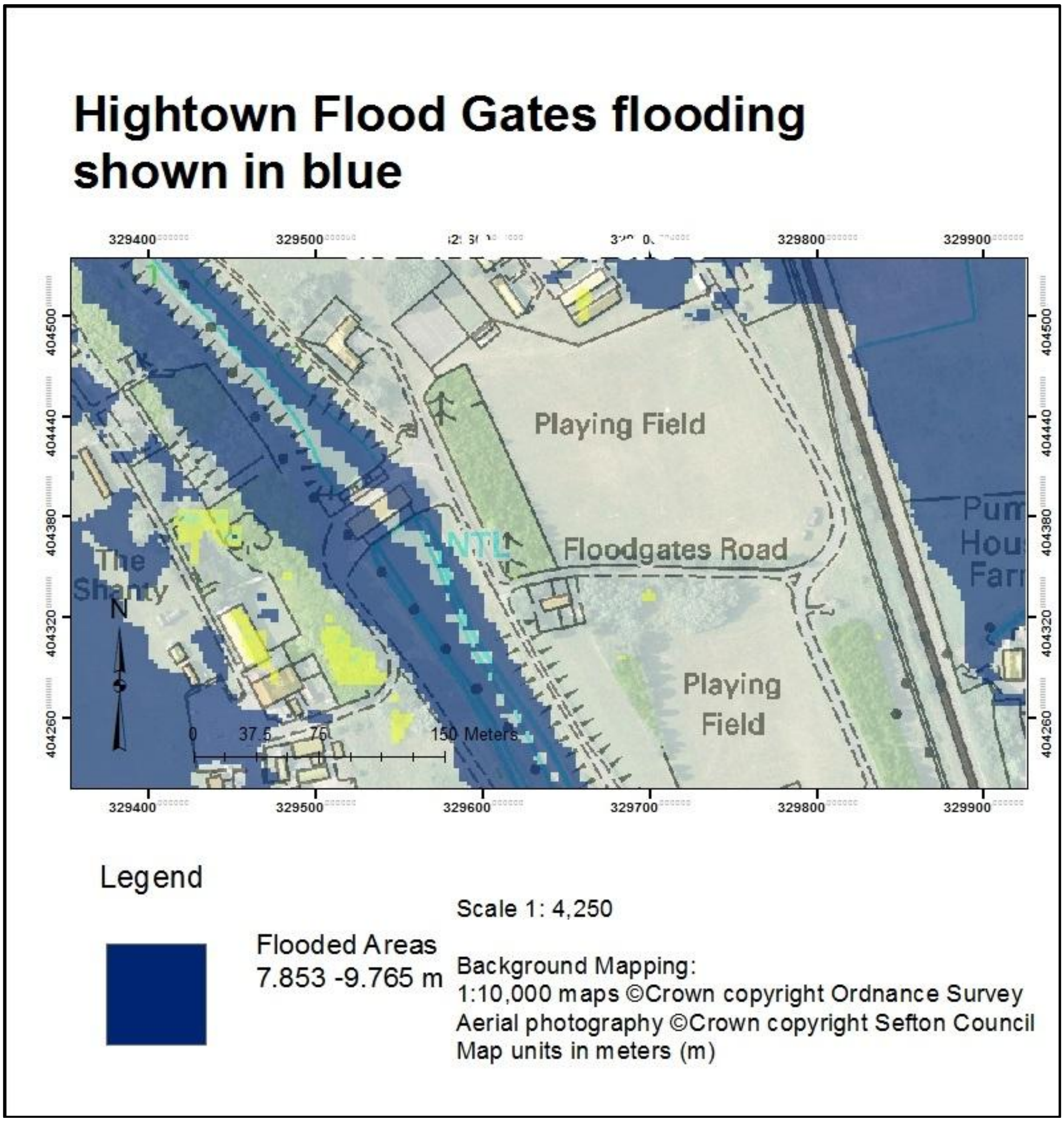


Figure 5.10: Hightown Flood Gates at high risk of a 2 m and 3 m flood increase.

5.4 Discussion

The manipulation of the ArcFLOOD geodatabase and the use of the process models provided the datasets to produce spatial analyses of flood water depth at a point and flood water depth increase which indicated the rate and extent of flooding when mapped. Through the **Timestep** data and **TimeID** all entities in a flooding system were related to provide the estimates of depth at a point (flood level) ($\mathbf{z_{s\ change}}$) and flood water increase which equated to significant wave height ($\mathbf{h_{schange}}$) increase. The latter value was related to the level of the water level on top of the tide. The ability to identify flood water levels at the time of occurrence of a flood is not provided by the Environment Agency flood risk mapping currently due to a lack of more accurate numerical modelling. With further XBeach modifications, future results in ArcGIS can include velocities of the flood water and the rate of flooding. The velocity fields of u and v simulation results were incomplete and unable to provide reliable predictions. However, time dependent flood polygons were produced which has represented advances in the modelling of floods.

In this research, the flood depth was indicated at any point and feature in the study site. The number of properties located within a floodplain has been mapped with the rasterised overlay of the OS Mastermap buildings and property layer identifying flooded buildings in Hightown, flooded roads and path; and river bed flood depth. This represents a significant improvement as flooding polygons currently supplied by the Environment Agency have not been attributed with feature water depths.

The flood risk mapping provided is an aid to flood mitigation warning the local authority Sefton Council of potential disaster locations and an indication of property damage in the local area. The failure of the infrastructure such as the pumping stations at Hightown is pertinent to utility companies' emergency preparedness. The identification of affected property and infrastructure can provide damage and loss estimates with insurance agencies when combined with property statistics from the Land Registry and re-insurance data. The flooding analysis will allow the planning of better flood defence systems as a result of the failure of the flood gates, levees and embankments. In the wider implication, the results aid the definition of future coastal defence needs.

Chapter 6

Practical use of ArcFLOOD

6.1 Introduction

The ArcFLOOD data model addresses the flood risk mapping problems currently encountered in integrating numerical flood modelling predictions in end-user environments. The use of the ArcFLOOD data model provides targeted end-user results on the potential impacts of coastal flooding. With the threat of an increase in the frequency and intensity of storms to coastal settlements such as Hightown, this research will aid in the broader context flood risk mapping. In addition, it is seen that the visualisation of flooding predictions on the internet's new generation of smart-mobile devices rely on XML schematisation to represent data. XML schema translates GIS data through a series of protocols into internet visualisations. The visualisation of ArcFLOOD in these platforms will aid emergency preparedness and public participation.

Discussions on the impact of how this complex data modelling can work in practice is discussed by examining the current use of flood risk mapping with the implementation of ArcFLOOD in the following areas:

a. Comparisons with current Environment Agency visualisations of flood risk mapping.
b. Global flood risk mapping which provides a benchmark for visualisation in the end-user environment.

c. End-user implementation of visualisations arising from the manipulation of data in ArcFLOOD.

6.2 Comparisons of Flood Risk Mapping

The Environment Agency is the leading authority on coastal flooding prediction and management in England and Wales which determines and manages the impact of climate change on the coasts and long-term coastal flooding. Data exchange partnerships exist with the Met Office and the National Oceanographic Centre for instance to provide up-to-date real time monitoring data to maintain flood risk mapping. One of the Environment Agency's primary roles is the determination of flood risk; flood forecasting; and disaster warning and preparedness (Environment Agency, 2013b).

Sefton Council is an end-user of the Environment Agency coastal flooding policies. At a regional local government level, the policy is focused on using the Catchment Flood Management Plans (CFMP's) to manage inland flooding risk and Shoreline Management Plans (SMP) for coastal flooding and erosion risk. Various interconnecting policies for coastal zone management include the projects *Making Space for Water* (DEFRA, 2005); and the coastal and maritime strategies with English Nature and the National Trust which Sefton Council to manage the physical landscape.

Sefton Council is given statutory responsibility for implementing government approved flood risk management strategies in alignment with the management of the borough council, guided by the priorities of the SMP as the main consultation document (Figure 6.1). This document is the basis of Sefton Council's flood policy. The policies prioritise data management of coastal flood risk as imperative to flood risk mitigation. Sefton Council will use SMP documents to plan and implement coastal defence strategies; and maintain sea defences on beaches, sand dunes and salt marshes consistent with the natural character and conservation of the coast (Sefton Council, 2010). The coastal policy is based on strategic defence options which maintain the strength of the flood defences along the shoreline. The shoreline management plan incorporates the prediction of the evolution of the coast due to climate change drivers such as extreme weather events which were investigated through the COFEE project (Williams et al., 2008). Sefton Council will use the outcomes of the GIS deliverables of the COFEE project to aid flood risk mapping.

The flood maps provided by the Environment Agency are the means by which flood risk is represented in England and Wales. They are used to map the predicted locations of floods with reference to flood defences, indicated flood plains, and urban settlement data from the Ordnance Survey such as OS MasterMap and national background mapping. These maps are constantly being revised from the analysis of topographic survey data and LIDAR techniques used to produce updated DEM to generate flood water levels.

On the Environment Agency website, public users of the system can access flood information through postcode searches in an online GIS mapping application. The flood information depicted are the chance of occurrence of 1 in 100 (1/100) and 1 in 200 (1/200) flood mapping events which are shown on various Ordnance Survey mapping backgrounds ranging from 1 in 50,000 (1:50,000) to 1 in 10,000 (1:10,000) scale mapping (Figure 6.2).

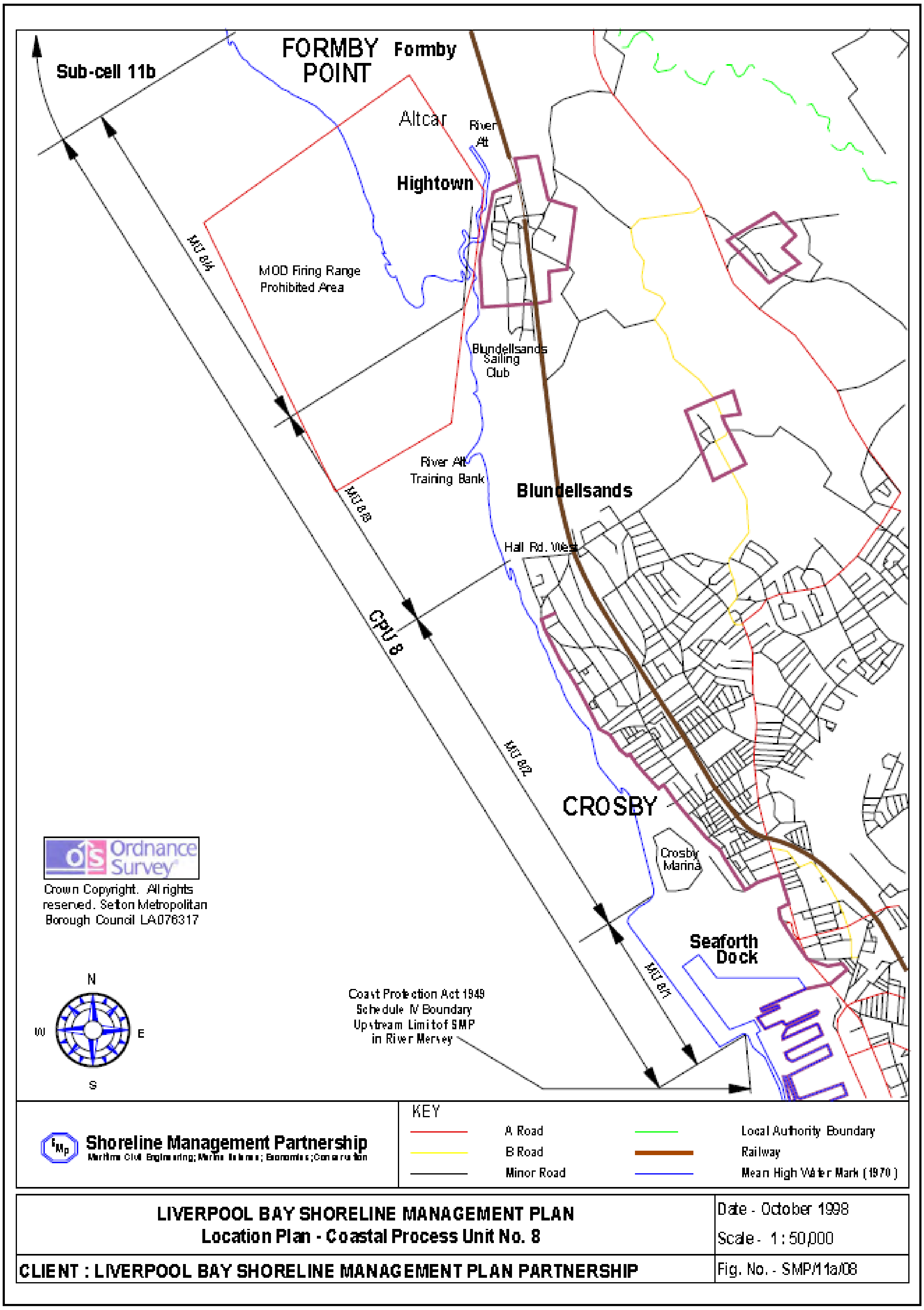


Figure 6.1: Liverpool Bay Shoreline Management Plan 2010 used to manage the Sefton Coast for coastal defence (Sefton Council, 2010). Permission to reproduce this image has been granted by Sefton Council.

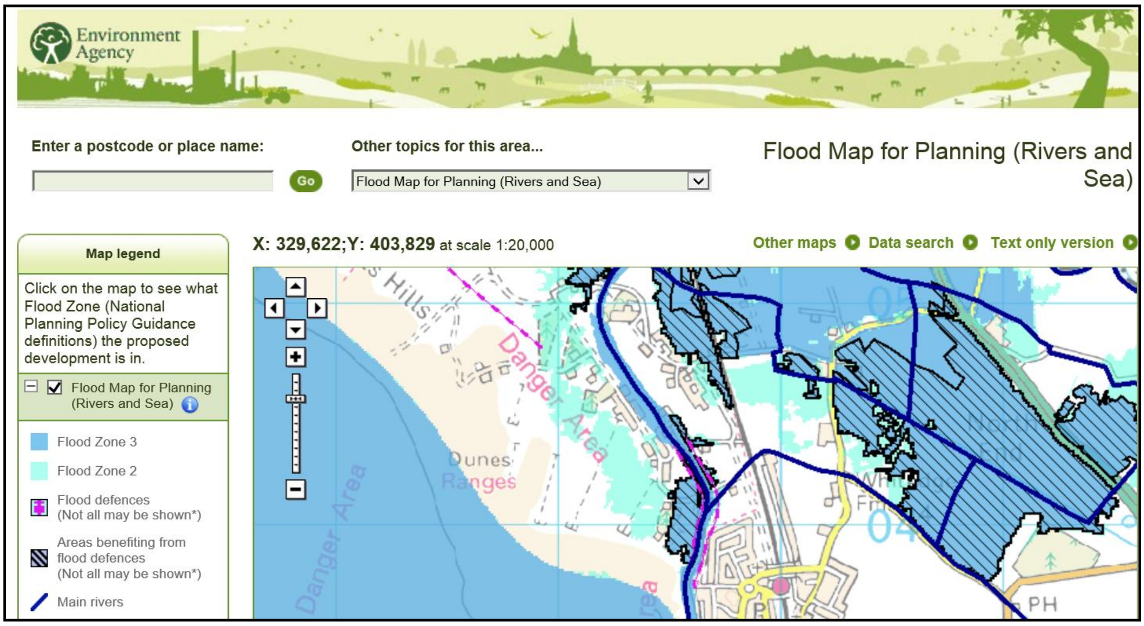


Figure 6.2: The Environment Agency online flood map designed for public access to national flood information (Environment Agency, 2014). Permission to reproduce this image has been granted by the Environment Agency.

The Environment Agency flood map predictions are generated based on a combination of 1D flood inundation models such as TUFLOW, without the complex hydrodynamic and morphological interactions of tide and surge, as found in the linking of the Liverpool Bay Model and the Coastal Flood Model. Extreme floods with a 1/1000 (0.1 percent chance of occurring) may be provided to end-users. However, the public flood map is the national flood information provided to end-users such as Sefton Council and the public alike. In Figure 6.2, it was seen that the land behind the sand dunes at Hightown were flooded which resembled the results of XBeach modelling. The similarities of this research to the flood map were that the predictions represent a 1 in 100 extreme event. However, the significant differences with the flood map and the results of this research included:

a. The use of tide and surge interactions as defined by hydrodynamic and morphological modelling in the Liverpool Bay Model and Coastal Flood Model which allow the more accurate depiction of a coastal flood due to storm surge characteristics.

b. The flood extents predicted differ slightly in the spread and amount of flooding specifically in the area behind the sand dunes at Hightown. It was found that the results of this research show more flooding in that locality as depicted in Figure 6.2 the Environment Agency tidal flood risk of a 1/100 year and; Figure 6.3, the Environment Agency tidal flood risk of a 1/200 year event. In Figure 6.4, the comparisons of the Environment Agency mapping with XBeach predictions in insert A showed that the simulation at 4 hours coincided with the flooding extent results of ArcFLOOD data modelling predictive analysis technique which assumed a correct pre-flood DEM and post-flooding up to 1.5 hours. The map in Figure 6.5 shows the 1/100 year flooding prediction supplied by the Environment Agency draped with the XBeach prediction results. The darker RGB colour was shown to represent XBeach predictions. The lighter blue Environment Agency colour identified the difference in mapping extent. More land was flooded behind the sand dunes in the Altcar Rifle Range location from XBeach predictions. This identified an area where an extreme flood will have a greater impact. The areas along the River Alt will experience the impact of the extreme coastal flood.

c. The results of this research has produced a *timestamped* flood polygon prediction which shows the predicted flood according to time of duration according to the analysis of time series data. It also provided a DEM map where any point was interrogated to provide an estimate of predicted flooding. The Environment Agency map is designed for query to return flood water depths.

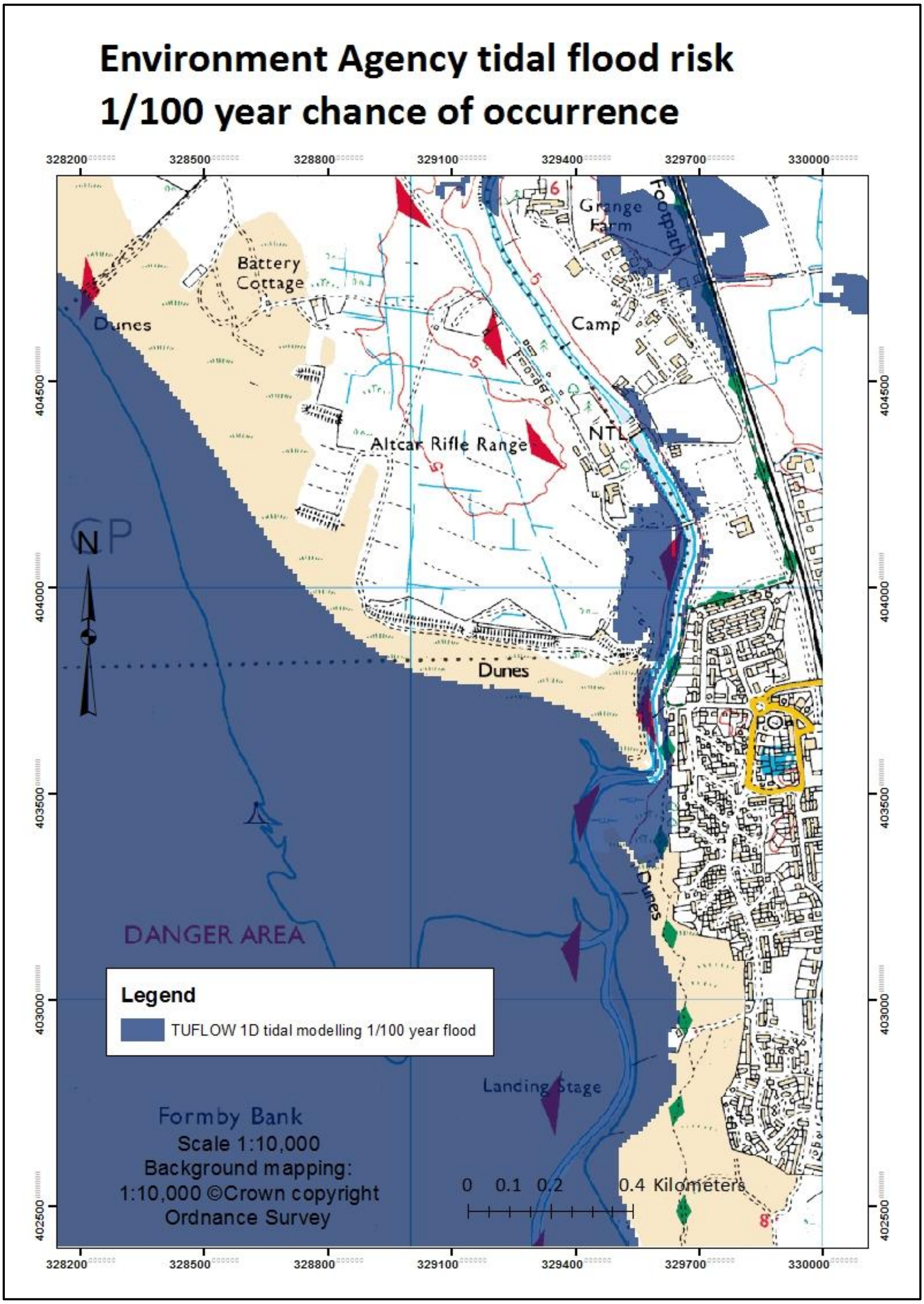


Figure 6.3: Environment Agency 1/100 year TUFLOW data mapped as a flood Map of Hightown (Source: Environment Agency flood polygons obtained through personal communication).

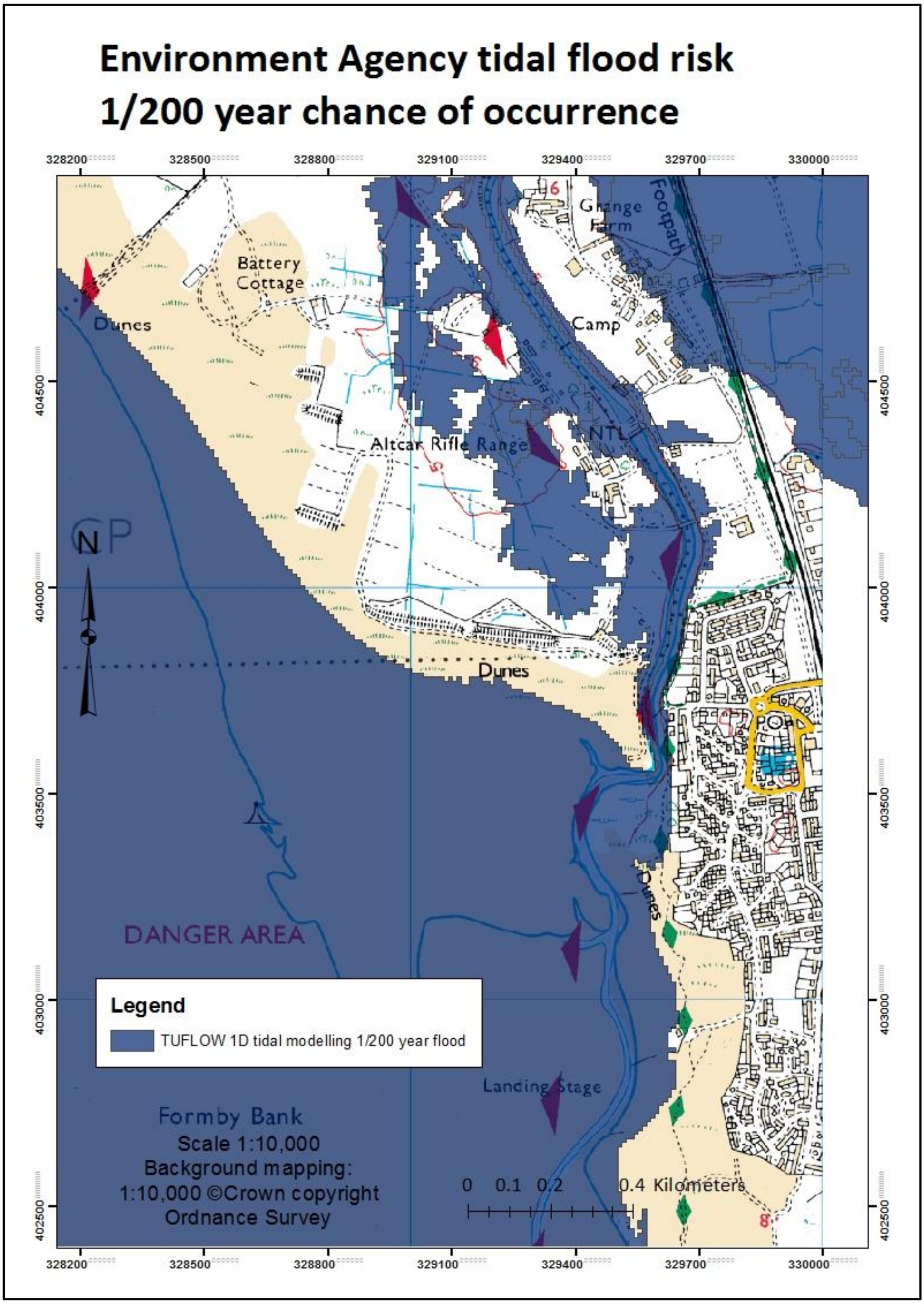


Figure 6.4: Environment Agency 1/200 year TUFLOW data mapped as a flood Map of Hightown (Source: Environment Agency flood polygons obtained through personal communication).

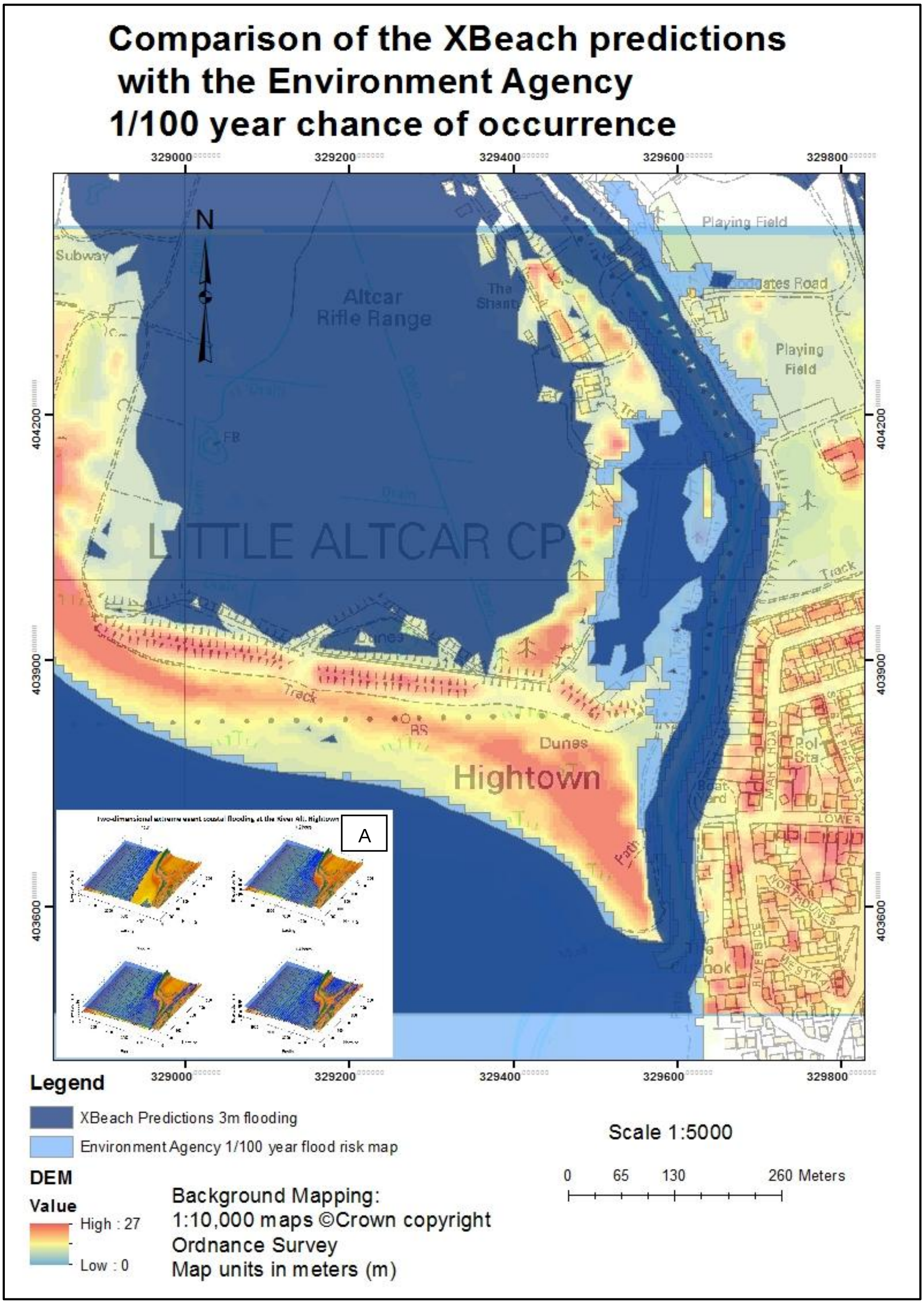


Figure 6.5: Comparison of the Environment Agency 1/200 year Flood Map of Hightown and XBeach flood polygons with insert A showing the XBeach simulation results in seconds (Source: Environment Agency flood polygons).

d. The XBeach predictions also accounted for the location of the main flood defence barrier which is located at the mouth of the River Alt, providing an improved prediction as the flood waters overtop the barrier.
e. The data modelling has produced the extraction of flood polygon layers at different times for instance **TimeID** = 0, 600, 1200, 1800, 2400, 3000, 3600, 4200, 4800, 5400 and 6000 s.

Sefton Council end-users can assess the flood predictions to produce impact assessments at various stages during a flood's duration to aid improved emergency preparedness. The implication of data modelling is that it offers Sefton Council a greater means to undertake advanced GIS analyses without the dependency on the Environment Agency. End-users are empowered with a range of GIS tools.

6.3 Global Flood Risk Mapping

Many similarities exist with flood risk mapping in the global context. The use of GIS internet mapping remains the communication method for flood risks. The Scottish Environment Protection Agency (SEPA) manages flood risk and flood warnings using similar GIS internet mapping as the Environment Agency. SEPA uses a GIS Scottish Flood Defence Asset Database (SFDAD) to store flood defence information and flood risk maps. Similarly in the US, the government agency Federal Emergency Management Agency (FEMA) utilises an internet based flood hazard mapping website for public and professional users. The national *flood hazard layer web map service* in Google Earth is the predominant tool. Another application, *Stay Dry GIS* provides a full range of flood hazard information and flood insurance data to the public for any location in the US using Google Earth (Figure 6.6). The *Stay dry GIS* flood hazard map allows users to download data and view flooding using Google Earth; it is similar type of internet mapping dissemination of coastal flooding predictions by the Environment Agency. In addition, the US National Oceanic and Atmospheric Administration (NOAA) *Sea level and Coastal Flooding Impacts Viewer* is another GIS online mapping system used to visualise potential future sea levels; simulations at points; and examines tidal flooding.

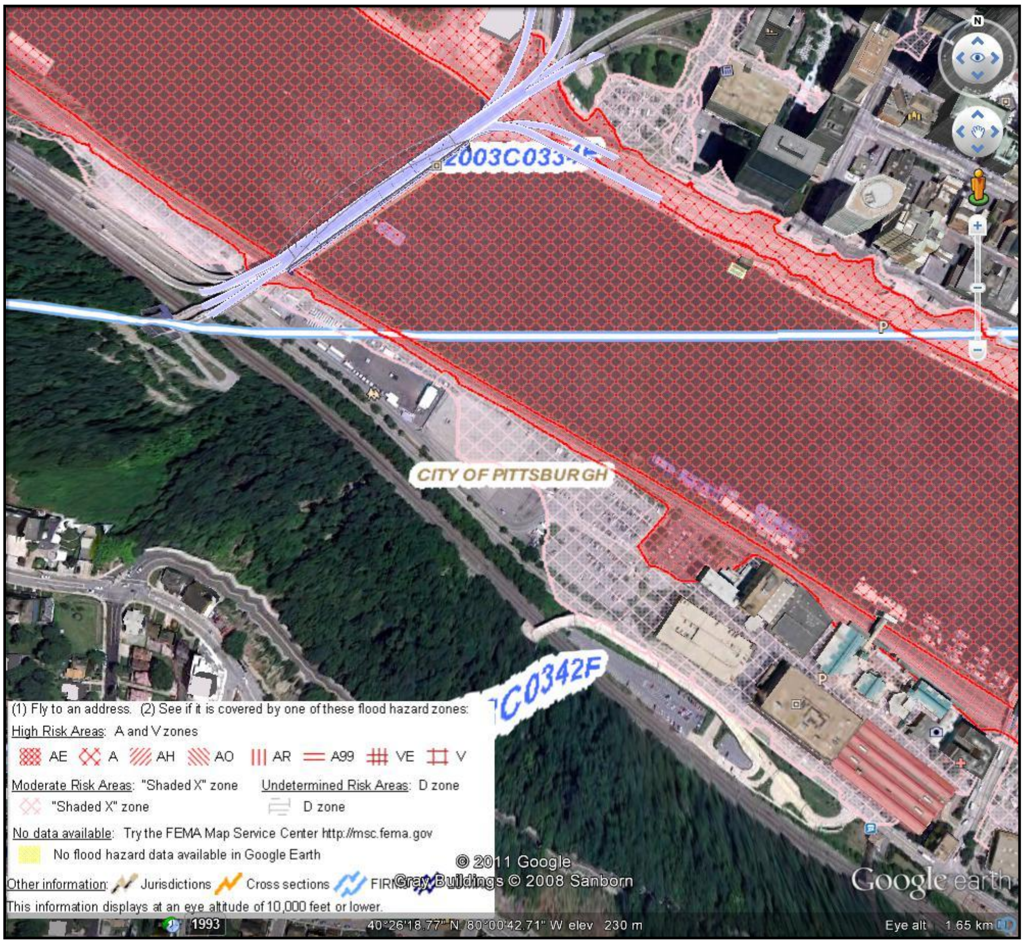


Figure 6.6: FEMA Stay Dry GIS Flood Hazard Map in Google Earth (FEMA) (Available from: http://www.fema.gov/library/viewRecord.do?id=3293. Permission to reproduce this image has been granted by the Department of Homeland Security, the Federal Emergency Management Agency (FEMA).

These mapping agencies are seen to use similar flood risk mapping on the internet to communicate public flood risk. The development of ArcFLOOD allows rapid assimilation of coastal prediction data into the internet mapping visualisations through its extensible and customisable structure; and XML schematisation. Sefton Council can now appropriately develop internet applications to a range of their requirements. The identification of coastal flooding data, relationships and technological framework enables a new generation of internet mapping visualisations for Sefton Council. In addition, the ArcFLOOD data model is relevant in the global context as the data model has outlined standard structures for coastal flooding modelling data in a widely used GIS platform enabling its use in the international context.

6.4 Advances in Data Exchange Standards

End-users of flooding predictions within the COFEE project are unable to share coastal flooding related data due to a lack of DBMS architecture. The ArcFLOOD data model allows the British Oceanographic Data Centre to integrate coastal flooding related data and predictions into their *National Oceanographic Database*. This database allows sharing between NERC centres such as the National Oceanographic Centre and other partners such as Sefton Council. ArcFLOOD has demonstrated that its data structures can be seamlessly integrated with the *National Oceanographic Database* by having satisfying the following data requirements (British Oceanographic Data Centre, 2014):

a. Formatted data which is well-documented and conformant with widely internationally agreed formats such as ASCII, netCDF and ESRI formats.
b. Data exchange formats are interoperable with open source tools such as XML which are readable by freely available open source tools.
c. Data structures and properties which are clearly consistent throughout and uniquely identify all tables and file properties.

As a result, the research of satisfying these *National Oceanographic Laboratory database* requirements, coastal flooding predictions and the improved information will be readily accessible across the COFEE partnership and to a wider international context for sharing and dissemination. Another advantage to both the British Oceanographic Data Centre and Sefton Council is the availability of XML schematisation of ArcFLOOD which allows end-users the capability to develop visualisation techniques using internet platforms, to improve flood mitigation and emergency preparedness. Most importantly, ArcFLOOD has allowed a bespoke data architecture upon which coastal flooding application development can be undertaken. The software development time is reduced allowing faster prototyping.

6.5 Discussion on Future End-User Implementation

It will be demonstrated in this section how third-party external agencies can use the results of ArcFLOOD to prototype interactive software on the internet, making use of technological innovations which widen the scope of coastal flooding to formerly un-related fields in IT in a *coastal flood visualiser* tool. This tool is explained firstly, in the context of technologies which are leading GIS mapping and visualisation on the internet. These tools include *map mashups* and *Digital Earth*. End-users have migrated desktop applications to the internet to meet a wider audience of users including the public.

6.5.1 Map Mashup Internet Mapping

Mapping visualisations in GIS has moved from the traditional desktop to the internet. Specifically, the mapping of disaster information on the internet through *map mashups* using Digital Earth (DE) software such as Google Earth have emerged as a popular public participation tools for the non-professional cartographer (Liu and Palen, 2010). Map mashups are generally user-created mapping merged from diverse sources of free mapping (Hakley et al, 2008). The technology supporting map mashups are based on using extensible markup language (XML), which is the programmable web language. XML is used to allow the fast integration of mapping from diverse sources and originated from web-hacking. Advances in computer based XML are important to support internet mapping on recent smart-mobile devices (O'Reilly and Pahlka, 2009). XML is known to be the backbone internet format to communication data and allow collaborative sharing amongst internet users (Spivak, 2013).

In this context, map mashup and digital earth visualisations are revolutionising the way end-users represent GIS spatial analyses. The XML schematisation provided in ArcFLOOD will enable complex phenomena such as coastal flooding to be more visualised on the internet in these multimedia formats. Hersman (2009) commented that map mashups are important tools due to its open source extensibility as provided ArcFLOOD. The concept of map mashups is to combine functionality and content provided by multiple, independent data services in order to enhance stakeholder and user experiences through open source platforms, protocols, data formats, and commons application programming interfaces (Rinner et al, 2008). They provide fast regeneration of mapping on the internet without having to load each page during navigation and eliminate the need for expensive desktop mapping software.

Hakeley et al., (2008) discussed the view that map mashups do not negate the importance of traditional spatial analysis in GIS, cartography or surveying. Turner

(2006) describes browsing a map mashup in Google Earth as a system enabling multi-user access to mapping at minimal cost from geographic information (GI) providers. The availability of crowdsourced data from end-users has been noted to be important to crisis situations. Liu and Palen, (2010) identified that mapping technologies have the ability to persuade a public audience with compelling visualisations. Examples of map mashups include *maps.yahoo.com*; *maps.msn.com*; *openstreetmap* and *maps.google.com*. However, these tools are generally user-generated and do not provide reliable sources of information. The advantage to Sefton is the ability to merge end-user mapping with other sources of free flood risk information online to the layman.

Map mashups were used in the Hurricane Katrina (New Orleans) repopulation indicator maps (Lui and Palen, 2010). The freely available *"climate shift" Flood.firetree.net* sea level rise map mashups vary the level of sea level rise and allow the user to view flooded areas online in a user created blog with Google Earth satellite imagery (Figure 6.7). A sea level rise layer value is visualised to show the extent of a non-geographers version of flooding. Despite the inherent lack of accuracy, the public's interest in these climate crisis maps is growing. Another free user-generated web map mashups is the *GlobalFloodMap.org* powered by the API maplarge.com which also is lacking in reliable data for the Sefton Coast for example (Figure 6.8).

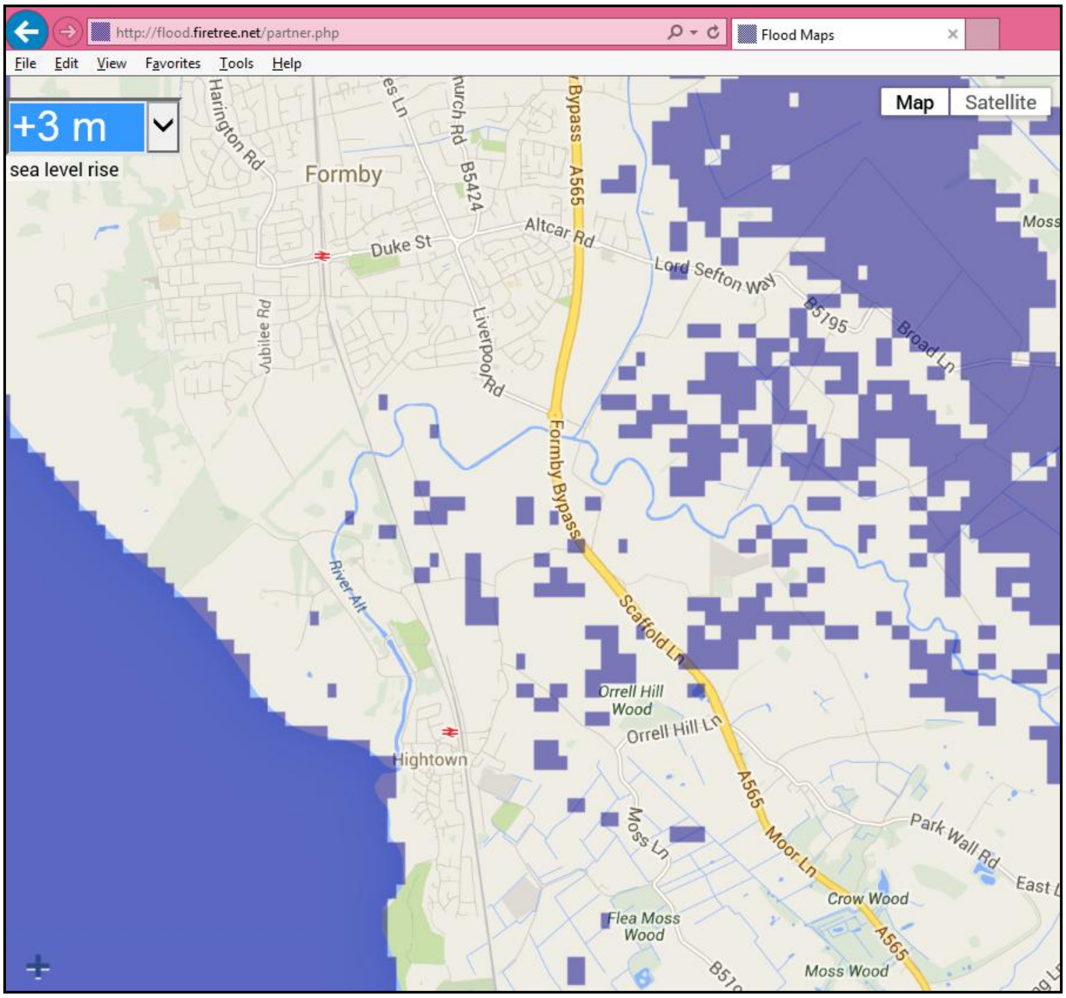


Figure 6.7: Sea level rise map mashup from Flood.firetree.net of the North West Coast United Kingdom at Southport where the user can select sea level rise and view the corresponding coastal flooding on the coast. Permission to reproduce this image has been granted by Firetree.net.

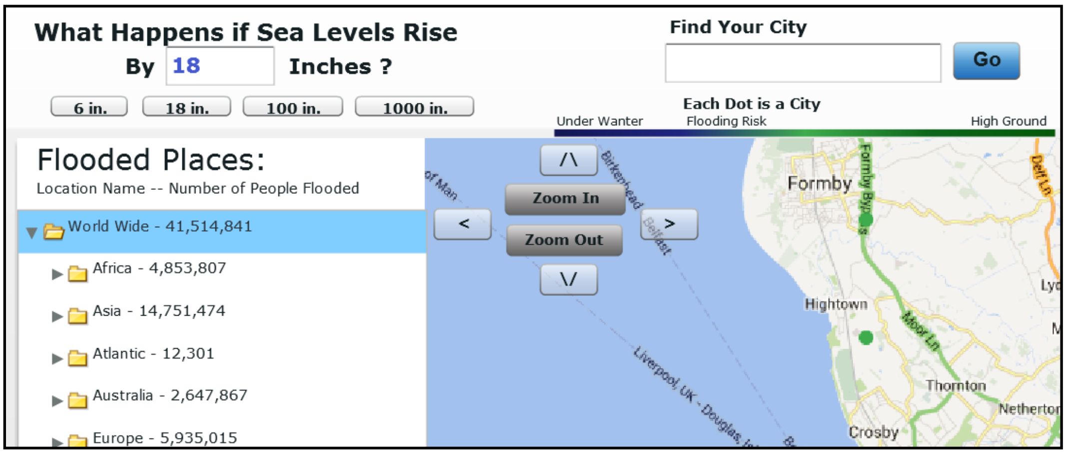


Figure 6.8: The GobalFLoodMap.org is a public map mashup tool with worldwide coverage. Permission to reproduce this image has been granted by GlobalFlodMap.org.

From the range of flood map mashups emerging on the internet, the public's interest is supporting the popularity of user-generated disaster information in the absence of scientific prediction data. One of the most obvious disadvantages of internet mapping is that greater accuracy and legitimacy is assigned to computer mapping introducing risk misinterpretation and misuse (Sheppard and Cizek, 2008). The issues of scientific truth and reliability of data are of grave concern, as public confidence is lost when displaying incorrect disaster or mitigation information. In addition, subjective human error is a problem with mapping visualisations (Sheppard and Cizek, 2008). For example, human misinterpretation is commonly interpreting 3D digital terrain models such draped photography or orthorectified images. However, these tools do not replace GIS desktop mapping applications. Sefton Council range of flood risk mapping is suitable to deploy on map mashups.

6.5.2 Digital Earth (DE) Visualisations

It is proposed that the next generation DE will act as a collaborative framework for end-users to allow the development of hybrid infrastructures such as spatial data infrastructures (SDI) which combine both voluntary and institutional data (Craglia et al., 2008. DE is seen as a powerful framework for developing novel information flows for end-users (c.f De Longueville, 2008). Its role is further expanded to promote collaboration between expert users and non-expert users (Grossner et al., 2008). Technologists postulate that by 2020, the usage of XMl schematisation and intelligence from data model frameworks will enable knowledge of best escape routes for natural disasters from end-user location coordinates (De Longueville et al., 2010). These systems will use mapping intelligence to determine escape routes based upon built environment, damage estimates, and real-time dynamic modelling of population movements. It is proposed that the portrayal of weather phenomena and emergency response on the internet may be the platform for the real-time reporting and delivery of disaster information (De Longueville et al., 2010). These studies further emphasise the need for data models which provide standardised information flows and interoperability standards to allow the widespread use of data on the internet.

Most importantly, DE has long been regarded as a platform for data publishing allowing non-specialists to collaborate with content provision (O'Reilly, 2006). This trend is referred to as volunteered geographic information (VGI) where non-specialists provide georeferenced information (De Longueville, 2010; Craglia et al., 2008). Various technical constraints to be considered in the use of DE include: the support of VGI's real-time integration into spatial infrastructures; and the creation of workflows to validate and distribute VGI datasets for crisis management activities (De Longueville, 2010). VGI has been used for flooding due to sea level rise (Lui and Palen, 2013). Within this application of VGI, a notable data quality constraint included the credibility of data from its data source creation methodologies. A structured data model is a solution to address these data quality concerns.

It is expected that the next generation DE will improve the modelling of the temporal and spatial real-world (De Longueville, 2010). The current OGC sensor web enablement (SWE) networks provide a primary source for real-time crisis information using near real-time geospatial data; and the integration of time series data from satellite imagery and other sensors pertinent to coastal flooding. De Longueville et al., 2010 describe the a futuristic view of DE in 2020 where a global human settlement layer (GHSL) is included as functionality merged with mobile technologies to pinpoint the locations of people at any point at any location. For instance, individual users are provided with the knowledge of a best route escape a flood based on characteristics of built environments, damage estimates, and real-time dynamic modelling of population movements. De Longueville proposes that the main areas of research of SWE is in the portrayal of dynamic weather phenomena and support for emergency response and disaster management where there is a need for the provision of timely information. This is necessary for the real-time reporting and delivery of disaster information to wide range of users and decision makers. It is argued that the next important step to SWE depends on the establishment of standardised data creation methods with data quality from the vast repositories of VGI data; and quality-controlled dynamic information flows commonly found in GIS data models (De Longueville, 2010). The linkage of the data model to these new advances are that SWE's operate within the well established SDI interoperability standards of the OGC such as Geography Mark-up Language (GML) (OGC 2007b (cf. De Longueville, 2010).

Publicly available scientific online data is becoming acceptable with commercially licensed data used to map crises. Tools such as Google Earth, Mapquest, ESRI ArcExplorer and Microsoft Virtual Earth are routinely used by scientists to provide free online mapping. These tools are commonplace due to their provision of digital mapping from around the globe in 3D (De Longueville et al., 2010). The Google Earth NASA Goddard Interactive Online Visualization and Analysis Infrastructure (Giovanni) system is the most advanced visualisation system to date allowing interactive analysis of gridded 3D data using Google Earth (Chen et al, 2008). Giovanni is a web application which provides access to remotely sensed earth data (water vapour, temperatures and clouds) from satellites online without having to download data. It produces visualizations of a curtain image in Keyhole Markup Language (kml) format repeated in time sequences of 15 seconds. The 3D Model is spliced together to comprise a seamless curtain of images spanning 103 km horizontal ground distance. The 3D rendered image is vertically viewed in Google Earth superimposed in 3D above the earth's surface (Chen et al, 2008). This technique is applicable to visualising coastal water level columns below mean sea level. In addition, NASA's Hurricane Portal also displays hurricanes in Google Earth. A commonality with this research is that NASA uses an open source XML schema called collaborative design activity (COLLADA) format to encode interactive visual scenes in 3D. Google Earth Sketchup tool interprets COLLADA and regenerates online mapping. Chen et al (2008) highlighted that XML and KML facilitate complex visualisation of time-stamped atmospheric modelling. The visualisation presented a thin curtain of cloud satellite data magnified, exaggerated and accurately positioned perpendicular to the Earth's surface on a virtual globe demonstrating the use of data exchange standards such as XML (Figure 6.9.)

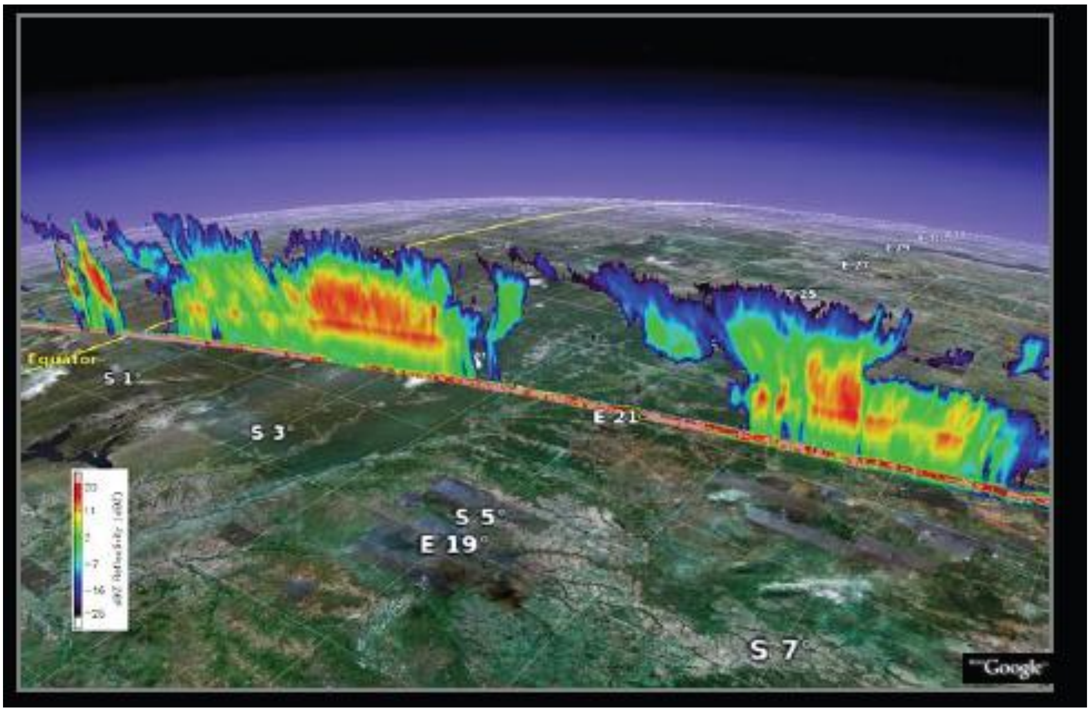


Figure 6.9: NASA GIOVANNI visualisation of atmospheric data in a seamless 3D curtain above the Earth's surface using Google Earth (Chen et al., 2008) (Available from: http://disc.sci.gsfc.nasa.gov/giovanni/overview/what-is-giovanni). Permission to reproduce this image has been granted by Elsevier.

The argument supporting these technologies is that open source tools are affordable low-cost technical solutions which offer fast development times for visualisations which appeal to end-users such as Sefton Council. In addition, the extensibility of data models allows data to be changed with end-user requirements. Thereby, visualisations online are easier to maintain with data structure organised in data models. Data modelling is becoming the underpinning architecture for the new generation of internet mapping. Sefton Council is best placed to use the ArcFLOOD data model to develop a range of DE tools.

6.5.2 Sefton Council Coastal Flood Visualiser

The visualisation of coastal flooding spatial analyses was explored using a rich internet application for a mobile tablet device in this research. The design of a graphical user interface (GUI) which would allow Sefton Council to foresee the future of flood emergency preparedness was conceptualised. A collaboration with technology company Adobe partners RMA Consulting Ltd UK was initiated to demonstrate end-user engagement and the wide application of XML schematisation. Through ArcFLOOD the results of the flood modelling was used as data input to design a GUI prototype. A fully functional tool can only be developed with funding from Sefton Council in the future. The tool has potential to be used as a flood warning service tool with Sefton Council. This type of tool could improve on current techniques which provide text messaging using mobile phone technology to registered end-users.

The in-house technical programming knowledge was available from lead designers at RMA Consulting Ltd UK who collaborated in this research to develop a prototype emergency preparedness interface. The main aim was to use the coastal flooding visualisations with Adobe Flash and AIR tools build an interface which can be ported onto mobile GIS applications. The proprietary rights over the GUI and programming code lie with RMA Consulting Ltd UK but the data is the property of Sefton Council. The developers used Adobe Flash and Flex applications to develop a prototype GUI.

A series of workshops were undertaken to design the interface (Bound in copies section). The requirements for a coastal flood visualiser were explained to the designers. Analyses of the data querying and corresponding results were provided to the designers to as GIS visuals for a 3m flood event. The aim of the GUI was the design of a tool to engage the end-user experience using the range of Adobe flash internet tools to navigate a coastal flooding event. A movie demo was produced which showed the synthesis of the visualisation images. The GUI data included aerial imagery, flooding polygons and the coastal flooding DEM. Though this prototype is not consistent with general Ordnance Survey mapping specifications, the purpose of this tool is the visual experience for the public and inexperienced map user accustomed to tablet devices.

The functions which were included in the limited time to build the GUI were:

a. Enhanced controls to allow end-user to navigate on a touch screen environment.
b. Cached images of coastal flooding to increase performance of navigation on screen.
c. Creation of an animated viewing effect.
d. Screens or windows showing a pre-flood DEM and a post-flood DEM.
e. A time lapse simulation to depict the time series sequence of a flood.
f. Access to use multimedia buttons with familiar icons to stop, play and fast forward a simulation.

The coastal flood visualiser was designed to allow an end-user to pick a point on the screen with the post flood DEM returned showing the flooding. The end-user navigates using the touch screen. A flood time slider was added at the bottom of the GUI to allow the end-user to select any point in time and be returned with the flooding image. The GIS *click on point* function returns to the end-user values for average flood water depth (Avg Z_s); average significant wave height (Avg Hs); average increase in flood water (Avg Increase in Flood Water); and average speeds (Avg u (x-velocity) and Avg v (y-velocity). The GUI window view is shown to depict a DEM showing the River Alt before flooding (Figure 6.10).

In a real-world implementation the end-user will be allowed to switch window views from a pre-flood DEM to various post-flood DEM. The end-user can interrogate the DEM to investigate the topography of features before the flood. It must be noted that the cartographic mapping and symbolisation will be improved in future versions. As the end-user moves, the location coordinates are dynamically displayed. The images were oriented towards north and a legend was displayed to indicate overall depths in the DEM as the end-user navigates and shifts position using touch screen technology. The end-user can interrogate the DEM map and be provided with flood water depth values at any point on the map.

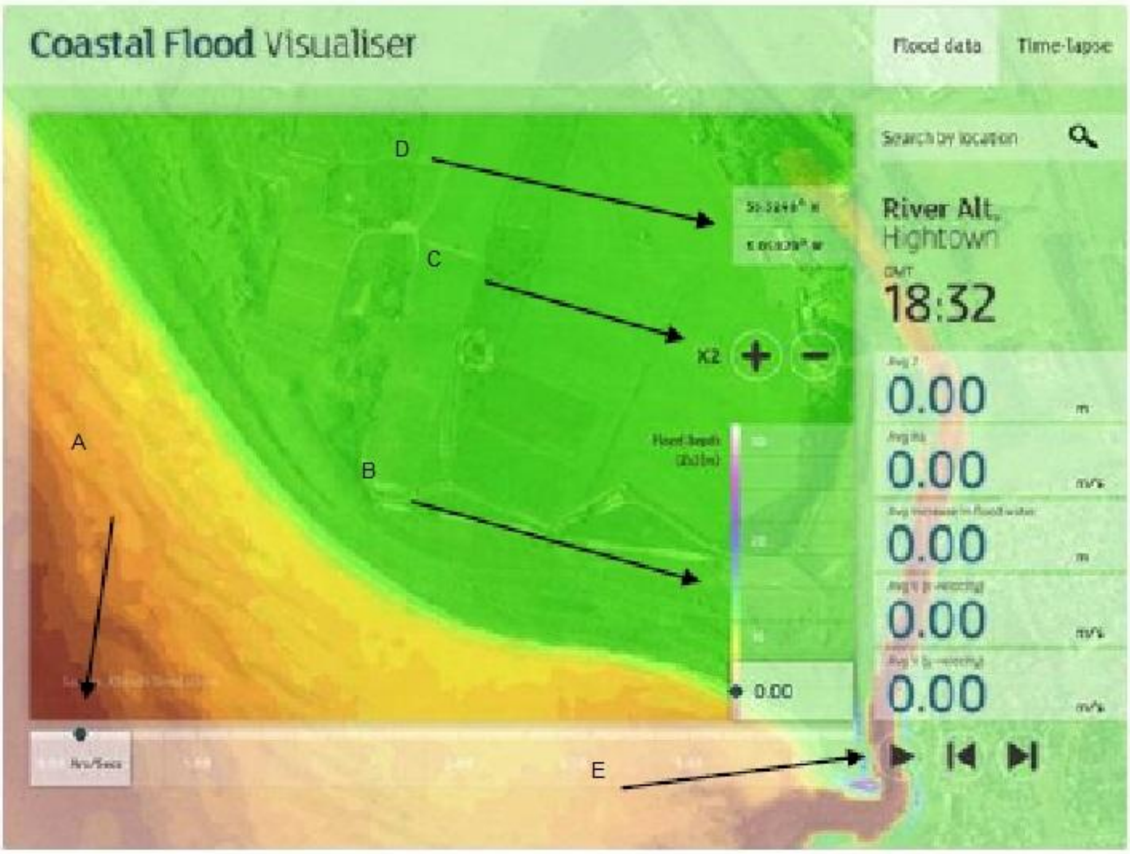


Figure 6.10: Coastal Flood Visualiser pre-flood DEM showing the River Alt before the coastal flooding impact. The arrows point to functions: (A). Time lapse slider; (B). Legend with displayed flood water depth; (C). Point on click; (D). Coordinates displayed dynamically; and (E). Multimedia buttons.

It is assumed that the end-user will decide to select the tab at the top right of the screen to change views to a time lapse window in order to view an actual flooding simulation (Figure 6.11). Using the timeslider function to select 03245 seconds the end-user was displayed with the appropriate time lapse flooding window. The end-user is also given the option to interrogate the map with point and click operations. In this example the end-user is provided with a flood water depth of 11.661m which is also represented on a time slider legend. By zooming in further using the touch screen, the end-user is allowed to access the Ordnance Survey 1 in 10,000 scaled mapping of Hightown to view property and infrastructure at risk of flooding (Figure 6.12). The demonstration of this proof of concept prototype will be used to convince the end-user of the wide range of applications possible when the data in their possession is structured in a format to be translated through internet protocols and innovative multimedia platforms.

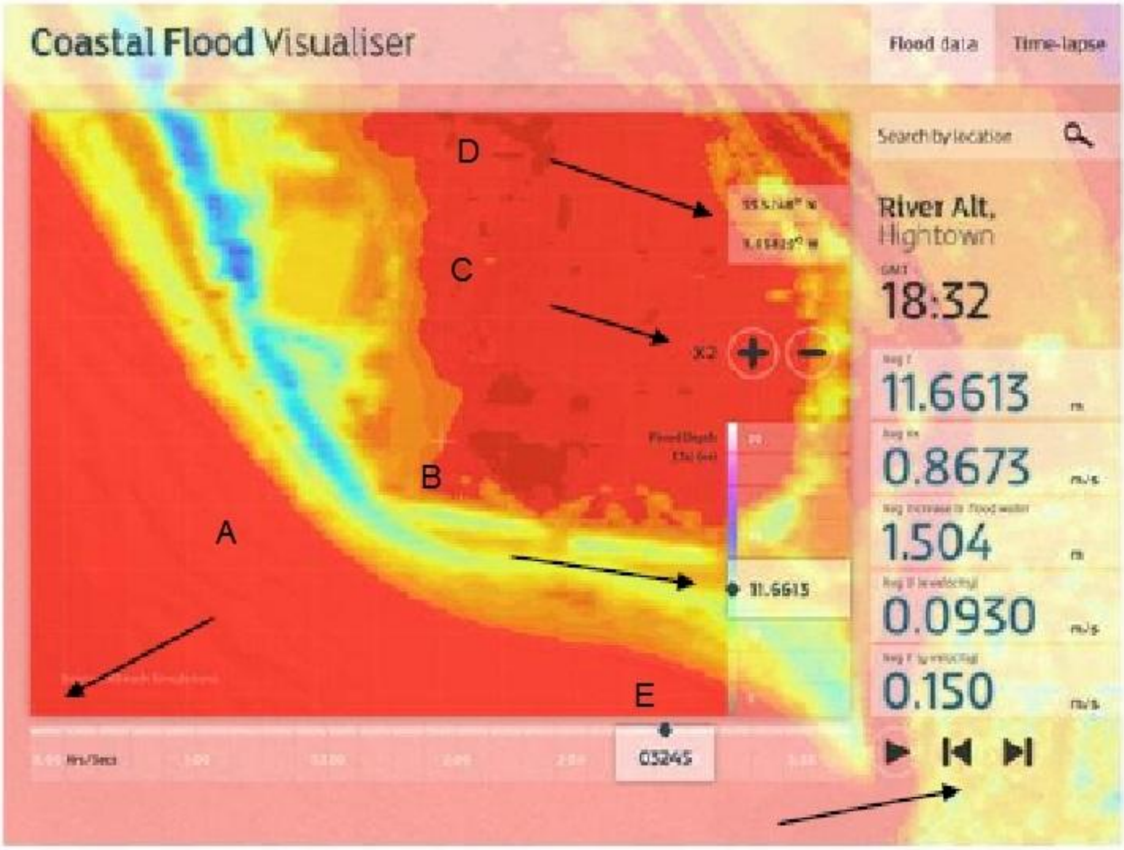


Figure 6.11: Coastal Flood Visualiser time-lapse flooding for t = 3245 seconds. The arrows point to: (A). Time lapse slider; (B). Legend with displayed flood water depth; (C). Point on click; (D). Coordinates displayed dynamically; and (E). Multimedia buttons.

Without funding for the development of the Coastal Flood Visualiser, it was not possible to continue development with consultants. It must be emphasised that working in partnership with IT companies allowed the exchange of valuable ideas and programming skills for Sefton Council. The Coastal Flood Visualiser can be built with commitment from Sefton Council in the future. In this case, the GUI was developed without DBMS spatial processing due to a lack of developed knowledge in that area. Simple data access was provided through tabular data exported from GIS geodatabases in XML schema.

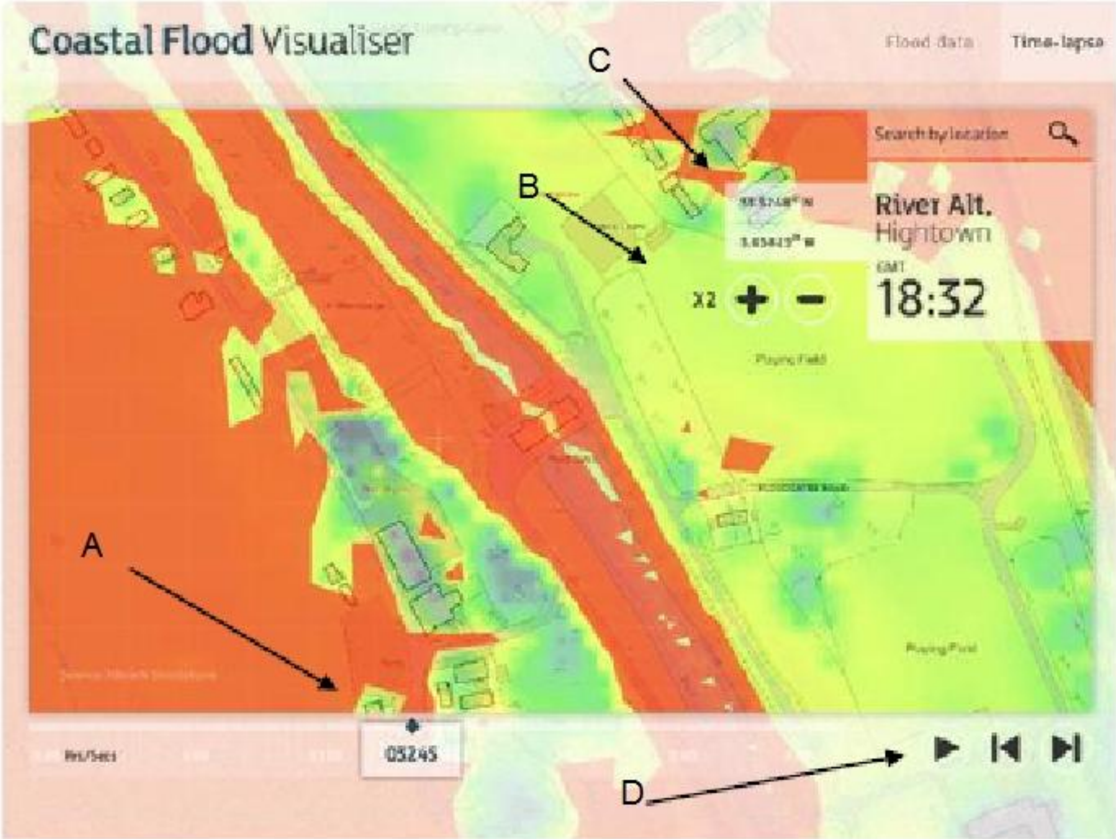


Figure 6.12: Coastal Flood Visualiser time-lapse flooding at the flood gates at Hightown for t = 3245 seconds. The arrows point to: (A). Time lapse slider; (B). Point on click; (C). Coordinates displayed dynamically; and (D). Multimedia buttons.

6.6 Summary

The development of RIAs for coastal flooding provides a strong argument for the use of GIS data modelling. However, these media platforms can only be used if coastal flooding data complies with the data exchange and internet protocol standards. The ArcFLOOD data model provides a practical means to visualise coastal flooding predictions on the internet. The practical use of ArcFLOOD will enable the long term benefits to end-users. The standardisation and harmonisation of coastal flooding datasets in an accessible, extensible and customisable data model framework is a major advance in coastal flooding. In addition, the science from flood modelling has been interpreted and translated into an end-user compliant format for its practical use. The problems identified with complex and disparate flood modelling predictions have been addressed. Without the approach used in this thesis, the results of XBeach remain unformatted in a standard exchange format and thus unable to be shared on the internet's range of applications.

Chapter 7

Discussion and Conclusions

This study has addressed the lack of GIS data modelling in coastal flooding which overlaps the fields of numerical modelling, flood risk assessments, information technology (IT) advances. A data model has been developed for coastal flooding which has improved the organisation and interpretation of generic flood model output from numerical flood modelling systems in an open geospatial-compliant geodatabase. The following goals have been achieved:

a. The harmonisation of the disparate data defining tidal/surge water levels, offshore and near-shore waves, beach sediments, bathymetry and topography results.
b. The combination of results in a GIS to produce analysis.
c. The integration of tide and surge interaction in the Coastal Flood Model (XBeach) represented a significant advance in numerical modelling which has been incorporated into ArcFLOOD data model spatial analyses. The manipulation of the results led to the analyses of time series XBeach predictions for the duration of a flood; the identification of flood water depth at a point and the flood water increase changes.

The research objectives achieved also included the extension of the ESRI ArcGIS Marine Data Model (MDM) to a bespoke ArcFLOOD data model by incorporating the complex coastal flood within a GIS flooding geodatabase. The results of the research produced spatial information flows, data model schematic diagrams and XML schema. In addition, an extensive database of contemporary historical and coastal field data was collected from the end-users and redesigned in GIS geodatabases. More importantly, ArcFLOOD was designed according to specific end-user requirements.

In Chapter Two, a discussion of the fundamentals of GIS data modelling was presented. As a justification for the research, evidence of data models in coastal and marine applications were provided. The pivotal MDM and ArcHydro data models were discussed as contributions to the ArcFLOOD data model. A literature review on the role of GIS in numerical modelling was presented, identifying specific flood modelling systems which have used GIS decision support systems and data models.

Discussion was focused on the evidence of the use of data exchange standards in marine, coastal GIS, climate change and weather. Most importantly, the research identified the absence of GIS data modelling for coastal flooding within the complex areas of numerical modelling and information technology (IT) advances; the lack of approaches to facilitate the synthesis of coastal flooding predictions; and its mapping and visualisation in end-user software GIS. A review of the evidence of coastal flooding models was provided.

In Chapter Three, a description of the study site at the River Alt, Hightown on the Sefton coast was detailed and the coastal morphology and meteorology of storms which produced coastal flooding were characterised. Storm dynamics which have contributed to coastal flooding in this location were discussed. The approach to the numerical modelling was defined by integrating the results of the Liverpool Bay model

(POLCOMS-WAM-GOTM) into the coastal flood model (XBeach). The linking of these models was shown to have produced the extent of coastal flooding based on the state-of-the-art tide and surge interactions. The models were seen to translate offshore forcing factors (waves, tidal currents and storm surges) into near-shore water elevations and wave conditions using XBeach to increase total water levels at the coast. The results of the XBeach modelling provided validated predictions of coastal flooding based on the morphological impact of observed storm events.

In Chapter Four, ArcFLOOD was extended, through data modelling, to identify the broad range of coastal flooding information, rules and interactions relevant to the marine and coastal environment. The use of datasets for GIS spatial querying in the data model was optimised. Consequently, it was proposed that the ArcFLOOD data model was important to scientists and decision-makers who increasingly need to integrate information from multiple, disparate and third party sources; extract predictions in a format to be spatially analysed in GIS; and produce information which are ready for visualisation.

In Chapter Five, specific flooding parameters from the Coastal flood model have been modelled for the first time using GIS spatial analyses. The parameters which were incorporated in the data model design included:

a. $\mathbf{z_s}$- flood water depth;
b. $\mathbf{h_h}$- significant wave height;
c. **u** (x-velocity in the x-axis direction);
d. **v** (v-velocity in the y-axis direction.

As a result of the optimisation of data querying in the data model calculations of the following based on time series analysis were produced:

a. **Flood water depth** for a given flood point **(z_{change}**);

b. **Flood water level change h_{change}** (difference in z_s flood water levels between timesteps which equates to the difference in significant wave height (**h_h**)).

The spatial manipulation of these parameters in GIS has validated an extreme event coastal flood of 3 metres (m). The research has improved on the flood risk mapping provided by the Environment Agency in its ability to analyse time dependent flooding at specific locations. The locations of vulnerable flooding sites been identified providing an improved delineation of coastal flooding in the study site.

Finally, in Chapter Six, the practical use of ArcFLOOD was discussed. Comparisons were made with the flooding predictions provided in Environment Agency flood risk mapping and the approaches currently used towards global flood risk were considered. As a method of highlighting the technological changes required in GIS, an implementation of an internet prototype application using RIA technology was presented.

7.1 Discussion of Data Modelling Approach

It is believed that the integrated approach presented in this thesis widens the scope of end-users understanding of coastal flooding whilst providing flood modellers with bespoke GIS flood risk mapping. The data modelling approach has been demonstrated satisfactorily to improve data accessibility; manipulate flooding predictions to produce flood risk analysis; identify the impacts of coastal flooding in the study site; and visualise flooding predictions using GIS techniques. The provision of appropriate flood risk mapping has validated the data modelling approach.

This approach has defined and detailed the interactions of coastal flooding tables to produce time series simulation data layers from numerical flood modelling output. Specifically, the data model has presented the detailed flow of inputs to XBeach and outputs from numerical modelling to develop GIS spatial analyses for coastal flooding. The ArcFLOOD data model comprised three components represented in diagrammatic schema:

a. Coastal Flood Data Model
b. River and Estuarine Data Model
c. Mesh Data Model

Within the ArcFLOOD data model it is proposed that the pertinent solution which advances the science of data modelling is the analysis and querying of the time series array **TimestepTotalSimulation** which incorporates an array of simulation sequences from **timestep** (**t**) = 1, **n** where **n** is timestep interval in seconds. Through a unique **TimeID** all flooding data is linked within ArcFLOOD.

As a result of the manipulation in GIS of these parameters, the data model has allowed the new calculation of **flood water depth = FloodLevel** for a given flood point; and the **flood water level change** $\mathbf{h_h}$ (difference in $\mathbf{Z_s}$ flood water levels between timesteps) which equates to the difference in ($\mathbf{h_{h\,(t=6000s)}}$ – $\mathbf{h_{h\,(t=0s)}}$) significant wave height between timesteps. With improved numerical modelling results, the speed of the coastal flood could be calculated in future analyses of ArcFLOOD. The additional river and estuarine data model was included to allow end-users the capability to merge riverine flooding with coastal flooding data through the data model descriptions, thereby promoting a wider definition of flood risk. In addition, the inclusion of the MDM Mesh data model has relevance for the future GIS applications investigating the flood water column and specific flood water levels in space and time.

Prior to data modelling, future coastal flooding end-users are advised to use the process models developed to generate the necessary datasets to conduct flooding analyses in ArcGIS. For the first time end-users possess an existing coastal flooding repository database upon which to develop bespoke databases with the aid of process models. The remainder of the database effort required by future end-users involve loading datasets from the ArcFLOOD schema and importing data into their respective geodatabases. The data model approach will reduce DBMS effort as the data properties, flooding data types and relationships are outlined for prospective developers of flood risk assessments reducing the development time in implementing coastal flooding GIS. Within the implementation of ArcFLOOD, it is required that all data properties are matched from ArcFLOOD before applying its schema. The data integrity rules in place in ArcGIS make it impossible to merge datasets without the same spatial reference; table properties and identifiers throughout the data. End-users are still required to perform conversions into ArcGIS format and pre-determine data schema specifications prior to importing new data into ArcFLOOD.

Before the development of ArcFLOOD, there was no benchmark from which potential coastal flooding end-users could begin to develop coastal flooding GIS analyses from numerical modelling. ArcFLOOD has improved end-users understanding of coastal flooding data and configured user-defined analyses for flood risk assessments. Technical GIS end-user have been provided with a consistent structure to develop coastal flooding applications in GIS using the common tools and interfaces provided in ArcFLOOD schemas. ArcFLOOD has allowed the harmonisation of numerical modelling data in a GIS geodatabase as a resource to end-users. More importantly, the ArcFLOOD schema bridges the gap between the scientific information derived from flood modelling and its use in GIS to create targeted information for decision-makers and emergency preparedness.

Given the time constraints of the research, it was not possible to fully test the data model's potential for re-extension in an end-user environment. This activity would have led to the refinement and validation of ArcFLOOD. Integration with the end-users such as the British Oceanographic Data Centre standards is an area of future research. In addition, further robust analyses through probabilistic methods may be required to determine an improved definition of flood risk in the numerical modelling. These tests are necessary to feedback the predicted results to the Environment Agency for review and incorporation. The ArcFLOOD data model is available to be published in the ESRI data model repositories online. At its present stage, it is available to be used by any flood software developer or end-user.

7.2 Errors and Uncertainty

7.2.1 XBeach Modelling

An identification of errors in the research is necessary. The prediction results were dependent on their source derivation from XBeach flood modelling. The reprogramming of XBeach produced only 1.5 hours of coastal flooding due to program crashes limiting the dataset. Server-side processing would have improved the performance of XBeach output to reproduce a complete 4 hour simulation of coastal flooding for GIS mapping. This is an area of future collaboration with flood modellers where XBeach is reprogrammed to provide an automatic exchange of data using import and export subroutines.

In addition, the lack of velocity parameter data prevented the spatial analysis on the rate of flooding. The uncertainties in XBeach modelling included a lack of data on sediment transport and morphology parameters as their effects were undetermined at the time (Williams et al., 2011). In addition, recent surveys of the River Alt bed topography were not possible to acquire within this study to provide a more accurate assessment within XBeach. The analysis depended on the Environment Agency LIDAR survey data mapping to provide topographical detail.

7.2.2 Data Modelling

The data modelling in ArcGIS would have incurred subjective human errors. ArcFLOOD was extended based on the MDM model and used the procedures outlined in its development to ensure consistency. The modelling was undertaken in a systematic manner to identify all entities and key attributes which were essential to produce flood risk mapping. One of these subjective errors is over-modelling which accounts for redundancy and contradictory data. In practice, over-modelling is sometimes intentional to optimise querying. Redundancy was kept to minimum in this case as the data modelling was focused on the time series data. ESRI end-user validation can identify these possible sources of error. The use of process modelling in this thesis acted as a control to limit inconsistencies and errors in over-modelling. The generation of results provides validation that the data model spatial relationships and table properties are consistent.

7.2.3 Uncertainty Analysis

The need for validation of spatial interpolation techniques in the flooding DEM is an area of future research. The DEM created were based upon the most accurate Environment Agency data supplied for LIDAR. The DEM were generated with 0.25 m resolution using linear interpolation. Future studies will be required to test the probabilities of errors in the flood grids generated providing a best estimate probability using MAST tools (Environment Agency, 2011). Other statistical testing to be investigated in the future may include deterministic and probabilistic models for flooding output (Bates et al., 2010; Mason et al., 2009; Dawson et al., 2005).

7.3 Future Implications of the ArcFLOOD Approach

The present technological trend is *big data* which is being explored in technological companies to handle *clouds* of digital data generated in applications around the world (Mayer-Schönberger and Cukier, 2012; Patil, 2011; O’Reilly Media Inc., 2012; O’Reilly Media Inc. and Pahlka, 2009). The process used to handle *big data* in DBMS is called *data science* (GilPress, 2013; Mayer-Schönberger and Cukier, 2013). Analytical techniques used by *data science* include typical GIS techniques such as spatial analysis, classification, modelling, and simulation (GilPress, 2012; O'Reilly Media Inc., 2012; Manyika et al., 2011). The results of this research is representative of work which will be able to practically utilize these new data paradigms in that, due to the volume of coastal data required, its multiplicity of sources and its complexity, coastal flooding software applications may rely heavily on cloud data and data science in order to meet end-user needs for internet-based mapping. The *big data* approach allows the manipulation of coastal flooding data on the internet to improve visualisation. The important technical contribution of the ArcFLOOD data model lie in object-relational databases, XML and spatial information flows produced from data modelling which are necessary to exploit the internet for mapping and visualisation. It was envisaged in this research that data science will provide a greater range of tailored data to end-users.

It can be predicted that public expectation is growing to convey weather phenomenon on mobile devices (Morris, 2013). Technology on its own delivers no value to the prediction of weather. However, in combination with high quality data, mitigation strategy, appropriate data science skills and processes, value can be created through a market for weather modelling. The role of scientific organisations are becoming intertwined with private corporations who require access to long term weather forecasting data for predictive analysis such as re-insurance agencies, financial modelling and energy trading futures markets. In the data science field big data concepts are already being used in prediction and meteorological forecasting models (Morris, 2013). Leading research agencies such as National Oceanic and Atmospheric

Administration (NASA) and the U.S. Geological Survey have been working with to develop a new range of internet applications.

Weather modellers from the US National Oceanic and Atmospheric Administration (NOAA) are collaborating in leading technological and commercial organisations such as IBM to provide customised weather forecasting outside traditional regional and national weather. In this particular example, analyses being produced are *hyper-local* forecasting requiring data within 24-48 hours. Other examples include the *IBM Deep Thunder Project* initiated in 1996 which provides targeted forecasting to organisations ranging from city corporations to energy utilities; *EarthRisk Technologies* which provide business weather forecasting; and *Earth Networks* which provide live weather data. The re-insurance sectors are planning for natural disasters ranging from tsunamis to coastal flooding by creating financial models from *big data* to examine the impact of extreme events on shipping routes (Morris, 2013).

Currently, the areas of exploration include city emergency management, wind energy and utility response to outages. Future commercial systems using validated scientific methods will include: (a) High resolution weather forecasting data and hydrological modelling for flood forecasting; (b) Wind direction and speed data to plan for wind energy turbines to minimise the damaging effects of storms on power lines and trees for repairs; (c) Better forecasting of snow for de-icing diagnostics at US Airports; (d) Management of flight delays due to bad weather; (e) Wildfire-fighting based on highly specific wind and temperature statistics; and (f) Future planning to anticipate mudslides and flooding in Rio de Janeiro triggered by severe storms for the World Cup 2012.

An array of possibilities is available to coastal flooding end-users to optimise their spatial querying based on ArcFLOOD data modelling and its linkages to data science. It is envisioned in this research that a future GIS end-user will use a mobile device application on Google Android or an iPhone. As the end-user moves from one location to the next, the predicted flood is projected on the landscape through the device camera which provides an augmented view of reality. The end-user is provided with escape mapping instructions to aid evacuation of a flood zone.

7.4 Conclusions

The work presented in this thesis has identified a unique niche in Geographic Information Systems (GIS) and flood risk assessment which is important to the development of many future flood risk applications. The understanding and quantification of flood processes has been translated into the ArcFLOOD data model by the amalgamation and harmonisation of a wide range of data. The ArcFLOOD data model provides a transferrable technological blueprint for coastal flooding which could underpin flood risk mapping in the global context. A range of end-users and software developers can immediately use the data model and geodatabases to develop application software within months rather than years. Most importantly, the improvements cannot be underestimated as ArcFLOOD has empowered software developers with little or no knowledge on coastal flooding predictions to develop applications through its data schema.

The integration of data has also allowed the potential of interdisciplinary data to be shared and disseminated through cutting-edge visualisation tools on the internet by software developers. Due to the ArcFLOOD data modelling approach presented in this research, the vision of a coastal flooding emergency preparedness tool is closer to fruition on the internet and mobile devices. As a result, decision makers will be informed about the implications of coastal flooding, eliminating the need for the arduous process of understanding complex numerical modelling. Without this data model, predictions lie unharnessed and locked away in complex and undecipherable numerical flood modelling code.

A view proposed in this research is that numerical flood modelling has focused heavily on the physical processes of coastal flooding and less on the impact on coastal communities and livelihoods. The deficiency in numerical flood modelling is the lack of data exchange tools and standards which allow the import and export of predictions into GIS; and the visualisation of predictions to identify vulnerable locations. In addition, GIS spatial analysis tools have been used to adequately visualise flood risk mapping. All these benefits have not been possible directly from numerical flood modelling systems but from the use of GIS data modelling.

The time-series representation of coastal flooding in the ArcFLOOD data model is fundamental to the definition of flood risk. The new prediction results generated from GIS spatial analysis has improved the flood modelling output provided from the Environment Agency and the National Oceanographic Centre. In addition, the knowledge transfer of coastal flooding predictions is improved to the wider flood risk management community through ArcFLOOD. Flood modellers now have a method to share and disseminate important predictions.

It is also now possible for decision makers to have a realistic indication of the impact of coastal flooding on the infrastructure and property affected by the identification of potential disastrous locations using GIS spatial analyses. Importantly the results have shown the failure of flood defences such as levees, embankments and flood gates to plan future coastal defence needs. The flooding of main roads and public utilities infrastructure such as the water pumping stations are crucial to evacuation and emergency preparedness. In the wider context, the results are in a format which can be shared now with the re-insurance sector and integrated with Sefton Council property data to address the specific concerns of those who will potentially be affected.

The way forward is the implementation of the ArcFLOOD data model in Sefton Council to integrate the results of the flood risk mapping with external data to address flood mitigation needs. Flood risk mapping will be used a consultation aid in the current flood defence strategy. The research will delve into the development of emergency preparedness visualisation tools using the ArcFLOOD data model results and geodatabases in collaboration with Sefton Council. The challenge ahead is the alternative processing of big data to provide new visualisations and innovative applications for coastal flooding.

Without the data structure provided in ArcFLOOD, it is likely that the future of coastal flooding applications will remain unsuitable for end-user requirements. Numerical flood modelling systems are unable to share coastal flooding predictions or produce targeted analysis for emergency management. Flood modelling must comply with the exchange standards promoted by organisations such as the OGC to ensure the appropriate standards for modelling results. As storm activity continues to increase the potential for severe coastal flooding in the UK, end-users will not be equipped to develop emergency preparedness applications to warn the public, if coastal flooding predictions are unable to disseminate. The implementation of an ArcFLOOD data model is an urgent requirement.

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Appendices

Appendix A

Table A.1: Comparison of common flood inundation models

Method	Description	Application	Example Models	Inputs	Outputs	Computation time (as of 2006)
0D	No physical laws included in simulations.	Broad scale assessment of flood extents and flood depths.	ArcGIS Delta mapper	DEM Upstream water level Downstream water level	Inundation extent and water depth by intersecting planar water surface with DEM	Seconds
1D	Solution of the one-dimensional St Venant equations.	Design scale modelling which can be of the order of 10s to 100s of km depending on catchment size.	Mike 11 HEC-RAS SOBEK-CF Infoworks RS (ISIS)	Surveyed cross sections of channel and floodplain Upstream discharge hydrographs Downstream stage hydrographs	Water depth and average velocity at each cross section Inundation extent by intersecting predicted water depths with DEM Downstream outflow hydrograph	Minutes
1D+	1D plus a storage cell approach to the simulation of floodplain flow.	Design scale modelling which can be of the order of 10s to 100s of km depending on catchment size, also has the potential for broad scale application if used with sparse cross-section data.	Mike 11 HEC-RAS Infoworks RS (ISIS)	As for 1D models	As for 1D models	Minutes to hours
2D-	2D minus the law of conservation of momentum for the floodplain flow.	Broad scale modelling or urban inundation depending on cell dimensions.	LISFLOOD-FP	DEM Upstream discharge hydrographs Downstream stage hydrographs	Inundation extent Water depths Downstream outflow hydrograph	Hours
2D	Solution of the two-dimensional shallow wave equations.	Design scale modelling of the order of 10s km. May have the potential for use in broad scale modelling if applied with very course grids.	TUFLOW Mike 21 TELEMAC SOBEK-OF Delft-FLS	DEM Upstream discharge hydrographs Downstream stage hydrographs	Inundation extent Water depths Depth-averaged velocities at each computational node Downstream outflow hydrograph	Hours to days
2D+	2D plus a solution for vertical velocities using continuity only.	Predominantly coastal modelling applications where 3D velocity profiles are important. Has also been applied to reach scale river modelling problems in research projects.	TELEMAC 3D Delft-3D	DEM Upstream discharge hydrographs Inlet velocity distribution Downstream stage hydrographs	Inundation extent Water depths u, v and w velocities for each computational cell Downstream outflow hydrograph	Days
3D	3D solution of the three-dimensional Reynolds averaged Navier Stokes equations.	Local predictions of three-dimensional velocity fields in main channels and floodplains.	CFX FLUENT PHEONIX	DEM Upstream discharge hydrographs Inlet velocity and turbulent kinetic energy distribution Downstream stage hydrographs	Inundation extent Water depths u, v and w velocities and turbulent kinetic energy for each computational cell Downstream outflow hydrograph	Days

Appendix B

B.1 Guide to Geodatabase Development

B.1.1 Building a Geodatabase

This content is taken from ESRI Inc. help. Permission to reproduce this text has been granted by ESRI Inc. Creating a new personal geodatabase involves creating an .mdb file on disk. This can be done using ArcCatalog, the Catalog window in ArcMap, or geoprocessing tools. In order to create a new personal geodatabase using ArcCatalog or the Catalog window in ArcMap the end-user must follow the instructions below:

a. Right-click the file folder in the Catalog tree where you want to create the new personal geodatabase.
b. Point to New.
c. Click Personal Geodatabase. A new personal geodatabase is created in the location you selected.
d. Type a new name for this personal geodatabase and press ENTER.

Personal geodatabases that correspond to older releases of ArcGIS can be created by using the **Create Personal GDB geoprocessing tool**. This ability will facilitate sharing data with users who have older releases of ArcGIS, since older releases of ArcGIS may not be able to open newer releases of the geodatabase.

B.1.2 Migrating Existing Data

a. The easiest way to copy data from a personal geodatabase into a file geodatabase is to use the Catalog tree **Copy** and **Paste** commands. Copy/Paste is flexible because you can choose exactly what you want to copy. You can select everything in the personal geodatabase or just particular items, such as a set of feature datasets which you want to migrate. For example, to copy a feature dataset from a personal geodatabase into a file geodatabase, create a new empty file geodatabase in the Catalog tree. Select the items in the personal geodatabase you want, right-click the selection, click Copy, then right-click the file geodatabase and click Paste.

b. Copy/Paste function are used to migrate any type of data in the geodatabase except attribute domains that are not referenced by any feature class or table. If you have such domains and want to migrate them, use the Export to XML Workspace Document method discussed next.

c. To copy an entire geodatabase, use the Export > XML Workspace Document command to export the entire database to an XML file. You can then create a new, empty file geodatabase and use Import > XML Workspace Document to import the data from the XML file into the file geodatabase. This method is also flexible in that you can choose which datasets to export in the Export wizard.

d. If you're migrating low-precision geodatabase data, the Copy/Paste and Export to XML Workspace Document methods automatically convert the data to high precision, setting the resolution to approximately 0.1 millimetres (mm). However, if you want the data to be stored at a different resolution, use the Upgrade Spatial Reference tool before migrating data with Copy/Paste or

Export to XML Workspace Document. Upgrade Spatial Reference converts the data to high precision, allowing you to choose the resolution. Another way to exercise control over the resolution is to migrate with the Import/Export geoprocessing tools.

e. To move shapefiles, coverages, or data in another format into a file geodatabase, use the same method that you would use to move the data into a personal geodatabase. Select the dataset in the Catalog tree, right-click, then choose the Export > To Geodatabase command; use the To Geodatabase (multiple) command to export multiple datasets at once. You can also find these tools in ArcToolbox under Conversion > To Geodatabase.

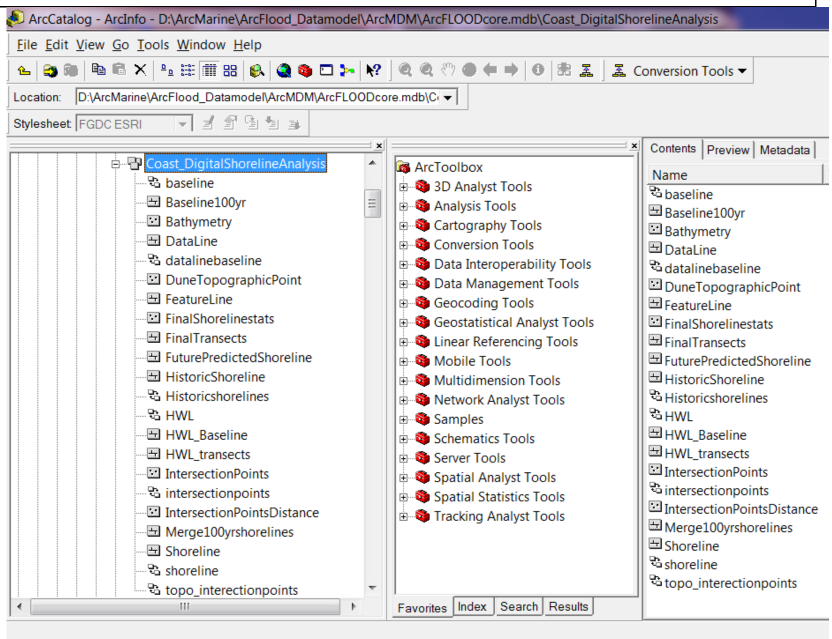
f. File geodatabases have configuration keywords that customize the storage of an individual dataset. You can specify a keyword when you copy and paste or import data, although the default is usually adequate.

B.2 ArcFLOOD Geodatabases

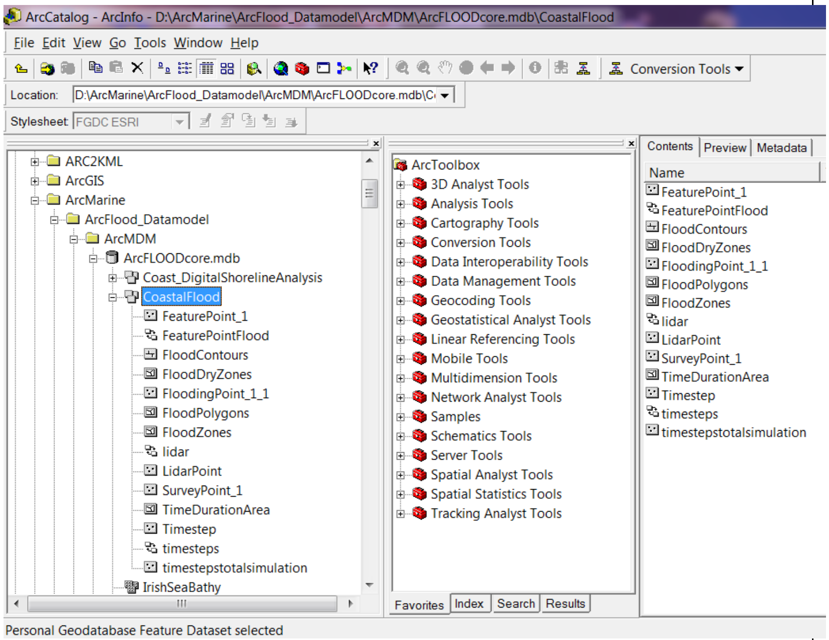
The following are the geodatabases and content created for ArcFLOOD.

Table B.2.1: ArcFLOOD feature datasets

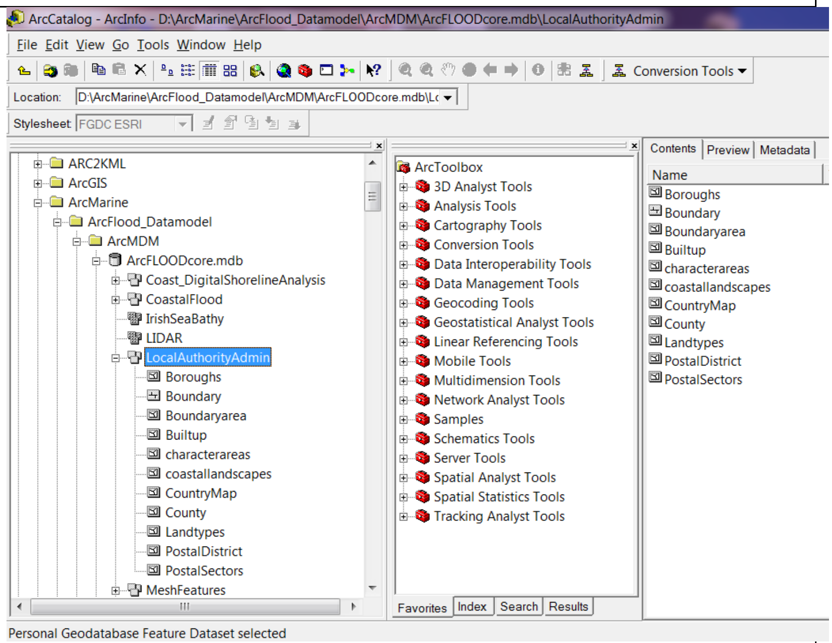
<table>
<tr><th>Feature Datasets</th><th>ArcCatalog Directories</th></tr>
<tr><td>Coast_DigitalShoreline

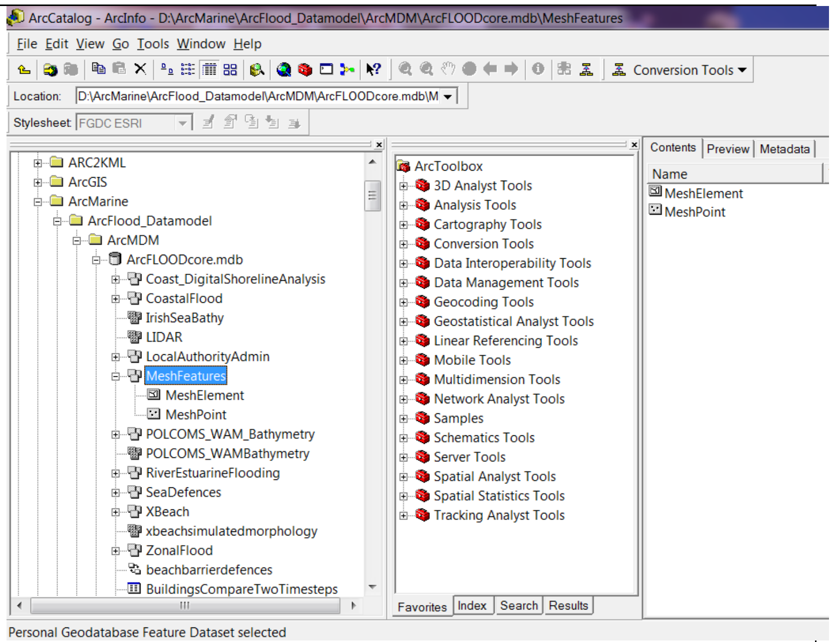
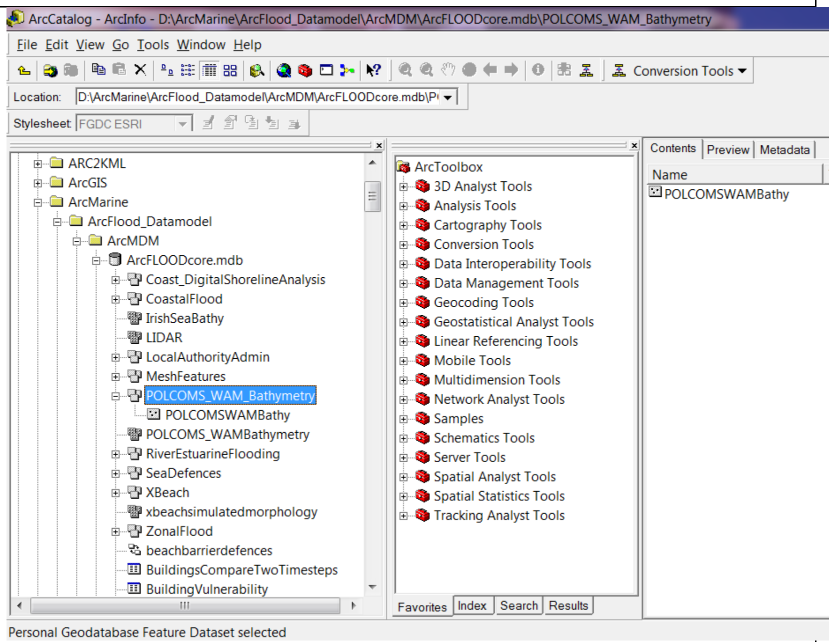
Analysis</td><td>
</td></tr>
</table>

CoastalFlood

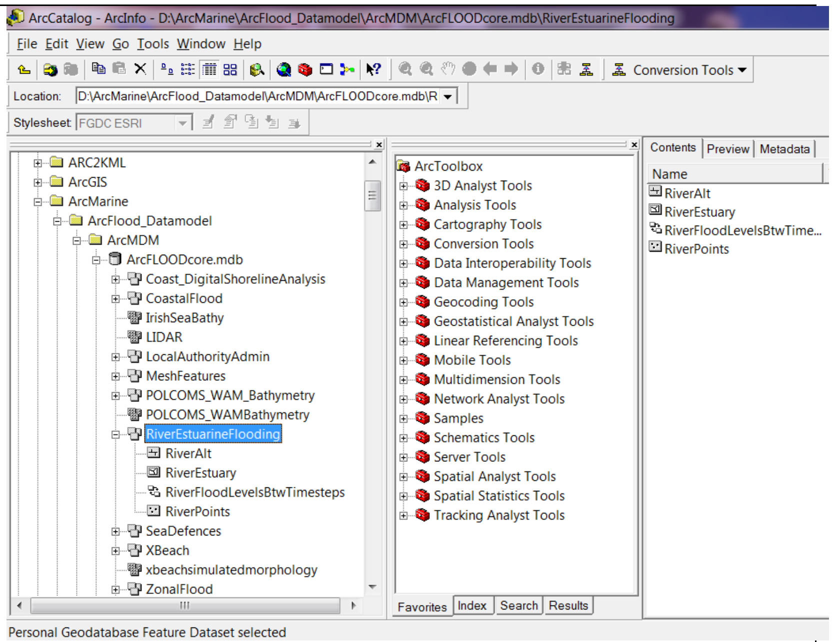


LocalAuthorityAdmin

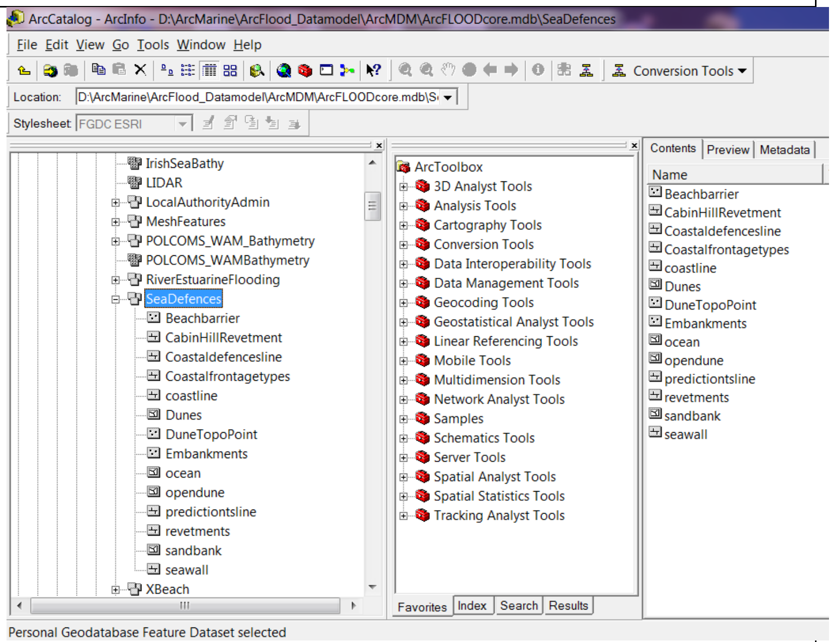


MeshFeatures	
POLCOMS-WAM- GOTM-Bathymetry	

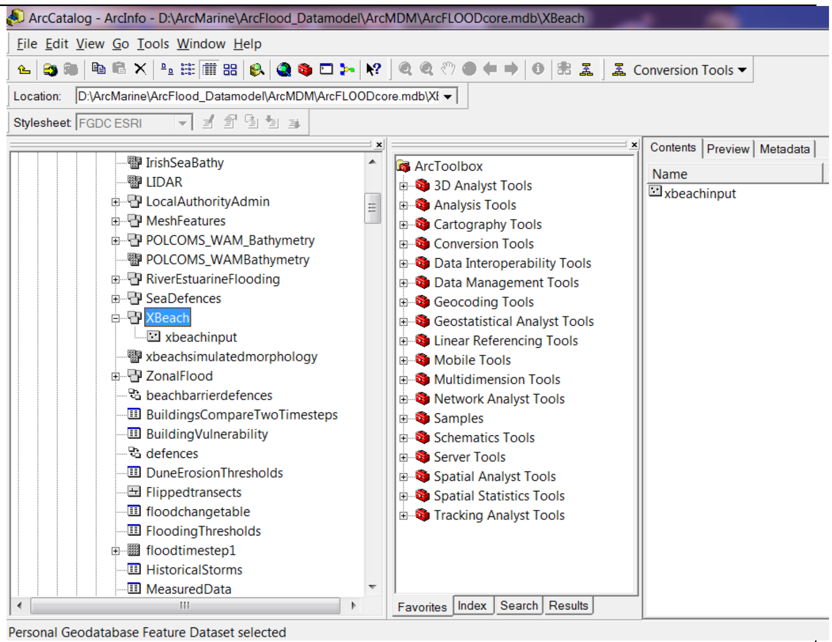
RiverEstuarineFlooding



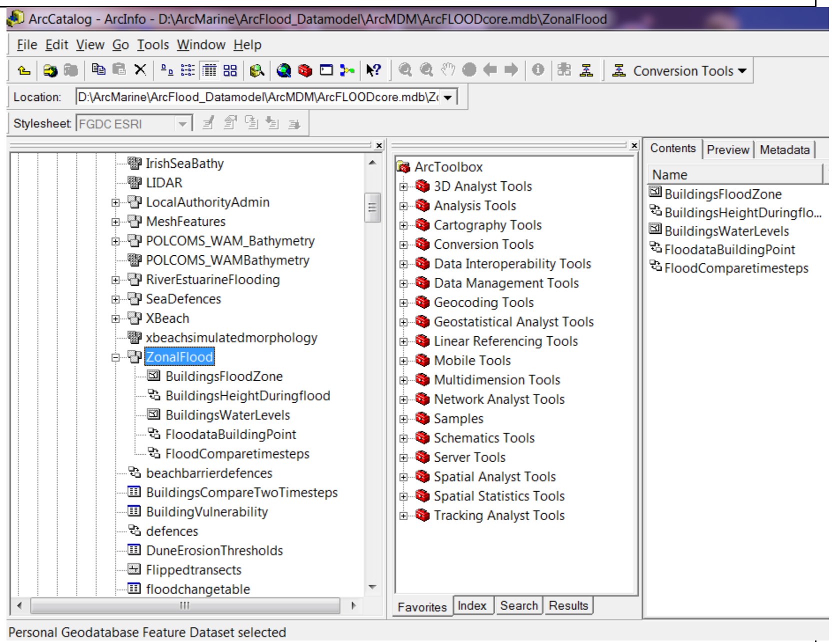
SeaDefences



XBeach

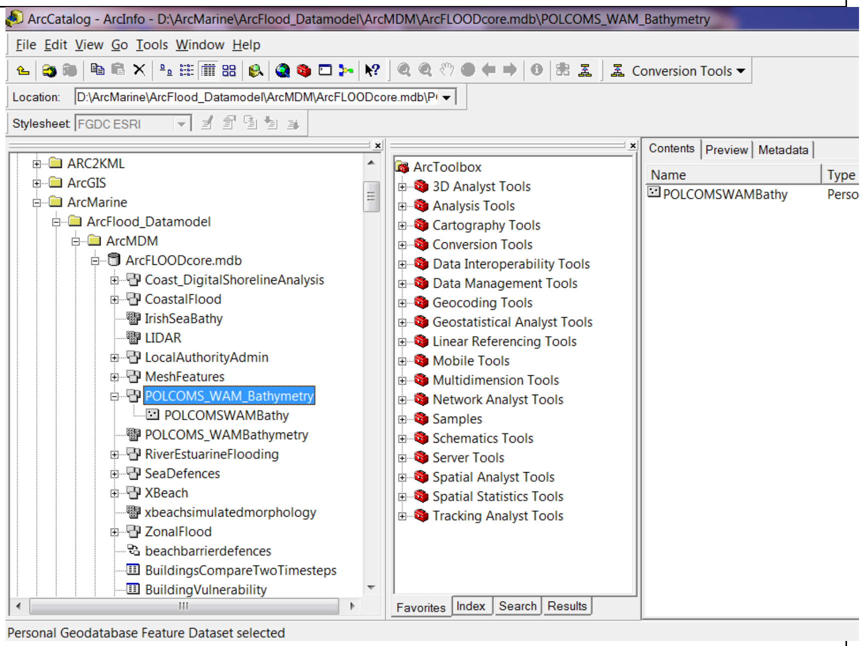
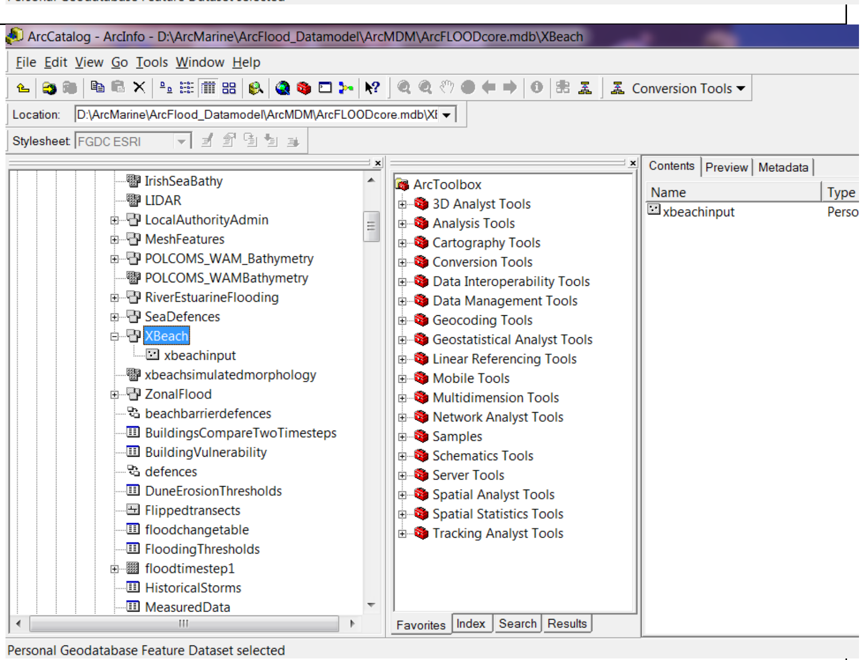


ZonalFlood



B.3 ArcFLOOD Raster Datasets

Table B.3.1: ArcFLOOD Raster Datasets

<table>
<tr><th>RasterCatalog</th><th>ArcCatalog Directories</th></tr>
<tr><td>POLCOMS-WAM-GOTM-Bathymetry</td><td>
</td></tr>
<tr><td>Xbeachsimulatedmporphology</td><td>
</td></tr>
</table>

B.4 Geodatabase Properties

The important database properties were:

a. Tables contained rows and all rows have the same column.
b. Rows in a table stored all the properties of a geographic object.
c. Each column had a data type which was specified initially: integer, decimal number, character and date. This is not changeable once the table is created.
d. The column types were: number, text, date, blobs and global identifiers. These cannot be changed after the table is created.
e. Build common keys in tables to create a relationship between tables to allow data editing and data integrity.
f. Indicate sub-types which are attribute sub-classes to define specific features of an object (feature class).

B.4.1 Feature Class Design

The important feature class design properties were:

a. Determine which geometry types of your feature classes: (point, line, and polygon).
b. Determine Common attributes fields and column types.
c. Determined the spatial reference- coordinate system, x-coordinate, y-coordinates, z-coordinates for each feature class.
d. Scale ranges.

B.4.2 Adding Datasets to the Geodatabase

To begin populating your geodatabase with existing data, use the ArcToolbox conversion tools to:

a. Import text to shapefile.

b. Import MIF to Shapefile.

c. Import Raster files such as aerial imagery.

B.5 Model Building

This appendix includes the guide to the model builder tools built in this thesis to perform 2d spatial analysis on coastal flooding data and to develop separate datasets upon which the ArcFLOOD data model was built. Process Models were developed using Model Builder in ArcGIS, geoprocessing menu. Using the Insert option, add data or tool. The tools to create the process models developed in this research are found in ESRI ArcGIS Help. The proposed models in this thesis are workflows that combine sequences of geoprocessing tools to allow the flow of data inputs and provide outputs. It is a visual programming language for building workflows. The workflows presented here are useful for constructing and executing data. Upon running the model, the results were saved in a geodatabase. The following are the instructions Copyright © 1995-2013 ESRI All rights reserved:

B.6 Process Models for Coastal Flooding

B.6.1 CreateFloodDEM

The CreateFLoodDEM automates the process of conversion of an XBeach flood prediction results file and creates a flooding raster grid. These functions can be performed in batches which make the tedious process improved for multiple timesteps. Process models were designed for natural neighbour and IDW interpolation techniques. The model builder schematics for the CreateFloodDEM tool are shown for two specific user dependant models in Figure B.6.1a and Figure B.6.1b.

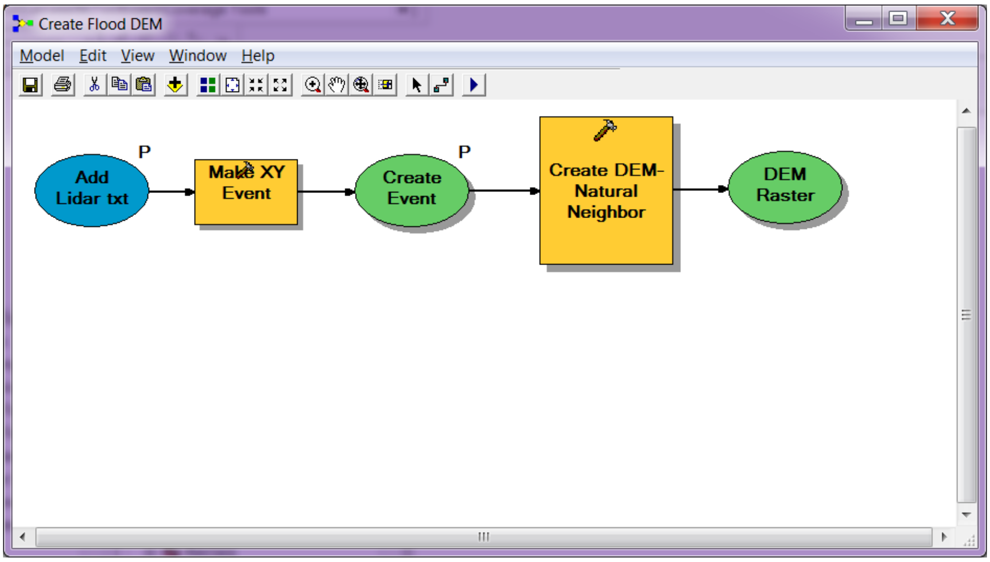


Figure B.6.1a: Create Flood DEM Natural Neighbour Interpolation Tool.

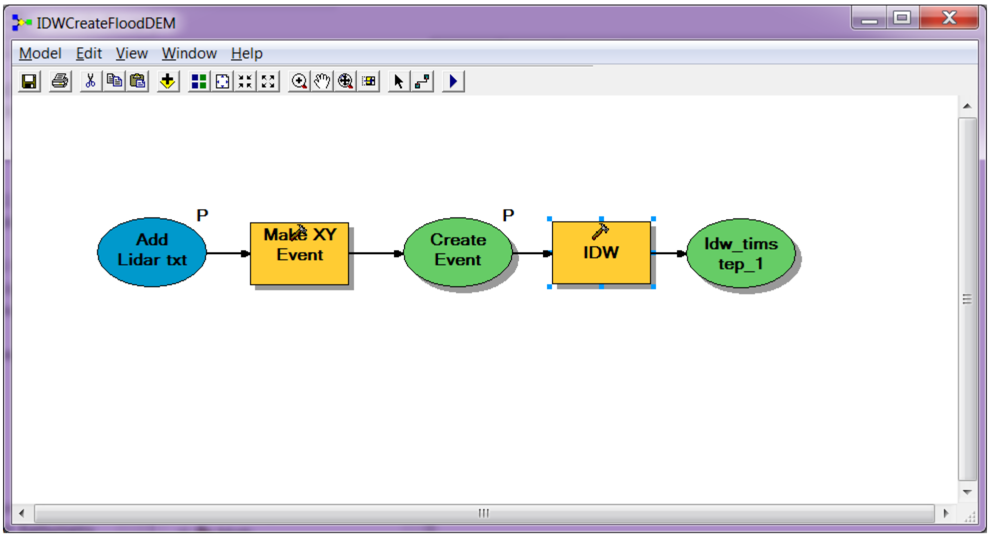


Figure B 6.1b: Create Flood DEM Inverse Weighted Distance (IDW) Interpolation Tool.

B.6.2 CreateFloodPolygons

The CreateFloodPolygons is a 2D spatial analyst technique which uses Boolean mathematics. Through a less than function a raster DEM which represents flooded and non-flooded categories was created by categorising a logical 1 for cells where the first input raster is less than the second raster and 0 if it is not. In turn, a raster of flood depth is returned which was converted to a polygon for flood mapping. The model builder schematic for the CreateFloodPolygons tool is shown in Figure B.6.2.

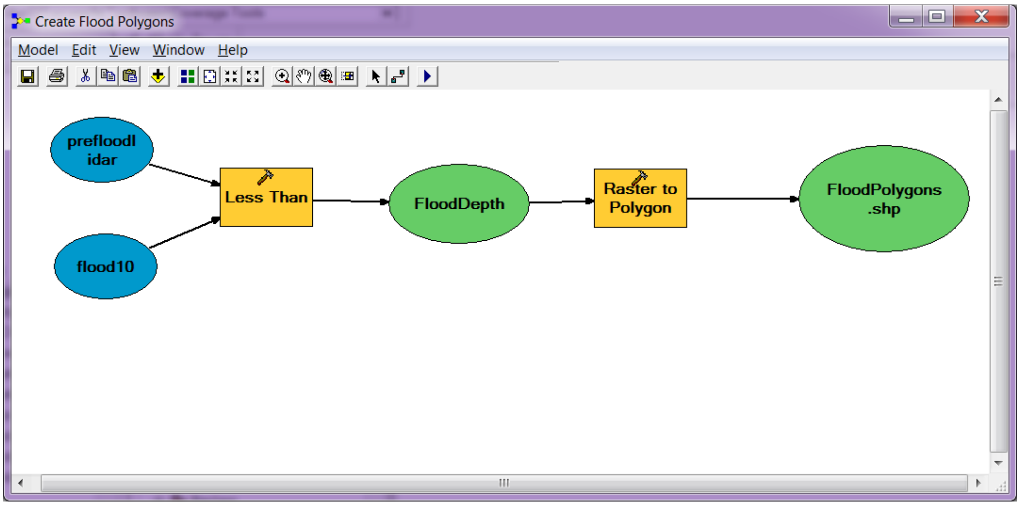


Figure B.6.2: Create Flood Polygon.

B.6.3 CreateFloodContours

The CreateFloodContour tools analysed XBeach DEMs and produced contours (vector line maps) at specified intervals per timestep. These flooding contours were converted into a raster map for improved visualisation and queried to output individual contour values as separate vector line maps with attributed slope and aspect values in a contour table. The model builder schematic for the CreateFloodContour tool is shown in Figure B.6.3.

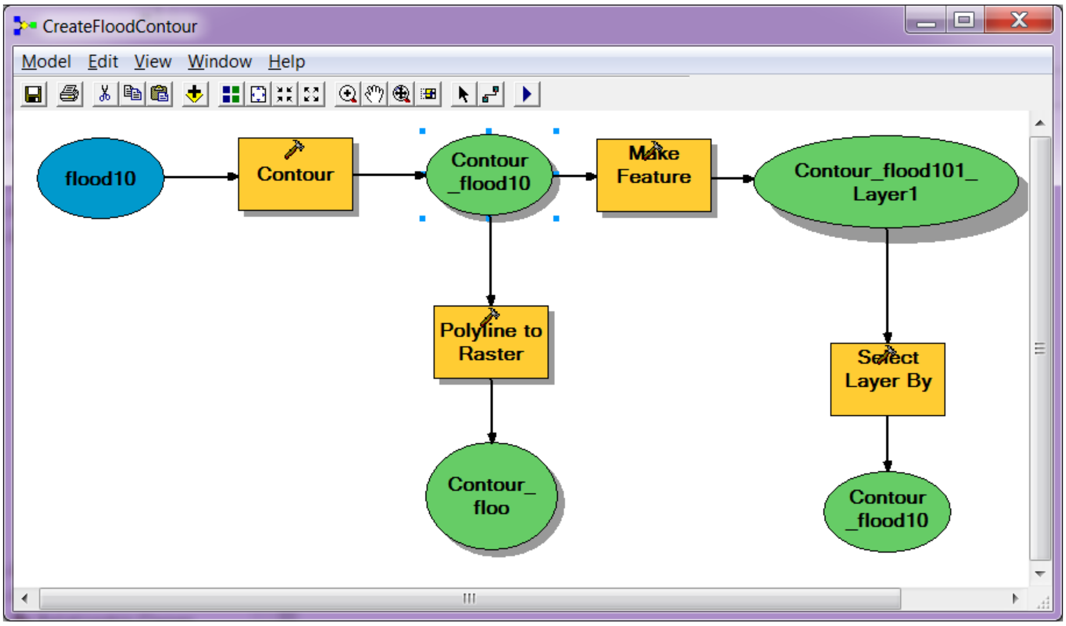


Figure B.6.3: Create Flood Contours Tool.

B.6.4 DissolveFloodedZone

The DIssolveFloodedZone was a utility developed to aggregate features based on specified attributes. In this case, it was used to aggregate the flooding polygons extracted into one flooding layer. The model builder schematic for the DissolveFloodedZone tool is shown in Figure B.6.4.

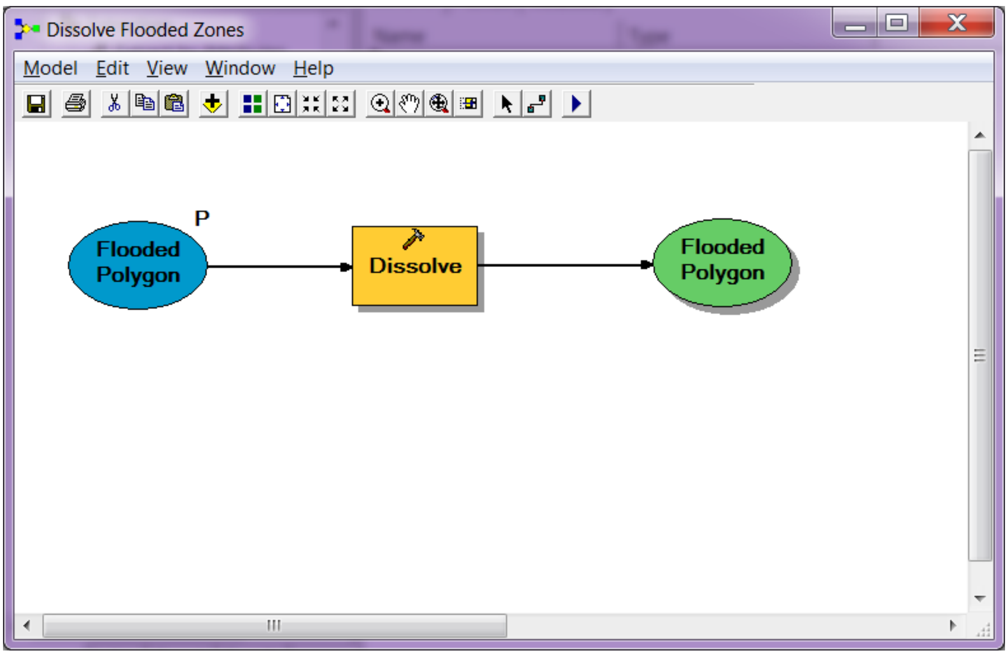


Figure B.6.4: Dissolve Flooded Zone Tool.

B.6.5 PostFloodingProperty

The PostFloodingProperty Query attached the flood water depth levels from the predicted XBeach DEM's to features such as buildings or points using a Zonal Statistics function which outputs tables with pre and post flooding levels and provided statistical measures such as mean, max, min and standard deviation. The Zonal function attached the flooding raster DEM Z_s values to a feature dataset which intersects with the DEM. The features were extracted and an attribute of Z_s attached to its attribute table. The model builder schematic for the PostFloodingProperty tool is shown in Figure B.6.5.

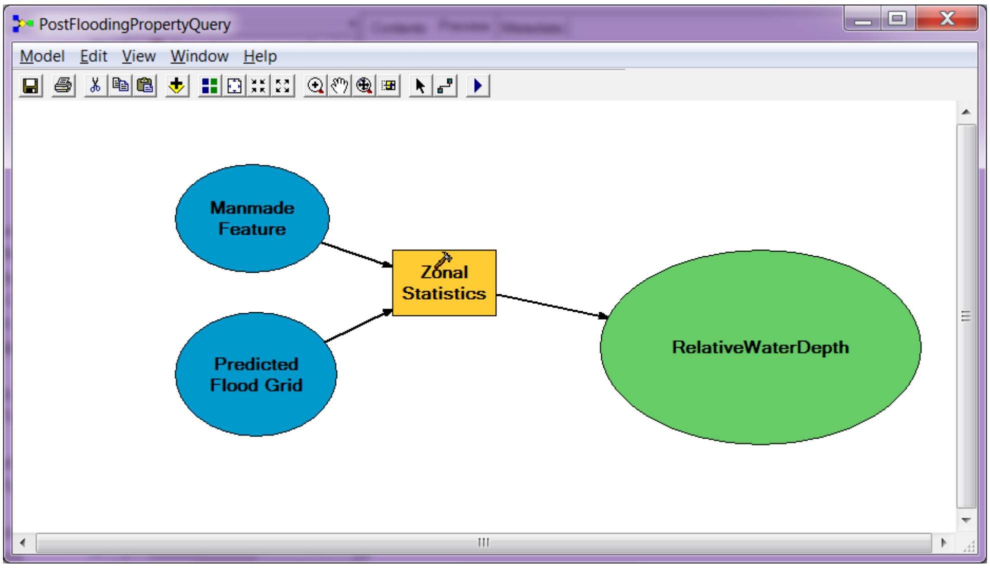


Figure B.6.5: Post Flooding Property Query Tool.

B.6.6 CalCHangeFloodWaterLevel.

This process model was used to query flooding raster DEMs. The difference between timesteps was calculated using a minus raster function to subtract two rasters to indicate a change in flood water level between any timestep interval. The resulting flood water depth change was converted to a point file and table for further analysis. The model builder schematic for the CalCHangeFloodWaterLevel tool is shown in Figure B.6.6.

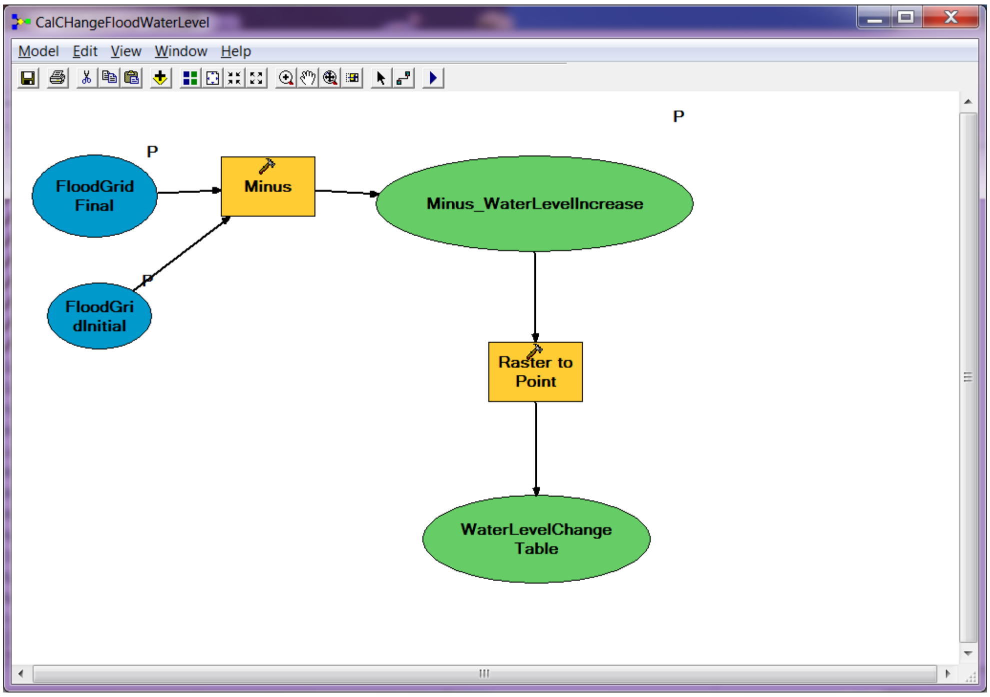


Figure B.6.6: Calculate Change Flood Water Level.

B.6.7 The BufferProperty_Map.

The BufferProperty_Map tool was developed with a buffer and Join field function. The function performed a distance buffer which was specified around any input feature such as points, lines and areas. As an option the dissolve function was used to dissolve the boundaries between buffered features to produce less map detail and remove overlaps. This function specified a search distance around features which were flooded and return probable flood water depths. The model builder schematic for the BufferProperty_Map tool is shown in Figure B.6.7.

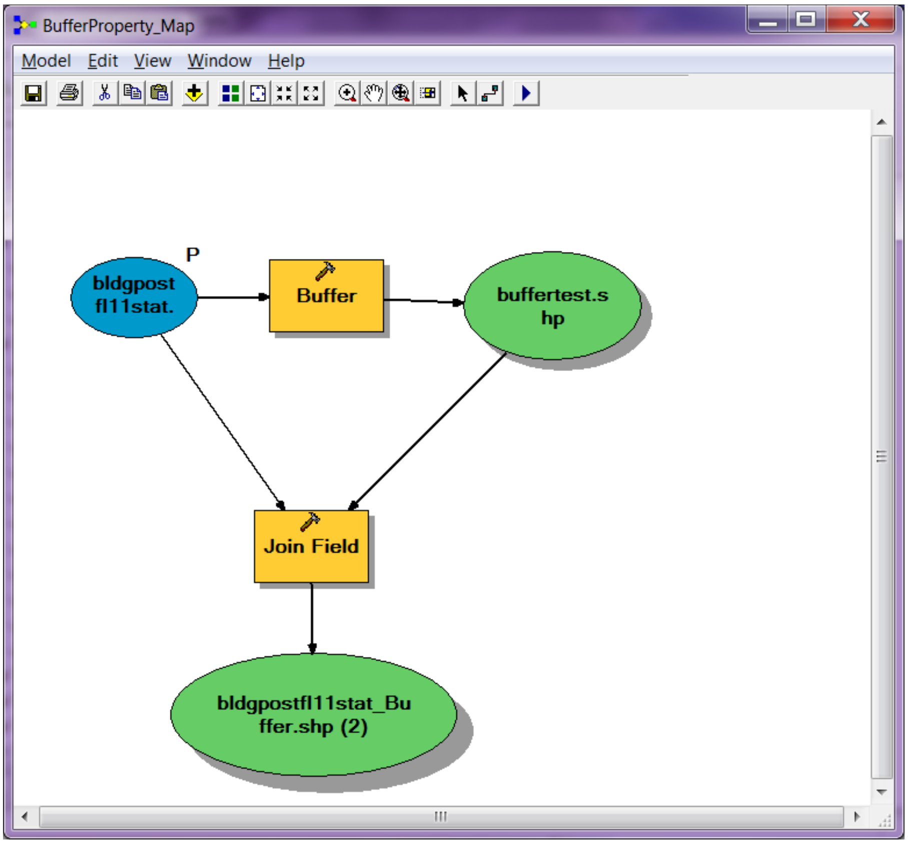


Figure B.6.7: Buffer Property Map Tool.

B.6.8 FloodFootprintBuildings

The tool used a Zonal Statistics as Table function to attach flood water depths to a feature in the flood hazard zone producing the floodwater depth for that feature at a particular timestep as a tabular file and raster file. The tool joined the table produced back to the raster file produced to attach attributes to the raster. All rasters were produced in GIS without attribution. The resulting flood footprint was exported to a geodatabase. The FloodFootprintBuildings represented the flow of flood information optimised to produce building footprints. This tool managed numerous datasets to achieve the desired flood footprint for buildings or any other feature. The model builder schematic for the FloodFootprintBuildings tool is shown in Figure B.6.8.

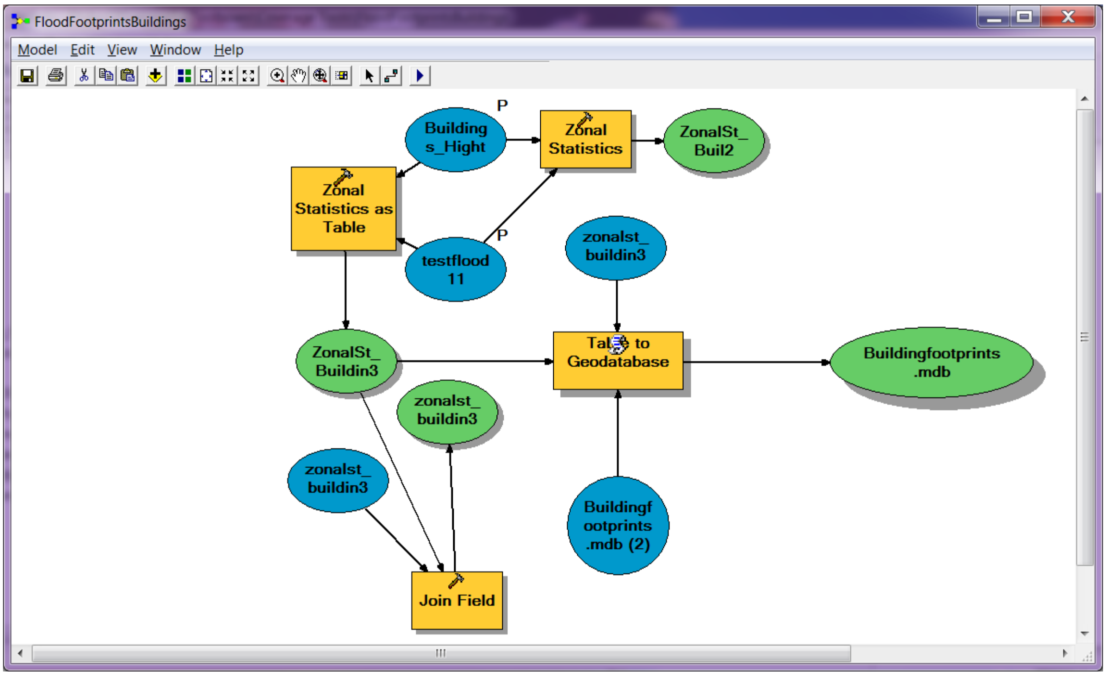


Figure B.6.8: Flood Footprint Buildings Tool.

B.6.9 FloodLevelChangeDiffTimesteps.

The FloodLevelCHangeDiffTimesteps produced flood change tables from a number of timestep rasters with their minus rasters obtained from the CalChangeFloodWaterLevel process model. The results include a flood change table which were exported as points and re-visualised as raster DEM''s. The model builder schematic for the FloodLevelCHangeDiffTimesteps tool is shown in Figure B.6.9.

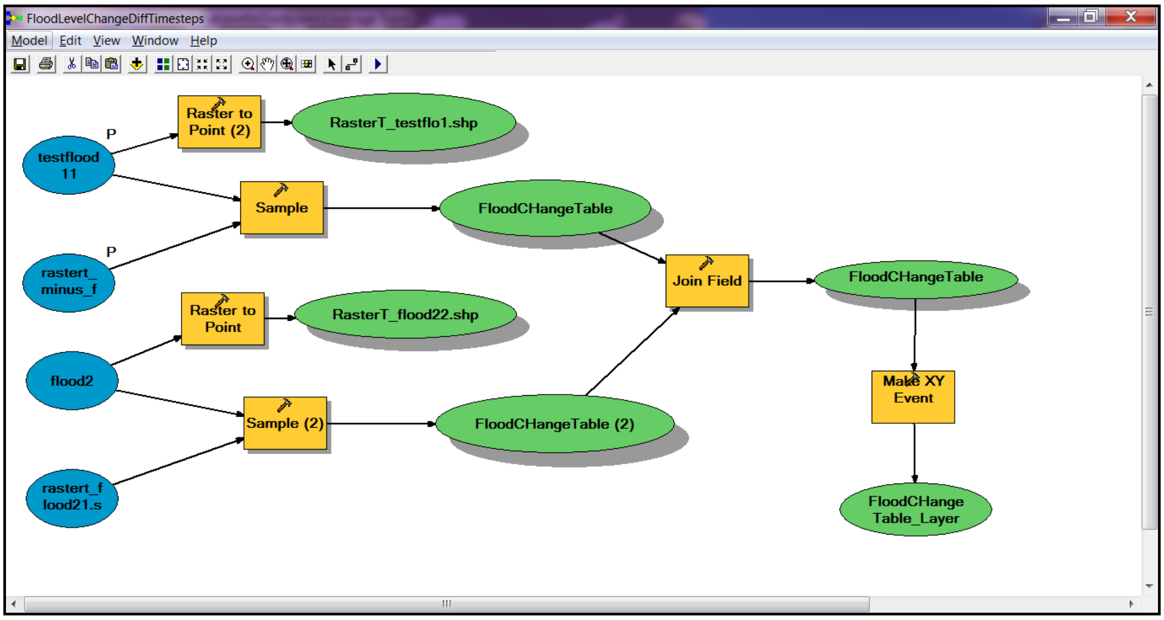


Figure B.6.9 Flood Level Change Between Timesteps.

Appendix C

C.1 Guide to Data Modelling

The MDM was downloaded from the ESRI support centre at: http://support.esri.com/datamodels. It is advised to create an empty test geodatabase. An instructional guide is found at the ESRI ArcMarine Data model website (http://support.esri.com/en/knowledgebase/techarticles/detail/40585). Permission to use this text has been granted by ESRI Inc.

C.1.1 Additional Information on Data Modelling

a. Assess your computer requirements to run the software and processing either on a desktop or server-side for ESRI ArcGIS.
b. Ensure the coordinate system and spatial extent must be same throughout the geodatabase, for example British National Grid (BNG) is applied to the data.

C.1.2 Setting up ArcFLOOD Geodatabases

The process of setting up a geodatabase involved:

a. Loading ArcFLOOD data model schema in ESRI ArcGIS – ArcCatalog.
b. Using ArcCatalog to automatically read all GIS formatted data including the schema.
c. Applying the ArcFLOOD data model schema to the geodatabase.
d. Assessing your data to determine the database setup.
e. Personalising ArcFLOOD to suit your data specifications.
f. Loading new data into the ArcFLOOD schema developed.

The ArcFLOOD data model schemas viewed in ArcCatalog geodatabase are seen in Figure C.1 for coastal flood data model; Figure C.2 for river and estuarine data model; and Figure C.3 for the MESH data model. The complete **coastal flood**; **river and estuarine;** and **mesh** data models are found in Appendices D.3.1, D3.2 and D.3.3 respectively.

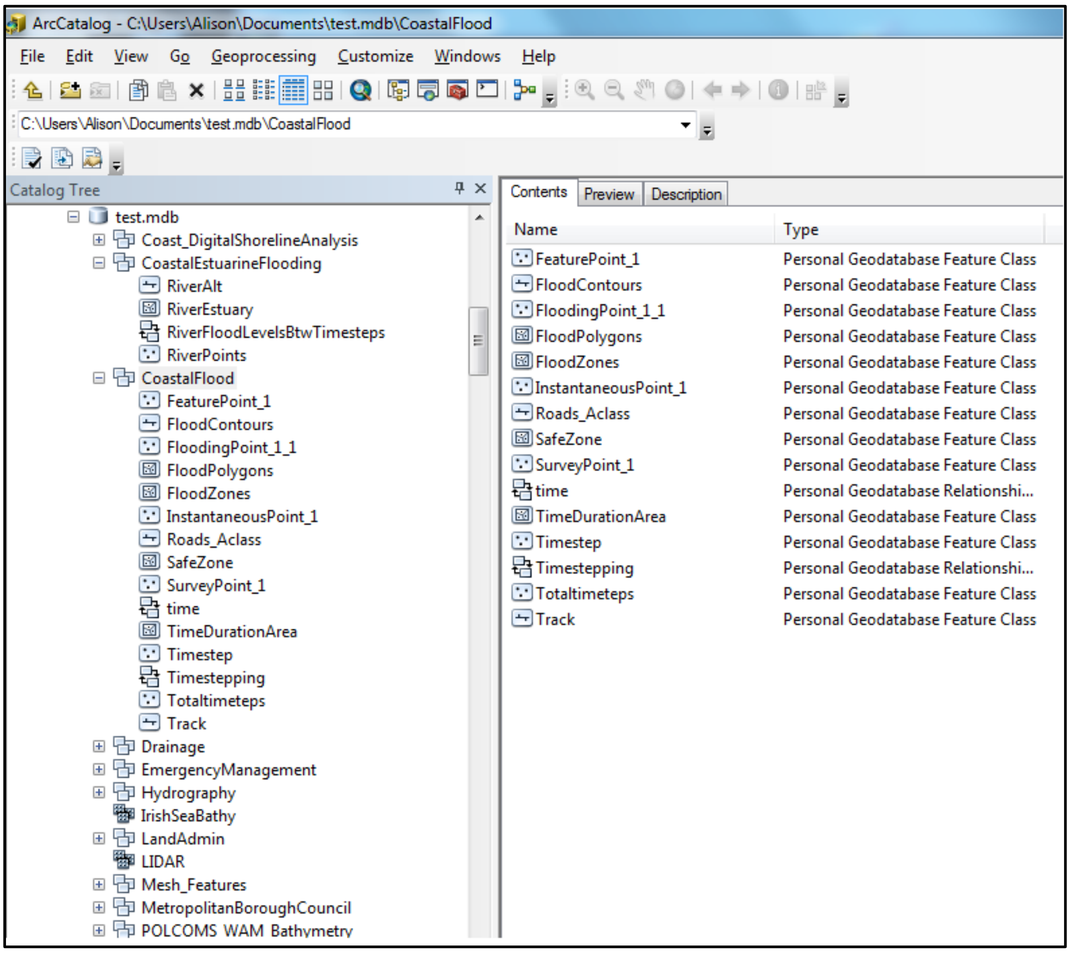


Figure C.1: The coastal flood data model in ArcCatalog. The left hand panel shows the coastal flood feature dataset in a geodatabase and the right hand panel shows the elements of the data model.

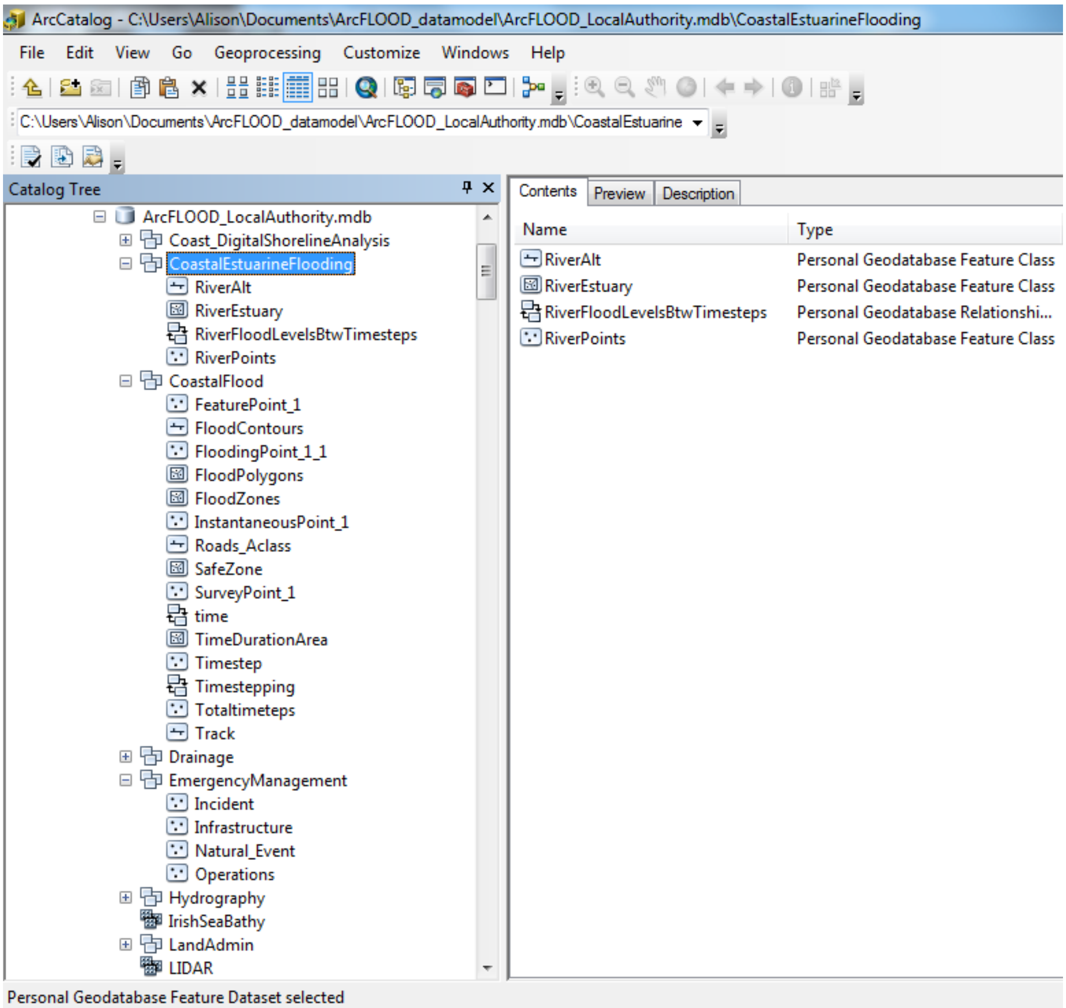


Figure C.2: The river and estuarine data model in ArcCatalog. The left hand panel shows the coastal flood feature dataset in a geodatabase and the right hand panel shows the elements of the data model.

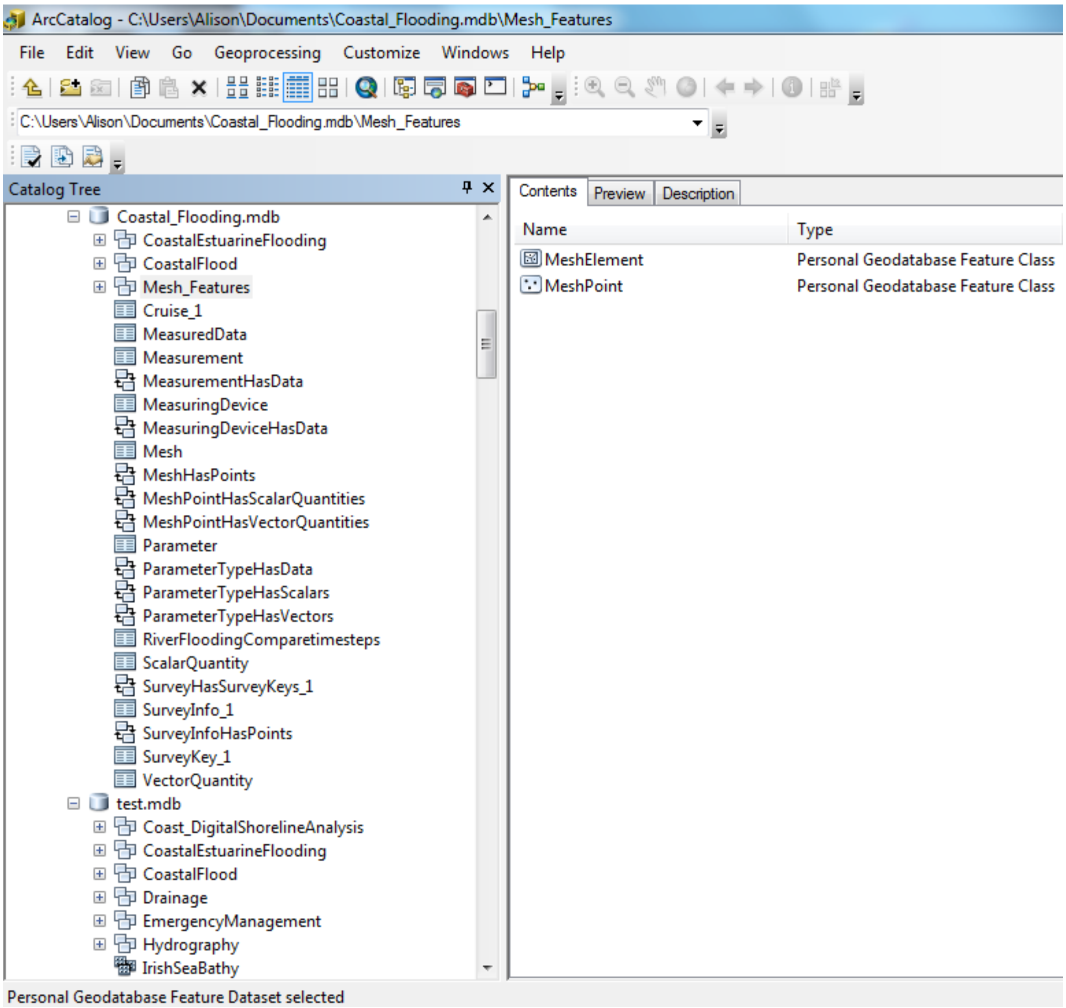


Figure C.3: The mesh flood data model in ArcCatalog. The left hand panel shows the feature dataset in a geodatabase and the right hand panel shows the elements of the data model.

C.1.3 Adding the Geodatabase Features to your Arc Map Project

All data imported must have the same coordinate system and spatial extent as the data model schema data. Use the Import option and select a shapefile/coverage with the largest extent needed and desired coordinate system when working in ArcMap.

C.1.4 Loading Data Using the Schema

a. Assess the data and determine database setup:

        i. Which feature classes should the data go into?
        ii. What are the attributes of each data set?
    b. Do you want to relate any of your data? If so, through what key fields?
    c. Matching data with feature classes using the ArcFLOOD data model geodatabase and poster.
    d. Matching spatial data with non-spatial data.
    e. Relationships between data columns can only be established if attribute data type is long integer.
    f. Personalising the data model to fit the data:
        i. Feature classes match with related tables.
        ii. Field names added to the feature class.
        iii. Once fields are populated with data, field can only be modified by recreating a new field and repopulating the data.
        iv. Make sure data types match up exactly, or your data will not load.
    g. Loading Vector Data into the MDM:
        i. Load data into feature class/table.
        ii. Match field names and data types.
    h. Creating a relationship.
    i. Loading raster data into the data model.

C.1.5 Applying the ArcFLOOD Schema to the Geodatabase in ArcCatalog

Please ensure that the ArcFLOOD data schema matches the data imported exactly as the file will not work:

a. Use the schema tool in ArcCatalog.

b. Select coordinate system and spatial extent.

c. Use import option and select a shapefile/coverage with the largest extent needed and desired coordinate system.

d. Make sure that the schema and your data match exactly.

For example, Figure C.4 shows the matching of data that you may import into an input file such as the **timesteptotalsimulation** shapefile in ArcCatalog, using the load tool which is found by right-clicking on the dataset. The user is prompted with a Schema Wizard which guides you through the process. In Figure C.5, the user will match the field names of the schema with their own data. The core parameters of ArcFLOOD are seen in this file. By matching the schemas, data can now be loaded into the file with the new schema. This must be done for individual feature datasets in ArcCatalog.

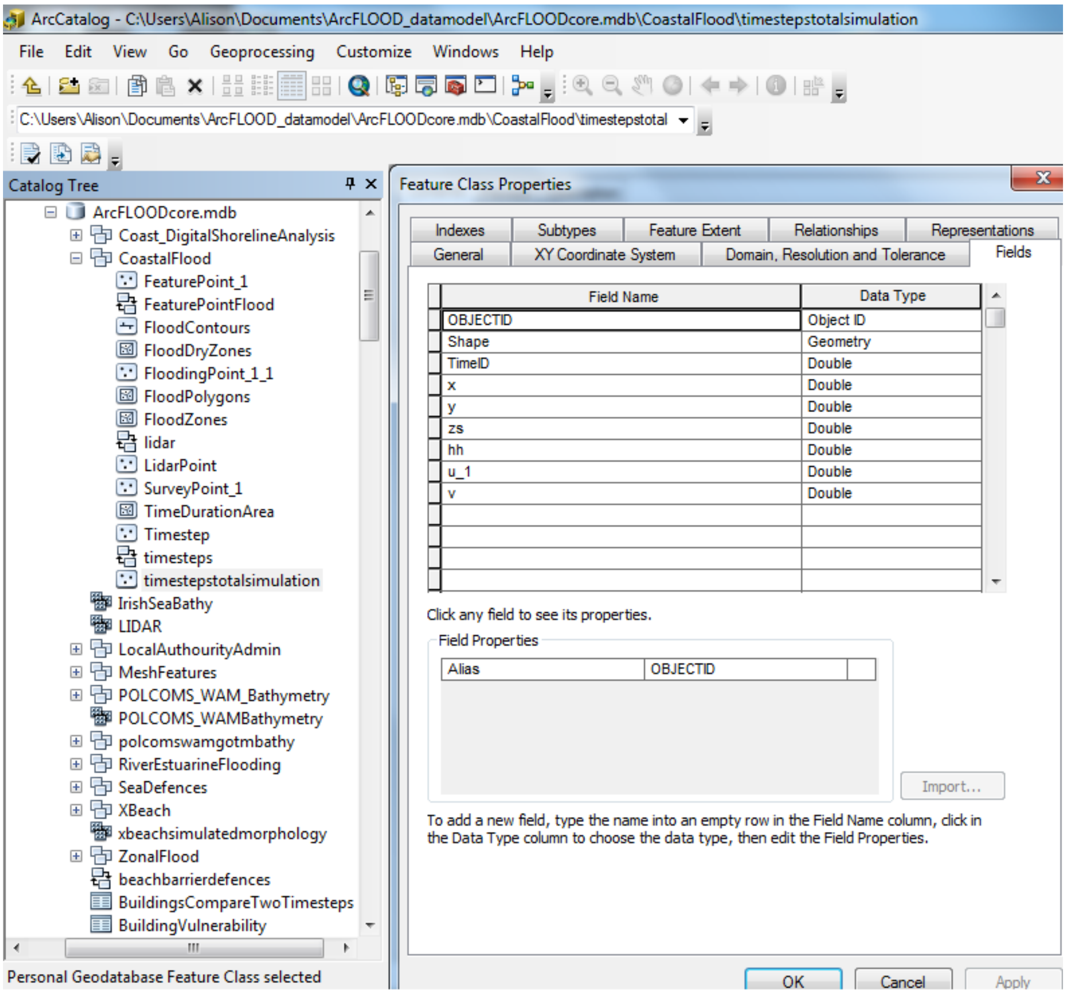


Figure C.4: The matching of fields in the new feature class with the ArcFLOOD feature class by using the load schema tool.

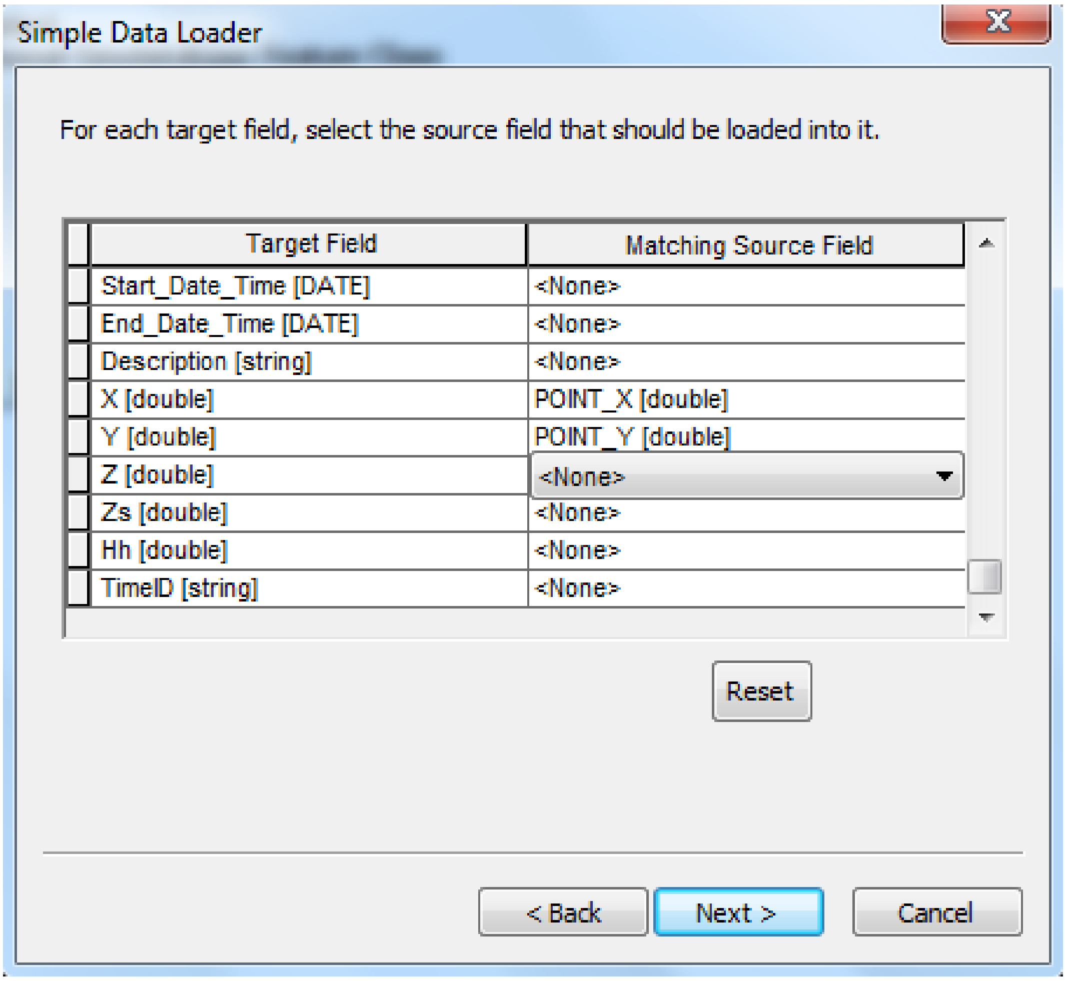


Figure C.5: Matching schema in ArcCatalog showing how the new feature dataset is modified by selecting fields to match in the source field column with the target field column.

By right clicking on your feature dataset in ArcCatalog, a wizard is launched which gives the option to load the XML recordset document – schema. The wizard guides through the process to match the fields which are important to analysis and mapping. In Figure B.5.6 the right panel shows how a feature dataset “incident” easting and northing fields- Point_X and Point_Y are matched to the data model X and Y fields. The field type is a double integer to allow the mapping of emergency management flood incidents. Through this method, all data is extended with ArcFLOOD properties. An end-user can begin to map coastal flooding data with a working structure for handling flood model output. The data model is easily amended in ArcCatalog which will export your schema to an XML format. The data model design in Microsoft Visio can be readjusted using ArcGIS Geodatabase Diagrammer tools. The importance of this schema is that software developers have a guide to begin understanding coastal flooding data, eliminating the need for significant DBMS processing.

C.2 ArcFLOOD Data Model Description

This section of the Appendix provides a guide to the important features of the ArcFLOOD data model. The ArcFLOOD data model comprises:

a. Coastal Flood Data Model (Appendix C.1).

b. River and Estuarine Flooding Data Model (Appendix C.2).

c. Mesh Data Model (Appendix C.3).

C.2.1 The Coastal Flood Data Model Specification

The complete **Coastal Flood Data Model** is found in Appendix C.1.

C.2.1.1 Objects

The Coastal Flood Data Model is the core of the ArcFLOOD data model. Its definition is completely new and not contained in the original MDM. The core components of the Coastal Flood Model within ArcFLOOD are:

a. The fundamental definition of a coastal flood simulation is based on **Timestep.**

b. **Timestep** is a vector point file containing water level at a point in a time series array. The time series array is represented uniquely with the **TimeI**D primary identifier. Many different timesteps can be loaded using this feature class (new).

c. **Timesteptotal** is the total flood model simulation run containing all timesteps for instance from t= 1, n (new).

d. **FeatureArea** is an object used to represent the FloodArea which is derived from the processing of LIDAR DEMs in process models to produce the data necessary for the producing flood results.
e. **FeaturePoint** is defined to represent any generic flood feature which can be added.
f. **FloodingPoint** is another unique object to represent **LIDARsurveyPoint.**
g. **TimeDurationArea** is another polygon table added to spatially represent to represent areas of flood.

C.2.1.2. Relationships

a. **Timesteptotalsimulation** is the parent table from which **timestep** tables are generated.
b. There is a 1 to many (**1: m**) relationship where **timesteptotalsimulation** table inherits many **timestep** tables.
c. Using the primary keys of **OBJECTID** and **TimeID** the individual rows of data are uniquely defined as points throughout the data model. These are related to the **Flooding Point** definition which is derived from **Survey Point** (MDM).
d. **TimestepTotalSimulation** incorporates an array of simulation sequences from **timestep** (**t**) = 1, **n** where **n** is timestep interval in seconds. In this case, 11 timesteps were converted due to processing limitations. Based upon this definition in ArcGIS tables, the querying across the time series array occurred to produce coastal flooding analysis.
e. The **TimeID** unique identifier key is a double integer which is used to link to all

other flooding data in ArcFLOOD.

f. **TimestepTotalSimulation** also includes additional XBeach parameters such as **u (x-velocity in the x-axis direction); v (v-velocity in the y-axis direction; Z_s- surface flood water depths; and H_s- significant wave height** which were used to compute the **actual flood water depth in the research**.

C.2.2 River and Estuarine Data Model Specification

The complete River Estuarine Data Model is found in Appendix C.2.2.

C.2.2.1 Objects

a. **River** which is a vector data line used to represent a river for example: the River Alt (new).
b. **River Alt Estuary Polyline** represents the extent of the coastal estuary.
c. **River Points** is created from processed raster grid created from the Flood DEM with flood water depths attached.
d. Relationships: 1:m **RiverFloodLevelBtwTimesteps**
e. Relationships: **FloodCompareTimesteps** linking to original CoastalFlood data model.

C.2.2.2 Relationships

The river has a 1:1 relationship **RiverFloodBtwTimesteps** with the **RiverFloodingCompareTimesteps** table. The key relationships include the following as seen in Figure B.4.

C.2.3 ArcFLOOD – Mesh Data Model Specification

The complete **MESH Data Model** is found in Appendix C.3.3.

C.2.3.1 Objects

a. **MeshElement** is a complex 4D and 5D grid in the MDM.

b. **MeshPoint** defines a point in multidimensions.

c. **Timestep** feature classis joined to **MeshElement** through an **OBJECTID.**

C.2.3.2 Relationships

Through **Timestep** and a relationship **Meshtotaltimesteps** (1:1) it is possible to have a direct relationship with the MeshPoint file. One timestep of data can be mapped as mesh points.

Appendix D

The poster presentations of the data models have been attached in Adobe pdf format.

D.1 Coastal Flood Data Model

D.2 River and Estuarine Data Model

D.3 Mesh Data Model