

# [Flood inundation modeling under stochastic uncertainty environmental sciences ess...](https://assignbuster.com/flood-inundation-modeling-under-stochastic-uncertainty-environmental-sciences-essay/)

With the onset of the first ever greenhouse gas (GHG) regulation for ships by the International Maritime Organisation (IMO) in 2011, the container shipping industry requires the combined use of technical and operational emissions reduction measures to improve the environmental performance of its vessels. Studies show that most existing measures are cost effective with a range of emissions reduction potential. However, the level of implementation is not depicted and the potential of the measures may be over-estimated. An evaluation of the GHG emissions reduction measures is thus conducted in this study. Critical issues in the implementation are identified so that solutions can be provided to overcome the barriers. Lastly, recommendations for companies with regards to GHG issues are made. This research project was carried out through survey of container shipping companies and interviews with industry professionals. The emissions reduction measures were evaluated based on 3 factors, namely level of implementation, emissions reduction potential and cost effectiveness. Cost effectiveness is defined as the monetary evaluation of the cost of implementing the measure relative to the cost savings that can be achieved through the usage of the measure. The strong link between cost effectiveness and level of implementation is highlighted in this study. It is shown that measures with higher perceived cost effectiveness generally have a higher level of implementation despite a lower perceived emissions reduction potential. Thus, improvement in the cost effectiveness of the measures is needed to increase the level of implementation. There is immense potential to reduce emissions from ships given the availability of measures with significant emissions reduction potential. However, the top barriers of implementation, namely cost of measure and lack of information, need to be addressed for a higher level of adoption. The cost effective measures can be implemented on a greater scale in view of the benefits of bunker consumption savings. GHG emissions reduction is often a by-product of efforts to improve the energy efficiency of vessels. It is advisable for companies to consider savings from reduction in fuel consumption as a main factor in the adoption of measures. Companies should also monitor demand changes amid the environmental situation to identify business opportunities. With the careful packaging of the GHG strategy, the environmental issue can be valuable for business creation. Support for GHG regulations is also encouraged as regulations can drive the development of more efficient technologies. Companies have to realise that green is the way forward in the shipping industry and it is prudent for shipping companies to adopt a greener operation. In recent years, there has been increasing concerns on environmental issues as Climate Change is occurring around the globe. Extreme weathers are occurring more frequently and flooding phenomenon is becoming more common to Singapore over the past few years. The unpredictable weather had become Singapore’s key issues to tackle. This project was initiated to further understand the global climate change and predict the future intensity of precipitation and temperature in Singapore. This will allow engineers and other professionals to gauge the intensity of the future weather and conduct necessary works to prevent unwanted event like flooding, from happening. However, predictions with these models are often deterministic and as such they focus on the most probable forecast, without an explicit estimate of the associated uncertainty. (R. S. Blasone, J A. Vrugt, 2007)The reasons why the uncertainty occurs in model predictions are in terms of the measurement errors of the input and output data, and model structural errors arising from the convert a real dynamic real flood processes into a mathematical model, as well as the problems of parameter estimation. Therefore, this research is carried out to assess the reliability of LISFLOOD-FP models, which is a grid based flood inundation models (Bates and De Roo, 2000) under uncertainty analysis. By applying the generalized likelihood uncertainty estimation (GLUE) methodology (Beven and Binley, 1992), we can evaluate the propagation of the uncertainty associated with the sensitive input parameters in LISFLOOD-FP model in order to improve the predictions accuracy. The GLUE methodology is one of the first attempts to represent prediction uncertainty within the context of Monte Carlo (MC) analysis coupled with Bayesian estimation and propagation of uncertainty (Beven and Binley, 1992). In this study, we will utilize the Monte Carlo based sampling strategy to randomly generate 1000 sensitive input parameters samples within the prior parameter space. And then the GLUE approach finds out the acceptable samples whose output model data with minimum deference comparing to the real observed data in a calibration process. Those acceptable samples are good in producing fit model predictions. This method is much better than Monte Carlo simulation in reduction the workload of computation. The outputs of the GLUE procedure are parameter distributions conditioned on the available observational data and associated uncertainty bounds. In this project, I will study LISFLOOD-FP model development through the technical codes in terms of physical simplification equations used and its assumptions from Literature Review, and find out the most sensitive primary input parameters, use GLUE methodology with Monte Carlo sample strategy to conduct the analysis of the uncertainty associated with sensitive input parameters in LISFLOOD-FP model. Thereafter, results analysis is carried out by using the model output data to determine the probability distribution of the sensitive parameters.

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## LIST OF ABBREVIATIONS

CATCHCost of Averting a Tonne of CO2 heatingCCWGClean Cargo Working GroupCDPCarbon Disclosure ProjectCH4MethaneCOCarbon monoxideCO2Carbon dioxideEEDIEnergy efficiency design indexEEOIEnergy efficiency operational indicatorEUEuropean UnionGHGGreenhouse gasHFCsHydrofluorocarbonsHFOHeavy fuel oilHSSEHealth, safety, security and environmentIEEInternational Energy Efficiency CertificateIMOInternational Maritime OrganisationLNGLiquefied natural gasMACMarginal abatement costMACCMarginal abatement cost curveMARPOLThe International Convention for the Prevention of Pollution from ShipsMBMMarket-based measuresMEPCMarine Environment Protection CommitteeMFOMarine fuel oilMPAMaritime and Port Authority of SingaporeNMVOCNon-methane volatile organic compoundsNOXNitrogen oxidesN2ONitrous oxideODSOzone depleting substancesPFCsPerfluorocarbonsPMParticulate matterR&DResearch and developmentSEEMPShip energy efficiency management planSF6Sulphur hexafluorideSOXSulphur oxidesTEUTwenty-foot equivalent unitVOCVolatile organic compoundWSCWorld Shipping Council

## GLOSSARY

## Container liner shipping

The trade which involves shipping containers on board vessels that sail according to fixed schedule. The vessels call at fixed ports along the service route. This distinguishes from tramp shipping which does not have a fixed schedule or published ports of call.

## Cost effectiveness

The monetary evaluation of the cost of implementing the measure relative to the cost savings that can be achieved through the usage of the measure over the investment timeframe. Cost of measure includes for example, equipment cost, opportunity cost, operating cost and staff training cost. Cost savings are mainly derived from the reduction in fuel usage.

## Greenhouse gas (GHG)

Gases that absorb and trap radiation within the atmosphere, causing a net retention of heat energy. According to the Kyoto Protocol, carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF6) are the six gases classified as GHG.

## Heavy fuel oil (HFO)

Oil that makes up the distillation residue and consists of large amount of impurities. It is used as the main engine driving fuel during a vessel’s voyage for the generation of power, resulting in the release of harmful GHG emissions.

## Marginal abatement cost (MAC)

The cost per tonne of GHG emissions of the abatement project.

## Marginal abatement cost curve (MACC)

A graph demonstrating all the marginal abatement costs (MACs) of available abatement projects to facilitate decision making.

## CHAPTER 1INTRODUCTION

In recent years, flood inundation models become important increasingly in both flood forecasting and damage estimation as it provides the basis for the decision making of flood risk management. Such models are mainly used to simulate flood inundation extent and depths at different sections of the studied flood rivers. With their help, hydrologists are able to study and analyse the hydrologic systems of floods well. This project was initiated to further understand the flood model Lisflood-FP global climate change and predict the future intensity of precipitation and temperature in Singapore. This will allow engineers and other professionals to gauge the intensity of the future weather and conduct necessary works to prevent unwanted event like flooding, from happening.

## Background

Floods are the most destructive and recurring natural disasters all over the world and a wide range of the world population and their property is at the risk of flooding. Thus, one of the crucial tasks in quantifying the damage estimation of the flood events is that determining the reliable prediction of potential extent and water depth of flood inundation. In General, flood inundation predications are used to service the decision-making in design urban planning in future. The principle of predication are derived from single realisation of numerical hydraulic models and applied on a forward-modeling framework (BatesandDe Roo, 2000). Despite calibration studies are underway to determine a single parameter set that optimises the model fit to some observed data, the confidence level of the predicted results becomes a major problem for decision makers. If the uncertainty is considered in terms of input parameters (e. g. geographical information, hydrological data, hydraulics parameters, and boundary conditions), only a small portion of a typical issue might be regarded as certain or deterministic. The rest inevitably contains uncertainty that arises from the complexity of the system, lack of knowledge or human-induced errors. In previous studies, the uncertainty sources associated with the flood inundation modeling have been generalised into three categories, such as input data, hydraulics parameters and model structures (Bales and Wagner, 2009). Different uncertainty techniques (e. g. Generalized Likelihood Uncertainty Estimation) have been applied into the flood inundation modelling to assess the uncertainty derived from one or multiple factors. However, limited studies have been further discussed the sensitivity of uncertainty sources like roughness coefficients. Moreover, the uncertainty analysis methods applied in previous studies relied heal

## Objective and Scope

This report is a write up on the research of Final Year Project, Flood Inundation Modeling under stochastic uncertainty, had been carried on by the author for the last 10 months. The objective of this project is to systematically study and analyse the impact or effects of uncertainties associated with parameter of roughness coefficient in flood inundation modeling, which is Lisflood-FP Modeling. The predicted data can be used for the predication of future flood inundation and damage estimation under risk analysis. In this report, the following preliminary study works will be covered. To review the one-dimensional (1-D) and two-dimensional (2-D) hydraulic models for flood inundation modeling, and to review the uncertainty sources associated with the flood inundation modeling process and the available uncertainty analysis methods. To conduct a Monte Carlo simulation to assess the propagation of uncertainty associated with roughness coefficients to the results of flood inundation modeling, in terms of water depths and inundation extent. The scope of this project includes a comprehensive literature review on flood inundation modeling process and recognition of the uncertainty effects from various sources. On the basis of literature review, the impact of the uncertainty of roughness coefficients is to be analysed a hypothetical study case. A conclusion will be made according to the preliminary data analysis and the ideas for futures work will be shaped.

## Methodology (GLUE)

Annual reports of companies and information from public domain were reviewed extensively to identify current GHG emissions reduction measures that are adopted by shipping companies. Academic research papers and reports from agencies such as IMO, DNV and World Shipping Council (WSC) were examined to gather information on the potential and effectiveness of the measures and to identify critical issues. Primary research was conducted through a two-pronged approach of surveys and interviews. Survey questions were designed in accordance to the objective of this study and the questionnaires were posted to container liner shipping companies, both with and without offices in Singapore. A small number of survey responses were anticipated and therefore the surveys were used to capture ground information. The interviews with governmental agency, classification societies and selected shipping companies serve as the second pillar of the primary information collection in this study.

## Report Structure

Figure 1. Report structureThis report includes 5 chapters as shown in Error: Reference source not found. A list of abbreviations and a glossary arealso included. This report consists of 6 chapters shown in Figure 1. 1. Chapter 1 is a brief introduction of background and scope of this study. Chapter 2 reviews the hydraulic models used for flood inundation modeling, the associated uncertainty sources and the uncertainty analysis methods. In Chapter 3, a 2-D hydraulic model is established for a study case adapted from a real world river system, where the model configuration and simulation results are introduced. Chapter 4 and Chapter 5 discuss the effects of the uncertainty of the roughness coefficients on flood inundation modeling. In Chapter 6, a summary is made and the ideas for future studies are presented.

## CHAPTER 2 LITERATURE REVIEWS

The information acquired through various literature reviews are discussed in this chapter to understand the background of floods and flood hazards, as well as the importance of flood inundation modeling. On the other hand, the 1-D/2-D hydrodynamic models for simulating both channel and floodplain flows were reviewed respectively. Subsequently, an overview of this chapter is provided.

## 2. 1 Introduction

2. 1. 1 FloodsThroughout the long human history, floods are the most frequently occurring natural hydrological phenomena, which consist of the futures such as water depth, flow velocity, and temporal and spatial dynamics. The regular-magnitude floods occur every year at the expected stream flow range. It is beneficial to provide fertilise soil with nutrients, transport large quantities of sediment and deposit on the floodplain, and clean-up a river with any stagnant contaminates. However, some floods become disasters due to the extreme events, which happen suddenly without any warning, such as storm, dam break, storm surge and tsunami. As a result, their significant impacts cause imponderable damage on human society and ecosystems, particularly in terms of life loss and property damage. Flood can be defined as water body rises to overflow the lands where is not normally submerged with the perspective of flooding wave advancement (Ward, 1978). This definition includes two main flood types, namely river floods and costal floods. River floods are mostly arising from excessively or long-drawn-out rainfall, thus the river discharge flow exceeding the stream channels capacity and overtopping the banks and embankments. Especially in urban area, floods may also take place at the sewage drains when the heavy storms water surcharged in and overflow the drains. In addition, some natural or man-induced catastrophe could result in the water level is risen up suddenly and then overflow the river bank or dam. The reasons why the costal floods appear are usually originated from the severe cyclonic weather systems in terms of a combination of high tides, elevated sea level and storm surges with large waves. The inundation at coastal areas may results from the overflowing as the water level exceeds the crest level of defense, or from the overtopping as the waves run up and break over the defense, or defense structure failure itself (Reeve and Burgess, 1994). Furthermore, tsunami can cause long ocean waves due to the great earthquake and resulting in coastal floods. 2. 1. 2 The flood hazardFlood hazard is defined that those floods generate pop-up threats to the life and properties of human beings at the flood-prone areas where man had encroached into. The hazard level is validated by a combination of physical exposure and human vulnerability to the flood inundation process. Floods have been regarded as the top of the most destructive hazards from everlasting. In China, floods account for about 1/3 of all the natural catastrophes and responsible for 30% of the overall economic losses (Cheng, 2009). Furthermore, some south-east Asian countries are flood-prone areas, such as Indonesia, Thailand, and Myanmar, which are bearing the disasters from the frequent river and coastal floods. In 2004, the mega-quake, which exceeds magnitude of 9. 0, induced a series of destructive tsunamis with the highest wave of 30 meters along the coasts bordering the Indian Ocean. There were over 230, 000 victims lost their lives in around 14 countries. Hence, Indonesia was the hardest hit, followed by Sri Lanka, India, and Thailand (Paris et al., 2007). Moreover, the tropical cyclone ‘ Nargis’ happened on 2nd May, 2008 attacked the Southwest Coast of Myanmar. There were 24 million people been affected and approximately 50, 000 to 100, 000 people been killed (Kenneth, 2008). However, flooding is not only the critical issue in Asian, but also in the entire world. In 1927, the United States met the most devastating flooding of the Mississippi River in American history. The levee system was broken out and submerged 27, 000 km2. Because of millions of population living along the Mississippi River, it led over 400 million US dollars in loss and 246 human deaths (Barry, 1998). In Europe, Netherlands had affected by the critical river floods in the past years since the most areas are below the sea level. The worst flood disaster happened in 1953 killed 1, 835 people, covered almost 200, 000 hectares of land, destroyed 3, 000 family houses and 200 farms, and drowned 47, 000 heads of cattle (Lamb and Knud, 1991). The facts mentioned above proven that the global flooding management is increasingly vital to protect millions of worldwide population from the severe threat. However, because of the high costs and inherent uncertainties, it is impossible and unsustainable to build up the absolute flood protection system, but it can be managed to reduce the hazard to lives and property by the most cost-effective measures. Therefore, flood inundation models become the most useful predictive tools which are used to evaluate and analyse the flood hazards, as well as to improve and mitigate the flood risk management. 2. 1. 3 The Importance of flood inundation modelingFrom the perspectives of physical processes and anthropogenic influence, the floodplain is a dynamic flow environment. Since it is much difficult to handle the confliction between maximising benefit-over-cost ratio and minimising the human impact, the application of inundation modeling becomes the most likely moderate approach for flood management strategy. Actually, the final objective of flood inundation studies could be minimise susceptibility and vulnerability to loss in both economy and human lives aspects (Parker, 1995). Therefore, it is necessary to use flood inundation models to simulate and predict the possible impacts of floodplain development. The principle of flood inundation models is to allow the upstream flood flow to discharge directly to the downstream flood extent. Those models become much valuable and helpful flood predictive tools which are able to apply in different real and virtual scenarios for analysis. In comparison with those traditional statistical models, which are according to all the numeral data observations of past flood events, the largest advantages of physically-based inundation models are their capability of spatial and temporal variables in terms of discharge, water level, velocity, flow duration and inundation extent, on the processive flood events. Meanwhile, they also support the hydro-system operation, flood warning, risk quantification and decision making for the design and planning of flood mitigation measures. Besides, the flood risk maps are able to be determined on the basis of the flood inundation modeling results. They are static two-dimensional maps indicating the flood probability with flood depth and extents, which is usually generated through flood uncertainty quantification techniques, i. e. Monte Carlo Simulation. They are widely adopted by government and insurance company to delineate areas of land at high risk and guide the investment and emergency response strategies.

## 2. 2 LISFLOOD-FP - Flood Inundation Model

A flood inundation model is an intergraded flood simulation model-chain which includes an estimation of stochastic rainfall, a simulation of rainfall-runoff and an inundation model of flood development (McMillan and Brasington, 2008). For stochastic rainfall estimation of certain catchment, according to the available precipitation records, a long synthetic rainfall series could be created. Hereafter, these series are applied into a rainfall-runoff model to generate the corresponding discharge estimation series. And the estimations of discharge are imported into a 2-D hydrodynamic model, which utilizes high-resolution elevation data to enable urban floodplain modeling at the smallest scales and paves the way for additional modules for vulnerability and damage assessment. Finally, the flood inundation model is expected to run within a proven uncertainty estimation framework and subsequently to compare with the real-world scenarios for model calibration and allow explicit uncertainties analysis. LISFLOOD-FP model is one of the most popular flood inundation models all over the world (Bates and De Roo, 2000). It is a coupled 1D/2D hydraulic model on the basis of a raster grid. LISFLOOD-FP model treats the flooding as an intelligent volume-filling process from the perspective of hydraulic principles by embodying the key physical notions of mass conservation and hydraulic connectivity. 2. 2. 1Principles of LISFLOOD-FP Model2. 2. 1. 1Model Structure and ConceptsThe basic components of the LISFLOOD-FP model is a raster Digital Elevation Model (DEM) (Bates and De Roo, 2000) of resolution and accuracy sufﬁcient to identify surface roughness for both the channel (location and slope) and those elements of the ﬂoodplain topography (dykes, embankments, depressions and former channels) considered necessary to ﬂood inundation prediction. A ﬂood consists of a large, low amplitude wave propagating down valley (Bates and De Roo, 2000). When the bankful ﬂow depth is reached, water stops to be contained only in the main river channel and water spills onto adjacent shallow gradient ﬂoodplains. These ﬂoodplains act either as temporary stores for this water or additional routes for ﬂow conveyance. C: UsersDaniel SunAppDataRoamingTencentUsers703775521QQWinTempRichOle[0E~@){LA]KX[A1$UE8M8AV. jpgFigure 1 Conceptual model of the LISFLOOD-FP flood inundation model (Wilson, 2003a; 2003b)2. 2. 1. 2 Assumptions for LISFLOOD-FP ModelIn order to design a physical model simulating the flood development and to simply the numerical computation, the assumptions are stated as followings: The flow within channel can be represented by the kinematic wave approximations. The channel is assumed to be so wide and shallow that the wetted perimeter is approximated by the channel width. The flood flow can be gradually varied. Both In-channel and Out-of-channel flooding flow are treated as raster grids by using a series of storage discretised cells. Flow between storage cells can be calculated using analytical uniform flow formulas, i. e. the Saint-Venant and Manning equations. There is no exchange of momentum between main channel and floodplain flows, only mass is exchanged. 2. 2. 2 In-Channel FlowThe hydraulic models consist of two main processes, representing the flow within the channel (In-channel Flow) and flow on the floodplain (Out-of-channel Flow). But we ignore the effects at the channel–ﬂoodplain interface development of intense shear layers leads to a strongly turbulent and three-dimensional ﬂow ﬁeld. In this project, one of the objectives is to quantify the uncertainty associated with the inundation process. In-channel Flow is defined that the channel flow is below bankful depth. Thus, the flow process is represented by using a classical one-dimensional hydraulic routine approach (1-D approach), which is described in terms of a simplification of the full one-dimensional St. Venant equation system (Knight and Shiono, 1996), which leads to a kinematic wave approximation obtained by eliminating local acceleration, convective acceleration and pressure terms in the momentum equation. 2. 2. 2. 1 Saint-Venant EquationsDue to simplicity of computation and ease of parameterization, the one-dimensional (1-D) Saint-Venant equations have been the most widely adopted approach for unsteady open channel flow. The partial differential Saint-Venant equations comprise the continuity and momentum equations under the following assumptions (Chow et al. 1988): Flow is 1-D, and depth and velocity vary only in the longitudinal direction of the channel. Velocity is constant, and the water surface is horizontal across, any section perpendicular to the longitudinal axis. Flow varies gradually along the channel so that hydrostatic pressure prevails and vertical accelerations can be neglected. The longitudinal axis of the channel is approximated as a straight line. The bottom slope of the channel is small and the channel bed is fixed. The effects of scour and deposition are negligible. Resistance coefficients for steady uniform turbulent flow are applicable so that relationships (e. g. Manning’s equation) can be used to describe resistance effects. The fluid is incompressible and constant density throughout the flow. Therefore, the continuity equation states that the change in discharge with distance downstream (), and the change in the cross-sectional area of flow over time () are in balance. Thus, the lateral inflow ( ) to or from the channel and floodplain can be expressed as (Wilson, 2004).(2. 1)where Q is the volumetric discharge in channel [L3/T], x is the longitudinal distance along the channel [L], t is time interval [T], A is the cross-sectional area of flow [L2] and q is the lateral inflow from other sources per unit length along channel [L2/T]. The momentum equation states that total applied forces is equal to the rate of momentum change in each unit of flow, plus the net outflow of momentum (Chow et al. 1988). For this project, the full dynamic wave equations can be simplified in terms of kinematic wave model. The assumptions are that local acceleration, convective acceleration and pressure terms are ignored, and the flow gravitational forces are equal to the frictional resistance force. The momentum equation can be written as:(2. 2)where is the down-slope of the bed [-] and is the slope of friction [-]Roughness coefficients are defined as the resistance to flood flows in channels and floodplains. To introduce Manning’s roughness ( n ), the Manning Equation is chosen. Therefore, the friction slope in the momentum equation can be described as:(2. 3)where R is hydraulic radius [L]. Substituting the hydraulic radius, the momentum equation can be written as:(2. 4)where n is the Manning’s coefficient of friction and P is the wetted perimeter of the flow [L]. However, for the Equation (2. 4), there are some limitations such as only considering the down gradient hydraulic characteristics, and neglecting the backwater effects and shock waves. 2. 2. 2. 2 Numerical SolutionThe 1-D Saint-Venant Equations are discretized using numerical methods of a finite difference approximation (Chow, 1988). Stream flow and cross section values are calculated with a simple linear scheme that uses a backward-difference method to derive the finite difference equations. Therefore, they are combined to obtain the following equations:(2. 5)where Q is the volumetric discharge in channel [L3/T], x is the longitudinal distance along the channel [L], t is time interval [T], q is the lateral inflow from other sources per unit length along channel [L2/T], and is the geometry and frication factor of channel which is written as:(2. 6)where is the Manning friction coefficient [T/ L1/3], is the channel width [L], and is the channel slope. Meanwhile, the finite difference equation can be set up in order to calculate the quantity Qi, j at each node (i, j), where i represents the space and j the time :(2. 7)(2. 8)in order to create a linear equation, the value of Q in the expression of Equation (2. 5) is found by averaging the following values :(2. 9)Note: All Equations variables refer to the definitions in Figure 2C: UsersDaniel SunAppDataRoamingTencentUsers703775521QQWinTempRichOleH37F%N4L(VS%DNUG`X\_(I4E. jpgFigure 2 Finite difference box for the linear kinematic wave equation2. 2. 3. Channel Discretisation by Mesh GenerationIn order to conduct the kinematic wave simulation, the flow domain is spatially discretised into discrete elements or grid cells to represent the arbitrary modling area by numerical mesh generation process. It starts at the inflow point of each grid cell with indicator of the direction to the next downstream cell. With the help of Airborne Laser Altimetry (LiDAR) and Stereo Air-photogrammetry, the high-resolution DEM grid cells are able to contain topographic data, such as channel width, bed slope, manning friction coefﬁcient and bankful depth. Therefore, the numerical solution can be approximate obtained with the advantage of high-performance digital computers and high numerical stability. In this project, the regular high resolution rectangular grids mesh generation is adopted. However, despite that the mesh resolution in the region is increased, it resulted in less smooth of friction coefficients. This is because the polygonal area over which the various friction contributions were averaged was reduced. 2. 2. 4 Out-of-Channel FlowOut-of-Channel flow (i. e. Floodplain Flow) is defined that water is transferred from the channel to the adjacent overlying floodplain areas when bankful depth is exceeded by flood. However, the 1-D approach is not suitable to simulate the floodplain flows due to its incapability of capturing velocity variations and free surface across the channel. Thus, floodplain flows can be similarly described in terms of classical continuity and momentum equations, discretized over a grid of square cells, which allows the model to represent 2-dimensional dynamic flow on the floodplain. Therefore, we assume that each cell is treated as a storage volume and the change in cell volume over time is therefore equal to the ﬂuxes into and out of it during the time step (See Figure 3, Wilson, 2003a; 2003b).(2. 10)where is the volume variation [L3] of each cell during time [T], and , , and are the volumetric flow rate [L3/T] respectively coming from the up, the down, the left and the right adjacent cells of the grid. C: UsersDaniel SunAppDataRoamingTencentUsers703775521QQWinTempRichOle7L0})O%E(YE$XCZ@7VPYH9B. jpgFigure 3 Flows between cells on the floodplain with LISFLOOD-FP(Wilson, 2003a; 2003b)Flow between two cells is assumed to be simply a function of the free surface height difference between these cells, hence the following discretisation of continuity Equation (2. 1) (See Figure 4 & 5)(2. 11)(2. 12)(2. 13)where  is the water free surface height [L] at the cell node (i, j), and are the cell dimensions [L],   is the effective grid scale Manning’s friction coefficient for the floodplain, and and describe the volumetric flow rates [L3/T] between the floodplain cell node (i, j). C: UsersuserDesktop1. jpgFigure 4 Discretization scheme for floodplain gridC: UsersDaniel SunAppDataRoamingTencentUsers703775521QQWinTempRichOleM`G%`D63ODY2$7)H3G4O7OQ. jpgFigure 5 Floodplain Flows between Two CellsThe flow depth, hflow, represents the depth through which water can flow between two cells, and is defined as the difference between the highest water free surface in the two cells and the highest bed elevation (this definition has been found to give sensible results for both wetting cells and for flows linking floodplain and channel cells).

## 2. 3 Uncertainty in flooding inundation modeling

It is the key factor to reduce or prevent the level of flood hazards that ensuring prediction accurately of the flood inundation area and providing reliable information of risk. In general, the result produced by flood models is only a single deterministic prediction for the peak flow of the flood. However, the confidence level of the output results would be affected by the uncertainty of input data in terms of peak flow, the topographic data, and the model parameters. As a result, the uncertainty associated with the flood inundation modeling is seldom quantified, It most likely because that the sources of uncertainty are not totally realised and lack of available data to study uncertainty. Uncertainty analysis of LISFLOOD-FP modeling has been studied in recent years. From those reports, the sources of uncertainty can be summarised into three major catalogues in terms of model data inputs, hydraulics parameters and model structures. 2. 3. 1Model data inputs2. 3. 1. 1 Hydrologic and meteorological dataOne of the most dominant input parameters is the design flow, which comes from flood frequency analysis and provides the boundary condition. However, the uncertainty of steamflow is inherent since it is derived from the stage-discharge rating curves on the basis of flood records, especially for the high-return-period flow events. In summary, there are four types of uncertainties associated with the hydrograph of steamflows, namely (1) watershed characteristics; (2) storm precipitation dynamics; (3) infiltration and (4) antecedent conditions. However, the storm precipitation dynamics has the largest impact on the prediction. Furthermore, the overall prediction of hydrologic models could be increase due to uncertainty-added by lacking of understanding of the spatial and temporal variability in precipitation, evapotranspiration, and infiltration. 2. 3. 1. 2 Topographic dataThe topographic data is including both land surface digital elevation model (DEM) and river bed bathymetry. It is one of the dominant factors to predict the flood inundation area accurately. It does not only influence the hydrologic modeling process, but also the mapping water surface elevations. Firstly, the extraction of watershed characteristics (e. g. slope, streams and watershed boundaries) from DEM is affected by its resolution, leading to varied discharge values estimated from the hydrologic model. Secondly, the resolution of DEM and the accuracy of bathymetry affect the cross sections extracted for 1-D channel flow simulation and the interpolated meshes (or grids) for 2-D overland flow simulation. Thirdly, Bales and Wagner (2009) investigated the Tar River basin and revealed that high-quality topographic data, along with the appropriate application of hydraulic models are likely the most important factors affecting the horizontal extent and vertical water surface elevations of flood inundation maps. 2. 3. 2 Model structuresThe flood inundation models are also sensitive to the channel geometry in terms of cross sections number, cross-sectional spacing in between, finite-element mesh quality and hydraulic structures. Additionally, the type of model (1-D, 2-D or coupled) used in simulating the river hydrodynamics also brings uncertainty to the overall results. The geometry representation of channel is more critical to 2-D and (3-D) models since the elevation is defined at each mesh node distributed throughout the channel and floodplains. Moreover, the mesh generation strategies will affect 2- and 3-D models not only in the prediction of inundation area, but also the computational time (Horritt et al. 2006). 2. 3. 3 Hydraulics parametersHydraulic models (e. g. 1-D, 2-D or coupled) used to simulate the river hydrodynamics and water surface elevation in floodplain are sensitive to a set of model parameters. Friction values (Manning’s roughness coefficient, n), accounting for effects of variable cross sections, non-uniform slope, vegetation and structures at the sub-grid scale, have a significant impact on hydraulic simulations (Merwade et al., 2008). Manning’s roughness coefficient (n), which is commonly assigned by using standard look-up tables for different substrate types, can range from 0. 035 to 0. 065 in the main channel, and 0. 080 to 0. 150 in the floodplains (Chow et al. 1988). Distributed data throughout the floodplain are seldom available as a basis for estimating friction values for the model domain. Many of the uncertainties in hydraulic models are lumped in the Manning’s n value, such that the models can be calibrated through adjusting such a parameter. The difference in magnitude and changing channel conditions will cause the " optimal" set of parameters to be found in a slightly different area of the parameter space for each different flood event. Wohl (1998) analysed the uncertainty of Manning’s n relative to a commonly used step-backwater model for channel reaches in five canyon rivers. The results indicated that the uncertainties in discharge estimation resulting from the roughness coefficients in step-backwater modeling of paleo-floods were comparable to or lower than those associated with other methods of indirectly estimation flood discharges. Pappenberger et al. (2005) analysed the uncertainty caused by Manning’s n (range from 0. 001 to 0. 9) in the unsteady flow component of the 1-D model HEC-RAS. The results showed that many parameter sets could perform equally well even with extreme values. However, this was dependent on the model region and boundary conditions. Pappenberger et al. (2007) employed a fuzzy set approach for calibrating flood inundation models under the uncertainties of roughness and cross-section. The roughness of channel has been identified as more sensitive than the standard deviation of the cross-section.

## 2. 4 Integrated modeling and uncertainty analysis framework

Flood risk maps are critical to help manage the risk of inundation, which are generated based on good understanding of the uncertainty associated with the various variables involved in flood inundation modeling. A sequential process is normally adopted, where hydrologic analysis starts first, and then hydraulic analysis and geospatial processing will follow. Merwade et al. (2008) proposed a conceptual framework that could connect data, models and uncertainty analysis techniques to produce probabilistic flood inundation maps. This framework was called floodplain modeling information system (FMIS), providing a workflow sequence where items such as terrain description, type of simulation model and parameters of the system, can be changed to study the relative effect of the individual variables on the overall system (Figure 2. 5). Essentially, in such a framework, each item (e. g. data and parameters) affected by uncertainty was assigned a probability distribution and the sequential workflow was run for randomly generated inputs that could yield the output as a probability distribution function. FMIS is able to determine: (1) the impact of individual input parameters on the overall variance of the model output (e. g. flood inundation extent); (2) the uncertainty zone at various confidence levels; (3) model parameters that bear the key uncertainties and (4) the factors (e. g. precipitation variability, terrain and hydraulic structures) that are significant for accurate identification of the flood inundation area. FMIS will not only address the propagation of uncertainty derived from model inputs and parameters to the model output, but also assess the relative importance of input uncertainties on the modeling output. Figure 2. 5 Integrated modeling and uncertainty analysis framework (after Merwade et al., 2008)

## 2. 5 Methodology of Uncertainty Analysis

The flood inundation model is, by definition, an approximation to reality. Inherently, the issue associated with the modeling is the confidence that the decision-maker can put in the results from a model. How safe and reliable the results from a model are will affect the decisions to be made. Imperfect knowledge about the procedures and data generates uncertainty in forecasting floods which has been discussed above. Historically, probability theory (Ross, 1995) and fuzzy set theory (Zadeh, 1965) have been the primary tools for representing uncertainty in mathematical models. The assessment of uncertainty in flooding inundation modeling requires the propagation of different sources of uncertainty through the model. Propagation of distributions (e. g. Monte Carlo Simulation) and moments (e. g. First-Order Second Moment) are the two typical propagation methods. The former one provides the estimates of probability or possibility (i. e. fuzzy distribution) of the model outputs and the latter one offers the evaluations of the distribution moments (e. g. mean and standard deviation) of the model results. Previously, a variety of methodologies have been reported for the treatment of uncertainty in flood forecasting, such as the Generalized Likelihood Uncertainty Estimation (GLUE) by Beven and Binley (1992), Bayesian Forecasting System (BFS) by Krzysztofowicz (1999) and Fuzzy Extension Principle (FEP) by Maskey et al. (2004). A detailed review of the major types of methods is given in the following sections. 2. 5. 1 Monte Carlo SimulationMonte Carlo Simulation (MCS) utilizes multiple evaluations with randomly selected model input and repeats the executions of numerical models to consider the entire range of input factors and their possible interactions with respect to model outputs. Each execution of the model produces a sample output. The output samples can then be examined statistically and the distributions of the predictions can be determined. MCS typically consists of the following steps (Saltelli et al., 2000a, b): (1) definition of model variables (input factors, Xi) used for the analysis; (2) selection of range and the Probability Distribution Function (PDF) for each Xi; (3) generation of samples based on the PDF information (sampling); (4) evaluation of the model output for each input sample; (5) statistical analysis on all the obtained model outputs (i. e. generation of output distribution information) and (6) sensitivity analysis. MCS has the following advantages: (1) the ability to handle uncertainty and variability associated with the model parameters; (2) the ability of being applied in a deterministic modeling structure and (3) flexibility with respect to the types of probability distributions that can be used to characterize model inputs. 2. 5. 2 Generalized likelihood uncertainty estimationThe Generalized Likelihood Uncertainty Estimation (GLUE) is a statistical method for quantifying the uncertainty of model predictions. It recognizes the equivalence or near-equivalence of different sets of parameters in the calibration of the models. It is based on a large number of runs of a given model with different sets of parameter values, generated from specified parameter distributions randomly. Each set of parameter values is assigned a likelihood of being a simulator of the system through comparing the predicted responses with observed ones. The term likelihood is used in a very general sense, as a fuzzy, belief or possibility measure of how well the model conforms to the observed behavior of the system. In the GLUE procedure, all the simulations with a likelihood measure significantly greater than zero are retained for consideration. Rescaling of the likelihood values (such that the sum of all the likelihood values equals to 1) yields a distribution function for the parameter sets. Such likelihood measures may be combined and updated using Bayesian theorem. The new likelihoods can then be used as weighting functions to estimate the uncertainty associated with model predictions. As more observed data become available, further updating of the likelihood function may be carried out so that the uncertainty estimates gradually become refined over time. The requirements of the GLUE procedure are listed as follows (Beven and Binley, 1992): A formal definition of a likelihood measure or a set of likelihood measures. An appropriate definition of the initial range of distribution of parameter values to be considered for a particular model structure. A procedure for using likelihood weights in uncertainty estimation. A procedure for updating likelihood weights recursively as new data become available. A procedure for evaluating uncertainty such that the value of additional data can be assessed. The GLUE procedure requires that the sampling ranges be specified first for all parameters to be considered. The ranges can initially be wide as long as it is considered feasible by physical argument or experience. Secondly, a methodology for sampling the parameter space is required. In most of the GLUE applications, this has been done by MCS, using uniform random sampling across the specified parameter ranges. Thirdly, the procedure requires a formal definition of the likelihood measure to be used and the criteria for acceptance or rejection of the models, which is usually a subjective choice. There may also be more than one objective function calculated from different types of data, and it will then be necessary to specify how these should be combined. Typically, continuously distributed measure (e. g. water depth or discharge) is used to define the likelihood weights. However, in flood inundation modeling, binary pattern data (inundated or non-inundated) usually are obtained in the form of a map (2-D in space but zero-dimensional in time) and are of interest because the modeler wishes to predict spatially distributed quantity and estimate distributed uncertainties. Various likelihood measures are defined as global model performance measures for binary classification data in historical studies based on the matrix listed in Table 2. 2, where a value of 1 is assigned to the presence of a quantity in either data (D) or model (M) and a value of 0 to its absence (Aronica et al., 2002). To establish likelihood measures in assessing performance of ﬂood extent maps predicted by the model against the observed ﬂood extent map, an objective function of the likelihood measure is shown below (Bates and de Roo, 2000): F <1>(3. 1)where is the observed area of inundation, and is the modeled area of inundation. In effect, the statistic determines the ratio between the number of grid cells classified correctly as being either dry or wet and the number of cells classified incorrectly, Eq. 11 can be reformulated asF <2>(3. 2)where obtains a value of 1 for cells classified as inundated both in observed and modeled data, and obtains a value of 1 for cells observed as dry but predicted to be wet, and obtains a value of 1 cells observed as wet but classified as dry. Hence, the likelihood measure by comparison of the modelled outputs with the observed data is more straightforward to calculate.

## CHAPTER 3 METHODOLOGY AND CASE STUDY

This chapter consists of 3 parts. The first part on methodology highlights the survey and interview procedures. The survey and interview results obtained are presented in part two and three, respectively.

## 3. 2 Survey results

## Study Area – River Thames, UK

The test site is located on the upper Thames in Oxfordshire, UK, where the river has a bankful discharge of 40 m3s-1 and drains a catchment of 1000 km2. A short (c. 5 km along channel) test reach has been identified, bounded upstream by a gauged weir at Buscot (which provides the model boundary condition), and with reasonably well-confined flows at the downstream end. The model topography was parameterized with a 50 m resolution stereophotogrammetric DEM (76 x 48 cells) with a vertical accuracy of +/-25 cm, and channel information obtained from large-scale UK Environment Agency maps and surveys. In December 1992 a 1-in-5 year flood event occurred, with a peak discharge of 76 m3s-1, resulting in considerable floodplain inundation along the reach. The flood event coincided with an overpass of the ERS-1 remote sensing satellite, which acquired a SAR (synthetic aperture radar) image of the flood. This provided a map of inundation extent with boundaries accurate to +/-50 m (Horritt and Bates, 2001) approximately 20 h after the hydrograph peak, but with discharge still high at 73 m3s-1. The broadness of the hydrograph, along with the short length of the reach, means that a dynamic model was unnecessary, and steady state simulations were instead used with discharge corresponding to the flow at the time of the SAR overpass. An initial sensitivity analysis indicated that the Thames model was sensitive to friction values and the friction values for the calibration process were distributed randomly and uniformly between 0. 01 m1/3s-1 and 0. 05 m1/3s-1 for the channel, and 0. 02 m1/3s-1 and 0. 10 m1/3s-1 for the floodplain.