Study of the Hydrodynamic Processes of Rivers and Floodplains with Obstructions

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DECLARATION

This work has not previously been accepted in substance for any degree and is not concurrently submitted in candidature for any degree.

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ABSTRACT

A study has been undertaken to supplement design methods and develop innovative approaches for the effective management of rivers and floodplains to reduce flood risk. The focus has been on enhancing the understanding and representation of the hydrodynamic processes of a variety of river and floodplain flow conditions (i.e. fluvial/flood discharges, tidal currents and tsunamis) and the associated hydraulic interaction with selected obstruction types, such as mangroves and vehicles, for the representative river basins of the Merbok and Klang, on the West Coast of Peninsular Malaysia, and the Valency, near Boscastle, in the UK.

For the study of the hydrodynamic processes of natural floodplains, a numerical model has been refined to investigate the effects of mangroves on tsunamis, with the inclusion of modelling idealised test cases for the influence of both the vegetation resistance and reductions in the cross-sectional area of flow. A similar model has then been applied to a mangrove fringed floodplain for the Merbok river basin in Malaysia. The findings showed that mangroves can have a significant impact on the hydrodynamic processes of tsunami currents, particularly in wave attenuation. In recognising the importance of mangroves as natural defences against flooding disasters, a novel innovative and environmentally friendly approach is designed by replicas of the natural mangrove stem configuration, namely the Artificial Mangrove Shelter (AMS), has been first initiated and modelled, for the sustainable restoration and rehabilitation of mangroves along floodplains. The study has shown that the model developed herein has the capability of being used as a useful hydroinformatics tool for the effective management of rivers and floodplains.

In studying the hydrodynamic processes of urban floodplains, a series of experimental investigations has been undertaken on stationary scaled model vehicles in laboratory flumes, to study the effects of vehicles on flood flow propagation and, the influence of the flood flows on the stability of the vehicles. The findings confirmed that the vehicles had a significant impact on the flood flow propagation and elevations in the flooded area. In order to develop a useful innovative approach to evaluate the degree of hydraulic stability for vehicles, a novel three colour zone envelope curve has been first introduced and developed, herein known as the Traffic Light of Hydraulic Stability (TLHS), to identify the likelihood of vehicle movement. This straightforward envelope curve is useful for assessing the vehicle hazard conditions in urban floodplains. By understanding such flood hazard assessment, the study has resulted in recommendations being made for a precise flood estimation method, which, in turn, has a key impact on the reduction of flood risk along rivers and floodplains.

With an enhanced understanding of floodplain hydrodynamics associated with obstructions in natural and urban environments, the study was then extended to investigate the consequential hydraulic impact of flooded vehicles on blocked bridges, through a physical modelling study in a laboratory flume, with the purpose being to replicate a typical section of prototype floodplain conditions for the Boscastle and Klang. The findings suggested that river and floodplain reach upstream of the blocked bridge becomes more of a hazard than that downstream of the bridge. In this study, eventually natural and urban environments along the rivers and floodplains have been considered in a pro-active manner to complement each other, which take into consideration the hydrodynamic processes and interaction between hydraulic obstructions and flood flows, with novel and practical approaches being developed for the effective management of rivers and floodplains.

CONTENTS

CHAPTER 3

MODELLING THE HYDRODYNAMICS OF FLOODPLAINS

CHAPTER 6

HYDRODYNAMICS OF FLOODPLAINS WITH VEHICLES AND BRIDGES

LIST OF FIGURES

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

LIST OF TABLES

ABBREVIATIONS

ADI	Alternating Direction Implicit
AMS	Artificial Mangrove Shelter
DEFRA	Department for Environment, Food and Rural Affairs
DID	Department of Irrigation and Drainage, Malaysia
DIVAST	Depth Integrated Velocities and Solute Transport
FAO	Food and Agriculture Organization
ICE	Institution of Civil Engineers
IHP	International Hydrological Programme
JICA	Japan International Cooperation Agency
OEHHA	Office of Environmental Health Hazard Assessment
OECD	Organisation for Economic Co-operation and Development
PEMSEA	Partnerships in Environmental Management for the Seas of East Asia
POST	Parliamentary Office of Science and Technology
PVC	Polyvinyl Chloride
TLHS	Traffic Light of Hydraulic Stability
UNDP	United Nations Development Program
UNEP	United Nations Environment Program
UNESCO	United Nations Educational, Scientific and Cultural Organisation
WCMC	World Conservation Monitoring Centre

CHAPTER 1

INTRODUCTION

1.1 General

Over the centuries, rivers have served a vital role in sustaining life and human civilisation. Floodplains along river systems have long since been a major source for economic development and settling areas, also providing strategic locations with a need for a plentiful for rich resources of water and food (Ward, 1978). Today, most of the major settlements of urban townships in Malaysia, and similarly in other part of the world are located along such floodplains. With the continuing increase in urbanisation and development along these floodplains, and especially the rapid growth in urban areas, coupled with associated land development and encroachment activities, has significantly altered the natural form of the floodplains.

Figure 1.1 illustrates a typical cross section of a floodplain, showing such encroachment activities of rural area with nature developments and urban area with developments of a township and infrastructure. Urban land development associated with encroachment and fill activities along floodplains has resulted in reduced flood storage and created new types of hydraulic obstruction to flood flows (i.e. hydraulic structures, bridge piers, buildings, infrastructure, vehicles, agricultural plants, vegetation, and more examples being shown in Figure 1.1), which form the main focus consideration in this study. Continuing developments in these urban areas are completely altering the water surface profiles and flood risks by increasing impermeable urban areas due to road pavements, house and building roofs, etc.

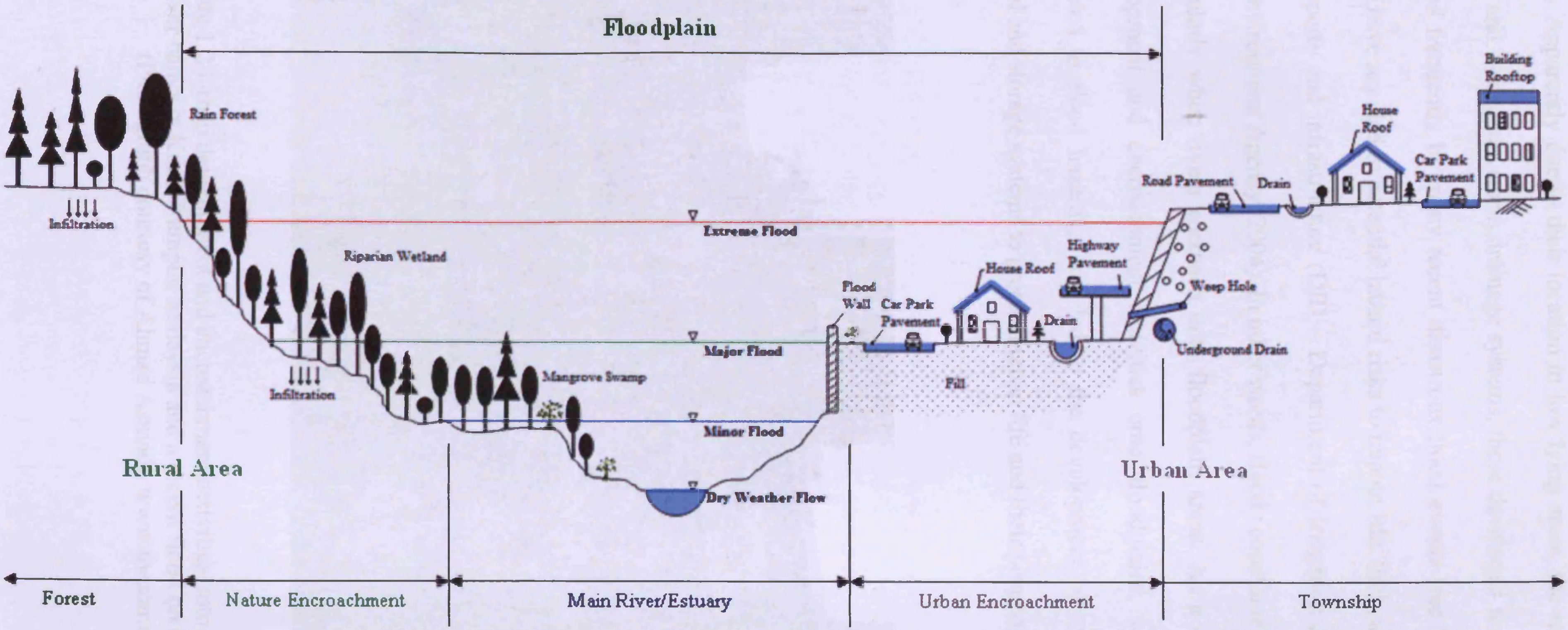


Figure 1.1 Typical cross section of a floodplain, showing related development and encroachment activities

Apparently due to their location in low lying areas, the spread of impervious areas, and inadequate storm drainage systems, these developed floodplains have been flooded frequently by many recent disastrous flood events (see Figures 1.2 to 1.4), which have resulted in potential hazard risks to human life, limb, and in much damage to property and infrastructure (DID – Department of Irrigation and Drainage, 2003 and Environment Agency, 2004). In other words, floods constitute a hazard to humans particularly when rivers encroach onto floodplain areas. As a consequence, urban development and encroachment activities onto floodplains, which at times are subjected to flood hazards, have led to the development of extensive new flood control and storage systems to protect human life and their property.

Figure 1.2 Urban development and encroachment activities onto floodplains along river banks in Kuala Lumpur, Malaysia and a recent flood on 03 March 2009 (Photograph courtesy of Ahmad Asmadi, www.thestar.com.my)

Figure 1.3 Urban encroachment activities onto floodplains along river banks at a car park in Kuala Lumpur, Malaysia and a consequent flood event on 26 April 2001 (Photograph courtesy of Department of Irrigation and Drainage Malaysia, www.water.gov.my)

Figure 1.4 Encroachment activities onto floodplains along river banks at a car park in Boscastle, UK and an extreme flood event on 16 August 2004 (Photograph courtesy of Art Mason, www.tintagelweb.co.uk)

On the other hand, floodplains in the rural areas have benefited from its important roles as flood prone areas and storage systems, where the waters and nutrients carried by floods create highly productive ecosystems for good agricultural lands and nature development along the river banks (Ward, 1978). Clearly, floods are beneficial to humans in rural areas for irrigation and soil fertilisation purposes where floods can be distributed large amounts of water and suspended sediment over vast areas, and restocking valuable soil nutrients to agricultural lands. Similarly, floods are valuable to nature development of riparian vegetation (i.e. mangrove swamps, salt marshes, woodlands, rainforests) along the rivers and its floodplains, where floods are natural phenomena to regularly water and fertilise the associated vegetation. Figure 1.5 shows such nature development of vegetation encroachment activities into floodplain along the river bank.

Figure 1.5 Natural development and vegetation encroachment on floodplains along the river bank at Kuching, Malaysia (Photograph courtesy of Delta Competition 2008, www.deltacompetition.com)

In addition, the benefits of the natural development of vegetation encroachment activities onto floodplains are well recognised for their potential as a form of flood control and protection (Othman, 1994 and FAO, 1994), where vegetation such as mangroves attenuate floods by obstructing the flows with their roots and trunks. These floodplains are usually found in rural areas where not there is less human settlement and property, and hence floods do not generate such severe flood hazards to humans. In contrast, activities without any control from vegetation encroachment and where urban development is rife on floodplains have frequently resulted in a deterioration in the health of the river and its floodplain, with more floods generated due to the associated infrastructure and vegetation creating massive obstructions to the flow and making flooding even worse. Figure 1.4 shown earlier gives such similar catastrophic flood event on 16 August 2004 at Boscastle, UK.

1.2 Statement of Problems

With the passage of time, land has been shaped by the passage of water from small streams to large rivers, carrying the sediments onto floodplains, which have contributed enormously to the growth of vegetation, and finally ending up in the seas. This interaction between land, water and vegetation is found in natural floodplains, and the rivers and streams form the arteries of a basin for its water and nutrients. Today, humans have placed their mark on this land with massive developments for residential, commercial and industrial activities, together with their infrastructure. With all of these developments associated encroachment activities in urban and rural areas either by humans or nature, mean that floodplains have been subjected to significant transformations to new physical characteristics and new management measures. The diversity of floodplains, together with the management pressures that are now faced globally, illustrate the need to develop a greater knowledge for effective management of rivers and floodplains, which are in accordance with the main aim of this study.

In recent decades, flood situations have generally been getting worse and flood damage has also increased by a number of measures that are not related to the traditional estimation of the magnitude and frequency of flooding. Often interactions between flood flows and obstructed floodplains are one of the major factors that intensify flood inundation extent. Focusing on a wide range of obstruction types in floodplains (e.g. buildings and vehicles, agricultural plantations, natural vegetation forests and swamps), further research is needed to establish a better representation of the hydrodynamic processes and interactions involved. This study aims to focus on the flood conditions created through coastal and estuarine flows, such as tsunami, storm surge, tidal current flooding; estuarine and river flows, such as river, fluvial discharge flooding; and localised overland flows, such as flash flooding, after exceptional events on the floodplains.

A better understanding of the hydrodynamic response and inter-relationships within the floodplains for a wide range of flow obstructions, caused either by urban or natural changes are very important for providing better predictions of real flood events on floodplains. A review of the literature indicates that there has been some appreciation by engineers and researchers of these processes, but their studies have rarely systematically investigated these interactions between obstructions and the floodplain hydrodynamics as an entity and generally their focus has been biased towards one particular aspect of the flow and not linked to the system. Urban and natural developments on floodplains should be considered in a systematic manner to complement each other for sustainable developments. Urban developments on the floodplains can benefit from an enhanced understanding on the interactions between natural developments and the floodplain hydrodynamics. Through this study, it is hoped that future developments on the floodplains will be eventually considered more in their entirety on flood flow hydrodynamic processes, and as a range of obstructions and their impacts, thereby contributing enormously towards effective floodplain management.

Floodplains are still one of the most complex and poorly understood regions in terms of flood risk management. Recent decades have seen great changes to engineering practice in terms of the approach adopted when undertaking development on floodplains and the surrounding regions. A far more environmentally sensitive approach has now become the remit for the modern engineer, scientist and environmental manager, working together toward sustainable development in these floodplains. The most useful tool to become increasingly important in many aspects of water resources and environmental engineering in recent decades has been the development of computational or numerical models. Recently, a wide range of improvements have been made to numerical models for predicting depth-averaged shallow water flows in floodplains, such as investigations by Falconer et al. (2004) and Liang et al. (2006b). These numerical models have been actively refined and applied in various circumstances to provide an effective and practical tool for the management of rivers and floodplains, which are also focus of this study.

For natural floodplains, the benefits of vegetation such as mangroves are now well recognised for their potential as a form of flood protection and alleviation. Mangroves attenuate flood flows by obstructing the flows with their extensive roots and broad trunks. Knowledge of the interaction between mangroves and the hydrodynamics processes provides an unproved understanding of natural developments on floodplains as obstructions to flood flows. Although research on the hydrodynamics processes associated with mangroves has made good progress in recent years, there are still major uncertainties concerning the impact of these riparian forests on flood storage and alleviation purposes, and flood inundation extent particularly on extreme flood events like tsunamis.

On 26 December 2004, a tsunami hit many countries surrounding the Bay of Bengal, including the Indian Ocean and East Africa. The effect of this tsunami raised awareness of the benefits of natural barriers, such as mangroves, with Malaysia less affected than many neighbouring countries due partly to mangroves (Abdullah et al., 2005). This statement is supported in general with less quantitative proof by the studies of Blasco et al. (2005), Dahdou-Guebas et al. (2005), Danielsen et al. (2005), Ong (2005), Kathiresan et al. (2005), and Siripong et al. (2005). In contrast, Kerr et al. (2006) and Chatenoux et al. (2007) disagreed with this statement. Thus, through this study, more quantitative support and more powerful approaches are needed and may well find an association to understand the impact of mangroves in particular on tsunamis, which is crucial for innovative and effective approaches to the management of rivers and floodplains. The nature of tsunamis, with their random occurrence, requires a lot of data for suitable analysis. Under such circumstances it is necessary to resort to simulation methods involving numerical computational models and enable this feature to be an input to the development of a floodplain modelling tool.

In another example for urban floodplains, on Monday 16 August 2004, a small picturesque town along the UK coast, namely Boscastle, was struck by a devastating flash flood. This flood took place over a short river basin reach with a steep terrain and a relatively flat urban development near the coast. The Environment Agency (2004) and North Cornwall District Council (2005) reported millions of pounds of damage (as shown in Figure 1.4) were caused as the waters inundated buildings, destroyed bridges and an estimated 115 vehicles were submerged. In this case, buildings, structures, and vehicles along the river bank all caused massive obstructions to the flood flow. Some of the vehicles were floated and swept off by flood flows, and were then caught under the local bridge, blocking the flow path and finally causing the bridge to collapse under the stress, and some were even swept into the sea.

At this point, the Boscastle flood highlights the problems caused by vehicles and their effect on flood flows. By disregarding the effects of buildings and structures which have widely researched over the past few years, this case highlights the need for further research studies urgently being needed to acquire a better understanding of the complex hydrodynamic processes of such flood flows over floodplains with vehicles, and also the influence of typical flood flows on the stability of vehicles.

In addition, further study was also required to investigate the consequential hydraulic impacts of flooded vehicles on blocked bridges. To the knowledge of the author, not much previous research has been reported on this relevant topic in the literature. With such improved understanding through this study, particularly through physical and numerical hydrodynamic modelling, possible disastrous consequences, such as occurred at Boscastle, can be reduced or ideally eliminated in the future.

1.3 Background of Study Areas

The study areas that have been focused in this study relate to the West Coast of Peninsular Malaysia and typical flood flow conditions in the UK. Both regions have been urbanised and were developed rapidly for residential, commercial, industrial, and institutional use; while several areas have still been maintained as rural or natural development areas, such as woodland forests, mangrove swamps, salt marshes and agricultural lands.

The region of the West Coast of Peninsular Malaysia is generally characterised by uniform high temperatures, high relative humidity, heavy rainfall and little wind. The average annual rainfall depth in the region is about 2,400 mm. The highest rainfall occurs in the months of April and November, with a mean of about 280 mm. The lowest rainfall occurs in the month of June, with a mean of about 115 mm. Figure 1.6 shows mean monthly and annual rainfalls at selected locations in Peninsular Malaysia. Two monsoons occur throughout the year; the North East monsoon occurs from December to March and the South West monsoon occurs from June to September. The wet seasons occur in the transitional period between the monsoons, from April to May and from October to November.

In addition to rains associated with the monsoons, rainstorms derived from convection occur occasionally throughout the year, in particular during late afternoons. The rainstorms last for a short duration, are isolated and usually of very high intensity. The temperature throughout the year is quite constant, with a mean of 27 °C. The highest temperature occurs at typically 13:00 with an average of 32 °C and the lowest temperature occurs at 07:00 with an average of 23 °C. The average value for humidity is around 82% throughout the year. The evaporation depth for open water is measured to be around 1,500 mm per annum or corresponding to a monthly mean of around 125 mm.

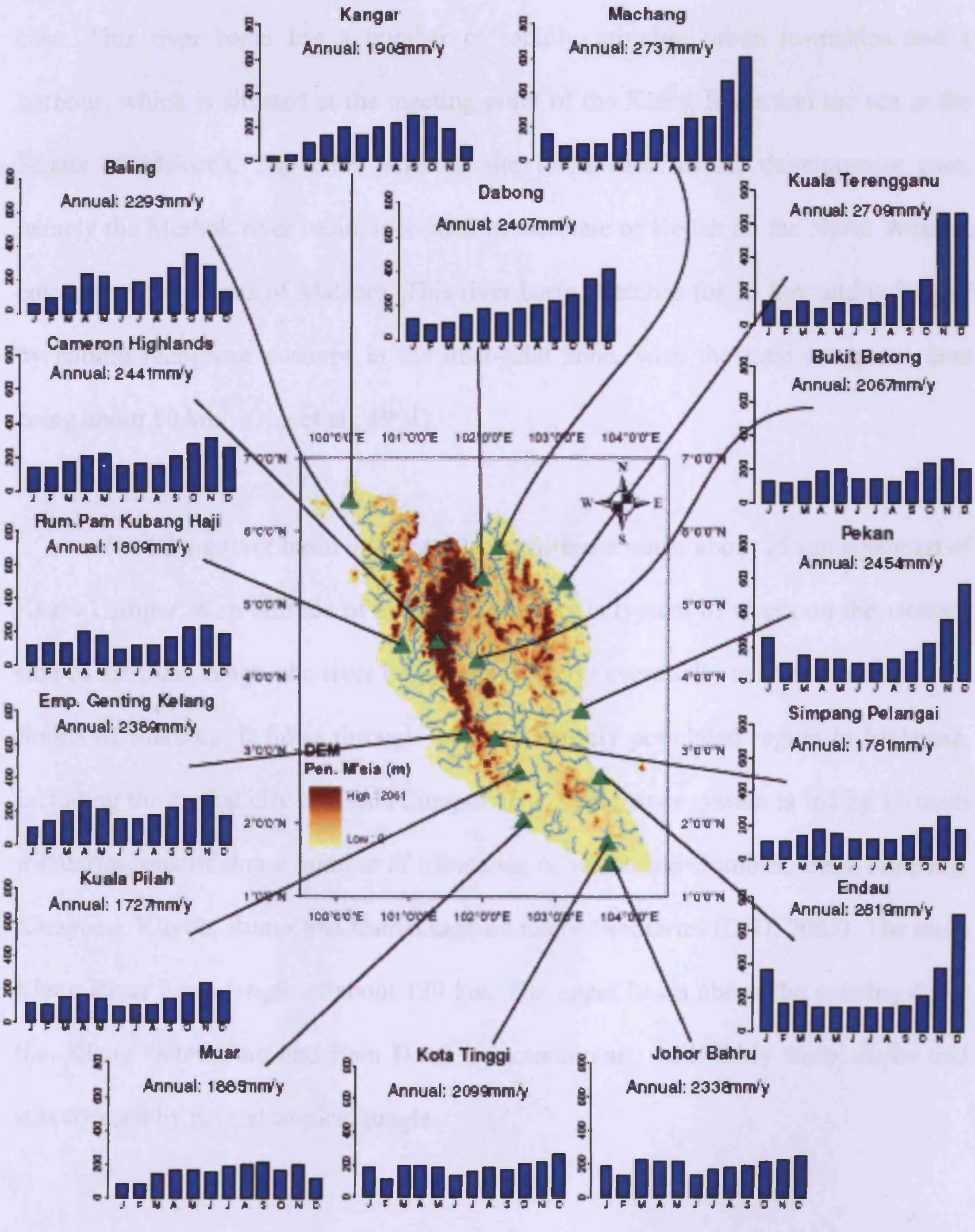


Figure 1.6 Mean monthly and annual rainfalls at selected locations in the Peninsular Malaysia (Wong et al., 2009)

Two representative river basins were selected from the West Coast of Peninsular Malaysia for the study case of urban and rural/natural development environments. The Klang river basin (see Figure 1.7) encompasses the entire Federal Territory of Kuala Lumpur and parts of the State of Selangor, which has an area of about 1288 km^2 (DID, 2003), and is suitable for the study of an urban development case. This river basin has a number of rapidly growing urban townships and a harbour, which is situated at the meeting point of the Klang River and the sea at the Straits of Malacca. The other selected site for a rural/natural development case, namely the Merbok river basin, is located in the State of Kedah on the North Western entrance to the Straits of Malacca. This river basin stretches for 35 km, and is fringed by natural mangrove swamps in the inter-tidal zone, with the total mangrove area being about 50 km^2 (Ong et al., 1991).

The Klang river basin originates from the main range about 25 km northeast of Kuala Lumpur at an altitude of about 1330 m. As is typical of rivers on the western side of the main range, the river basin falls westerly eventually to meet the sea at the Straits of Malacca. It flows through the most densely populated region in Malaysia, including the capital city of Kuala Lumpur. The Klang river system is fed by 11 main tributaries, comprising a number of tributaries of which the Gombak, Batu, Ampang, Kerayong, Kuyoh, Bunus and Damansara are major tributaries (DID, 2003). The main Klang River has a length of about 120 km. The upper basin above the existing dams (i.e. Klang Gates Dam and Batu Dam) is mountainous, with fairly steep slopes and still covered by natural tropical jungle.

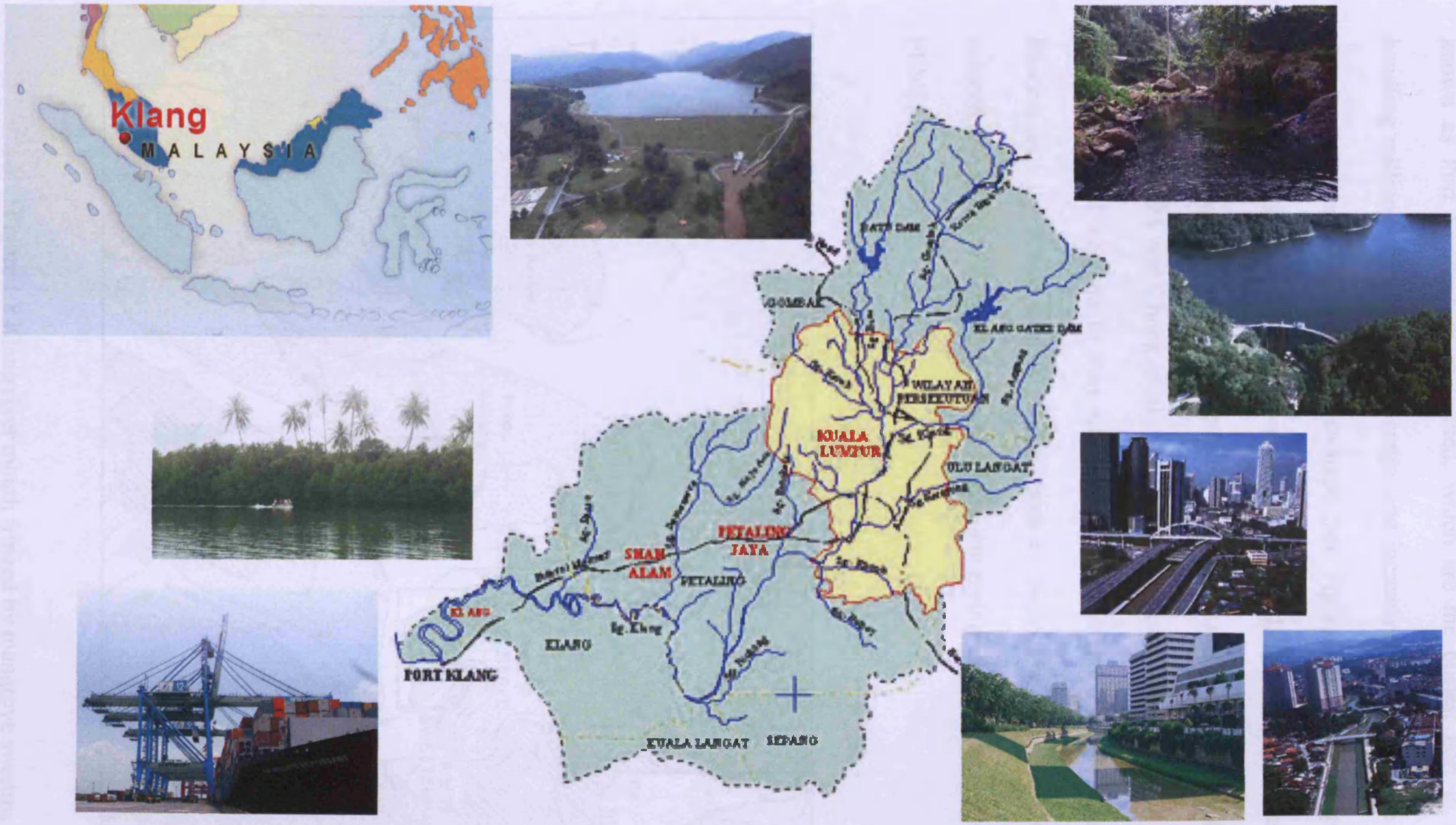


Figure 1.7 Location of the Klang river basin and photographs showing its system (Photographs courtesy of PEMSEA, 2005 and Department of Irrigation and Drainage Malaysia, www.water.gov.my)

At the mouth of the Klang River (3° 02N, 101° 21E), Port Klang or previously known as Port Swettenham is located, which are the busiest port in Malaysia, handling millions of metric tons of cargo, and increasing annually. In the past, this estuary was fringed by mangrove swamps (see Figure 1.8), where Kapar Forest Reserves is a coastal mangrove forest system, while Klang Islands consists of more than nine mangrove islands associated with large mudflat and sandflat areas (Sasekumar, 1974 and Chong et al., 1996). Continuous developments in the areas surrounding and adjacent to Port Klang have been extended to the Kapar Forest Reserve and the Klang Islands. Today, both of these forest reserves have been reduced as a result of development and subsequent reclamation works, as reported by PEMSEA (2005).

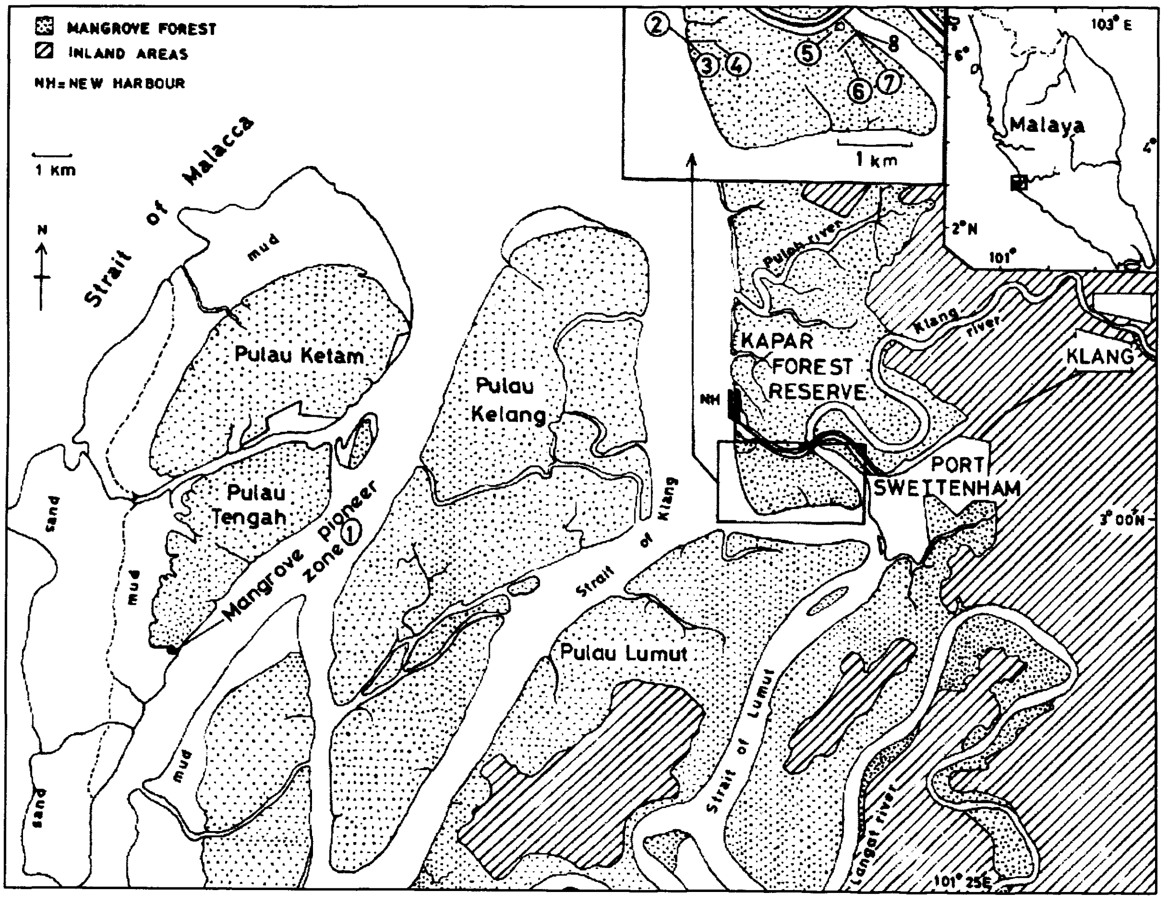


Figure 1.8 Klang river mouth fringed by mangrove swamps
(Sasekumar, 1974)

Urbanisation and industrialisation in the river basin has been rapid with major portions of natural forest, agricultural and ex-mining land being converted for urban use. Furthermore, this river basin is also the most densely populated area of the country, with an estimated population of over 3.7 million, including about 18% of the national population and growing at almost 5% per year (DID, 2003). The basin has an annual growth rate of approximately 5% and land use is dominated by urban residential development (44%), followed by forest reserves (34%), agriculture (15%) and commercial/industrial use (7%). This rapid growth in the Klang river basin has resulted in increased pressure on the flow capacities of the Klang River and its tributaries (see Figure 1.9), resulting in frequent occurrence of flooding causing damage to property, disruption of services and general inconvenience to the river basin population. Flooding is a regular occurrence, with flash flooding regularly occurring in the centre of Kuala Lumpur and significant river/estuarine flooding also occurring in the lower Klang river basin.

Flooding in this river basin is mainly attributed to thunderstorms and depression type monsoon storms, as reported by DID (1989, 1994 and 1996). Depression type monsoon rains are generally low in intensity, long in duration and are wide spreads over the whole catchment, causing the rivers to overflow their banks, such as the event that contributed to the largest recorded flood in 1971 in this river basin. On the other hand, thunderstorms occur more frequently, are short in duration with high intensity rainfall, giving rise to flash floods as a result of the inability of localised drainage systems to cope with high flows. The flood events of 26 April and 29 October 2001 are examples of such occurrences (as shown in Figure 1.3), which caused fairly significant damages and disruption of services, mainly in the Kuala Lumpur city centre and extending to some of the surrounding areas (DID, 2003). Both of the flood events mentioned were widely reported in the media and had generated a lot of negative public reaction.

Figure 1.9 Klang and Gombak river confluence in the centre of Kuala Lumpur (Photograph courtesy of Department of Irrigation and Drainage Malaysia, www.water.gov.my)

The other selected site for the rural/natural development, namely the Merbok river basin is situated in Kedah (5° 409N, 100° 259E) and is shown in Figure 1.10. The northwest wind blows over long periods and fetches of the Andaman Sea, which develops waves and swells. These waves act on the coastal shallow waters to induce appreciable littoral drift. The mean annual discharge is estimated to be 20 m^3/s, and the mean neap and spring tidal ranges are about 0.8 and 2.3 m respectively. According to Ong et al. (1991), the 35 km long river is mostly estuarine, except for a few kilometres of the upper reaches which are freshwater (see Figure 1.11). The river depth varies from 3 m to 15 m, with a few 20 m deep holes where tributaries join the main river (Kjerfve et al., 1979). Various physical aspects of this estuary also have been described in the research studies by Uncles et al. (1990 and 1992) on stratification; Dyer et al. (1992) on salt balance; Ong et al. (1994) on the transverse structure of semidiurnal currents; and Simpson et al. (1997) on the net fluxes from a mangrove estuary system.

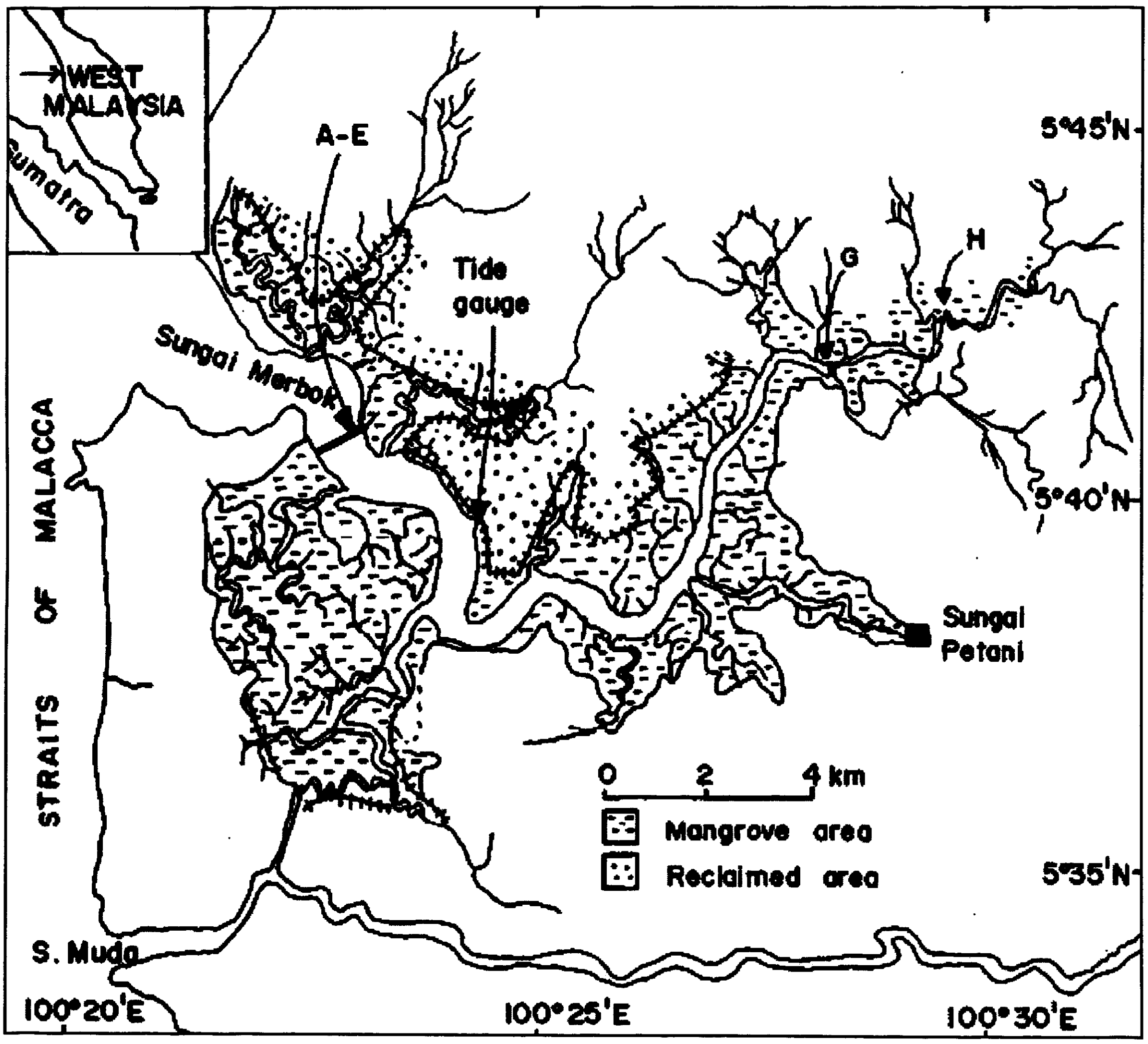


Figure 1.10 Overview of the Merbok river basin including reclaimed mangrove areas (Ong et al., 1991)

This river basin mainly constitutes mangrove swamps along the river, which contain one of the highest recorded levels of biodiversity species in the world. The region is also surrounded by rice, rubber, oil palm cultivation (Wetland International, 1986). From the early 1970s to the end of the last century, shrimp and aquaculture farming were actively pursued in this river basin (Ong, 1982). Mangroves around Merbok are used for pole and charcoal productions. Forest management and replanting of mangroves is carried out in the estuary. There is a fast growing town, namely Sungai Petani, sited at the head of the river basin. Samarakoon (2004) analysed the impacts of this urbanisation on the downstream mangrove ecosystems. Following 26 December 2004 tsunami, Komoo and Othman (2006) undertook an assessment of the impact of tsunami on this area, with a particular emphasis on the environmental, socio-economic and community effects along the river basin.

Figure 1.11 Photograph showing upstream of Merbok River at Kg. Sg. Lalang

1.4 Aim and Objectives of Study

This study therefore aims to supplement design methods and develop innovative approaches for the effective management of rivers and floodplains, which enhances the hydrodynamic response of a variety of flood flow conditions (i.e. fluvial/flood discharges, tidal currents and tsunamis) and the interaction along the rivers and floodplains with selected hydraulic obstruction types such as mangroves and vehicles at representative study sites.

These study sites include the river basins of the Merbok and Klang, on the West Coast of Peninsular Malaysia, and the Valency, near Boscastle, in the UK. In accordance with the main aim, five primary objectives have been identified that lead to a logical progression through the study as follows:

1. To review and develop a fundamental understanding of the hydrodynamic interactions between a variety of flood flow conditions and a wide range of hydraulic obstructions for encroachment activities along rivers and floodplains;

2. To investigate and analyse the theoretical background and governing equations for the hydrodynamic processes of obstructed river and floodplain flows, to provide guidance on the selection of suitable design procedures;

3. To select and extract available sources of data for typical flood flow conditions including: fluvial/flood discharges, tidal currents and tsunamis, for representative study sites along rivers and floodplains of the West Coast of Peninsular Malaysia and the UK;

4. To understand and identify the parameters for correctly ascertaining the hydrodynamic processes of flood flows over obstructed rivers and floodplains for modelling the propagation of flood flows; and

5. To refine and verify the modelling of complex hydrodynamic processes and interactions between a variety of flood flow conditions and selected obstruction types along rivers and floodplains, and the impact on flood inundation extents on the floodplains, both with and without obstructions.

1.5 Scope of Study

This study addresses the hydrodynamic response of river and floodplain associated encroachment activities (as previously illustrated in Figure 1.1), in particular on selected hydraulic obstruction types (such as mangroves and vehicles), with a variety of floodwater flow conditions (e.g. fluvial/flood discharges, tidal currents and tsunamis), for representative study sites of the Merbok and Klang river basins on the West Coast of Peninsular Malaysia, and the Boscastle with typical flood flow conditions in the UK.

Firstly, a numerical model has been refined for an idealised natural floodplain to investigate the effects of mangroves on tsunamis. A similar model has then been applied to simulate hydrodynamic processes of tsunamis for a real floodplain in the Merbok river basin. In recognising the importance of suistainable restoration and rehabilitation of mangroves as natural defences against flooding disasters in floodplains, a novel innovative solution, namely the Artificial Mangrove Shelter (AMS) has been first initiated and modelled in this study.

Secondly, the hydrodynamic interaction between vehicles in urban floodplains and flood flow propagations has been studied in theoretical and experimental using physical models in laboratory hydraulics flumes. In order to develop a useful guide or procedure to evaluate the degree of hydraulic stability for vehicles, a novel innovative approach for three colour zone envelope curve has been introduced and developed in this study, herein known as the Traffic Light of Hydraulic Stability (TLHS).

Thirdly, with an enhanced understanding on the floodplain hydrodynamics for natural and urban environments (i.e. mangroves and vehicles), the investigation was extended to study the consequential hydraulics impact of flooded vehicles with blockage bridges, through experimental studies in a laboratory hydraulics flume. The experimental studies have been investigated using a physical model of a straight compound channel and floodplains, in order to replicate a typical section of prototype floodplain that may be found in the study sites at Boscastle and the Klang.

Finally, natural and urban environments on floodplains have been considered in this study in a systematic manner to complement each other, which take into consideration the hydrodynamic response and interaction between hydraulic obstructions and flood flows, with novel and practical approaches being developed for the effective management of rivers and floodplains.

1.6 Outline of Thesis

The outline of the thesis (as summarised in Figure 1.12) follows closely the chronology of the research works carried out in this study. The present study examines in detail the hydrodynamic processes generated by the passage of flood flows over obstructed floodplains, for a range of flow conditions and hydraulic obstruction types.

The introduction is given in chapter 1, with a literature review for hydrodynamic processes of flood flows over floodplains being given in Chapter 2. The review is concerned with the origins and characteristics of flood flows along floodplains, and the interactions with a wide range of obstruction types associated with developments and encroachment activities, as well as the appropriate management practices. This review is essential before proceeding into further studies. Next, chapter 3 outlines in general the theoretical approaches and governing equations of the hydrodynamic interactions in modelling.

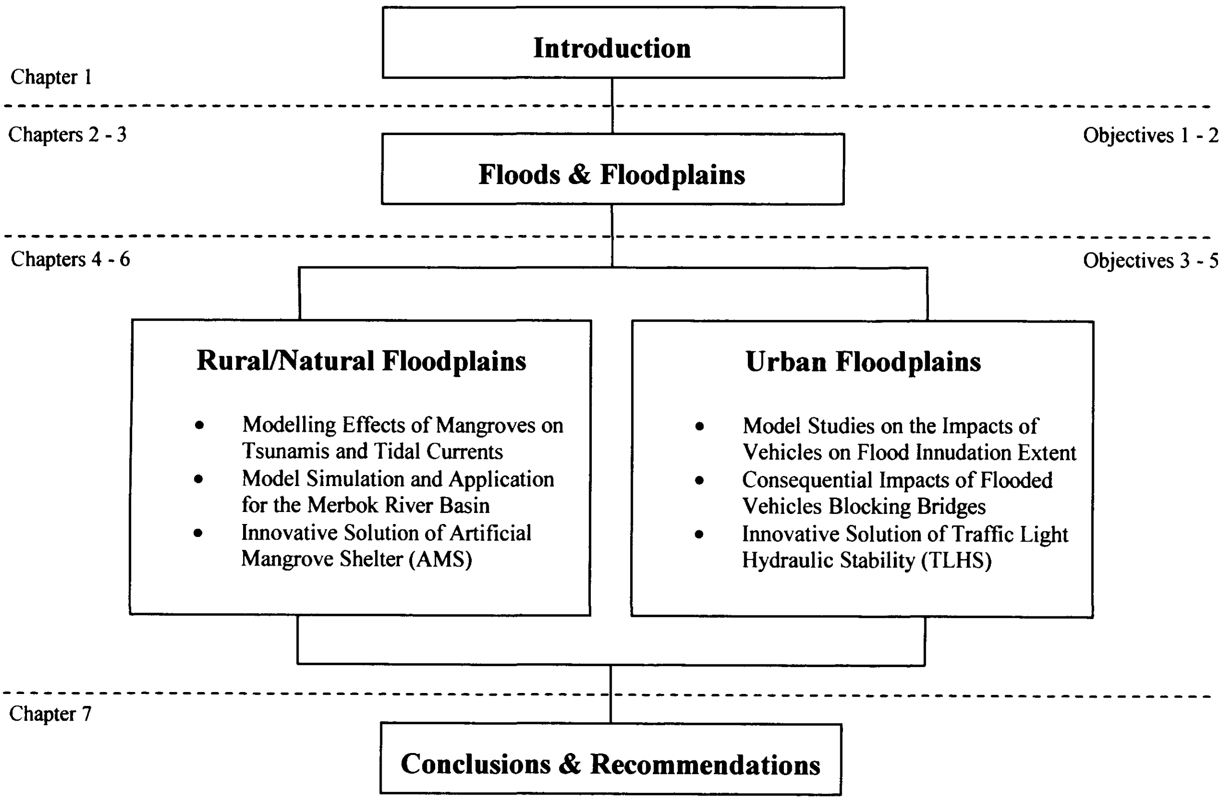


Figure 1.12 Outline of thesis

Chapter 4 details the rural/natural developments of floodplain encroachment activities for mangroves as the obstruction to tidal currents and tsunamis. This chapter presents the effects of mangroves on tsunamis, with the inclusion of modelling idealised test cases and the application of representative study sites for the Merbok river basin. The model study has focused on investigating the influence of both the vegetation resistance and reductions in the cross-sectional area of flow using mangroves and the consequential impact on tsunami currents. In this chapter, mangroves are recognised as natural defences against flooding disasters (i.e. tidal currents and tsunamis) and have been investigated using model simulations. Consequently, an innovative solution and environmentally friendly approach, referred to herein as the Artificial Mangrove Shelter (AMS) has been initiated and modelled. This novel approach has been developed for the sustainable restoration and rehabilitation of mangroves in floodplains.

Chapters 5 and 6 describe the urban developments of floodplain encroachment activities associated with vehicles as hydraulic obstructions to fluvial/flood discharges. Chapter 5 focuses on the physical modelling studies undertaken to investigate the effects of vehicles on flood flow propagation and, the influence of the flood flows on the stability of vehicles. In order to develop a useful approach to evaluate the degree of hydraulic stability for vehicles, a colour zone envelope curve has been first introduced and developed, herein known as the Traffic Light of Hydraulic Stability (TLHS). Chapter 6 studies the consequential hydraulic impacts of flooded vehicles on blocked bridges, which have been interpreted from the real prototype typical conditions for Boscastle and the Klang. Chapter 7 then draws together conclusions from the study, for both natural and urban developments on floodplains and alludes to recommendations for future works.

CHAPTER 2

AN OVERVIEW OF FLOODS AND FLOODPLAINS

2.1 Introduction

This chapter reviews the background information of floods (as sources) and the responses on floodplains (as pathways), and occupied developments (as receptors), as well as the management practices (as solutions) by either nature or humans. Firstly, a brief overview is given of the origins, causes and conditions of floods, despite the hazards that may lead to their damaging consequences. Many terms and definitions are established in this overview, which will be used throughout the thesis. Next, the chapter reviews the nature and development of floodplains, particularly with regard to natural developments and human encroachment activities (i.e. urban and rural developments), in conditions with the complex hydrodynamic flows and interactions with a wide range of obstructions on floodplains. Finally, an overview into the current practices for floodplain management is essential to provide a clear understanding and knowledge before proceeding into further studies on floodplain hydrodynamic modelling in the next chapter.

2.2 Overviews of Floods

The subject of floods is briefly introduced in this chapter. The differences between types of flooding are summarised, as well as some common characteristics between them. A considerable extent of the flood hazards involved and their consequential damages are also discussed.

2.2.1 Definitions of Floods

A flood is a natural phenomenon that can have far reaching effects on humans and the environment. A flood is usually defined as a relatively high stream flow, which overtops the natural or artificial banks in any part of a stream, river, estuary, lake or dam, and/or overland runoff before entering a watercourse, and/or coastal inundation resulting from super elevated sea levels and/or waves overtopping coastline defences. Given the concepts of flooding that are being addressed, it is important that the terminology used is consistent. To define a flood is difficult, this is because floods are complex phenomena that viewed differently by different researchers (Ward, 1978). The following definitions of floods are from different hydrologists and researchers as referenced by:

- A flood is a relatively high flow as measured by either gauge height or discharge rate whenever the stream channel in an average section is overtaxed, causing overflow to the usual channel boundaries (Jarvis, 1949).
- A flood is a relatively high flow, which overtaxes the natural channel provided for the runoff (Chow, 1959).
- A flood is a stage at which the stream channel becomes filled and above its overflow banks (Wisler et al., 1957).
- A flood is the result of runoff from rainfall and/or melting snow in quantities too great to be confined in the low water channels of a stream (Linsley, 1964).
- A flood is any high stream flow, which overtops natural or artificial banks of a stream (Rostvedt, 1968).
- A flood is a body of water, which rises to overflow land that is not normally submerged (Ward, 1978).

2.2.2 Origin, Causes and Conditions of Floods

Generally, floods are part of the Earth's natural hydrological cycle and originate from a number of basic causes, the most frequent of which climatologically occurs in nature. Smith and Ward (1998) summarised the causes of floods and their intensifying factors as shown in Figure 2.1. Although floods are mainly caused by climatological events, a number of other factors are often important, such as excessive water runoff with inadequate storm water systems, uncontrolled development on floodplains along rivers, and excessively high sea levels can all lead to flooding. Knight (2006) described the causes of floods as being highly varied, but may be categorised broadly under the following headings: (i) natural causes (i.e. precipitation, landslides, storm surges, high groundwater levels, glacier melt or collapse, and climate change) and (ii) human causes (i.e. dam failures, embankment failures, floodplain encroachment, changes of land use, inadequate planning controls, inadequate drainage capacity, inadequate integration and inadequate maintenance).

Overall, it is also useful to consider the formation of floods based on two categories of causative events: (i) floods directly caused by climatological events, which result from heavy rainfall, rain-on-snow, and snow-ice melt water on natural (or substantially modified by man) catchments; and (ii) floods partially or indirectly caused by climatological events, due to rising tides, tidal storm surges, tsunamis which are caused by enormous wave oscillations produced by submarine earthquakes, volcanic eruptions, landslides and slumps in enclosed water bodies, and the release of impounded waters by a sudden failure of a hydraulic control structure such as a dam or other natural or man-made embankment.

It is also important to distinguish between different types of floods (i.e. flash floods and long period floods), as well as predominant settings (i.e. river and coastal). All of these floods usually occur in conditions of seaward flows (i.e. river floods), landward flows (i.e. coastal floods) and localised overland flows (i.e. flash floods) as discussed further in the following section. The differences between river, estuarine, coastal and overland flooding are summarised, as well as some common features between them.

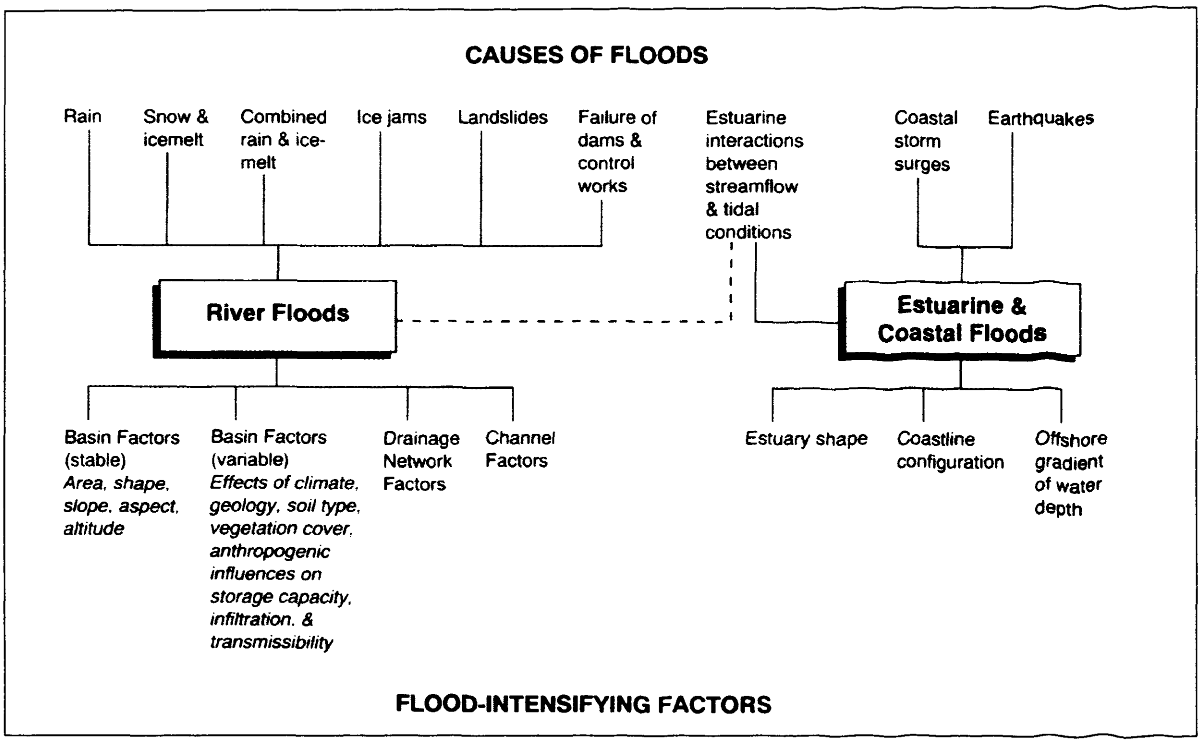


Figure 2.1 Causes of floods and flood intensifying factors (Smith and Ward 1998)

2.2.2.1 River Floods

Most of river floods result directly or indirectly from climatological events, such as excessive and/or prolonged rainfall. This type of flood occurs mostly on floodplains as a result of flow exceeding the capacity of the stream channels and over spilling the natural banks or artificial embankments (DID, 2000), also known as overbank flooding. In this case, the river channels usually can carry only a fraction of the flows occurring during floods, so that the remainder must spill on to the floodplain, which is normally a dry land area (Chow et al., 1988). Therefore, in flood conditions, the channel and the adjacent floodplains are complementary and together form the proper conveyance for the transmission of floodwaters.

Sometimes inundation of the floodplain occurs in wet conditions, when an already shallow water table rises above the level of the ground surface. This type of water table flooding is often an immediate precursor of overspill flooding from the channels (Smith and Ward, 1998), where rainfall usually after satisfying the catchments storage will appear as surface runoff. However, in very dry conditions, when the ground surface is baked hard or becomes crusted, extensive floodplains may be flooded by water overflowing on the surface or became overland flows.

In cold winter areas, where snowfall accumulates, substantial river flooding usually occurs during the period of snow and ice melt in spring and early summer, particularly when melt rates are high. River floods may also result when landslides fall directly into upstream reservoirs causing a sudden rise in water level, which overspills embankments.

2.2.2.2 Overland Floods

Overland floods are inundation by localised runoff rather than over bank discharges from a stream, river, estuary, lake or dam (DID, 2000). These floods derive directly from rain falling mainly from hydrological responsive source areas, which vary in size depending on the interaction of rainfall and catchments conditions. The source areas have usually saturated ground surfaces, which effectively shed, virtually all the rain falling on them, as saturation overland flow.

Smith and Ward (1998) documented these flooding mechanisms as follows: from early stages of a storm as shown in Figure 2.2 (a), all rainfall (*P*) infiltrates into the soil surface. Then, as a result of infiltration (*I*) and through flow (Q_t) in the soil profile, the riparian areas and the lower valley slopes become saturated as the shallow water table rises to the ground surface as shown in Figure 2.2 (b). In these surface saturated areas, infiltration capacity is zero so that all precipitation falling on them, at whatever intensity (*i*), becomes saturation overland flow ($Q_o(s)$).

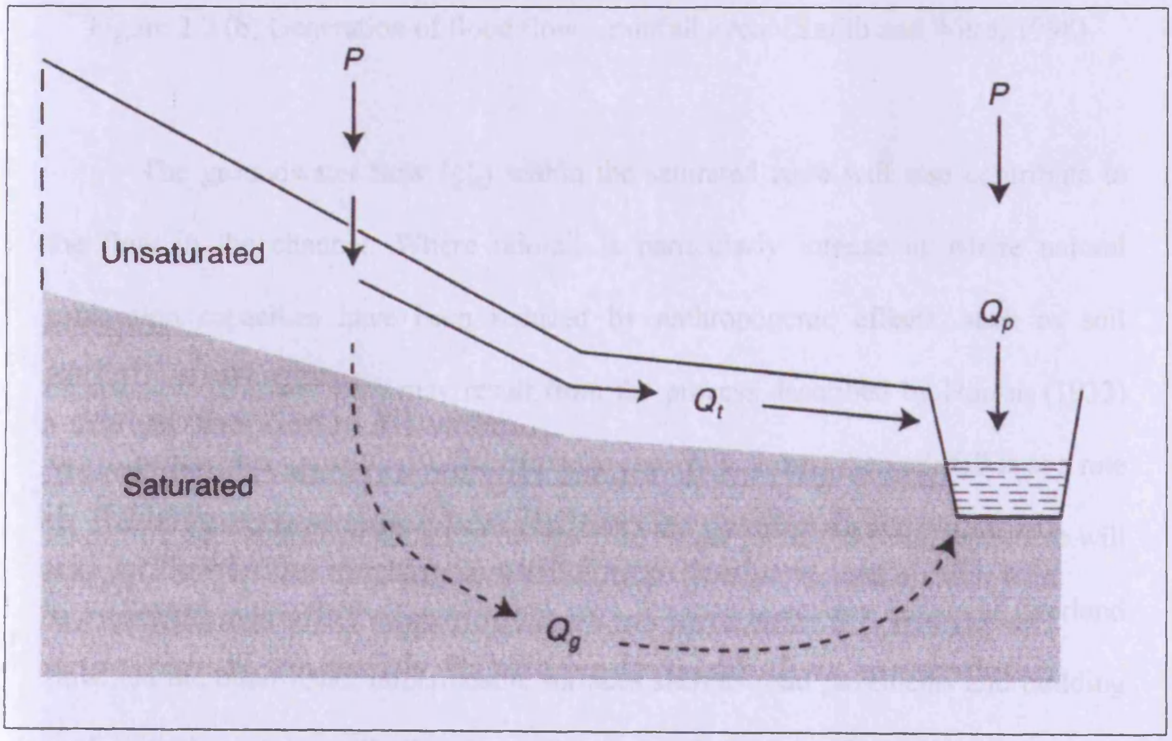


Figure 2.2 (a) Generation of flood flow – early stage of rainfall
(Smith and Ward, 1998)

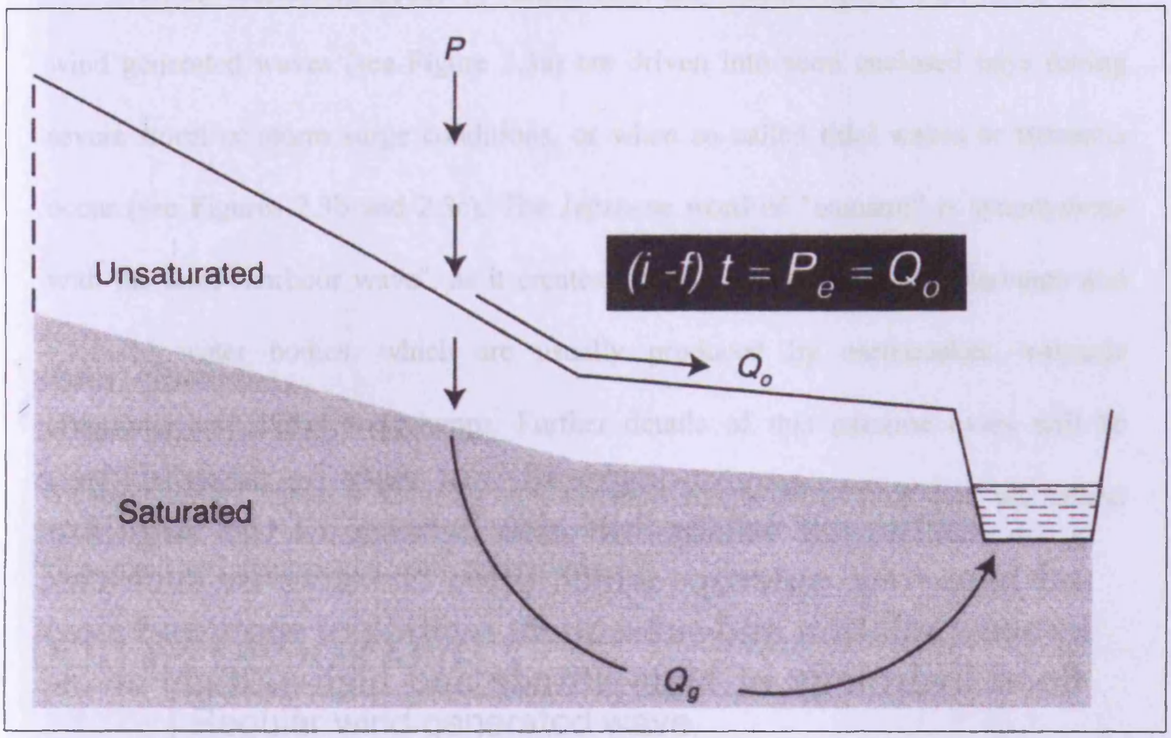


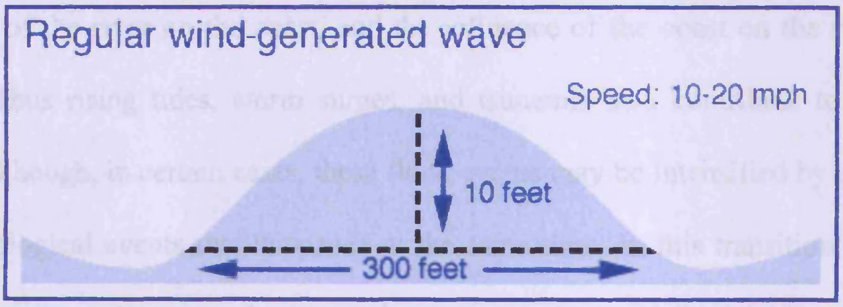
Figure 2.2 (c) Generation of flood flow – the formation of overland flow in areas of low infiltration capacity (Smith and Ward, 1998)

2.2.2.3 Coastal Floods

Floods in these low lying coastal areas, including estuaries and deltas, involve the inundation of land by brackish or saline water. Brackish water floods occur when a river overspills its embankments in coastal reaches with the flow being impeded by high-tide conditions and the floodplain being inundated partly by salt water. Overspill is exacerbated when high tide levels are increased above normal by storm surge conditions or when large fresh water flood flows are moving down an estuary (Smith and Ward, 1998). Coastal floods also usually caused by a combination of high tides and elevated sea levels and large waves associated with storm surges and hurricanes, which result from severe cyclonic weather systems and low atmospheric pressures (Munk, 1951).

Direct inundation floods by saline water may occur when exceptionally large wind generated waves (see Figure 2.3a) are driven into semi enclosed bays during severe storm or storm surge conditions, or when so called tidal waves or tsunamis occur (see Figures 2.3b and 2.3c). The Japanese word of "tsunami" is synonymous with the term "harbour wave", as it creates large wave oscillations in harbours and enclosed water bodies, which are usually produced by earthquakes, volcanic eruptions, land slides and slumps. Further details of this extreme event will be investigated in Chapter 4, focusing on the hydrodynamic interactions with the natural floodplain and in particular, with mangroves.

a)



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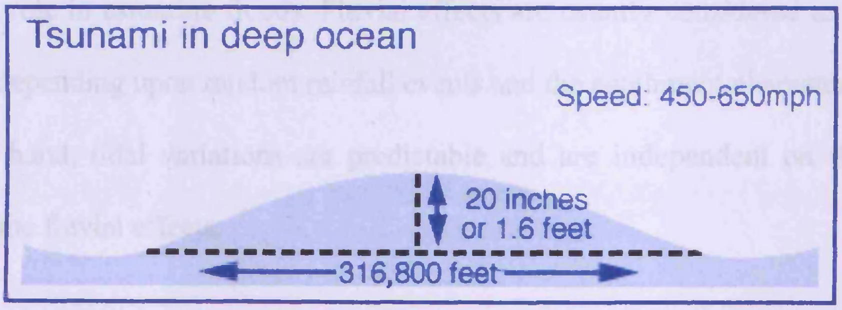

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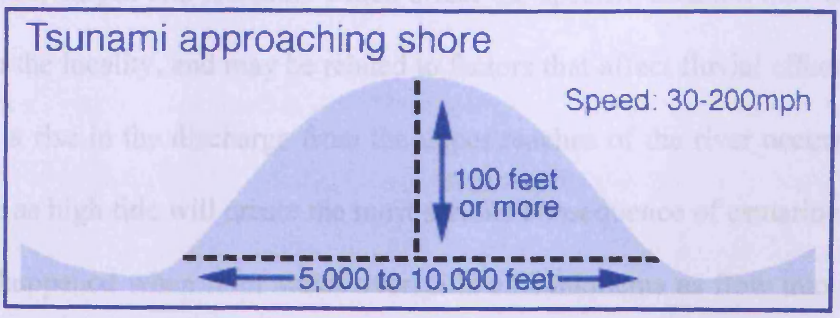


Figure 2.3 Direct inundation by saline water floods (Pictures courtesy of NASA)

2.2.2.4 Estuarine Floods

Estuarine floods usually involve the inundation of land that resulted from the interaction of the seaward flow of a fresh water discharge from the river and the alternating seaward ebb and landward flow of saline water caused by the tidal oscillation (Ward, 1978). Estuaries are semi enclosed coastal embayments of water (Pritchard, 1967) that are located at the mouth of rivers and interact physically with the open coast, as shown in Figure 2.4 (Pontee and Cooper, 2005).

This interaction can be expressed in terms of water movements for both the influence of the river on the coast, and the influence of the coast on the river in an estuary. Thus rising tides, storm surges, and tsunamis also contribute to estuarine floods. Although, in certain cases, these flood events may be intensified by the effects of climatological events that happened at the same time. In this transition zone of a river with a coastal system, the interaction between tidal and fluvial effects plays an important role in estuarine floods. Fluvial effects are usually considered as a random variable, depending upon random rainfall events and the catchment characteristics. On the other hand, tidal variations are predictable and are independent on the factors affecting the fluvial effects.

Storm surges and tsunamis which affect the specific location may or may not depend on the locality, and may be related to factors that affect fluvial effects. In most instances, a rise in the discharge from the upper reaches of the river occurring at the same time as high tide will create the most serious consequence of estuarine flooding. This can happened when river water overspills embankments as flow into the sea is impeded by high tide conditions. Overspill is exacerbated when high tide levels are increased above normal or when large freshwater flood flows are moved down an estuary. Sometimes estuarine floods can be intensified by storm surges, which are caused high sea levels arising from adverse weather and atmospheric conditions.

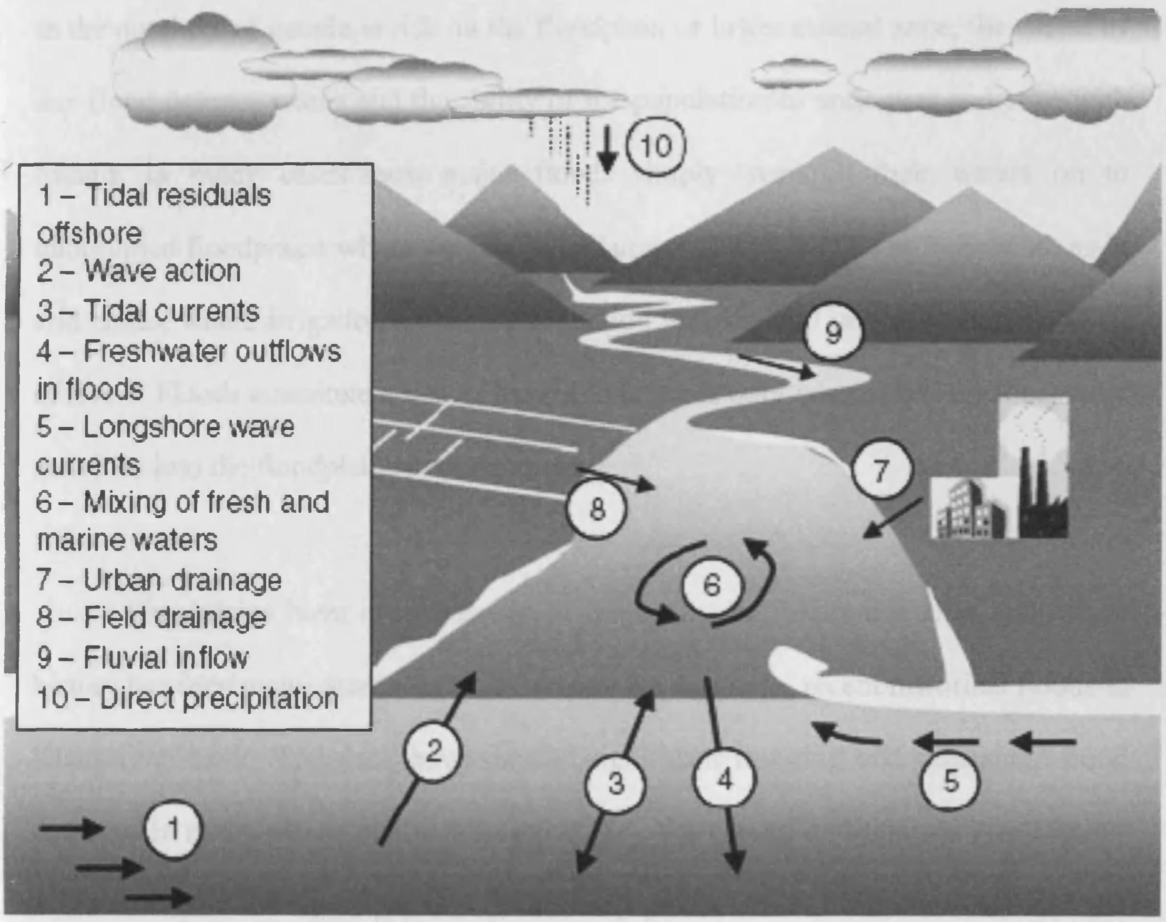


Figure 2.4 Interactions between estuaries and coasts (Pontee and Cooper, 2005)

2.2.3 Hazards and Damages of Floods

Flood hazards world wide account for about a third of all natural disasters by number and economic losses (Knight, 2006). The hazards comprise mainly of risk to life and limb, and potential damage to property and infrastructure. The degree of hazard varies with circumstances across the full range of floods.

Smith and Ward (1998) highlight that flood hazards result from a combination of physical exposure and human vulnerability to geophysical processes. Physical exposure reflects the type of flood events that can occur, and their statistical pattern at a particular site, whilst human vulnerability reflects key socio-economic factors such as the numbers of people at risk on the floodplain or lower coastal zone, the extent of any flood defence works and the ability of the population to anticipate and cope with hazard. In many cases even major floods simply overspill their waters on to unoccupied floodplains where they do little damage and may even be beneficial, as in arid zones, where irrigation and soil fertilisation may depend on the natural flooding of rivers. Floods constitute a risk of hazard to humans only where their encroachment activities into the floodplains have occurred.

Floodplains have been interrupted frequently by major tragedies and recent history has seen many disastrous flood events. For example, recent historical floods in Klang river basin, Malaysia, have showed significant flooding and substantial flood damages in many places of Kuala Lumpur City, the capital of Malaysia (see Figures 1.2 and 1.3). The city centre and particularly places around the confluence of the rivers are most affected (DID, 2003). These floods resulted in much damage to human property. Besides causing damage to property, floods also resulted in traffic congestions, social and economic disruptions. Floods have seriously disrupted public transportation systems by cutting off roads and railway lines, as well as communication networks when telephone lines have been damaged, etc. These floods have also disrupted normal drainage systems in cities, and sewage spills are common, representing a serious health hazard, along with standing water and wet materials in houses. Bacteria, mould and viruses, cause diseases, trigger allergic reactions, and can continue to damage properties after a flood.

In the last decade of the 20th century, flood hazards have attracted increasing attention, both by the media and politicians. Based on OECD International Disasters Database, floods accounted for 12% of all deaths from natural disasters, claiming about 93,000 lives across the world (HR Wallingford, 2005). In 1953, the North Sea floods caused approximately 2,500 deaths across Europe. In Malaysia, the impact of flooding in terms of fatalities has been far less severe in comparison with many other far eastern countries. The Japan International Cooperation Agency (JICA), in a National Water Resources Study for Malaysia in 1982, conducted a nationwide estimation of flood damage exercise. The average potential flood damage within Malaysia at that time was estimated to be RM 100 million per annum.

Generally, this flood damage was classified to include both the tangible and intangible costs of flooding. Tangible costs can be quantified in monetary terms. On the other hand, intangible damages represent the increased levels of physical, emotional and psychological illness in flood affected people attributed to a flooding episode, and are less easy to quantity in monetary terms. Following the year 2000, and based on Malaysia's National Register of River Basin study, the estimated annual average flood damage for the whole country increased dramatically to RM915 million (DID, 2003) and these damage costs are now rising from annually.

In the UK, the floods of Easter 1998, Autumn 2000, August 2004 in Boscastle (see Figure 1.4), January 2005 in Carlisle, and November 2009 in Cumbria have caused a small number of fatalities and considerable flood damages to property. The Parliamentary Office of Science and Technology (POST) in the UK pointed out that flooding due to drainage systems being overwhelmed by rainfall was estimated to cost £270 million a year in England and Wales, with 80,000 homes being at risk. Its impacts are expected to increase if no policy changes are made (POST, 2007). A special report by Foresight stated that the costs of flooding could rise to between £1-10 billion per annum by year 2080 if no action were taken to reduce the risks (Foresight, 2004). The damage costs are worryingly upwards. Considerable changes in the climatic and meteorological conditions being experienced worldwide means that floods are going to be more frequent and thus flood damage is also going to increase significantly in the future.

2.3 Overviews of Floodplains

Floodplains are the water pathways that provide a considerable connection between particular flood flows (i.e. the sources) being realised and the development areas (i.e. the receptors) that may be harmed. In referring to this type of hydrodynamic interrelationship as the main focus to be discussed hereafter, floodplains are first introduced in brief with definitions, and then discussed in the context of their potential developments and consequential impacts, as well as the necessity to manage them as valuable natural resources for flood mitigation. Floodplains can reduce flood hazard risks to humans with appropriate strategies and tools, being used through hydrodynamic modelling, with these models discussed further in the subsequent chapter.

2.3.1 Definitions of Floodplains

In general, floodplains form the flat land adjacent to rivers created by the deposition of sediment as the channel migrates laterally (Marriot, 1998) and are inundated during floods due to excessive water (Nanson and Croke, 1992). In other words, rivers have a limited capacity for water and sediment when this is exceeded, flooding of the adjoining land as floodplain occurs, which then act to store this water and sediment. In the physical aspects of floodplains, there are strong interrelationships between the processes associated with the morphological (i.e. sediment movement) and the hydrodynamics (i.e. water movement) of floodplains. The hydrodynamic and morphologic processes on floodplains are complicated by variables associated with the floodplain characteristics and surface topography (i.e. channels, depressions, mounds of sediment, such as levees and embankments, vegetation, and structures produced by humans or other animals, etc.), and the varying quantity and size of available sediment, etc.

The term floodplain may take on different definitions, depending on a particular discipline. To the hydrologist, Chow et al. (1988) defined floodplains as the strip of dry land adjoining rivers, estuaries, lakes, bays or seas that are subjected to inundation during seasonal or extreme flood events. The recurrence interval of these flood events in floodplains is generally from less than one year to two years (or once per year on average as highlighted by Leopold et al., 1964). Floodplains in general are natural features that provide floodwater storage and conveyance to reduce flood velocities and flood peaks, and curb sedimentation, and indirectly help to maintain water quality. The UK Flood Studies Report (Natural Environment Research Council, 1975) documented the attenuation of flood peaks on the River Wye. Sutcliffe and Parks (1989) reported that large floodplain wetlands in West Africa reduce flood peaks. Similar results for floodplains in India were found by Nielsen et al. (1991) and in West Africa by John et al. (1993). All of these studies have demonstrated the flood attenuation properties of floodplains. In fact, floodplains can also improve water quality through deposition of sediment, as well as absorption or recycling of nutrients and pollutants (Brookes and Shields, 1996).

To the geologist, floodplains are underlain by the deposits of river channels, of overbank floods, and of lakes (Bridge, 2003), where floods are dynamic agents that can alter the physical geography of floodplains and recharging groundwater. In terms of their ecology, Junk et al. (1989) defined floodplains as areas that are periodically inundated by the lateral overflow of rivers or lakes, and/or by direct precipitation or groundwater; the resulting physio-chemical environment caused the biota to respond by morphological, anatomical, physiological, phonological, and/or ethological adaptations to produce characteristic community structures. On the other hand, to the development engineer, floodplains are the low lying and flat areas which provide valuable resources, which are the popular developing and settling areas for humans.

2.3.2 Development of Floodplains

Generally, floods have naturally inundated and altered floodplains throughout time and space to create a state of dynamic equilibrium. In other words, inundations of floodwaters have generated erosion and deposition of sediments in a period of time to form natural floodplains. Over the years, these floodplains have developed their own ways of responding to floodwaters and sediments, with their vital roles being to provide storage and conveyance. Floodplains are continuously shaped by the forces of water and the transport of sediment, which may vary in their characteristics, depending mainly on the associated environments. As an example, the coastline in the UK is dissected by over 170 estuarine floodplains that differ markedly in their physical characteristics (DEFRA, 2001).

Throughout time, developments on floodplains have contributed to changes in their overall physical characteristics, in particular as shown in Figure 1.1. Both natural and urban floodplain developments and encroachment activities have resulted in the removal of existing flood storage and conveyance, and creating a variety of hydraulic obstruction types (i.e. vegetation, agricultural plants, hydraulic structures, bridge piers, buildings, vehicles on roads, etc.) to floodwater flows. Often the effects of flooding are made worse due to these obstructions encroaching on floodplains and blocking floodwater flows. Consequently, these have caused significant impacts on the hydrodynamic interactions with a wide range of obstructions, which is the subject of this thesis. Both of these development types on floodplains are briefly discussed as follows, to provide the basic concepts for further investigations in the next few chapters.

2.3.2.1 Natural Development of Floodplains

Natural floodplains provide ideal lands for habitat, where flora and fauna mix in a myriad of diversity forms. This part of a river system supports a great variety of fishes, gastropods (i.e. crabs, prawns, etc.), bivalves, and other aquatic animals, and there are often other rich riparian vegetation, forests and swamps on floodplains, including mangroves. All of these habitats form an interaction and they interlink with one another in a complex web of life that either directly or indirectly contribute to the natural developments of floodplains.

These floodplains are regularly beneficial with rich resources of water and nutrients from the natural processes of flooding through the features of irrigation and soil fertilisation. Accordingly, floodplains encourage the establishment of natural development in particular riparian vegetation, forests and swamps, which contribute a lot to alter their physical characteristics (see Figure 1.5). Most of these vegetations have survived well along natural floodplains, which are frequently inundated and generated hydraulic obstructions to floodwater flow. For example, mangroves play a significant role in the more affluent nations along the floodplains, as noted by Wolanski and Ridd (1986). They cover a significant fraction of the estuary for floodwater storage and conveyance, help to stabilise the banks of tidal rivers and creeks, help to maintain deep tidal channels and control sediments, and are also well known for natural coastal protection and flood defence.

Even though floods and natural floodplains are beneficial to each other in many cases, uncontrolled natural development with massive hydraulic obstructions, may make flood situations worse and can cause subsequent damage to adjacent areas in certain conditions. In such cases, floods constitute a risk of hazard to humans where their encroachment activities into these natural floodplains have occurred. Further investigation studies into this subject of natural development of floodplains will be discussed in Chapter 4.

2.3.2.2 Urban Development of Floodplains

Over the past few hundred years, many of the world's natural floodplains have been transformed, mainly by humans for rural and urban development particularly for agriculture, development including: buildings, roads, pavements, parking lots for vehicles, etc. (see Figure 1.1). As an example, Wheater (2006) reviewed flooding for UK practice and found that rural land use had intensified significantly over the past 30 years, where this potentially had lead to an increase of flood risk at the local scale.

Indeed urban development in floodplains, particularly the continuing increase of urbanisation, coupled with associated land encroachment and in filling activities along the river banks or coastal areas, has drastically distorted the natural form of floodplains and created a new variety of hydraulic obstructions to floodwater flows.

It also reduces the floodplain's ability to store excess water, sending more water downstream and causing higher flood peaks and increased floodwater velocities. Continuing urban developments in floodplains are also completely altering the surface profiles by increasing the impermeable urban areas. Before urbanisation, rainwater gets intercepted by the vegetation, infiltrates into the ground and takes time to travel to the river, but now it is quickly collected from the roofs and other paved ground and drained efficiently to public drains, which in turn rapidly delivers the water to the nearest river. Hence, flash floods are now more frequent than ever, where the rising water occurs within a matter of a few hours after a storm (DID, 2000). In addition, as infiltration has decreased, the water table has dropped and, consequently this has reduced the groundwater resource for wetlands, riparian vegetation, wells and other uses.

Due to the rapid growth in urbanisation, high intensity of rainfall and in addition the uncontrolled development over the past years within floodplains have caused a gradual deterioration in the efficiency of rivers to act as conduits of water and sediment, which has resulted in an increase in the frequency and magnitude of flooding. Consequently, incidences of floods in urban areas are now on the rise. These developments have led to the construction of extensive flood protection systems by building embankments along the rivers, enlarging and deepening the river channels, etc., which have restricted the natural morphological evolution of floodplains and eliminated flood attenuation properties. Natural waterways have ended up being used as drainage channels, and are frequently lined with rocks or concrete to move water more quickly and prevent erosion (OEHHA, 2006). Further studies into this subject of urban development of floodplains will be discussed in Chapter 5.

2.4 Management of Floodplains

With the passage of time, natural lands have been shaped by the flow of water from small streams forming larger rivers; accordingly the silts deposited onto the land and the vegetation grows naturally after floods, on the other hand humans have placed their mark on floodplains, despite potentially the risk of flooding. In fact, floods are a critical factor in the health of floodplains, rivers and coastal estuaries. Floods can not be ignored and are a challenge which humans are going to have to learn to live along with rivers and floodplains. At some point there is a need to learn to accept and understand the natural processes and environment of rivers and floodplains in which humans choose to live (ICE, 2001 and Knight, 2006).

As highlighted previously, a floodplain is a valuable resource of land and its development must concern a broad spectrum of issues. Thus, floodplain management is vital to create rich natural resources and avoid hazards associated with human occupation on floodplains (DID, 2002). In general, floodplain management can be defined as a continuous process of making decisions about whether and how floodplain lands and waters are to be used (Federal Interagency Floodplain Management Task Force, 1994). It is a solution or decision making process that aims to achieve the wise use of floodplains in reducing flood losses and protection of the natural resources and functions of floodplains. In other words, floodplain management is a broad spectrum of water resources activities that need to be taken into a consideration, for both the hazard avoidance and protecting the natural values before implementing any action that will alter floodplains.

Over a period of time humans have builds their townships in the encroachment areas over the lower and flatter floodplains, often in response to the pressure to find suitable land for their settlements, where the social, economic and environment benefits arise. The encroachment activities along floodplains have made the balance between the risk of damage and the benefit more difficult to evaluate. As mentioned, having developed the floodplain which is a natural flood storage and conveyance area, this area is more subjected to the risk of periodic flooding. Therefore, there is an inevitable pressure to protect this area by means of some protection measures for flood alleviation. Provided the floods are moderate, then such defences will be protected, affording the area safe to live.

However, in the extreme event likes tsunamis and flash floods, the protection measures may be overtopped and failure will lead to catastrophic consequences. These floods cannot be prevented but by understanding and planning the appropriate measures through management can often reduce the disastrous consequences (IHP-UNESCO, 2001). It is now realised that the encroachment activities of floodplains and the introduced measures can interfere markedly with the overall physical characteristics and functions of floodplains and particularly the hydrodynamic processes, which forms the main focus of this thesis. As a result, more investigations into this relevant subject will be discussed in the subsequent chapters.

2.4.1 Management of Floodplains in Malaysia

Due to the rapid growth of urbanisation, high intensity of tropical rainfall and in addition the uncontrolled development over the past few years within floodplains have caused the gradual deterioration of the rivers and estuaries as efficient conduits of water and sediment, resulting in an increase in the frequency and magnitude of flooding.

It is a known fact of Malaysia and other parts of the world that urbanisation has led to an increase in urban runoff and making urban areas highly prone to flooding. As mentioned previously, this is mainly due to the increase of the total impervious surfaces, which have resulted in rapid overland runoff and little infiltration. With respect to floodwater runoff, an increase in areal imperviousness from zero to 40% would cut the time to peak discharge by about 50% and increase the discharge magnitude by about 90% (DID, 2000). As highlighted, some floodwater remains on the surface, or is held in the soil or underground aquifer as ground water, a portion of the water is used directly by vegetation, while a large amount of the remainder flows over the surface as overland flow. Flash floods have been happened where the rapidly rising overland flow occurs during or after associated heavy rainfall. It is also often caused by over spilling when inadequate urban storm water drainage systems have surcharged and overflowed (DID, 2000).

For an example, development along the Klang river basin has been concentrated on the banks of the rivers, particularly on the floodplains, in order to gain ready access to the waters for domestic, industrial and agricultural purposes, river transport, fertile floodplain soils, and convenient disposal of effluent and refuse.

As a result, much of the development is on land that has always been subjected to frequent flooding. For floodplain management, the local government has embarked on a comprehensive flood mitigation programme involving expenditure of RM 500 million, construction of large dams and extensive channel works (DID, 2002). Flood alleviation works have been rendered ineffective because flood discharges have increased threefold since 1986, due to the effect of urbanisation and continuous development along floodplains, which have been greatly underestimated in the past and there are some other factors that have contributed to an increase in flood discharges, including channel works, creation of large areas of impervious surface, filling up of most of the floodplains, and climate change, etc.

Overall, floodplain management in a country like Malaysia involves focus on reducing hazard losses and utilising the natural resources. To implement floodplain management in the Malaysian context, a series of best practice principles have been identified and implemented (as shown in Figure 2.5), which covering roles and responsibilities, prevention activities, preparation activities, response activities and recovery activities (DID, 2002). Apparently, flood mitigation measures are being primarily undertaken to reduce damage to a minimum, consistent with the relatively high costs involved. Accordingly, the local government adopted both structural and non-structural measures to reduce the hazard losses. The structural measures include river channel improvement works and the construction of embankment bunds, flood bypass, flood storage dams and reservoirs, floodwalls, flood attenuation ponds, retention and detention basins and so on. Non-structural measures are used where structural measures are not applicable, or viable, or where supplemental measures are required and they include restrictions of land use activities, resettlement of population, flood proofing and flood forecasting and warning systems. In order to minimise flood losses and to better coordinate flood management activities, flood forecasting and warning systems are provided as an important and effective management measure.

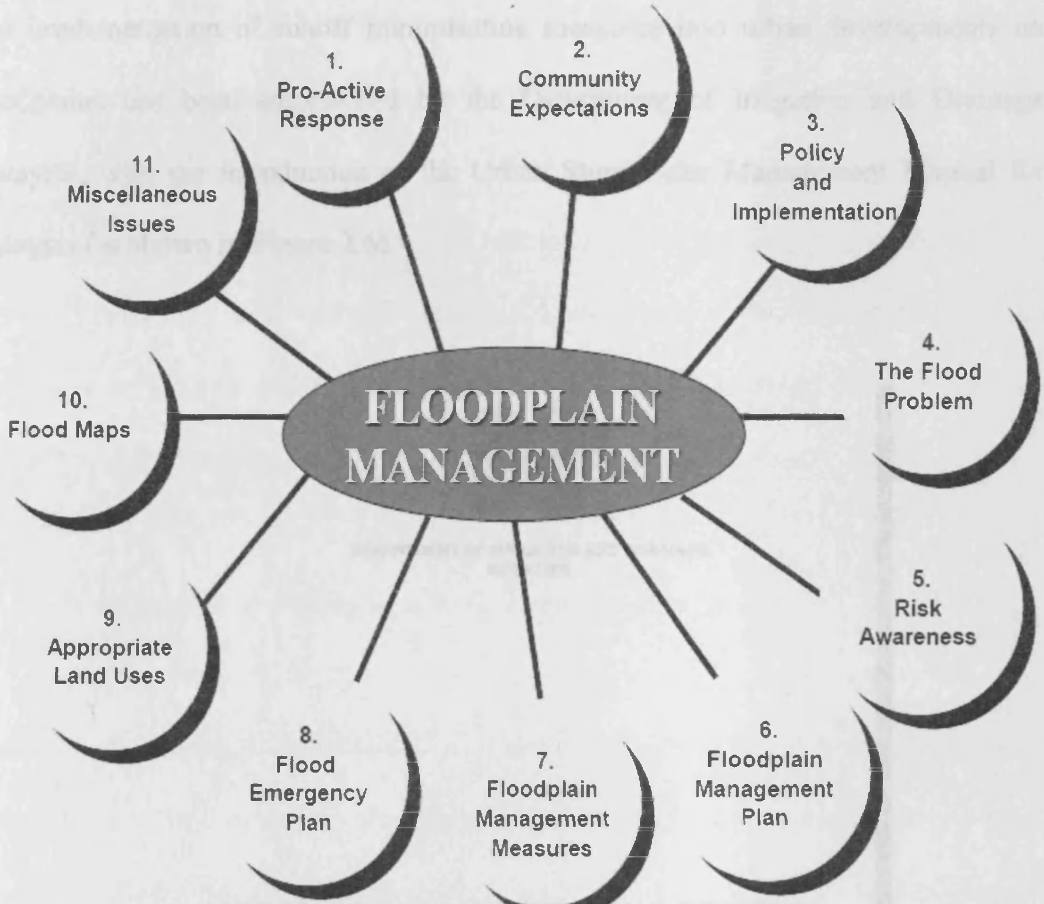


Figure 2.5 Floodplain management best practice principles for Malaysia (DID, 2002)

It needs to be appreciated that whilst structural measures are a key component in reducing the impact of flooding on existing developments, it is absolutely essential to implement strong planning and building controls to ensure inappropriate development is not allowed over floodplains. Whereas inappropriate land use planning and development decisions have played a significant role in shaping the main flood issues in the country, it is important to consider the flood risk when planning for a development on floodplains. As a result, a new development must be required to utilise runoff minimisation measures to control at source, where it can be classified by function as either detention or retention facilities to ensure that post-development peak discharges do not exceed pre-development discharges (DID, 2000). The implementation of runoff minimisation measures into urban developments on floodplains has been emphasised by the Department of Irrigation and Drainage Malaysia, with the introduction of the Urban Stormwater Management Manual for Malaysia (as shown in Figure 2.6).

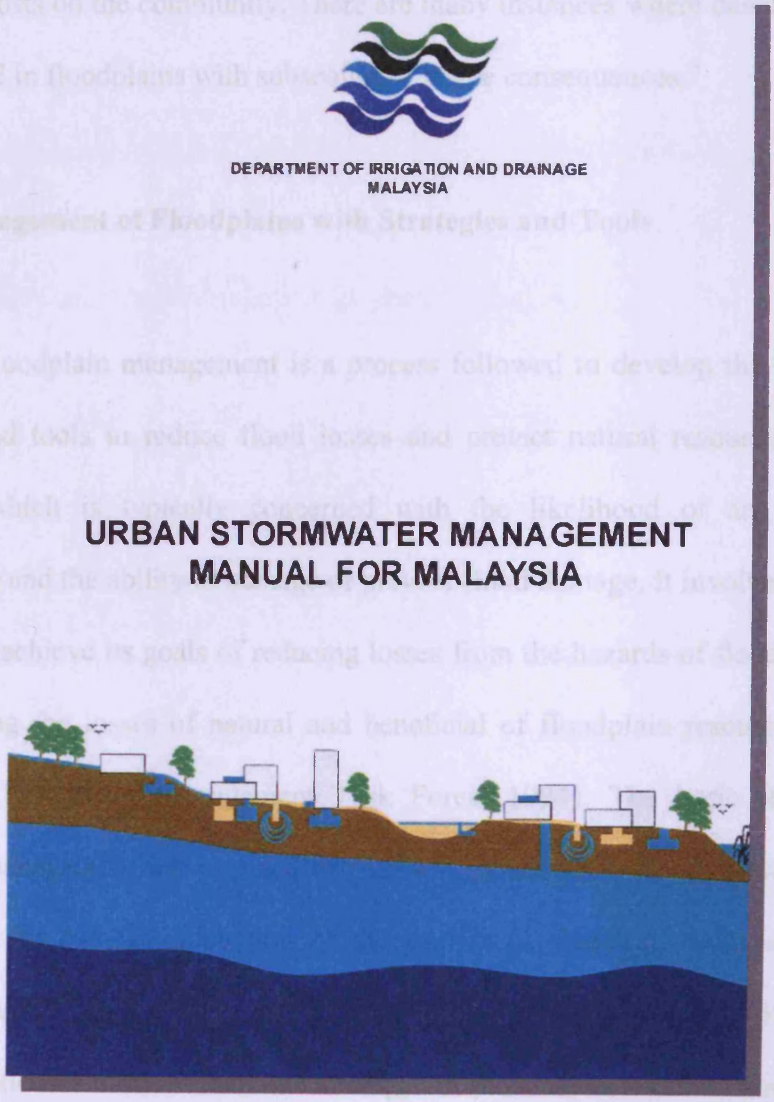


Figure 2.6 Urban Stormwater Management Manual for Malaysia (DID, 2002)

In fact, this comprehensive manual has recognised the considerable necessity for integration between flood planning, catchment management and urban planning (DID, 2000), which notes: "Existing and future stormwater quantity and quality problems are closely tied to existing and future landuse patterns. The nature and density of landuse will significantly influence the volume and rate of runoff and the quantity and quality of pollutants carried from the land surface to the stormwater system. Landuse is therefore a primary determinant of the location and severity of urban flooding and pollution problems. Decisions on landuse, which do not consider stormwater quantity and quality management, may limit opportunities and impose significant costs on the community. There are many instances where development has been allowed in floodplains with subsequent adverse consequences."

2.4.2 Management of Floodplains with Strategies and Tools

Generally, floodplain management is a process followed to develop the best mix of strategies and tools to reduce flood losses and protect natural resources and their functions, which is typically concerned with the likelihood of an undesirable consequence and the ability to manage or prevent flood damage. It involves four basic strategies to achieve its goals of reducing losses from the hazards of flooding as well as minimising the losses of natural and beneficial of floodplain resources (Federal Interagency Floodplain Management Task Force, 1994). The basic strategies of floodplain management are outlined as follows: reduction in flooding, reduction in susceptibility to damage, reduction of the impact of flooding, and restoration of natural resources. Each strategy is supported by an array of tools and many of the tools are applicable in more than one strategy. In most cases, a combination of these tools is needed to reduce the risks and to protect natural resources and their functions.

Basically, the strategy of reduction in flooding is mainly structural measures to control floodwater and may involve the tools like construction of dams, flood embankments, floodwalls, retention and detention basins, river engineering and coastal protection works, etc. While, the strategy of reduction in susceptibility to flood damage is mainly non-structural measures to minimise the destruction and may involve the use of tools like regulating floodplain development, as well as the development of improved flood forecasting and warning systems, setting up of flood risk maps, etc. The strategy of reduction of the impact of flooding is mainly non-structural measures to improve the quality of life by taking necessary actions on flooding consequences and may involves public awareness and education, flood emergency management, flood insurance, post-recovery plan, etc. After all, the strategy of restoration of natural resources is mainly to maintain the unique functions of floodplains and may involve restoration and rehabilitation of wetlands, natural rivers and floodplains, land acquisition for preservation, etc.

Overall, the strategies and tools of floodplain management are mainly explained in terms of structural or non-structural measures, and appropriate methods for managing the floodplains on its natural resources and hazard risks. In the other words, the effective floodplain management needs to be based on an integrated approach that recognises, considers and, where appropriate, accommodates the impacts of natural resource management on flood hazard risks. Examples of such uses include non-residential land development, the disturbance of natural vegetation and other hydraulic obstructions with the consequent effects on runoff, environmental management requirements and the need and demand for recreational facilities.

In order for effective floodplain management, recently it has been relied heavily on the use of models to explore the response of floodplains, particularly with regard to the hydrology and hydraulics. Management of floodplains using models is briefly discussed in the following section, and with more details being given in Chapter 3 for the best understanding of the appropriate tools to be used in current study on the hydrodynamic processes of floodplains, for a wide range of hydraulic obstructions.

2.4.3 Management of Floodplains with Models

In general, models are representations of real systems. Models are essentially the description of how things work and a mathematical model is commonly described as a set of general laws or mathematical principles and set of statements of empirical circumstances (Hempel, 1963). The Oxford English Dictionary defines a model as a representation of a designed or natural object, proportioned in all dimensions. At present, engineers and researchers prefer to resort to models due to the real system being too complex or the system is currently being non-existent (i.e. a proposed system). As expected, most models are simplifications of the ideal real system. To be effective in terms of effort, time and money, while getting results which are realistic and helpful in decision making of floodplain management, or to enhance our understanding of the system, models should not be any more complex than need be.

Floodplain management is basically founded upon modelling sound engineering practice instead of statistical or probabilistic analyses, which is very common in flood risk management. With increasingly sophisticated computers, numerical models with engineering consideration are now being widely used to support floodplain management. The management of floodplains through the incorporation of models can be used to assess flood hazards and their resources efficiently. Models are also able to describe the hydraulic response for a variety of flood flow conditions and various types of hydraulic obstructions, which are the primary focus of the current study. Further discussions will be covered in detail in subsequent chapters. The philosophy of floodplain modelling will be shown to lead to problems of definition, as well as limitations of modelling capability at both spatial and temporal scales.

It has become necessary to develop an understanding of the hydrodynamic processes of floodwater flows involved in obstructed floodplains, so that effective and sustainable management tools may be developed for future applications. In order to develop an effective tool for the analysis of floodwater flows over floodplains, the first stage of research obviously involves the development of an effective hydrodynamic model. The floodplain model should therefore be capable of accurately representing the flow through the various types of hydraulic obstructions, which may be present for each floodplain type being considered, as well as considering the shallow depths, which typify these ecosystems.

As will be discussed in much greater detail in the next few chapters, the topic of analysing the flow through natural floodplain with vegetation in particular mangroves has been the subject of much research, to a varying degree of details, such as studies by Wolanski et al. (1980) on hydrodynamic of mangrove swamp; Sengupta et al. (1986) on vegetative obstruction to flows; Kadlec (1990) on wetland vegetation resistance; Ridd et al. (1990) on flow in mangrove fringed tidal creeks; Nepf (1999) on flow through emergent vegetation; Choi (1999) on vegetated open-channel flows;

Struve and Falconer (2001) on the hydrodynamics of mangrove region; and a recent study by Wilson (2007) on flexible submerged vegetation flows.

On the other hand, the impact of floodwater flow through other hydraulic obstructions in particular infrastructure and buildings, vehicles, etc. have rarely been considered, in the past. Full details into these investigations are given in subsequent chapters.

2.5 Summary

This chapter has reviewed the background information relating to floods (as sources) and the responses on floodplains (as pathways), and the occupied developments and encroachment activities (as receptors), as well as the appropriate management practices (as solutions). An understanding of the background information is fundamental to the preparation for detailed investigations as covered in the study. The literature shows that the effective management of floodplains can help to reduce flood hazard risk with appropriate strategies and tools.

CHAPTER 3

MODELLING THE HYDRODYNAMICS OF FLOODPLAINS

3.1 Introduction

As highlighted in the last chapter, the ultimate goal of floodplain management is the improvement in the quality of life by reducing the impact of flooding and protecting the valuable natural resources for sustainability. In order to achieve this goal, management of floodplains through the application of models has been widely used over the past decades to assess these hazards and resources. For example, significant progress has been made in research with regard to the impact of flooding on floodplains and related anthropogenic activities (such as investigations by Liang et al., 2007; and Soares-Frazão and Zech, 2007). The cause and effects of this impact on the relationship between floods and floodplains have been better understood through research with the support of a variety of models, which have subsequently contributed to the effective management of floodplains. However, there has not been much in the way of systematic studies on floodplain hydrodynamic processes, in particular on the hydraulic interactions with obstructions, and only limited observations in the real environments due to the rare occurrence of extreme events.

In this study, the challenge will be to identify prudent, effective and innovative solutions, and adaptive management approaches for floodplains with the support of models that yield multiple benefits for a more sustainable future, particularly in reducing the impacts of flooding. With the purpose of developing an effective hydrodynamic model for the analysis of flows over floodplains, in the initial stage of current study, both physical and numerical methods will be applied to investigate the hydrodynamic responses of floodplains, as well as the hydraulic interactions with selected obstruction types. This model will therefore be capable of accurately representing the flows through the selected types of obstruction, which may be present in each floodplain being considered, as well as considering the shallow water depths, which typify the real ecosystems.

This chapter investigates in modelling the hydrodynamic processes on floodplains, which cause complex interactions and the consequential hydraulic responses for a wide range of hydraulic obstructions. It is aimed at disseminating knowledge and understanding from previous research on modelling the hydrodynamic processes of floodplains, as well as giving up to date views on the management of floodplains with models. The chapter begins with a brief introduction to floodplain hydrodynamic modelling from the past perspective, for both physical and numerical of applications, proceeding through to modern day techniques by using the latest computer programmes, with the focus on natural and urban floodplains, and finally concerning the governing equations and numerical methods of the applied model in the current study.

This corresponding applied model was refined from an existing two-dimensional depth integrated finite difference model, which was originally developed by Falconer (1986). Details are given of the applied model, providing considerable background for further investigations in the subsequent chapters. The philosophy of floodplain modelling will also be shown to lead to problems of definition, as well as limitations of modelling capability at both spatial and temporal scales.

3.2 Floodplain Models

As highlighted previously, models attempt to provide a representation of the real system to be, which essentially describe how things work. The basic purpose of a model is to simulate and predict the operation of the system, that is unduly complex, and the effect of changes on this system (Singh, 1989). All models seek to simplify the complexity of the real world by selectively exaggerating the fundamental aspect of a system at the expense of incidental detail (Anderson et al., 1985). Dooge (1981) and Anderson et al. (1985) suggested a possible methodology for selecting a mathematical model as shown in Figure 3.1. Today, hydrologic and hydraulic engineers and researchers are continuously obtaining an improved understanding of the complex floodplain processes with the help of models for better management practices.

In general, modelling of floodplains can be classified into hydrological and hydraulic models. Firstly, most of the hydrological models aim to provide a prognosis of the future performance of the hydrological system, such a judgment may be made with respect to real time (forecasting) or without specific time reference (prediction). This study is not giving too much consideration into this investigation as the hydraulic model is the main focus of the current study. However, just for a brief introduction, Anderson et al. (1985) classified hydrological model as:

i. Black box models – where no physically based transfer processes is included to relate input and output.
ii. Conceptual models – where an intermediate position is included between the deterministic approach and empirical black box analysis.
iii. Deterministic models – where complex physical theories are included.

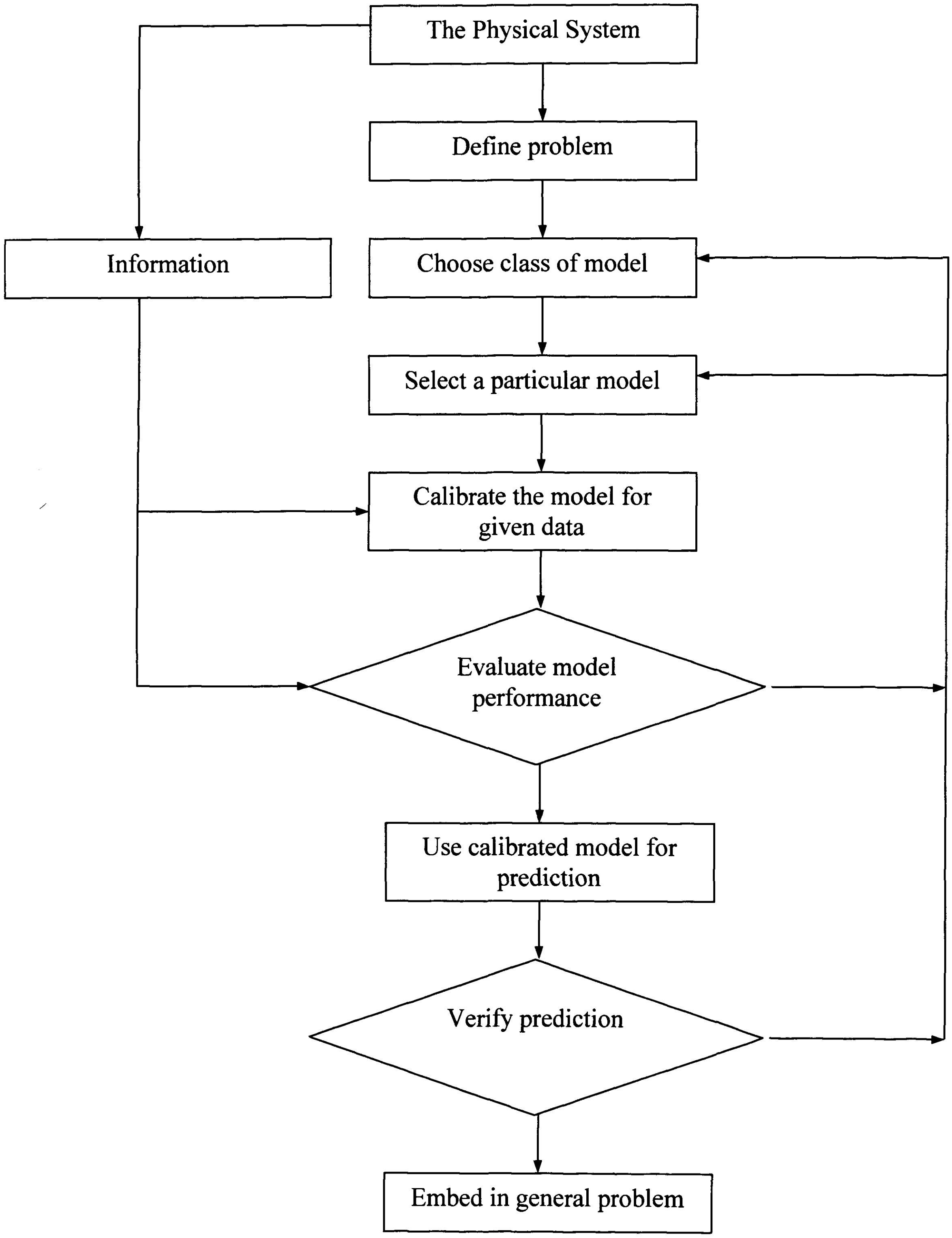


Figure 3.1 A possible methodology for selecting a mathematical model (Dooge, 1981 and Anderson et al., 1985).

On the other hand, issues concerning floodplain hydraulics and modelling are widely researched, for example by Shiono and Knight (1991), Knight and Shiono

(1996), Knight and Abril (1996), etc. Basically, hydraulic models aim to provide a good understanding of the hydrodynamic processes and interactions within floodplains. The modelling of floodplain hydrodynamic is a complex process, because of the large number of factors that affect the system. Significant uncertainties exist in many of these factors and as a result simplifications in the methods of analysis and simulation are necessary and need to be undertaken. Two methods are usually available for an engineer or a researcher to address a floodplain hydraulic model: physical modelling and numerical modelling, which will be discussed in detail in the following. For many studies both physical and numerical modelling methods are used at the same time for verification and validation of the hydraulic design purposes.

3.2.1 Physical Models

A physical model is a scaled representation of a hydraulic flow on a river and floodplain, where the flow conditions and the flow fields are scaled in an appropriate manner. In other words, a physical model is usually a smaller size representation of the prototype. The application of physical models in hydraulic design is still common nowadays, primarily with increased sophistication and precision in measuring techniques and instrumentations, although numerical models are increasingly replacing physical models. Physical modelling in the earliest days was largely confined to flume studies at hydraulic laboratories. Thus, the physical modelling studies performed in earliest studies were not directly applicable to floodplain modelling, where as specified earliest the compound channel required herein.

Today, physical modelling is mostly performed at large hydraulic laboratories and is not often applied when the numerical or mathematical models will suffice, where certain hydraulic phenomena in nature are too complex to be described by rigorous and sophisticated mathematical techniques and formula. Normally, numerical models are the most convenient method to represent the behaviour of a physical system. However, numerical models sometime may not work well when the situation becomes complex. For example, one of the projects in current study of the impact of vehicles on floodwater flows is not a single issue and easy to solve, which includes many complex of hydraulics theories and phenomena. Therefore, the use of suitable physical scale models becomes an effective method to assist the current research study on investigating the hydrodynamics of flow patterns and movements around the vehicles.

On the other hand, physical hydraulic models are used during the design stages to optimise and to ensure a safe operation of the structure. They are normally carried out to increase or lend confidence in design. Furthermore, they are also used to diagnose and solve problems with existing hydraulic structures and equipment along floodplains. The physical model study in floodplain management includes: storage basins and conveyance channels; interactions with bridge piers, built infrastructure, and natural vegetation; and transport of sediments, to mention but a few. Most of these interactions have been widely researched and their findings are generally well known. Such physical models are generally expensive to construct and operate, require special engineering expertise, and are typically only practical for some river systems and floodplains. Model studies are undertaken in laboratories under controlled conditions.

For floodplain physical models in which the motion of the bed is unimportant, then can normally be classified into two types: undistorted and distorted models. For an undistorted model, the geometry of the model is similar to the prototype, which means that the vertical and horizontal scale dimensions of the model are the same. An undistorted model is recommended if the study involves the reproduction of wave patterns or water surface profiles (French, 1994). The use of an undistorted model is straightforward and presents the modeller with a minimum of design and analytical problem.

A distorted model is a physical model in which the geometric scale is different between each main direction (Chanson, 1999). A distorted model is usually used to reproduce channel capacity and storage capacity (French, 1994). With a distorted model, it is possible to save space and cost of operation, improve the dynamic similarity with larger Reynolds number, and increase the accuracy of flow measurements where the vertical scale and turbulence in the model are larger, to mention but a few of its advantages.

3.2.2 Numerical Models

Numerical modelling is one of the deterministic procedures used for floodplain hydraulic modelling. In the past, the procedures were first handled with hand calculations and then transferred to computer programmes that have been consistently improved and expanded, and made progressively more user friendly. Today many programmes are available for modelling a variety of floodplain problems using computer methods. The increased availability of these computer programmes for floodplain modelling has allowed detailed analyses for application with a wide range of structures, including bridges, culverts, road embankments, dams, levees, channels, diversions, etc.

Due to the increasing use of computational methods in numerical models, along with the rapid development of information technology and the provision of powerful computers, a relatively new area of floodplain management tools has developed. Hydraulic modelling of hydrodynamic processes has become more widespread as numerical schemes have been improved, the costs of computer time and storage space have decreased, the grid spacing have refined, and methods to visualise the results have improved, etc. In modelling of floodplains, this increased computational power is used most efficiently if the requirements for reliable predictions are satisfied at the same time, i.e. if reliable input information on the water body of interest is available, and if the predictions can be tested rigorously against appropriate field data.

This field of modelling is encompasses many different facets of engineering management into typically one software tool, which can then be used as a predictive and integrated management tool for various engineering or environmental management schemes for floodplains. Computational hydrodynamic models are powerful tools in assessing the impact of flood hazards, in deciding the appropriate measures for management of floodplains, etc. Computational models usually offer the possibility to test numerically extreme scenarios that could never be tested physically. Here lies their enormous potential role in decision making. However, there are limits in the use of computational models. For example, the discretisation of the underlying model equations can yield inaccurate and unrealistic results. Modelling floodplains presents specific problems because of their complex hydrodynamic behaviour, which makes their simultaneous modelling more difficult.

In fact, the numerical modelling of fluid flow is based on the principles of conservation of mass and momentum within the body of fluid to be modelled. In many cases, the flow is defined by the Reynolds equations, which describe the three dimensional turbulent motion of the incompressible fluid. For flows which show little variation in the vertical direction, it is appropriate to integrate these equations over the depth of water, resulting in simplified or two dimensional equations of motion, which will be discussed in details in this chapter.

3.3 Hydrodynamic Modelling of Floodplains

Generally, when the flow in a river exceeds the bank full discharge, the river changes from inbank to overbank, or so called floodplains flow, and there is a significant increase in the complexity of this flow behaviour (Knight, 2006). There have been many studies on the hydrodynamic processes of this flow, with some being based on physical modelling (e.g. Zheleznyakov, 1965; Toebes and Sooky, 1967; Yen and Overton, 1973; Ghosh and Kar, 1975; Myers and Elsawy, 1975; Wormleaton et al., 1982; Knight and Demetriou, 1983; Myers, 1987; Knight and Shiono, 1990, 1996; Myers and Brennan, 1990; Shiono and Knight, 1991; Ervine et al., 1993; Sellin et al., 1993; Willetts and Hardwick, 1993; Sellin and Willetts, 1996; Willets and Rameshwaren, 1996; Wormleaton, 1996; Lai et al., 2000; Patra and Kar, 2000; Knight and Brown, 2001; Myers et al., 2001; and Valentine et al., 2001), some based on numerical modelling (e.g. Lewin and Hughes, 1980; Prinos and Townsend, 1984; Anderson and Bates, 1994; Rhodes and Knight, 1994, 1995; and Lai et al., 2008), and some theoretical investigations (e.g. Anderson et al., 1996; Marriott and Alexander, 1999; and Knight, 2006). Most of these studies have been focused on steady flows over relatively simple channel floodplain geometries, as well as with immobile boundaries, and without any consideration of hydraulic obstructions existing on the floodplains. Despite theses severe simplifications, they have elucidated some important features on floodplain flows, when the flow covers the floodplain, is steady and in the downstream direction (Bridge, 2003).

Most natural channels, except where engineered to confinement, are by their very nature of a two stage form. This is to say that most rivers have a floodplain, since it is a natural occurrence that a floodwater flow should overtop its normal flow channel in extreme events, to use the wider carrying and storage capacity of its existing floodplains. This is noted by Knight and Shiono in Anderson et al. (1996) that "rivers do generally burst their banks once the discharge and water level reach certain critical values. This commonly used idiomatic phrase... has undoubtedly served to reinforce a misunderstanding of basic fluvial processes... the floodplains are therefore an integral part of the whole river system...Inevitably there is also a significant increase in the complexity of the flow behaviour once overbank flow starts." Nalluri and Judy (1985), and Patra and Kar (2000) also noted this physical characteristic of natural channels, where almost all natural rivers exhibit a compound with a two stage geometry form, consisting of a deep main channel flanked by one or two shallow depth floodplains.

The two stage geometry is the predominant factor contributing to the hydrodynamic conditions prevalent in floodplains under flood conditions, where this geometry is necessary to take into consideration for model simulation. Due to different hydraulic conditions prevailing in rivers and floodplains, the mean velocity in the main channel and along the floodplain are generally significantly different. Just above the bank full stage, the flow in the main channel exerts a pulling or accelerating force on the flow over floodplains, which naturally generates a dragging force or retarding force on the flow through the main channel. This leads to the transfer of lateral momentum between the main channel and floodplain as well as produce strong lateral shear layers and consequently generating additional flow resistance and reducing channel conveyance (Knight and Shiono, 1996; and Sellin and Willetts, 1996).

At the junction region between the main channel and that of the floodplain, Sellin (1964), Knight and Demetriou (1983), Ikeda and Hasegawa (1994), Ikeda (1999), and Bousmar and Zech (2002) indicated the presence of artificial banks made of vortices, which acted as a medium for transfer of momentum between the main channel and floodplain (Patra and Kar, 2000). Shiono and Knight (1991) present the lateral mass and momentum transfer mechanisms of overbank flow for a compound channel as shown in Figure 3.2. Another aspect of turbulence for consideration in modelling, typically observed in such compound channels, is the intermittent upward flow motion of the normal Reynolds stresses originating from the complex nature of the channel cross section (Knight, 2006). This turbulence is often observed in the form of a series of helicoidally vortices rotating in the stream wise direction. These vortices are generally present in all turbulent flows in a straight conduit with a non-circular cross section, due to anisotropic turbulence (Einstein and Li, 1958; Naot and Rodi, 1982; Nezu and Nakagawa, 1993; and Perkins, 1979).

Overall, with all of these considerations, most of the floodplain models have been developed relatively simple structure and are easy to implement, while the solution of hydrodynamic equations presents a number of numerical difficulties. Nevertheless, it is not considered worthwhile giving too much consideration to all of these previous investigations as the theories and models behind simplification of compound or two stage channel flows have become more or less widely accepted for the analysis of over bank flows (e.g. Shiono and Knight, 1991; Naot et al. 1993; Bates et al. 1992, 1998, 2000; Nicholas and McLelland, 1999; and Ervine et al., 2000), and therefore only a brief introduction is given in this chapter. On the other hand, several other processes of interest in floodplains are still not well understood, with most of them requiring a considerable amount of input data and information if the results are to describe a real water body.

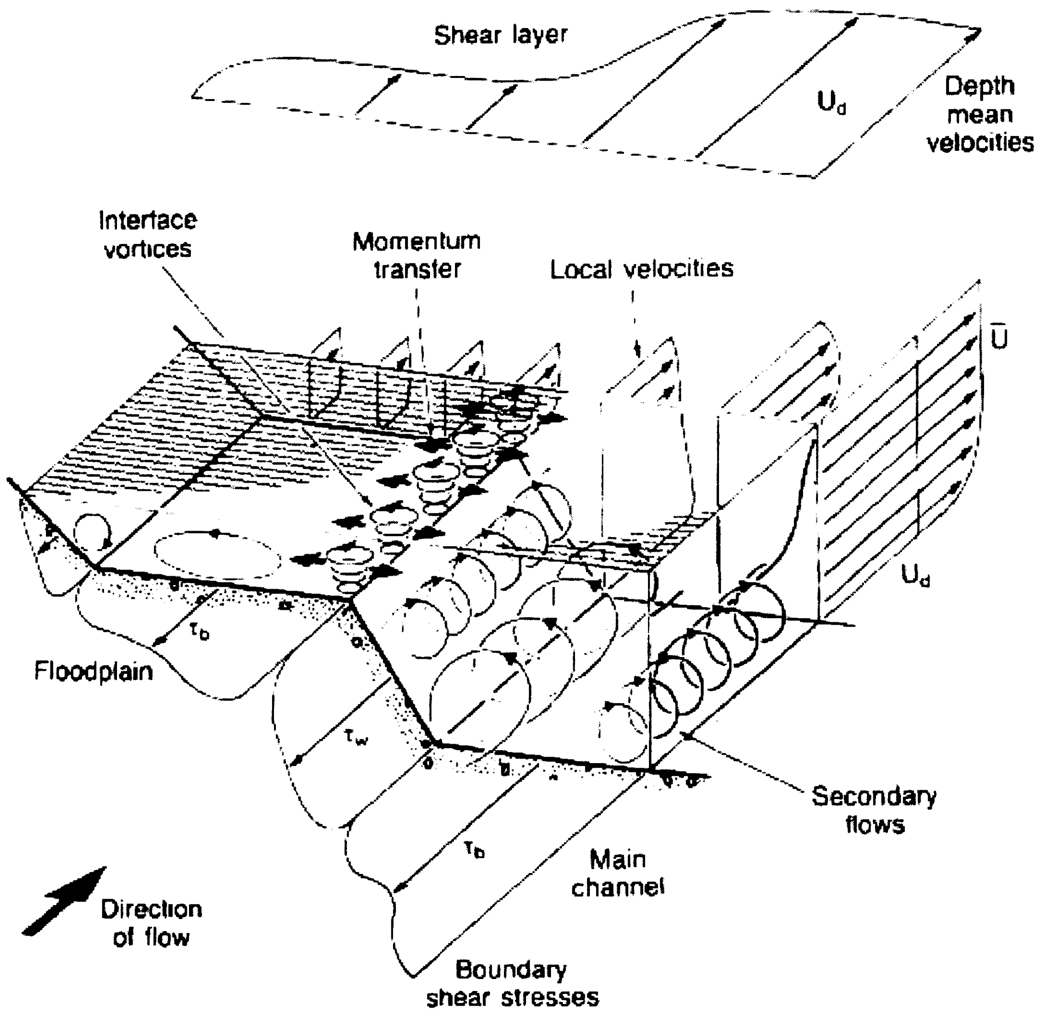


Figure 3.2 Mechanisms of overbank flow in a straight compound channel (Shiono and Knight, 1991).

The current study focuses on modelling the comprehensive hydrodynamic processes and interactions between the complex floodplains and a variety of hydraulic obstructions which result from an environment of natural and urban/rural development, as will be discussed in subsequent paragraphs. It is essential to develop an understanding of the hydrodynamics processes for floodwater flows involved in floodplains with obstructions so that effective and effective management tools may be developed for the real environment. In order to develop an effective tool for the analysis of floodwater flows along floodplains, the first stage of research obviously should be the development of an effective hydrodynamic model, either in physical or numerical form, which is the primary focus of this study. This floodplain model should therefore be capable of accurately representing the flow through the various types of hydraulic obstructions, which may be present in each floodplain being considered, as well as considering the shallow water depths, which typify these environments.

3.3.1 Hydrodynamic Modelling of Natural Floodplains

Before investigating the hydrodynamic modelling of natural floodplains it is necessary to determine what constitutes the floodplain area. Natural floodplains are generally typified by areas of shallow water flows and they are generally governed by bed shear as well as resistance due to drag imposed by vegetation. As mentioned earlier, most of the vegetation has contributed a lot to alter the overall physical characteristics of the natural floodplains and consequently generated hydraulic obstructions to the floodwater flows. For example, floodplains in estuaries are basically populated by a diverse range of species, with reed phragmites being quite typical for Britain (Purseglove 1989), cypress swamps in the United States, and mangrove swamps in subtropical and tropical climate countries.

Although the type of vegetation and the climate may vary, the basic hydrodynamics of floodplains are essentially similar, with shallow water flows and vegetation both providing drag, as well as blocking to the flow. The main differences are whether the vegetation penetrates the surface of the water and if it is subject to bending due to the force of the flow exerted upon it. There are of course other geometric differences, such as whether the vegetation is bushy or stem like, and the typical dimensions such as maximum diameter of the stem. Other considerations for modelling the hydrodynamic of natural floodplains include: whether the vegetation typically grows in dense well distributed populations, or whether the vegetation tends to be randomly distributed and mixed, or even if the vegetation stems are managed and therefore are of average geometrical properties and density.

Overall one of the key elements to be considered in hydraulic modelling of natural floodplain is the selection of hydraulic roughness involved. In the past, Chow (1959) adopted the empirical relationship between bed friction and depth of flow as in the Manning equation, and then simply adapted the friction coefficient to encompass an empirical value for the vegetative roughness, which may vary from 0.03 for short grass to 0.1 for dense trees. Eventually, this roughness can vary significantly in different parts of the system, even within the channel or floodplain (Robert et al., 1992). In fact, this method is having some limitations for the applications in shallow water flows for floodplains and apparently it is subjective to practical experience, and therefore less useful for inclusion in numerical models. However, this method may be appropriate for the general engineering stage of design and analysis.

In the present study, the topic of analysing and modelling the flow through vegetation has been the subject of much research, to varying degrees of details (such as investigations by Wolanski et al., 1980; Sengupta et al., 1986; Kadlec, 1990; Ridd et al., 1990; Nepf, 1999; Choi, 1999; Wu et al., 2001; Struve and Falconer, 2001; Struve et al., 2003; Wilson, 2007; etc.). Most of the research undertaken to date for the finer analysis of vegetative effects has used the assumption that vegetation is well represented as a simple cylindrical obstruction (Li and Shen, 1973; Petryk et al., 1975; Pasche and Rouve, 1985; and Kadlec, 1990).

Besides this assumption, in most types of this research study, the common theme has always been that the important term which required defining was the drag factor attributable to the presence of vegetation. The drag force caused by vegetation is considered as a key hydraulic parameter in determining flow resistance for natural floodplains. In numerical modelling, many researchers have utilised the mathematical equation, with an additional drag force term, so that the resistance due to emergent vegetation could be modelled and accordingly a drag coefficient is required hereafter. This drag coefficient relates to the shape of the boundary layer around the vegetation elements, which are subject to changes in the diameter and geometry of the individual vegetation form.

Petryk et al. (1975) considered the influence of the drag force introduced by vegetation on the flow structure, with the drag force effect through the vegetation being incorporated into the Manning coefficient; and vegetation resistance being proportional to the projected surface of the vegetation in the flow direction. Some research studies have focused on modelling the effects of vegetation on flow mechanisms and resistance in more detail, for examples depth dependent vegetation effects (Fathi-Mahagdahan et al., 1997; Kutija et al., 1996); and the spatial distribution and hydraulic interactions between the vegetation elements (Naot et al., 1997). On the other hand, Furukawa et al. (1997) addressed that vegetation was responsible for enhancing friction, with much of this enhancement being due to the vegetation presenting obstacles to the flows. These obstacles generated complex two-dimensional currents, with jets, eddies and stagnation regions, as well as vegetation scale turbulence.

In modelling vegetation as a cylinder, with the consideration of a drag force, Nepf (1999) introduced a dimensionless population density ($AD = D^2/S^2$), where A is the projected area per unit volume; D is the cylinder diameter; and S is the mean spacing between cylinders. The study suggested that the drag coefficient for a single cylinder in a two-dimensional flow is about 1.0 at the Reynolds number of 1000. For a group of cylinders, the drag coefficient for different cylinders could be different due to the wake characteristics, and probably decreases as the vegetation population density increases. For cylinder Reynolds numbers between of 4000 to 10000, Nepf (1999) showed that the drag coefficient decreased roughly from 1.2 to 0.6 as the population density increased from 0.008 to 0.07 respectively. Based on this study, the drag force was mainly found to be dependent upon the cylinder geometry, cylinder displacement, cylinder density and flow conditions. The turbulence intensities increased as the population density decreased, but decreased as the population density increased (Nepf, 1999).

As previously mentioned the majority of subsequent research undertaken has used the assumption that vegetation is well represented by a cylinder. Accordingly, most of the research has been in the development of algorithms for analysis of the finite effects of single and multi wakes of cylinders for simplification. Figure 3.3 shows the pattern of flow around a bluff shape (i.e. a cylinder) and presenting the low pressure zone at the rear body draws in fluid from further out in the boundary layer, where the pressure is higher, consequently forming the wake zone, as well as powerful eddies which are generated and carried downstream. However, it should be noted that in making this cylindrical assumption for ideal vegetation, certain governing factors of the hydrodynamics of the real environment have been neglected.

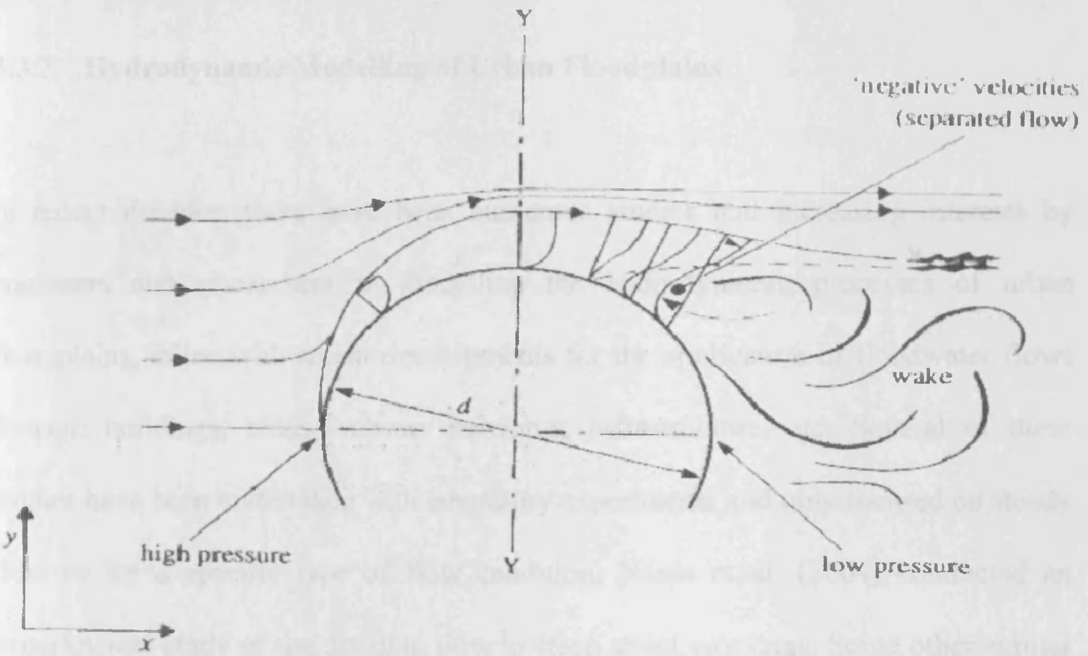


Figure 3.3 Flow around a bluff shape (Chadwick et al., 2004)

In taking account of all the assumptions and considerations herein, and in extending the previous research work undertaken by Struve (2000), Westwater (2001), and Wu et al. (2001), for the purpose of this study, an existing two-dimensional numerical model has been refined to investigate further the hydrodynamic processes of natural floodplains, with the focus on mangroves as the main hydraulic obstructions to floodwater flows. It was the refinement of an existing hydrodynamic model, with which this research study was primarily concerned, and this model has been calibrated and validated with the data from the laboratory experimental work, previously carried out by Westwater (2001) on a model floodplain with the main channel running through the centre. Detailed investigations into modelling the hydrodynamics of natural floodplains with mangroves will be carried out in the next chapter. The study will also focus on investigating the consequential impact of mangroves on the dissipation of extreme flood events, and in particular on tsunamis.

3.3.2 Hydrodynamic Modelling of Urban Floodplains

In recent decades, there have been numerous studies and increasing interests by engineers and researchers in modelling the hydrodynamic processes of urban floodplains, inline with recent developments for the application of floodwater flows through buildings, roads, subway networks, infrastructure, etc. Several of these studies have been undertaken with laboratory experiments and only focused on steady flow or for a specific type of flow condition. Nanía et al. (2004) conducted an experimental study of the dividing flow in steep street crossings. Some other similar studies, to mention but a few, were investigated by Shabayek et al. (2002), Soares-Frazão and Zech (2002), and Rivière and Perkins (2004). Ishigaki et al. (2003) studied flood propagation, both through streets and subway networks for an urban area. Soares-Frazão and Zech (2007) presented an experimental study of dam break flow against an isolated structure. Most of these physical models were typically distorted scales, since generally due to the large scale project, for example, it would prove impossible to maintain the same scale in the horizontal and vertical planes. These models obviously were very limited by the fact that construction of the model would require an extensive time period, and then only limited variations in the boundary conditions would be possible.

On the other hand, due to the increasing use of computational methods in numerical models, along with the rapid development of information technology and the provision of powerful computers, which have greatly shortened the computational time required to process data, an increasing number of the researchers have modelled urban floodplains using numerical approaches for certain applications. As a result, this progress has allowed more routine detailed modelling and analysing of hydrodynamic processes and interactions with a wide range of hydraulic obstructions. Mark et al. (2004) outlined a modelling approach and principle for analyses of urban flooding using a one dimensional hydrodynamic model. Liang et al. (2007) modelled supercritical flow past buildings in urban floodplains, Boonya-Aroonnet et al. (2002), Mark et al. (2001), Ishikawa et al. (2002), Kolsky et al. (1999), Holder et al. (2002), and Schmitt et al. (2002) have all further studied the modelling of urban floodplain with different applications for a variety of hydraulic obstructions (i.e. bridges, buildings, infrastructure, etc.).

To the knowledge of the author not much previous work has been reported in modelling floodwater flows over urban floodplains with consideration being given to vehicles as hydraulic obstructions. Thus, further investigations into this relevant topic will be discussed in much greater detail in subsequent chapters, and forming a key part of this study. Detailed investigations have been mainly aimed at creating an appropriate design method which will give guidance to engineers and researchers on the selection of a limited choice of variables to arrive at a design event and be more confident with the estimation for modelling the hydrodynamic of urban floodplains, in particular for vehicles as obstructions to floodwater flows.

In order to develop an effective hydrodynamic model for the analysis of flows over urban floodplains with vehicles, the first stage of research obviously should be the development of an effective physical model using laboratory experiments. Such experiments should therefore be capable of accurately representing the flow through the various types of vehicles, which may be present in each floodplain being considered, as well as considering the shallow depths, which typify these environments. Also, as these experiments were aimed at providing valuable data for calibration and validation of numerical models in the future.

3.4 Governing Equations of Hydrodynamic Processes

Numerical modelling of fluid flow is based on solving the principle laws of conservation mass and momentum within the body of fluid to be studied. In most cases, the flow is defined by the Reynolds averaged Navier-Stokes equations, which describe the three dimensional turbulent motion of an incompressible fluid. For flows which show little variation in the vertical direction, these equations can be integrated over the depth of water (= $\eta + h$, see notation given in Figure 3.4), resulting in a simplified set of two-dimensional depth averaged equations of motion. The governing hydrodynamic model used in this study is further refined based on an existing model, which was originally developed by Falconer (1986). This refined model is based on a Cartesian co-ordinate system, which solves the following depth integrated two-dimensional mass and momentum conservation equations (Falconer et al., 2001).

The depth integrated conservation equation of mass can be written as:

$$\frac{\partial \eta}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=q_m \tag{3.1}$$

and for a constant density turbulent flow on a rotating earth, the conservation of momentum equations for flow in the x and y horizontal co-ordinate directions to give:

$$\underbrace{\frac{\partial q_x}{\partial t}}_{1}+\underbrace{\frac{\partial(\beta q_x^2/H)}{\partial x}+\frac{\partial(\beta q_x q_y/H)}{\partial y}}_{2}=\underbrace{fq_y}_{3}\underbrace{-gH\frac{\partial \eta}{\partial x}}_{4}+\underbrace{\frac{\rho_a}{\rho}C_w W_x\sqrt{W_x^2+W_y^2}}_{5}$$
$$\underbrace{-\frac{gq_x\sqrt{q_x{}^2+q_y{}^2}}{H^2C^2}}_{6}+\underbrace{\varepsilon\left[2\frac{\partial^2 q_x}{\partial x^2}+\frac{\partial^2 q_x}{\partial y^2}+\frac{\partial^2 q_y}{\partial x\partial y}\right]}_{7}\underbrace{-F_x}_{8} \tag{3.2}$$

$$\underbrace{\frac{\partial q_y}{\partial t}}_{1}+\underbrace{\frac{\partial(\beta q_x q_y/H)}{\partial x}+\frac{\partial(\beta q_y^2/H)}{\partial y}}_{2}=\underbrace{-fq_x}_{3}\underbrace{-gH\frac{\partial \eta}{\partial x}}_{4}+\underbrace{\frac{\rho_a}{\rho}C_w W_y\sqrt{W_x^2+W_y^2}}_{5}$$
$$\underbrace{-\frac{gq_y\sqrt{q_x{}^2+q_y{}^2}}{H^2C^2}}_{6}+\underbrace{\varepsilon\left[\frac{\partial^2 q_y}{\partial x^2}+2\frac{\partial^2 q_y}{\partial y^2}+\frac{\partial^2 q_x}{\partial x\partial y}\right]}_{7}\underbrace{-F_y}_{8} \tag{3.3}$$

where,

x,y	co-ordinates (m)
$q_x(=UH)$, $q_y(=VH)$	discharges per unit width in the x and y directions respectively ($m^3/s/m$);
q_m	source discharge per unit horizontal area ($m^3/s/m^2$);

U, V	depth average velocity components in the x and y directions respectively (m/s);
β	momentum correction factor for a non-uniform vertical velocity profile;
f	Coriolis parameter due to the Earth's rotation ($=2\omega\ Sin\phi$, with ω is the angular rotation speed of the Earth and ϕ is the geographical angle of latitude; $\omega = 2\pi$ / (24x3600) = 7.27 x 10^{-5} radians/s, see Kundu, 1990 and Martin and McCutheon, 1999);
g	gravitational acceleration (= 9.806 m/s^2);
H	total water depth = $\eta + h$;
η	water surface elevation above (or below) datum, see notation given in Figure 3.4 for co-ordinate system;
h	water depth below datum, see Figure 3.4;
ρ_a	density of air ($\cong$ 1.292 kg/m^3);
ρ	density of fluid (kg/m^3);
C	Chezy roughness coefficient (m$^{1/2}$/s);
C_w	air/fluid resistance coefficient (assumed to be 2.6 x 10^{-3} by Falconer, 1991)
W_x,W_y	wind velocity components in the x and y directions respectively (m/s)
ε	depth averaged turbulent eddy viscosity (m^2/s)
F_x, F_y	drag force components induced by hydraulic obstructions (i.e. vegetation, infrastructure, vehicles, etc.) per unit area in the x and y directions respectively

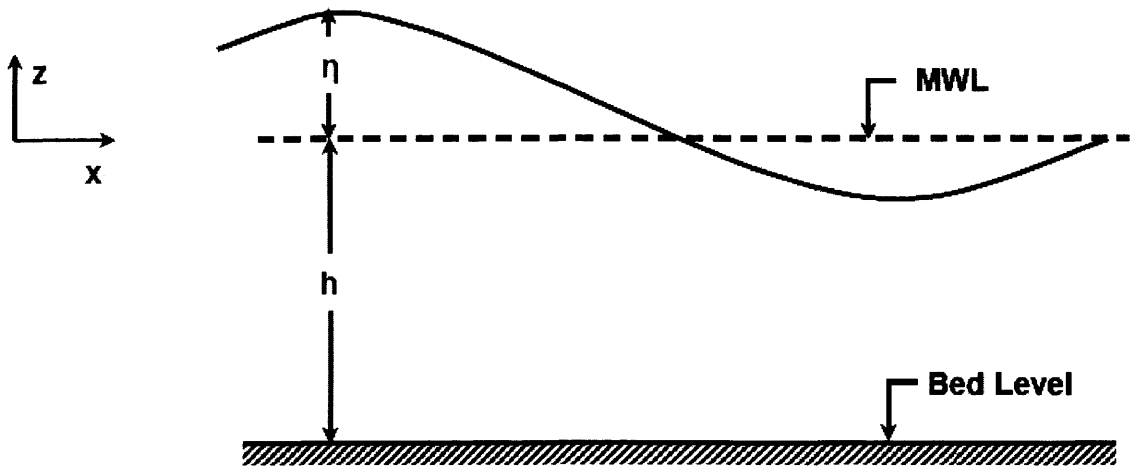


Figure 3.4 Co-ordinate system for depth integrated equations (Falconer et al. 2001)

Further details of the derivation of the continuity and momentum equations can be found in Kundu (1990), Falconer (1993), and Versteeg and Malalasekara (1995). The hydrodynamic module of the current model is based on the solution of the depth integrated Navier-Stokes equations and includes the effects of various terms as shown in Equation 3.2 for the: (1) local acceleration, (2) advective acceleration, (3) Coriolis force, (4) pressure gradient, (5) wind shear force, (6) bed shear resistance, (7) turbulence induced shear force, and (8) hydraulic obstruction resistance.

3.4.1 Local Acceleration

Term 1 in Equation 3.2 denotes the change of momentum or acceleration of the flood with time.

3.4.2 Advective Acceleration

Term 2 in Equation 3.2 describe the change of momentum or acceleration of the flood in the direction of flow. The non-cross term $U\partial U/\partial x$ contains information on the velocity gradient in the same direction as the flow, while the cross product term $V\partial U/\partial x$ contains information on the velocity gradient in the other co-ordinate direction. These terms are important to describe the flow field in curved channels, around objects, etc. and in generating vortices. They are the more important for the larger the Reynolds numbers of the flow, and are linked to the turbulence through time averaging. Due to their non-linearity, they may cause computational instability and may be neglected under low Reynolds conditions for the sake of stability.

For an assumed logarithmic vertical velocity profile, the momentum correction factors may be calculated from:

$$\beta = 1 + \frac{g}{C^2 \kappa^2} \tag{3.4}$$

where κ is the von Karman's constant which is 0.4. The value of β equates to 1.0 for a uniform velocity distribution, 1.016 for a seventh power law velocity distribution and 1.20 for assumed quadratic velocity profile (Falconer and Chen, 1991).

3.4.3 Coriolis Force

Term 3 in Equation 3.2 describes the effect of the earth's rotation on the flow. It is dependent on the latitude and the flow velocity and the effective force acts at right angles to the flow. It deflects the currents in a channel and can indirectly influence river alignment and sediment transport. On the coast it affects tidal currents and amplitude, causing the flow to rotate around points of zero amplitude. In estuaries, the Coriolis influence is generally small compared with other effects, unless the modelling domain is very large.

3.4.4 Pressure Gradient

Term 4 in Equation 3.2 represents the action of gravity and takes into account both the topography and the water elevation. The pressure gradient term contains both the mean depth and water elevation, and the derivative of the water elevation, making the term non-linear. In the case of computational instability, the mean depth may be approximated by the mean depth and the water elevation. This term usually represents the driving force of the flow.

3.4.5 Wind Shear Force

Term 5 in Equation 3.2 describes the wind which exerts a drag force as it blows over the water surface. The shear stress at the air-water interface is calculated by assuming that it is proportional to the square of the wind speed at a particular height above the water surface. Various empirical formulae have been proposed to calculate an air-water resistance coefficient, similar to the drag coefficient in turbulent flow field. For the surface shear stress due to wind action, resolving forces horizontally for steady uniform flow gives for the x-direction:

$$\frac{\tau_{xw}}{\rho} = \frac{\rho_a}{\rho} C_w W_x \sqrt{W_x^2 + W_y^2} \tag{3.5}$$

where τ_{xw} is the wind shear stress for the x-direction, C_w is the air-water resistance coefficient and, W_x and W_y are the wind velocity components in the x and y directions respectively.

In water bodies with strong currents such as estuaries and rivers, the wind stress is often relatively small compared to the bottom shear stress. In contrast, wind generally plays a predominant role in the open sea and in lakes (Falconer et al., 2001). However, for flood studies, wind effects are generally relatively small.

3.4.6 Bed Shear Resistance

Term 6 in Equation 3.2 is the bed shear stress which is usually represented in the form of a quadratic friction law, based on a relationship derived for steady uniform open channel (Henderson, 1966). Therefore, the bed shear stress in the x-direction, τ_{xb} can be written as:

$$\frac{\tau_{xb}}{\rho} = \frac{g q_x \sqrt{q_x^2 + q_y^2}}{H^2 C^2} \tag{3.6}$$

The bottom friction has a non-linear, retarding effect on the flow and requires an empirical coefficient. The Chezy coefficient is a semi-empirical bottom friction coefficient, which was originally developed to describe uniform flow in open channels. Under a rough turbulent flow condition and a logarithmic velocity profile, the Chezy bottom friction coefficient is assumed to be independent of the Reynolds number and varies only with the relative roughness of the bed and can be defined as follows (Henderson, 1966):

$$C = \sqrt{\frac{8g}{f}} = -2\sqrt{8g}\log_{10}\left(\frac{k_s}{12.0H}\right) \tag{3.7}$$

where k_s is the Nikuradse equivalent sand grain roughness and f is the Darcy-Weisbach resistance coefficient.

Under transitional flow conditions, i.e. the Chezy coefficient varies with the Reynolds number. The corresponding Chezy coefficient can be obtained by using a slightly modified Colebrook-White equation of the form:

$$C = -2\sqrt{8g}\log_{10}\left(\frac{k_s}{12.0H} + \frac{2.5}{\sqrt{8g}\,\mathrm{Re}}C\right) \tag{3.8}$$

where Re is the Reynolds number.

The advantage of using the Colebrook-White equation to calculate C is that the value of roughness coefficient k_S can be more closely related to bed features, such as ripples or dunes, and the representation of the Chezy value can include transitional turbulent flow. This refinement can be particularly important when modelling the flooding and drying processes of tidal floodplains, where Reynolds number effects may not be insignificant (Falconer, 1991).

3.4.7 Turbulence Shear Force

Term 7 in Equation 3.2 refers to the flow resistance associated with the random fluctuation of the flood with regard to space and time. The momentum exchange brought about by turbulence causes the vertical velocity distribution to be more uniform through most of the depth than under laminar conditions. The lateral shear stress is often represented by the Boussinesq eddy viscosity, and a zero-equation turbulence model. The turbulence model in this study applies Boussinesq's approximation for the mean shear stress τ_e in turbulent flow to give:

$$\tau_e = \varepsilon \frac{dV}{dy} \tag{3.9}$$

where τ_e is the turbulent shear stress, and ε is the depth average eddy viscosity, which is dependent on the turbulence characteristics of the flow and may be several times larger than the molecular viscosity (Falconer et al., 2001). If the turbulent shear stress is dominated by bottom friction, a relationship between the Chezy coefficient and the eddy viscosity exists. The depth integrated eddy viscosity can be derived from a logarithmic velocity profile (Fischer, 1979) to give:

$$\varepsilon = C_e \frac{H}{C} \sqrt{g\left(U^2 + V^2\right)} \tag{3.10}$$

where C_e is eddy viscosity constant, with Fischer's (1979) suggestion of the value of $C_e \approx 0.15$ based on laboratory data. Values of C_e are frequently found to be much larger for actual values, and the value of C_e = 1.0 was used in the current study based on general model condition that recommended by Falconer et al. (2001).

The turbulence model gives an indication of the impact of bed generated turbulent momentum exchange on the overall time averaged flow profile. This approach assumes that the turbulent shear stress is dominated by turbulence near the bottom and that it is equal in x- and y-directions (Falconer et al., 2001). It cannot describe the turbulent fluctuation of the velocity, or specific flow features such as turbulent wakes behind objects. Its effect is to smooth velocity gradients and to enhance the stability of the numerical solution. It also contributes to the generation of vortices.

3.4.8 Hydraulic Obstruction Resistance

Term 8 in Equation 3.2 shows the hydraulic obstruction resistance which retards the flow in a similar way to the bottom roughness, but it is generally much larger locally than ordinary bottom friction. As highlighted previously, there are a variety of hydraulic obstructions in floodplains with a majority being natural vegetation and recently an increasing number of urban built structures. All of these hydraulic obstructions have created both drag force and blockage effect to the water flow along floodplains. For example, vegetation resistance is proportional to the projected surface area of the vegetation in the flow direction, according to Petryk et al. (1975).

In this case, the drag coefficient relates to the shape of the boundary layer around vegetation elements, and generally, a value for cylinders may be applied for consideration in hydrodynamic modelling. It is usually assumed that the vegetation is not submerged, i.e. its effects extend over the whole water column, that the vegetation is stiff, i.e. no change of its projected surface with the flow velocity and that the drag coefficient is independent of the flow conditions. Further investigations into this related topic of interests will be discussed in much greater detail in subsequent chapters, and forming a major part of this study.

3.5 Numerical Methods

The most widely used numerical method to solve the governing equations which are used to predict the hydrodynamic processes on floodplains is the finite difference method; other methods include the finite element and the finite volume methods. The finite difference approximation is the oldest method applied to obtain the numerical solution of the differential equations, and the first application was developed by Euler in 1768 (Hirsch, 1988). The finite difference method has been commonly applied to two and three dimensional hydrodynamic studies by many researchers, such as Falconer (1980, 1986), Stelling et al. (1986), Falconer and Owens (1987), Abbott and Basco (1989), Lin and Falconer (1995, 1997a, 1997b), Tannehill et al. (1997), Huang and Li (1997), Shu and Chew (1998), Zoppou and Roberts (2000), Liang et al. (2006a, 2006b, 2006c, 2007), to mention but a few.

3.5.1 Finite Difference Method

In this study, the finite difference method has been applied to solve the governing differential equations (see Equations 3.1-3.3), given previously for the hydrodynamic processes. Subsequently, a regular computational mesh has been set up, which consists of a series of grid cells and covers the modelling area. The partial differential equations are then replaced by finite difference equations on the computational mesh based upon the Taylor's series approximation. Solutions of the finite difference equations will introduce numerical errors, mainly due to computer round-off errors. In order to obtain correct computational predictions, it is necessary to analyse the numerical properties associated with the finite difference scheme representation, including: consistency, stability, convergence and accuracy.

Several important terms have been introduced which require definition and discussion including:

Consistency is defined as the substantiation that the finite difference representation of a partial differential equation is converges to the original equation and its difference representation vanishes as the mesh is reduced in size. The finite difference equation must be consistent with the partial differential equation so that both equations describe the same physical phenomena.

Stability is defined as the criterions which assess the behaviour errors from any source (e.g. round-off, truncation) with time. For a scheme to be stable it is necessary for the errors to decay with time. The finite difference scheme must be stable so that the cumulative effects of all the round-off errors of a computer at any stage of the computation are negligible, and that the computed solutions only differ insignificantly from the exact solutions of the finite difference equation.

Convergence is defined as where the solution of the finite difference equations approach the solution of the partial differential equations as the mesh is refined. The convergence condition relates the computed solution of the finite difference equation to the exact solution of the partial differential equation.

Accuracy is defined as the permissible magnitudes of the truncation error for a finite difference scheme. A good finite difference scheme should satisfy the first three conditions and maintain a high order of accuracy.

3.5.1.1 Discretisation of the Governing Equations

Discretisation is the process by which finite difference approximations are used to replace derivatives with an approximation at a discrete set of points (i.e. the mesh). This introduces an error, due to the truncation error arising from the finite difference approximation and any errors due to the treatment of the boundary conditions. In this study, the hydrodynamic governing equations involve only first and second order derivatives. The first and second order difference approximations of these derivatives can be found in Falconer et al. (2001). For different approximations of the first and second order derivatives, various finite difference schemes can be found in Tannehill et al. (1997) and Abbott and Basco (1989).

3.5.1.2 Alternating Direction Implicit

The particular type of finite difference scheme used in current two-dimensional generic model is based upon the Alternating Direction Implicit (ADI), technique which involves splitting each time step into two half time steps (see Figure 3.5). As a result, a two dimensional implicit scheme can be solved by considering only one dimension implicitly for each half time step, without the solution of a full two dimensional matrix. On the first half time step, the water elevation (η) and the velocity component U (or the unit width discharge, q_x) are solved implicitly in the x-direction, whilst the other variables are represented explicitly. Similarly, for the second half time step, the water elevation (η) and the velocity component V (or the unit width discharge, q_y) are solved for implicitly in the y-direction, with other variables being represented explicitly. With the boundary conditions included, the resulting finite difference equations for each half time step are solved using the method of Gauss elimination and back substitution (Gerald and Wheatly, 1992).

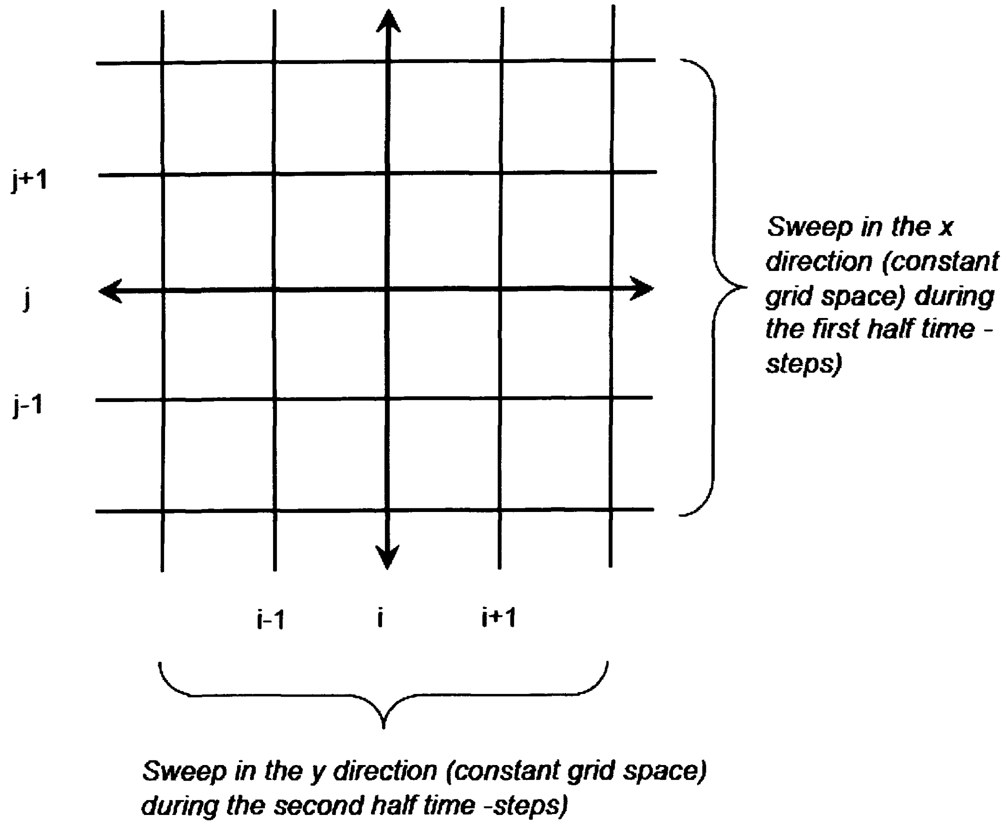


Figure 3.5 Implementation of ADI (Fletcher, 1991)

3.5.1.3 Staggered Grid System

In applying the finite difference method to solve the equations of mass and momentum for the current model, there are a number of advantages in not representing all of the variables: U (or q_x), V (or q_y), and η at the same grid points. The use of a space staggered system prevents the appearance of oscillatory solutions, which tends to arise for a collocated grid for space centred differences (Fletcher, 1991). In the space staggered grid system, which is used in this study, the variables of η are located at the grid centre and with the variables of U (or q_x) and V (or q_y) being at the centre of the grid sides (as shown in Figure 3.6). The depths are specified directly at the centre of the grid sides so that twice as much bathymetric detail can be included as compared to the traditional way and where the depths are written at the corners. This method allows the bed topography to be represented more accurately, particularly for non-linear bed variations and complicated bed elevations. Further details of the numerical methods used in current model can be found in Falconer (1986).

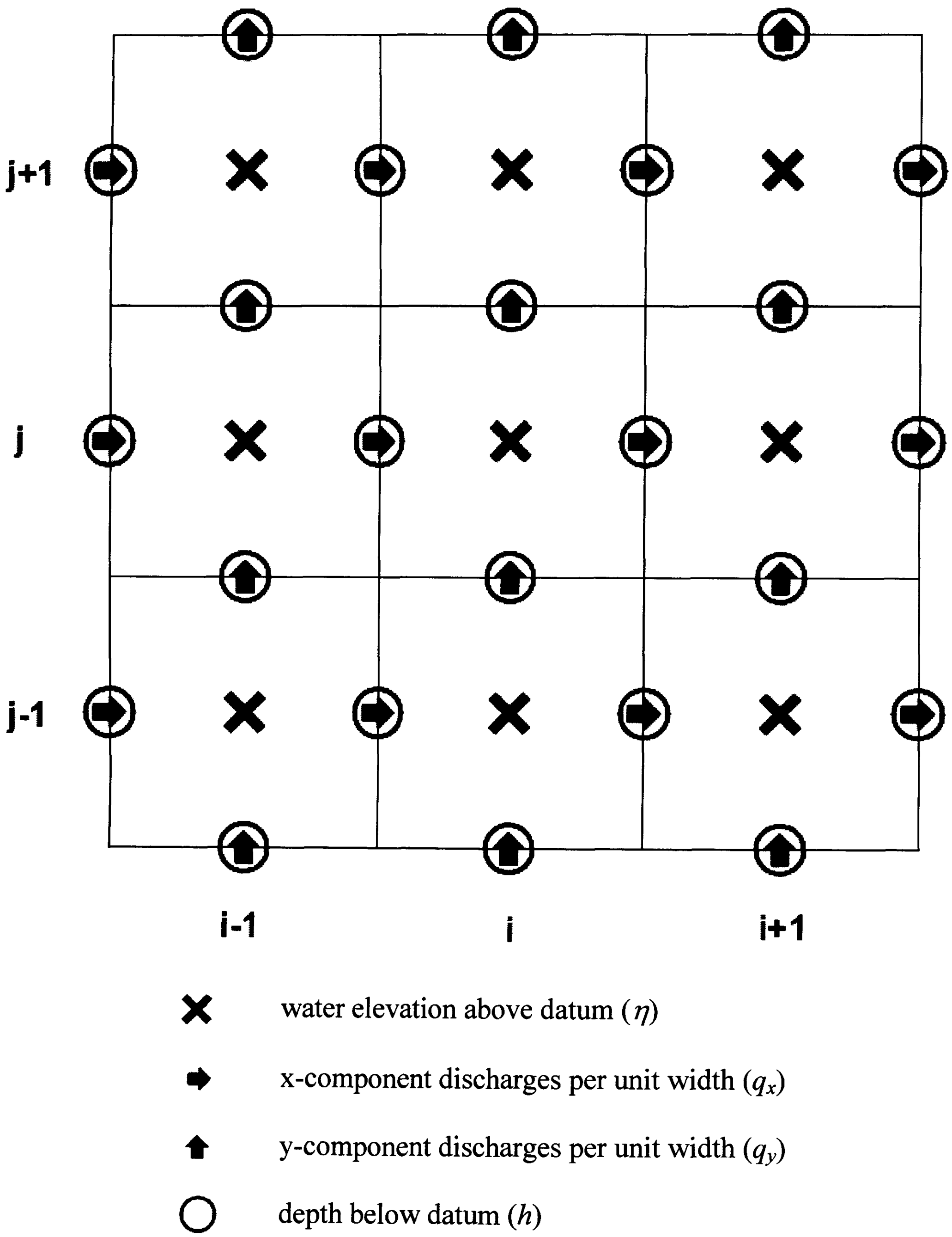


Figure 3.6 Computational space staggered grid system (Falconer et al. 2001)

3.6 Summary

This chapter has reviewed modelling the comprehensive hydrodynamic processes on floodplains, for both physical and numerical modelling applications, with the focus on natural and urban floodplains, as well as the consequential hydraulic response with a wide range of hydraulic obstructions. The literature highlights that the management of floodplains through the application of models can be used to assess flood hazards and their resources effectively and efficiently. In modelling the hydrodynamics on floodplains, the governing equations and numerical methods of the applied model in the current study have been reviewed briefly. Different terms and parameters of the mass and momentum equations have also been discussed and outlined. The governing finite difference equations are solved using the Alternating Direction Implicit method and formulated using a space staggered grid scheme.

CHAPTER 4

HYDRODYNAMICS OF NATURAL FLOODPLAINS WITH MANGROVES

4.1 Introduction

The hydrodynamic processes of natural floodplains with mangroves have been studied in this chapter. The study has been partially extended from previous research studies undertaken in particular by Struve (2000), Westwater (2001), and Wu et al. (2001) on modelling the hydrodynamic processes on floodplains with mangroves. An existing two-dimensional depth integrated numerical model (described in detail by Falconer, 1986 and Wu et al., 2001), which included both the effects of the drag force induced by mangroves and the blockage effect on the water flow through floodplains with mangroves, has been further refined. The model study has focused on investigating the influence of both the vegetation resistance and the reduction in the cross-sectional area of flow through floodplains with mangroves and their consequential impacts particularly on floods. Effort has also been placed into developing a graphic user interface for the output of the model simulations.

By considering the vital roles of mangroves and their impacts on the biggest catastrophic tsunami in 2004, this chapter has highlighted the complementarily of computer model studies. To investigate how mangroves affect the attenuation of the tsunami currents, a numerical model has been refined for an idealised natural floodplain, with mangroves distributed along the whole channel. This model has been used to simulate the water level variations and velocities induced by tsunami currents at three locations along the centre of the channel. For the purposes of modelling, a recorded data of tidal elevations during the last tsunami has been used to set up the open seaward boundary condition. Three cases of different diameters and densities of idealised mangrove vegetation and the case without mangroves, have been studied to examine the significance of the vegetation effects on the attenuation of tsunamis along the river and estuarine basin.

The similar model has been applied to simulate a real case of tsunami currents in an estuary, namely the Merbok estuary, Kedah sited along the North-West coast of the Peninsular Malaysia, where many fishing boats and houses were destroyed during the 2004 tsunami. Simulations have been undertaken for the swamp area and main river channel, for both conditions i.e. with and without mangrove trees, with the aim of studying the effect of the mangroves on the hydrodynamic processes during the tsunami and on a potential of tsunami propagating up the estuary. Comparisons of velocity profiles and water elevations for both cases have been undertaken, with model simulation providing that mangroves can help in reducing the effects of tsunamis in the main river channel and swamp areas.

Recognising the view that mangroves are an important part of a green belt that need to be critically preserved to provide protection from future flood disasters, the conservation of mangroves is now an endeavour which is wholeheartedly supported by all parties. As a result, the restoration and rehabilitation of mangroves is now being extensively promoted to enhance natural regeneration. In the presence of extreme flooding events, then this natural regeneration of mangroves becomes more complex at exposed sites, where no shelter is provided by other mature mangroves. Thus, to duplicate the natural environment of such shelters, a novel innovative solution for sustainable management of floodplains, referred to herein as the Artificial Mangrove Shelter (AMS), has been first introduced in this study.

The hydrodynamic effects of AMS have been simulated with the similar model. The study focuses on investigating the capability of AMS particularly with influence regard to the AMS on the tidal flow structure and the consequential impacts on tsunami currents. Simulations have been undertaken for various conditions, i.e. with different densities and diameters of AMS, as well as the condition without the AMS. Comparisons of velocity profiles and water elevations for all of these cases have also been undertaken to provide a good knowledge for the long term sustainable management of floodplains with mangroves.

4.2 Natural Floodplains with Mangroves

Mangroves are the primary focus of the study considered herein, and as such it is worth giving some consideration to their typical properties found in natural floodplains. Generally, natural floodplains with mangroves are found in low energy intertidal coastal areas of subtropical and tropical climates countries, such as Indonesia, Malaysia, South Africa, Thailand, Vietnam and Australasia. Figure 4.1 is a map showing the distribution of mangroves in Southeast Asia (sources from UNEP-WCMC, FAO and Wetlands International, 2006), which gives an indication of the location for the most important mangrove sites shown in green, and coral reefs shown in red.

These intertidal floodplains are typified by areas of shallow water flows, with relatively slow moving currents and as a result they are generally governed by bed shear as well as resistance due to drag imposed by the vegetation. They also regularly benefit from rich resources of water and nutrients that help to encourage the establishment of natural development, in particular mangroves through regular flood events. Mangroves in these floodplains have specially adapted stilt roots, known as pneumatophores and salt-excreting leaves, with their extent and shapes varying for the different species. Their root and leaf structures enable them to thrive along sheltered intertidal coasts and estuaries where rivers flow into sea.

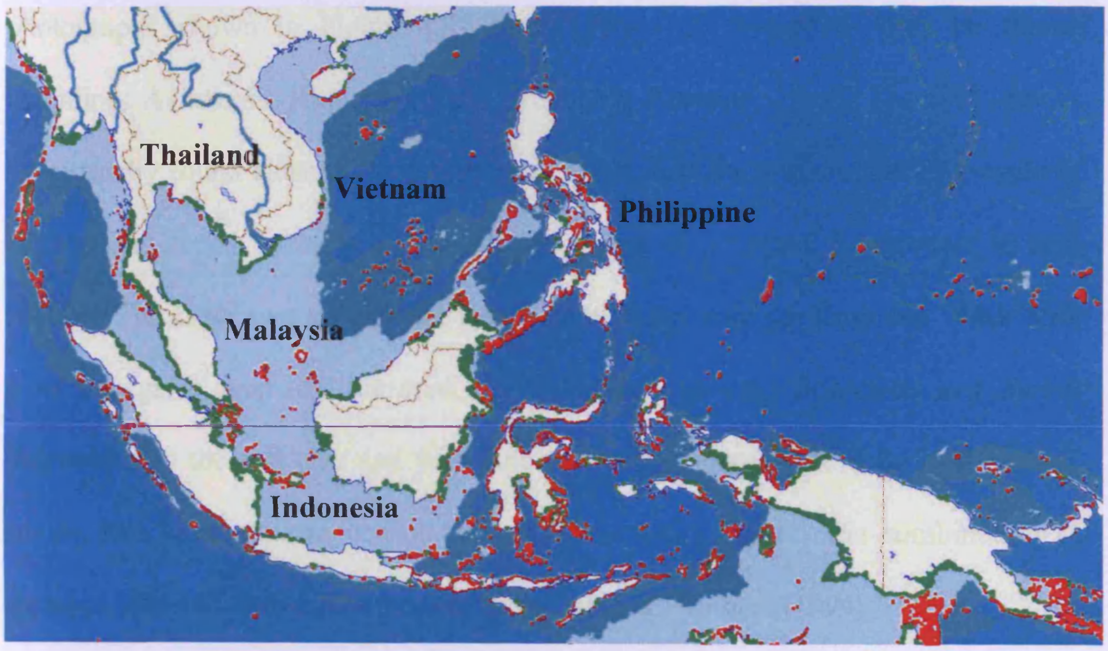


Figure 4.1 Map showing the distribution of mangroves in Southeast Asia (Sources from UNEP-WCMC, FAO and Wetlands International, 2006)

Mangroves typically occur between spring low and high tide, and have only few other plant species associated with them. They are usually located on sheltered coasts and soft substrate dominates. Red mangroves (Rhizophora species) are often a pioneer, growing where the area is more continually flooded, with seedlings and small trees sprouting even below water (Ong et al., 1991). These give way first to a full-grown Rhizophora species with prop roots and then, towards the high tide zone, taller black mangroves grow. Once established, the network of roots anchor the trees to the soft mud and trap more sediment, which contribute to soil formation and stabilises the coastline, in other words they provide the mitigation against erosion processes. Different species normally appear to be dominant in different tidal inundation zones (Jimenez et al., 1985). Figure 4.2 shows different species of mangrove vegetation in different zones of floodplains and the extent of the floods.

For example in the typical type of Malaysian mangrove swamps (as photographs shown in Figure 4.3), three species of mangroves may be found, including: Avicennia, Rhizophora and Bruguieria (Othman, 1994). The first species are typically found close to the foreshore of the floodplain, and are part of a cycle of erosion and replacement, which create the effect of a natural breakwater to stop erosion. The latter two species are responsible for holding the shoreline "with their roots that grow deep into the mud, the Rhizophora and the Bruguieria can anchor themselves in the soft clay and withstand the natural forces. The soils in this zone, having had more time to consolidate are also usually firmer...the combination of stronger soils and deeper root system retards erosion" Othman (1994).

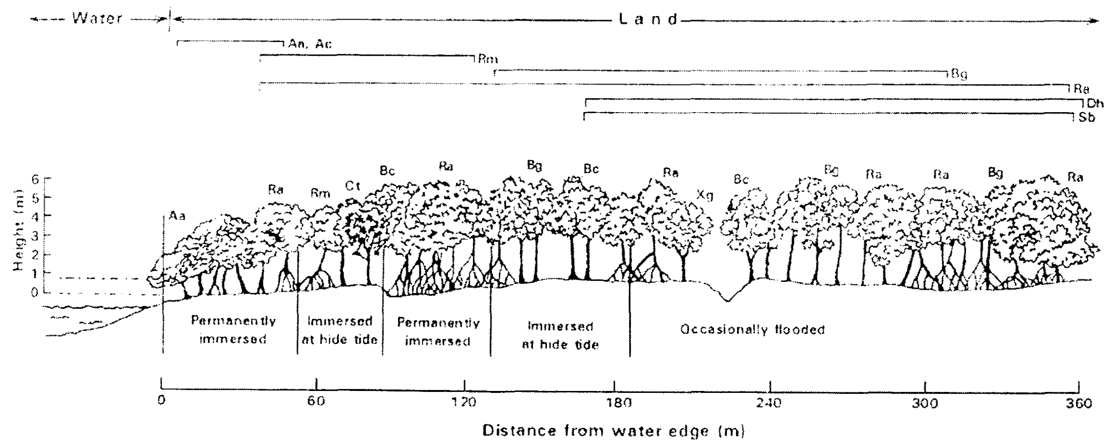


Figure 4.2 Example of mangrove zones (Source from White et al., 1989 after FAO and Wetlands International, 2006)

(a)

(b)

Figure 4.3 Typical Malaysian mangroves, found at (a) the Muar and (b) Klang estuary

Figures 4.3 (a) and (b) show how densely packed mangrove swamp can be, and how the complex root system may lead to attach and stabilise the soil; the plants themselves dissipate wave and current energy along the coastline; and the vegetation as a whole can trap sediments. Figure 4.3 (b) also shows the formation of the prop root system, which typically lie as shown, during low tide, at Klang estuary. As well as acting as a natural coastal protection and flood defence (Davies and Claridge, 1993; Othman, 1994), mangroves also act as a natural filter system for the runoff and enable ground water to retain and recycle nutrients and remove toxins, including excess amounts of nitrogen and phosphorous, petroleum products, and halogenated compounds, through a process called rhizofiltration. As a result, mangroves help to control water quality and are able to sequester carbon (Ong, 1993), where the upper layers of mangrove sediments have a high carbon content.

Mangroves are valuable ecosystems, which have important ecological functions to provide habitat for migratory water birds, and the provision of shelter and feeding grounds for juvenile fish and crustaceans, as well as provide food (Morin et al., 2000) for their adjacent communities with a plentiful supply of fish, crabs, and prawns. They facilitate to clarify adjacent open water, which helps photosynthesis in marine plants. Mangroves are also an important natural resource for human. Mangroves themselves provide wood for construction and the production of charcoal, which contributes significantly to productivity. Floodplains with mangroves are widely used for various types of aquaculture, such as the cultivation of mussels and mangrove oysters. Mangroves are important for supporting the fisheries industry which generates a high amount of revenue for the country. They are also important in terms of tourism, as they promote public awareness of the natural habitat (FAO and Wetlands International, 2006).

4.3 Floods and Natural Floodplains with Mangroves

Mangroves have always been regarded as a means of flood attenuation and they play an important role in the coastal areas as natural defences against natural flooding disasters in preventing or reducing damage to property and often even loss of life. Over the past decade or so, there has been a significant degree of research into various aspects of the potential use of mangrove swamps (Wolanski et al., 1980 and 2001; Wolanski and Ridd et al., 1990; Othman, 1994; Mazda et al., 1995, 1997, 2006, and 2007; Struve and Falconer, 2001, Wu et al., 2001). These studies of the effects of mangroves on flood flows are an important component of floodplain management. The benefits of mangroves are generally well known and have been documented widely in the literature (e.g. Chan and others in UNDP/UNESCO, 1987 and FAO, 1994). They are also described in the guidelines for mangrove forest management produced by Wetlands International (1996).

The protection afforded by these riverine, estuarine and coastal natural dense trees appears substantial, not only for storm-generated waves (Massel et al., 1999), winds (Wolanski et al., 2007), typhoons and tidal surges, but also for tsunamis (Environmental Justice Foundation, 2006; FAO and Wetlands International, 2006). As a wave passes through the mangroves, the mechanism of transmitting the wave energy is obstructed by their network of roots and trunks, as well as the leaf structures during extreme events. At low tide the water is confined to the main river channel but as the tide rises floodplains are inundated, and then the estuary overflows its banks and progressively floods the mangrove vegetation (Ong et al., 1991). The entire area of mangrove vegetation floods only during high spring tides or rare extreme events like tsunamis.

Recalling the outcome of the biggest catastrophic tsunami in recent times, which occurred on 26 December 2004, many countries surrounding the Bay of Bengal, including the Indian Ocean and East Africa, were severely affected. It was caused by a 9.0 Richter-scale earthquake, centred near the north-west coast of Sumatra, Indonesia (see Figure 4.4 for the epicentre and the affected countries). The countries most severely impacted by the tsunami were Indonesia, Sri Lanka, India, Thailand, Malaysia and Myanmar. The effect of this tsunami on world opinion has had the overall effect of raising the awareness of scientists and researchers, as well as the public, of the destructive power of tsunamis and that mangroves can provide a valuable resource for their ecological and geomorphic roles as tsunami buffers in reducing wave impacts.

Figure 4.4 Epicentre of tsunami on 26 December 2004 (Source from Reuters)

In Malaysia the impact of this tsunami was far less severe than in neighbouring countries. Most lives were lost in Pulau Pinang, and many fishing boats and houses were destroyed, particularly along the north-west coast of the Peninsular. Abdullah et al. (2005) reported the passage of this tsunami along the coastline and recorded the tidal elevations at Pulau Pinang. Figure 4.5 (a) shows the location map of this referred tidal recorder station and affected surrounding area. This recorded data set is kindly provided by the Department of Survey and Mapping Malaysia as illustrated in Figure 4.5 (b), which will be used as input for the model simulations.

The effect of the 2004 tsunami on Malaysia was to have an overall effect in raising awareness: with natural barriers such as mangrove swamps being regarded as very important in reducing tsunami induced wave impacts and inundation (Abdullah et al., 2005). This experience has also strengthened the perception of mangroves as a green belt that need to be critically preserved for coastal protection and the rehabilitation of mangrove swamps, complementing the implementation of the Prime Ministers' call.

The protection of mangroves is now an endeavour which is wholeheartedly supported to provide future protection from large tsunamis or even for any extreme flood event. Many countries including Malaysia have also experimented with the re-establishment of mangroves to help serve as a natural barrier to tropical storms and tsunamis. It was found that re-establishing mangrove habitats has a positive impact on the natural ecosystem, contributing to the restoration and rehabilitation of mangrove habitats.

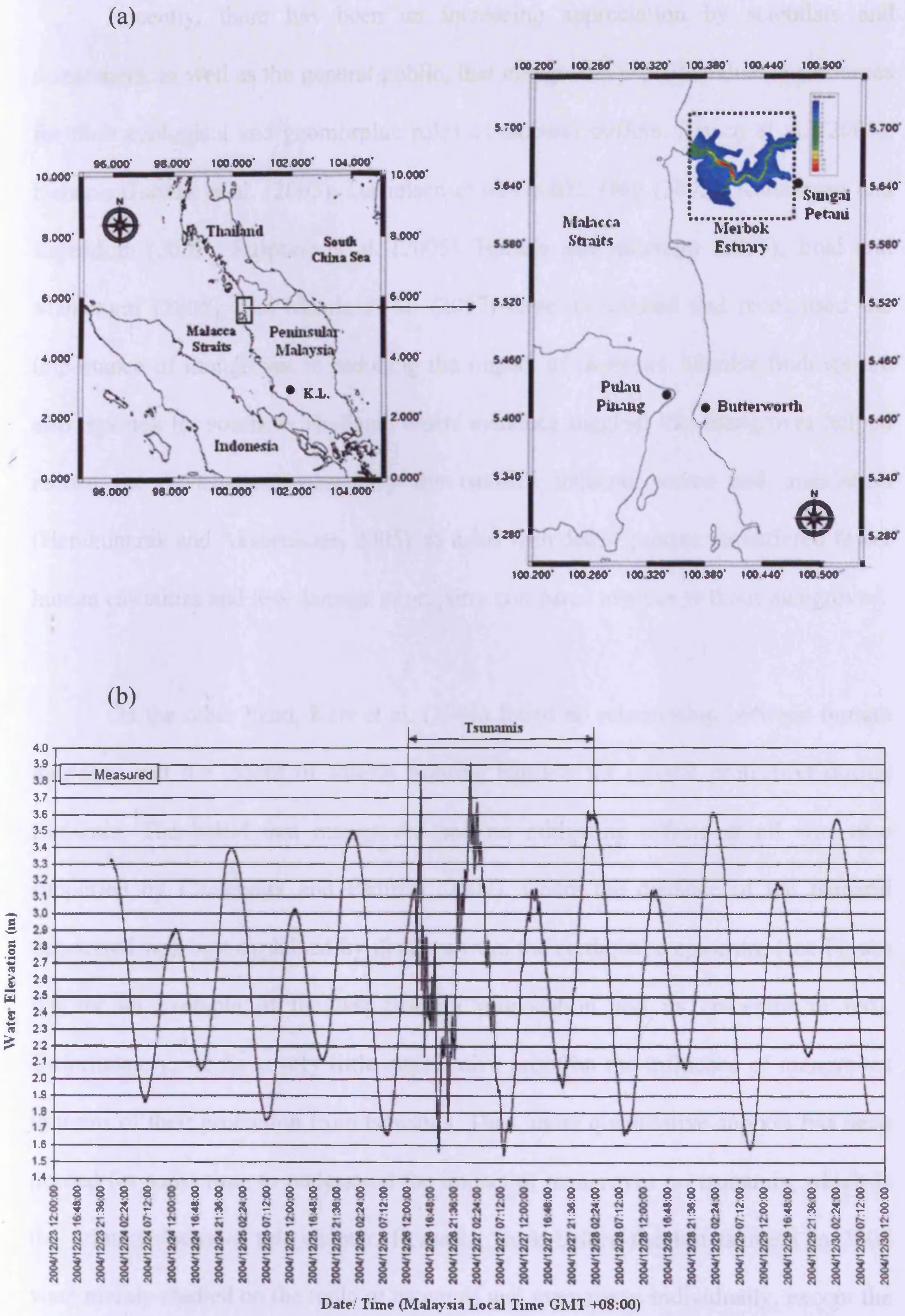


Figure 4.5 (a) Location Map of Pulau Pinang tide elevation recorder station (5 ° 25' N, 100 ° 21' E) and the Merbok estuary. (b) Recorded sea water elevations for Pulau Pinang showing the passage of the 26 December 2004 tsunami (Data sources from Department of Survey and Mapping Malaysia, modified after Abdullah et al., 2005).

Recently, there has been an increasing appreciation by scientists and researchers, as well as the general public, that mangroves provide valuable resources for their ecological and geomorphic roles as tsunami buffers. Blasco et al. (2005), Dahdou-Guebas et al. (2005), Danielsen et al. (2005), Ong (2005), Kathiresan and Rajendran (2005), Siripong et al. (2005), Harada and Imamura (2005), Imai and Matsutomi (2005), and Mazda et al. (2007) have all studied and recognised the importance of mangroves in reducing the impact of tsunamis. Similar findings are also reported for southern Thailand, where evidence suggests that mangroves helped reduce the devastation caused by the tsunami induced waves and inundation (Harakunarak and Aksornkoae, 2005), as areas with dense mangroves suffered fewer human casualties and less damage to property compared to areas without mangroves.

On the other hand, Kerr et al. (2006) found no relationship between human mortality and the extent of forests fronting hamlets for coastal protection during tsunamis. The belief that mangroves had no mitigating effects at all was also supported by Chatenoux and Peduzzi (2007), where the distance of the tsunami penetrated was best explained by distance from the earthquake epicentre (see Figure 4.6 for an example of the last tsunami propagation and its epicentre in red). Unfortunately, we have very little quantitative proof on the influence of mangroves in terms of their protection from tsunamis. Thus, more quantitative support has been needed for some time to understand the impact of mangroves on tsunamis, which is the primary focus of this chapter. Research work before the last tsunami in 2004 were mainly studied on the topic of tsunamis and mangroves individually, except the work of Hamzah et al. (1999) and Hiraishi and Harada (2003) who investigated with laboratory experiments on idealised tsunamis and the behaviour of the drag force by taking into consideration the vertical configuration of mangroves.

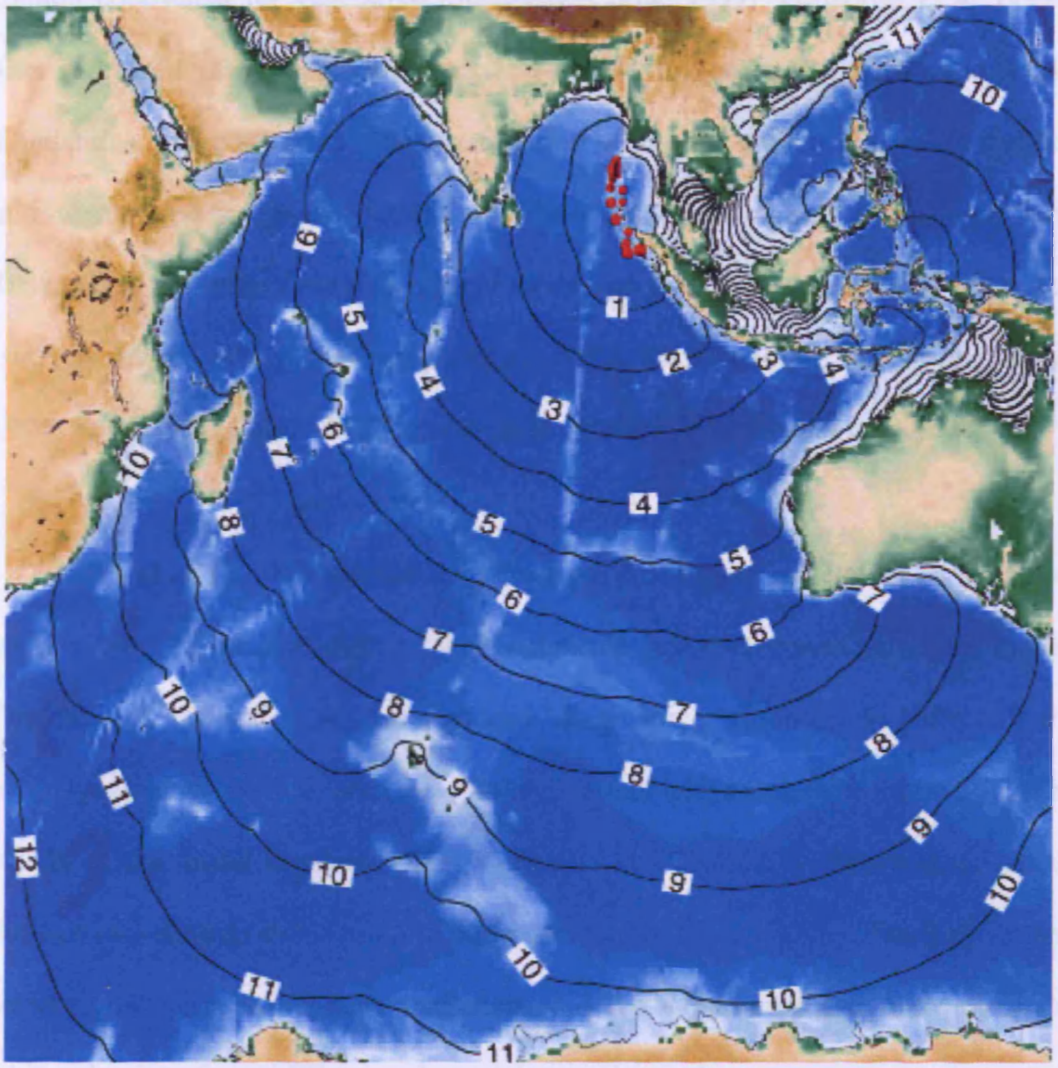


Figure 4.6 Propagation of tsunami and epicentre (Source from Kenji Satake, AIST)

4.4 Numerical Model and Governing Equations

Previous research has focused on modelling vegetation resistance by considering the spatial distribution and the hydraulic interaction between the vegetation elements (Naot et al., 1997), and the depth dependent vegetation effects (Wolanski and Bunt, 1980; Kutija et al., 1996; Fathi-Mahagdahan et al., 1997; Mazda et al., 1997), which widely used a modified Manning friction coefficient to represent the effects of the mangroves on the flow structure (Petryk et al., 1975) instead of simply adapting the friction coefficient for vegetative roughness (Chow, 1959). Furukawa et al. (1997) also addressed that mangroves were responsible for enhancing friction in model simulations. There has been significant interest with other varying degrees of detailed investigation being carried out towards the formulation of one dimensional, two-dimensional and even three dimensional models on flow processes through vegetation (such as investigations by Sengupta et al., 1986; Kadlec, 1990; Darby and Thorne, 1996; Nepf, 1999; Choi, 1999; Stoesser et al., 2003; to mention but a few).

Wu et al. (2001) modelled the influence of mangrove vegetation on the cross-sectional area of the flow with a two-dimensional depth integrated numerical model. The results showed that the induced drag force significantly affected the hydrodynamic processes, and the blockage effect played an important role. The effects of the model mangrove trees were also investigated by Struve et al. (2003) through experiments in a hydraulic flume and numerical modelling. Good agreement between the numerical model predictions and the experiment data were obtained. Although a lot of previous research work has made good progress over previous years, there are still a number of uncertainties of concern in term of modelling flow through mangroves, and which will be further discussed in this chapter.

In order to develop an accurate numerical model, there is an obvious need for a better understanding of the hydrodynamic flow processes through mangroves. In this study, it was decided that there was no need to consider a three-dimensional model since the problem was essentially reduced to two-dimensional through the hydrostatic pressure assumption. The two-dimensional shallow water equations describing flows in coastal and estuarine waters are generally based on the depth integrated three-dimensional Reynolds equations for incompressible and unsteady turbulent flows, and include the effects of the earth's rotation, bottom friction and wind shear. For flow in mangrove swamps, the dense trees have a significant impact on the velocity structure, and therefore an existing two-dimensional depth integrated numerical model (described in detail by Falconer, 1986 and Wu et al., 2001), has been refined, which includes both the effects of the drag force induced by mangrove trees and the blockage effect from mangrove swamps by introducing the porosity of the mangrove trees.

With the common theme that may be modelled as simple cylindrical obstructions, these cylinders may be regarded as being flexible or rigid. A mature mangrove will be subjected to little bending due to the flexural rigidity of the vegetation. The analysis will be focused upon a non-submerged rigid vegetative element and being simplistically modelled as a cylinder. It should be noted however, that in making this non-submerged rigid cylindrical assumption for ideal mangrove swamps certain governing factors of the hydrodynamics of real mangrove vegetation have been neglected. The cylindrical representation of a mangrove tree relies on the assumption that the submerged portion of the stem is of uniform diameter, and that the prop roots can be ignored (Struve, 2000). These are obviously quite significant assumptions, since a lot of the bottom resistance of the mangrove tree is due to the root system. However, it may be assumed that the root system can be incorporated into the average tree diameter over the depth of flow (Struve and Falconer, 2001). This means that an average tree diameter can be assumed, in order to attempt to include some of the drag effects caused by a wide based tapering cylinder (Westwater, 2001). These assumptions also make it significantly simpler to model the mangrove tree and calculate its influence on the fluid flow.

In this study, the drag force induced by the mangroves per unit area for the x and y directions respectively has been included in the model in the following form:

$$F_x = \frac{1}{2} C_d D_t \rho_t \frac{q_x \sqrt{q_x^2 + q_y^2}}{H} \tag{4.1}$$

$$F_y = \frac{1}{2} C_d D_t \rho_t \frac{q_y \sqrt{q_x^2 + q_y^2}}{H} \tag{4.2}$$

where C_d is the drag coefficient (dimensionless), which is approximately 1.0 for circular cylinders under turbulent conditions, though it depends on vegetation conditions (Mazda et al., 1997 and 2005) and Reynolds number (Schlichting, 1962); D_t is the diameter of a typical tree, which is assumed to be a circular cylinder; and ρ_t is the density of tree, which is defined as number of trees per unit area for this study; q_x, and q_y are the depth integrated discharges per unit width in the x and y directions respectively; and H is the total water column depth.

It is also assumed that mangroves are uniformly distributed with the same width for each stem, thereby making the test case similar to that of a managed forest as described by Gong and Ong (1995). Once again these assumptions make the analysis simpler, and also for the purposes of numerically modelling the swamp, individual tree spacing is not so significant since it is the mangrove density which influences the numerical process for the most part. The density of the mangrove tree arrangement is taken into consideration, since mangrove swamps frequently are shown in district zones. Thus, blockage effect induced by mangrove trees on the flow, which relates to density, is taken into account by introducing the porosity θ of the mangroves to describe the degree of penetration of fluid through the mangroves, or simply the area left available to the fluid due to the cross section of the mangroves occupying a gross cross-sectional portion of the platform area, whereby:

$$\theta = 1 - \frac{\pi}{4} D_t^2 \rho_t \tag{4.3}$$

By including all of these effects of mangroves in Equations 3.1 - 3.3 with a similar manner as Falconer (1993), the model solves the continuity equation for the conservation of mass as:

$$\theta \frac{\partial \eta}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = q_m \tag{4.4}$$

and the conservation equations of momentum in the *x*, *y* horizontal co-ordinate directions respectively can be written as:

$$\begin{aligned}\frac{\partial q_x}{\partial t} + \frac{\partial(\beta q_x^2 / H)}{\partial x} + \frac{\partial(\beta q_x q_y / H)}{\partial y} = f q_y - gH \frac{\partial \eta}{\partial x} + \frac{\rho_a}{\rho} C_w W_x \sqrt{W_x^2 + W_y^2} \\ - \theta \frac{g q_x \sqrt{q_x^2 + q_y^2}}{H^2 C^2} + \varepsilon \left[2\frac{\partial^2 q_x}{\partial x^2} + \frac{\partial^2 q_x}{\partial y^2} + \frac{\partial^2 q_y}{\partial x \partial y} \right] - F_x\end{aligned} \tag{4.5}$$

$$\begin{aligned}\frac{\partial q_y}{\partial t} + \frac{\partial(\beta q_x q_y / H)}{\partial x} + \frac{\partial(\beta q_y^2 / H)}{\partial y} = -f q_x - gH \frac{\partial \eta}{\partial x} + \frac{\rho_a}{\rho} C_w W_y \sqrt{W_x^2 + W_y^2} \\ - \theta \frac{g q_y \sqrt{q_x^2 + q_y^2}}{H^2 C^2} + \varepsilon \left[\frac{\partial^2 q_y}{\partial x^2} + 2\frac{\partial^2 q_y}{\partial y^2} + \frac{\partial^2 q_x}{\partial x \partial y} \right] - F_y\end{aligned} \tag{4.6}$$

where *t* is time; η is the water surface elevation above (or below) the still water datum; q_m is the source discharge per unit horizontal area; β is the correction factor for the non-uniform vertical velocity profile; *f* is the Coriolis parameter due to the Earth's rotation; g is the acceleration due to gravity; ρ_a is the density of air; ρ is the density of fluid; C_w is the air/fluid resistance coefficient; W_x and W_y are the wind velocity components in the x and y directions respectively; C is the Chezy bed roughness coefficient, which can be determined from the Manning formula or Colebrook-White formula; and ε is the depth averaged eddy viscosity.

For the purpose of this study, the derived continuity equation and conservative equations are also taking into consideration of the floodplain conditions. Although tidal flooding and drying processes are found typically in the intertidal limits of floodplains, this research will not, for the most part, examine the flooding and drying because extensive work has previously been carried out in the refinement of the numerical representation of this process for this model (for further details, see in Falconer and Owens, 1987, Falconer and Chen, 1991, Liang et al., 2006b).

4.5 Hydrodynamic Modelling of Natural Floodplains with Mangroves

As highlighted at the start of this chapter, this study has focused primarily upon modelling the hydrodynamics of floodplains with mangroves, in continuation of previous work undertaken by Struve (2000), Westwater (2001), and Wu et al. (2001). Throughout these studies, considerations have been given to the characteristics of vegetation to be modelled and the limitations of the approach to be adopted for an effective hydrodynamic model, with the aim of demonstrating the true sensitivity for the complex hydrodynamic processes of floodplains with mangroves. Subsequently, the model study has focused on the non-submerged rigid vegetative elements, which has been previously described as being simplistically modelled for a cylinder to represent mangroves.

For hydrodynamic flow through floodplains with mangroves, an existing two-dimensional depth integrated numerical model, which includes both the effects of the drag force and the blockage effect induced by the mangroves has been refined and used herein this study. It was the refinement of an existing hydrodynamic model with which this study and previous work were concerned, and this refined model has been calibrated and validated with some data sources. The refined numerical model was initially calibrated against data generated with a physical model based in a laboratory flume by Struve (2000) and Westwater (2001), in order to validate the numerical representation of the drag force and blockage effect of mangroves. Cylindrical wooden elements were used for the representation of mangroves in the experiment study. With that calibration and validation, the newly refined model is now ready to be used for further study on the hydrodynamics processes of floodplains with mangroves.

4.5.1 Tidal Currents in Mangrove Swamps

The effects of mangrove swamps on the flow structure in estuaries for steady and tidal flows had been extensively studied by Wu et al. (2001) with numerical model and many researchers as mentioned previously. Thus, this section will only briefly discuss for information. In general, it was found that mangroves have a significant impact on the flow structure in estuaries, where mangroves reduce the peak current and absorb the energy of tidal waves. Wu et al. (2001) showed that the drag force and blockage effect from the mangroves play an important role on the hydrodynamic processes of tidal flow structure in the mangrove swamps, in turn, have a key impact on the natural ecosystem of mangrove habitats.

4.5.2 Effects of Mangroves on Tsunamis

To investigate how mangroves impact on the attenuation of tsunami currents along floodplains, an idealised case was modelled and considered with circular cylinder trees being distributed along the whole channel, which had a rectangular shape. The definition sketch is given in Figure 4.7 for the idealised channel with three selected locations for comparison. These locations were selected based on the potential propagation distances of tsunamis (i.e. the transmitted locations at upstream, middle and downstream reaches of channel). The channel width was 2,200 m, with a length of 9,400 m. Circular cylinders were used for simplification to represent mangrove trees in this study, though the vertical profile of mangrove trees is very complex. Three cases of different diameters and densities of mangrove trees were selected based on actual observation made by Wu et al. (2001) for Malaysian mangrove swamps and mangrove population data analysis from Jimenez et al. (1985), in order to examine the significance on attenuation, as well as comparing the effects for the case without mangroves. Table 4.1 shows the selected diameters and densities of the mangroves and the calculated porosity of mangroves for these three cases.

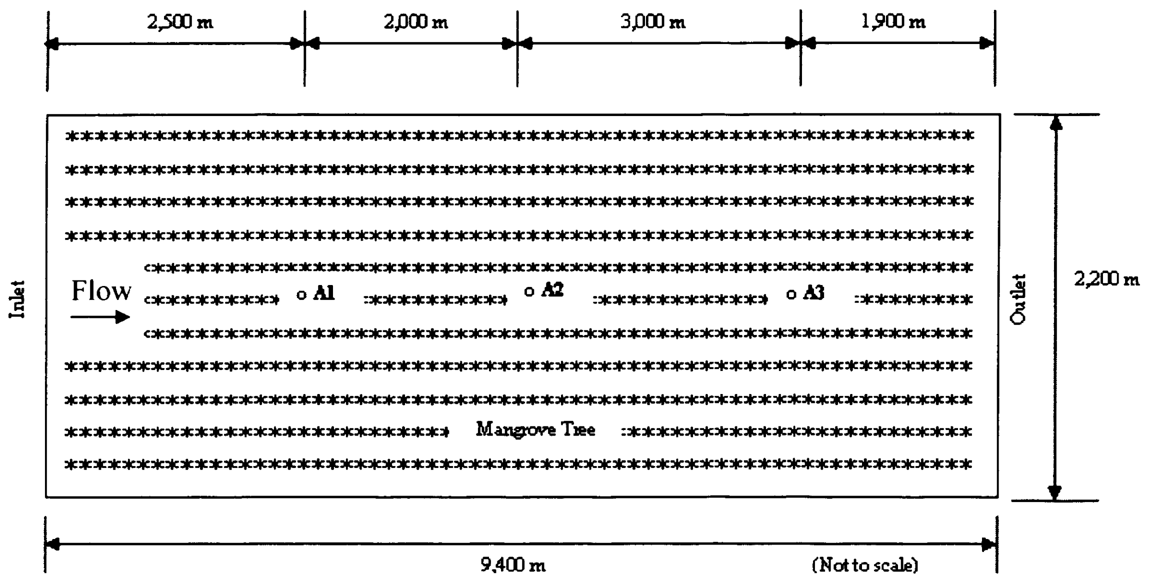


Figure 4.7 Sketch of the channel with three selected locations for comparison

In model simulations, a mesh of 22 × 94 grid squares was used with a uniform grid spacing of 100 m, and with the half time step being set at 6 s. The mean water depth was set to 3 m high. The drag coefficient was set to 1.0 for all test cases. Comparisons of the longitudinal velocity profile and water elevations for three locations along the channel were undertaken at points: A1 (at grid 11, 25), A2 (at grid 11, 45), and A3 (at grid 11, 75). At the open seaward boundary, recorded data of sea water elevations, as given in Figure 4.5 (b), were applied to drive the tsunami currents in the idealised channel. The total time of simulation was set to 156.5 hours, based on the total duration time of the recorded data.

Table 4.1 Combination test cases of mangrove diameters and densities

Test Case	1	2	3
Diameter, D_t (m)	0.1	0.3	0.3
Density, ρ_t (no. of tree/m^2)	4	3	4
Porosity, θ	0.969	0.788	0.717

Figure 4.8 shows the longitudinal velocity at selected locations A1, A2 and A3 for three cases of different mangrove diameters and densities in the swamp. It was found that the mangroves had a significant impact on the hydrodynamic processes affecting the tsunami currents. The results showed that the drag force induced by the mangroves greatly affected the flow in the mangrove swamps during tsunamis. For the condition with mangroves, velocities were reduced by up to 1.6 m/s from the condition without mangroves. On the other hand, for the condition without mangroves, velocities were significantly high and not reduced as observed for the condition with mangroves. Thus, these results implied that the blockage effect would

make a big contribution to the velocity profile due to a considerable fraction of the flow volume being taken up by the mangroves. The findings in this study were consistent with Othman (1994) and Wu et al. (2001), confirming that the closer the trees were located to one another (i.e. the higher density) and the bigger the trees (i.e. the tree diameter), then the greater was the reduction in the wave energy. Consequently, these results show that mangroves play a key role in wave attenuation, in slowing down the speed of tsunami currents.

The influence of mangroves on the water elevations was notably shown in the comparison for the case without mangroves (see Figure 4.9). From these results it can be seen that the peak water elevations for the condition with mangroves were reduced during the propagation of tsunamis. Referred to the input data (as shown in Figure 4.5), tidal disturbances in the form of multiple rising and falling of the tide elevations were observed. These disturbances of the tide elevations were continuous for a prolonged duration of almost 2 days. The results in Figure 4.9 show that tidal disturbances in the form of rising and falling of the tide elevations due to tsunamis were significantly decreased. Based on these observations, two highest tide elevations for two different time durations were reduced in their magnitudes for the case with mangroves. It was also found that the mangrove trees had a significant effect on the attenuation of the tsunami currents at the head of the floodplain, where the effect of the tsunami currents was less at the upstream end of the floodplain. As such, any proposals to remove or replant mangroves will have the effect of increasing or reducing the flow velocity, and may potentially result in a decrease or increase in flood levels upstream of the area considered. In contrast, for the case without mangroves, the effects of tsunamis were significant and extended to the upstream end of the floodplain, where the floodplain itself carried a full amount of the flow volume.

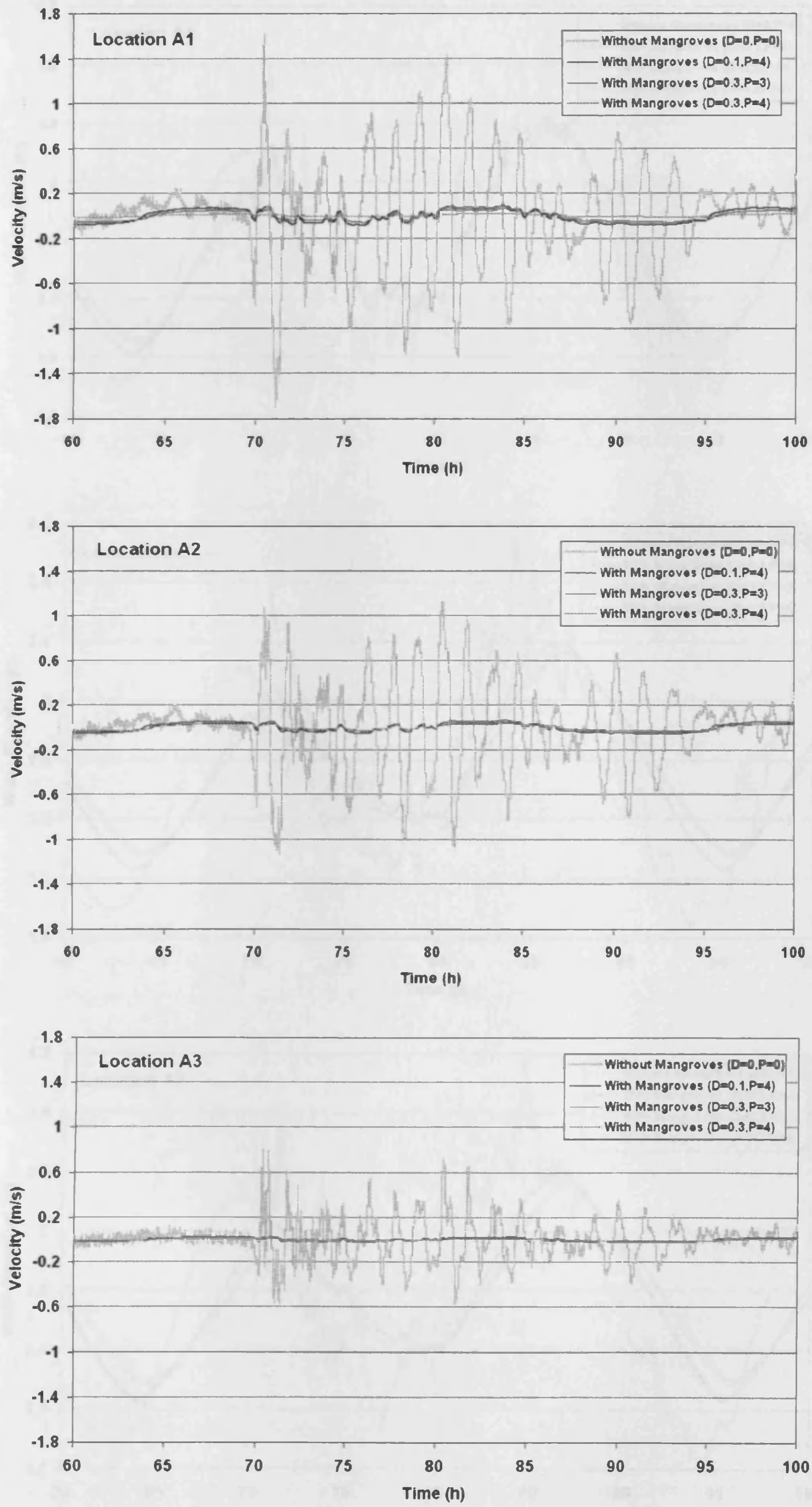


Figure 4.8 Time series of longitudinal velocities at selected locations A1, A2 and A3

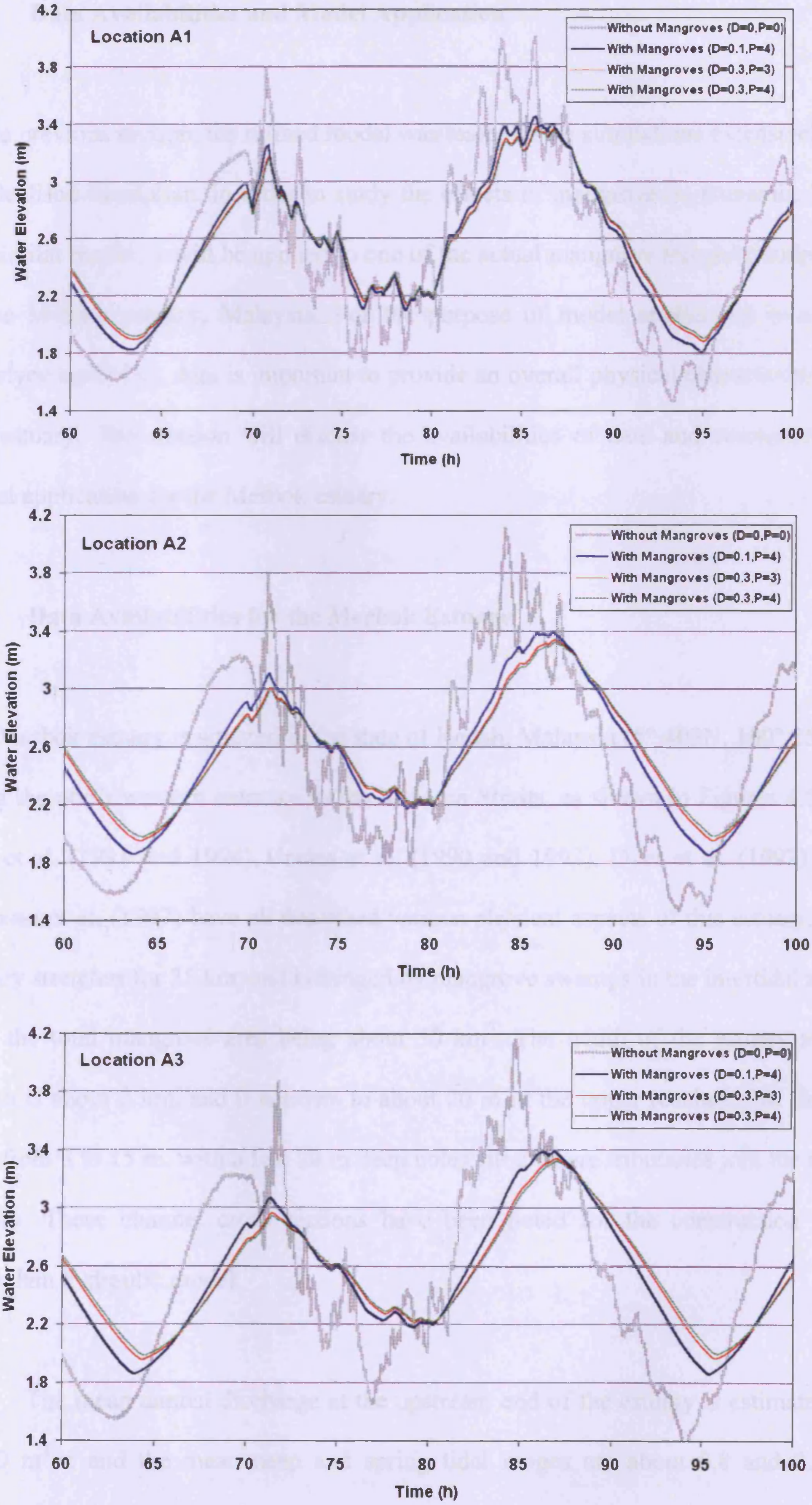


Figure 4.9 Time series of water elevations at selected locations A1, A2 and A3

4.6 Data Availabilities and Model Application

In the previous section, the refined model was tested in the simulations extensively on an idealised floodplain, in order to study the effects of mangrove on tsunamis. With the similar model, it will be applied to one of the actual mangrove fringed floodplains at the Merbok estuary, Malaysia. For the purpose of model application in a real prototype condition, data is important to provide an overall physical characteristic for this estuary. This section will discuss the availabilities of data and corresponding model application for the Merbok estuary.

4.6.1 Data Availabilities for the Merbok Estuary

The Merbok estuary is situated in the state of Kedah, Malaysia (5° 409N, 100° 259E), along the north western entrance to the Malacca Straits, as shown in Figures 4.5 (a). Ong et al. (1991 and 1994), Uncles et al. (1990 and 1992), Dyer et al. (1992), and Simpson et al. (1997) have all described various physical aspects of this estuary. The estuary stretches for 35 km, and is fringed by mangrove swamps in the intertidal zone, with the total mangrove area being about 50 km^2. The width of the estuary at the mouth is about 2 km, and it narrows to about 20 m in the upper reaches. The depths vary from 3 to 15 m, with a few 20 m deep holes sited where tributaries join the main estuary. These channel cross sections have been noted for the construction of a floodplain hydraulic model.

The mean annual discharge at the upstream end of the estuary is estimated to be 20 m^3/s; and the mean neap and spring tidal ranges are about 0.8 and 2.3 m respectively, giving the downstream hydrodynamic boundary conditions (Ong et al., 1991). These fluvial data describe the flow of water mass into and out of the system, from the upstream to the downstream boundaries. All of these data have been considered for model set up. The accuracy of the model outputs depends heavily upon the accuracy of these data. Further information on coastline bathymetry was based on the Admiralty Sea Charts. According to the Admiralty Sea Charts, the mean sea level value is recorded to be 1.56 m at the Pulau Bidan (5 ° 45' N, 100 ° 17' E), 1.60 m at the Tanjung Dawai (5 ° 40' N, 100 ° 21' E), and 1.57 m at the Kedah Pier (5 ° 25' N, 100 ° 21' E), as well as 1.37 m at the Pulau Rimau (5 ° 15' N, 100 ° 17' E) as shown in Figure 4.10 for the exact location. Observational data of tide level in the study area are available through four closer tidal stations located in the west coast of Peninsular Malaysia. Based on the reported harmonic constants of four major tidal constituents, M_2, S_2, K_1 and O_1 (Admiralty Tide Tables, 2005), temporal variations in tide level at the open boundary were estimated. The tidal amplitudes and the phase lags of these stations are shown in Table 4.2 (Admiralty Tide Tables, 2005).

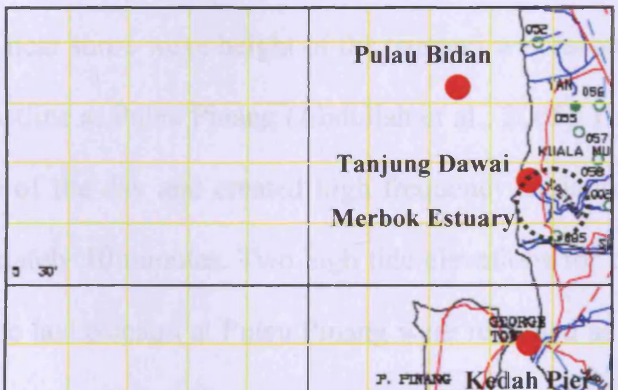


Figure 4.10 Location of referred tidal stations and the Merbok estuary

Table 4.2 Harmonic constants of the four major tidal constituents (Data source from Admiralty Tide Tables, 2005)

Station	M_2		S_2		K_1		O_1	
	Amp. (m)	Phase (deg.)	Amp. (m)	Phase (deg.)	Amp. (m)	Phase (deg.)	Amp. (m)	Phase (deg.)
Tanjung Dawai	0.68	15	0.39	61	0.20	8	0.04	311
Pulau Bidan	0.64	9	0.41	58	0.21	354	0.05	320
Kedah Pier	0.62	25	0.37	68	0.20	357	0.05	293
Pulau Rimau	0.53	38	0.29	79	0.22	1	0.04	272

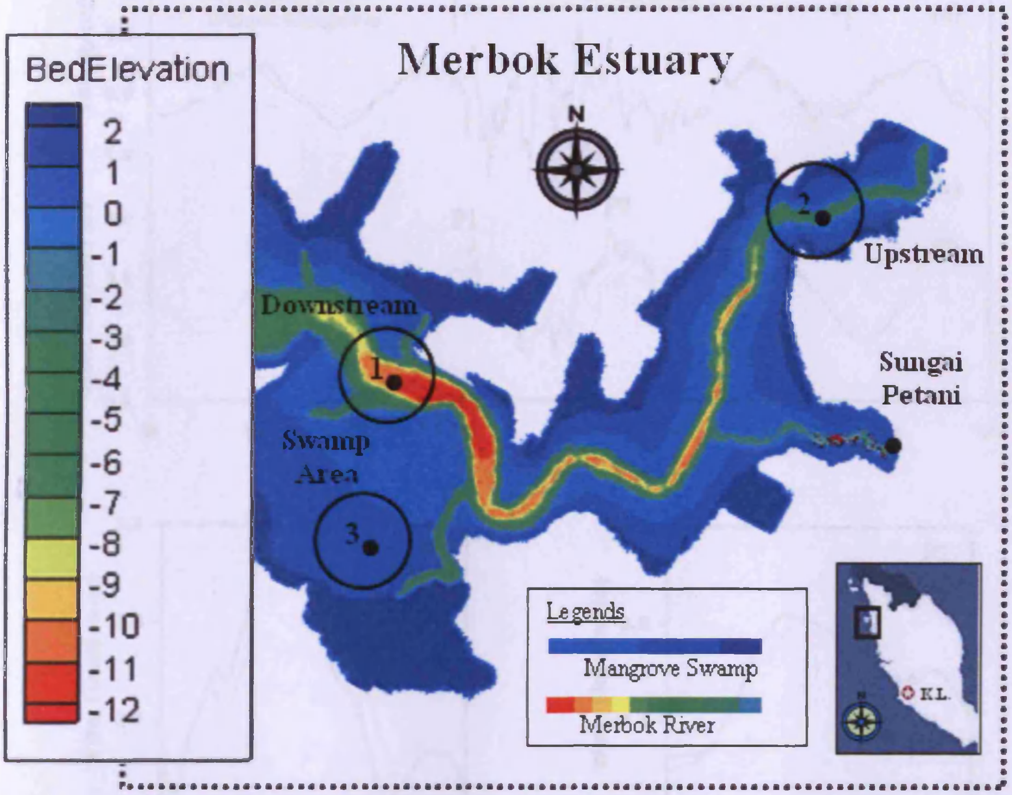
4.6.2 Model Application for the Merbok Estuary

As seen in Figures 4.5 (a) and 4.10, the Merbok estuary and Pulau Pinang are located at the same coastline and close to each other in distance, where there are similarities in several physical aspects. Based on observations from the last tsunami, as shown in Figure 4.5 (b), the near shore wave height of the tsunami was recorded for up to 2 to 3 m along this coastline at Pulau Pinang (Abdullah et al., 2005). This tsunami struck during a high tide of the day and created high frequency variations with a shorter period of approximately 10 minutes. Two high tide elevations for two different time durations during the last tsunami at Pulau Pinang were recorded as 3.86 and 3.91 m. Tidal disturbances in the form of multiple rising and falling tide elevations were observed and continuous for a prolonged duration of almost 2 days. In this model study, the seaward boundary condition was set according to these recorded data in order to drive tsunami currents. The quality of these data were reviewed and revised to provide good quality inputs for the study.

The refined model has been used to simulate the hydrodynamic processes in the Merbok estuary. The model area was represented using a mesh of 243 x 265 uniform grid squares, with a grid spacing of 50 m. The model was run for both conditions, i.e. with and without mangrove trees. The total simulation time of the model was 156.50 hours. Based on the observation made by Wu et al. (2001), and mangrove population data analysis from Jimenez et al. (1985), the typical diameter of the trees that used in this study was 0.1 m, the density of the trees was set to 4 per m^2, and a drag coefficient of 1.0 was used. Two locations along the main river (i.e. the downstream and upstream) and one location in the mangrove swamp area were selected to investigate how the mangrove trees have affected the behaviour of the tsunami currents (as shown in Figure 4.11). Figure 4.11 (a) illustrates the bed elevations of the computational domain contours and Figure 4.11 (b) shows satellite image of the Merbok estuary for comparison with the model set up.

Figures 4.12 and 4.13 show the time series plots of the velocities and water elevations at two selected locations along the main river for both conditions. Slight influences of the mangroves on the velocities can be observed in Figures 4.12 (a) and 4.13 (a). The influence of the mangroves on the water elevations and their effects along the main river channel are shown in Figures 4.12 (b) and 4.13 (b), together with more detailed views during the two considerable highest water elevations of the tsunami (i.e. P1 and P2). As shown in Figures 4.12 (b) and 4.13 (b), the water elevation at the downstream reach of the main river in the case with mangroves is larger than the case without mangroves, while this relationship is reversed at the upstream end of the main river. The reason for this was that the mangrove swamp along the main river functioned as a temporary water storage region, rather than a flow pathway to extend the effect of the tsunami propagating up the estuary.

(a)



(b)

Figure 4.11 Merbok estuary showing: (a) selected locations and bed elevations of the computational domain contours in metres, and (b) satellite image (Source from Google, 2008)

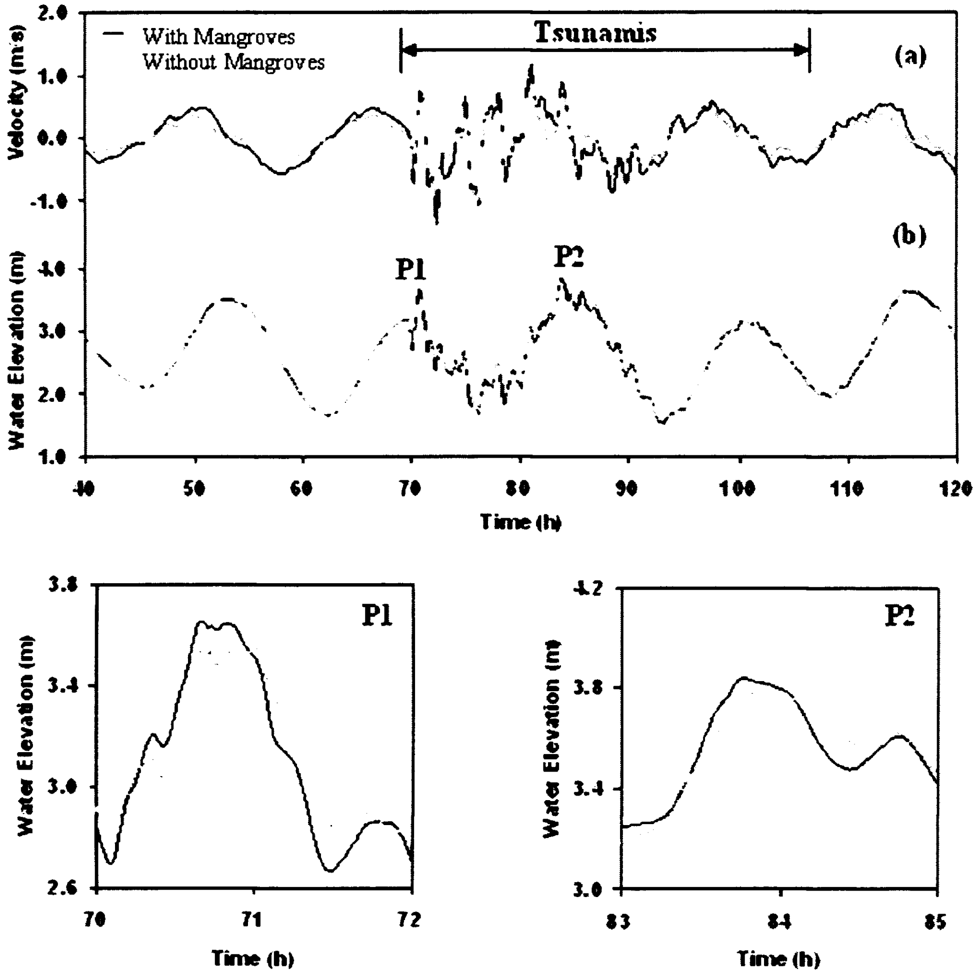


Figure 4.12 Time series of (a) velocities and (b) water elevations with details (i.e. P1 and P2) at selected location 1, downstream of the main river

The drag force and blockage effect from the mangrove trees reduced the flow into the mangrove swamps and caused a rise in water level at the downstream end of the main river. This increase in the water elevation due to the tsunami currents in the main river was much smaller at the upstream end of the river. The results showed that the mangroves helped in reducing the effects of a tsunami in the main river and would also reduce the impact of flooding by such a current on some major township at the head of the river, thereby confirming the need to include the terms of drag force and blockage effect of mangroves in the numerical model.

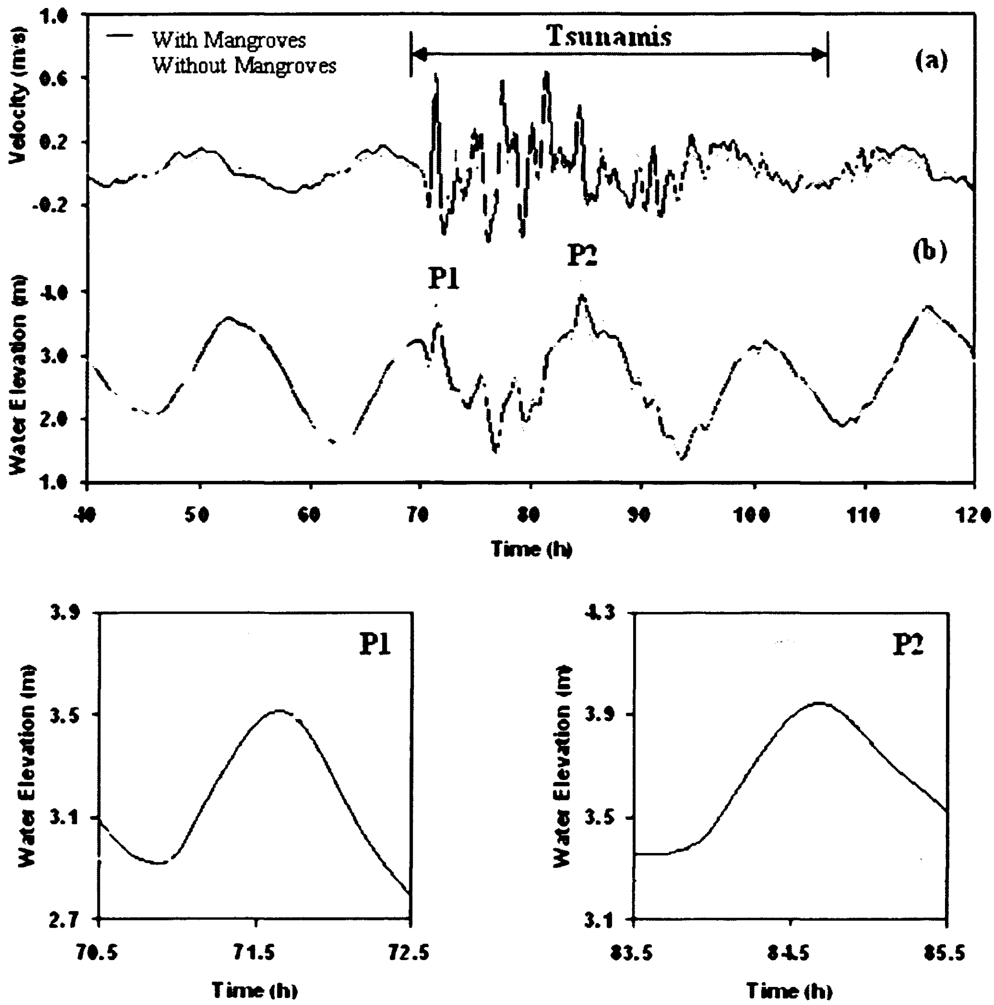


Figure 4.13 Time series of (a) velocities and (b) water elevations with details (i.e. P1 and P2) at selected location 2, upstream of the main river.

The findings also show that the effect of the tsunami propagating up the estuary and into the mangrove swamp area. Figure 4.14 illustrates a time series of velocities and water elevations at the selected locations in the mangrove swamp area. Velocities for the condition with mangroves were significantly reduced as shown in Figure 4.14 (a). Disturbance effects on the tsunami waves in the form of multiple rising and falling for the time series of velocities were lessened with mangroves. It was found that drag force induced by the mangroves had an impact on the tsunami flow patterns in the swamp area. On the other hand, the blockage effect of the mangroves decreased the peak current during tsunamis. There were slight influences the mangroves on water elevations and the effects are shown in Figure 4.14 (b).

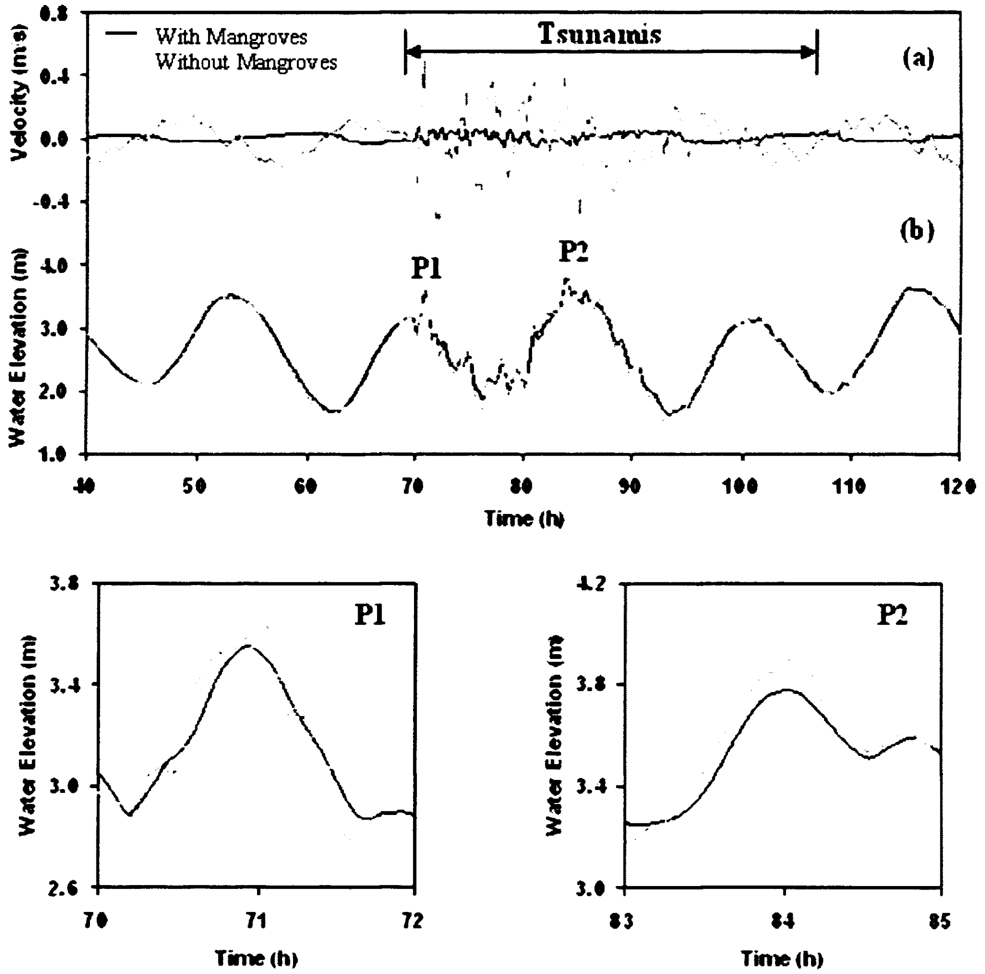


Figure 4.14 Time series of (a) velocities and (b) water elevations with details (i.e. P1 and P2) at selected location 3, mangrove swamp area.

In inundation conditions, the channel areas carry very limited amounts of flow due to their vegetated state and overbank areas (or floodplains) help to carry the greater proportion of flows. In such situation, any proposals to remove or replant mangroves will have the effect of increasing or reducing the flow velocity, and may potentially result in a decrease or increase in flood levels upstream of the area considered, and/or a decrease or increase in overbank flooding. Thus, mangroves play an important role on the hydrodynamic processes of flow structure in the floodplains.

4.7 Innovative Solution of Sustainable Natural Floodplains with Mangroves

Abdullah et al. (2005), Asian Development Bank (2005), and the Environmental Justice Foundation (2006) have strengthened the perception of mangroves as a green belt that need to be critically preserved for sustainable coastal protection and natural flooding disaster defences. This realisation of the huge potential offered by these complex ecosystems has led to a change in management strategy. In recognition of this need, the study of hydrodynamics of floodplains with mangroves, undertaken in this chapter is an excellent example of an adaptation strategy of innovative management practice, eventually for an effective floodplain management.

In the previous section, detailed model simulations have been used to describe the effects of the presence of mangroves on the force of the tsunami induced waves and the level of potential damage of inundation. It was found that re-establishing mangroves has a positive impact on the natural ecosystem, contributing to the restoration and rehabilitation of mangrove habitats. This section attempts at simulating the positive effect of the presence and re-establishment of mangroves, in helping to protect the hinterland, is an original concept that works well with the principles of resource economics for sustainable floodplains.

4.7.1 Innovative Solution of Artificial Mangrove Shelter

The protection of mangroves in the coastal areas is now an endeavour which is wholeheartedly supported by all parties in the world to provide protection from future disasters. As a result the restoration and rehabilitation of mangroves in coastal areas is now being extensively promoted to enhance sustainable natural regeneration. It involves renewing natural mangroves that have been lost or degraded and reclaiming their functions and values as a vital component of the ecosystem, to protect and increase their habitat areas and which the natural ecosystem will return to what the mangrove region was like before (Westwater, 2001).

Consequently in the presence of extreme natural events, this process of natural mangrove re-colonisation is compromised and becomes more complex (Jimenez et al., 1985). Clear cutting by human activity has often led to a significant impact on the ecological system in mangrove swamps and possibly also exposed the site to erosion, which makes subsequent reforestation difficult; as a result seedlings have often been washed away, where this is also noted by Wu et al. (2001). Mangroves have to withstand these actions, especially on exposed sites and where they colonise cleared or newly established mudflats. Tidal currents and wave energy will hardly be so large as to cause problems to mature mangroves, but the establishment of seedlings and young mangroves may be difficult in the presence of such wave environments (Ong, 1982; Jimenez et al., 1985; Ong et al., 1991). Both human-induced and natural stresses make the restoration and rehabilitation of mangroves more complicated. Other problems encountered also include barnacle infestation, inappropriate site selection, attacks by crabs, dying out anchorage of the sediments and deep inundation, which may adversely result in seedlings being washed out.

In general, the restoration and rehabilitation of mangroves can only be undertaken in areas that are suitable for them, for example in estuaries, areas sheltered by a stretch of coastline or in protected bays, embayments and offshore islands protected by reefs and shoals (Chatenoux and Peduzzi, 2007). However, besides the selection of ideal sites for mangroves, the establishment of seedlings and young mangroves may be easier in the shelter of other mature mangroves as these sites also help to rehabilitate damaged mangrove ecosystems and to protect existing mangrove stands. At the exposed site where there is no shelter provided by other mature mangroves, there is a need to duplicate the real natural environment of this shelter for sustainable restoration and rehabilitation. Hence, an innovative and environmentally friendly system, namely the Artificial Mangrove Shelter (AMS), has been first introduced and discussed in more detail in this chapter. Also, to confirm that the AMS can have the same effect as a natural mangrove shelter for coastal protection, the hydrodynamic effects of the AMS have been studied and modelled.

As noted by Struve and Falconer (2001), "Mangroves are woody and mature trees are rigid, but young mangroves can bend with the flow. Mature mangroves and stems will always protrude above the water surface, whereas young mangroves and stilt roots may be submerged, in which case their effects are depth dependent and stems are similar to straight cylinders." The AMS system is designed by replicas of the mangrove stem configuration (as shown in Figure 4.15). The system consists of wooden circular cylinders of different sizes, which are easy to construct and simple for installation on site, though the vertical profile of natural mangroves is very complex. Figure 4.15 illustrates a setting up design for the AMS system.

The AMS would be the frontier in this system to play an important role as a coastal defence and preventing seedlings or young mangroves from being washed away by strong waves and currents, or even tsunamis, by the sea or river. In this system, mature mangroves would remain at the same location to play the same roles as before, and even backup the role of an AMS as a coastal defence. The sustainable innovation of the AMS will provide 4 As and 4 Es as follows:

1. Artificial defences against natural disasters by absorbing and obstructing the energy of tidal currents, waves and even tsunamis.
2. Attenuation and mitigation of floods by increasing the storage capacity and dissipating wave energy propagation.
3. Artificial shelter to encourage restoration and rehabilitation of mangroves.
4. Artificial sediment traps for soil formation and stabilizing the coastline.
5. Erosion control and protection from strong waves and currents at exposed sites.
6. Environmentally friendly with little change to the environment and habitat.
7. Enhancement of the natural environment's aesthetic aspects for recreation.
8. Enrichment and enhancement of the natural habitat for natural regeneration.

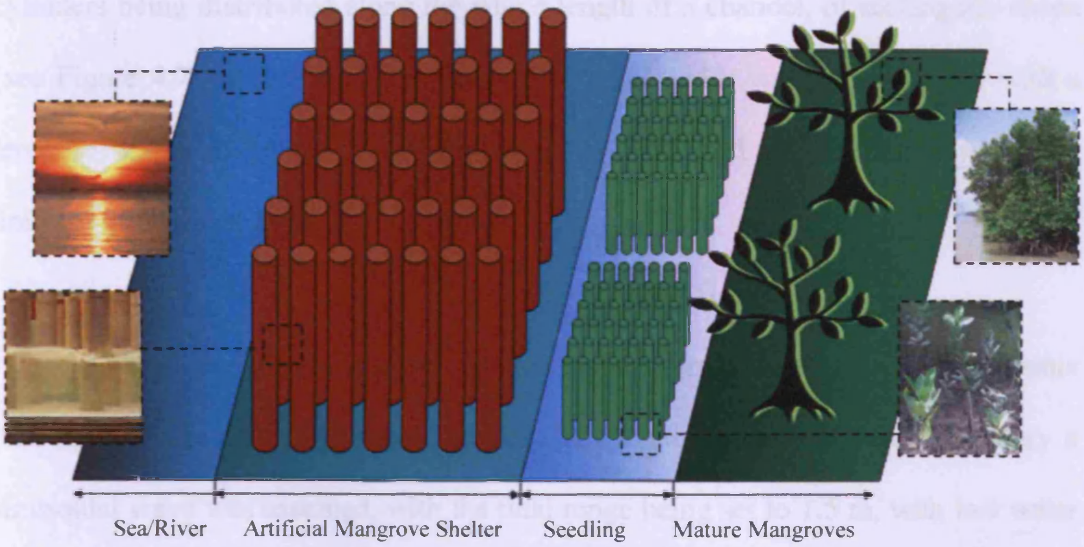


Figure 4.15 Setting up design for sustainable innovation of the AMS system

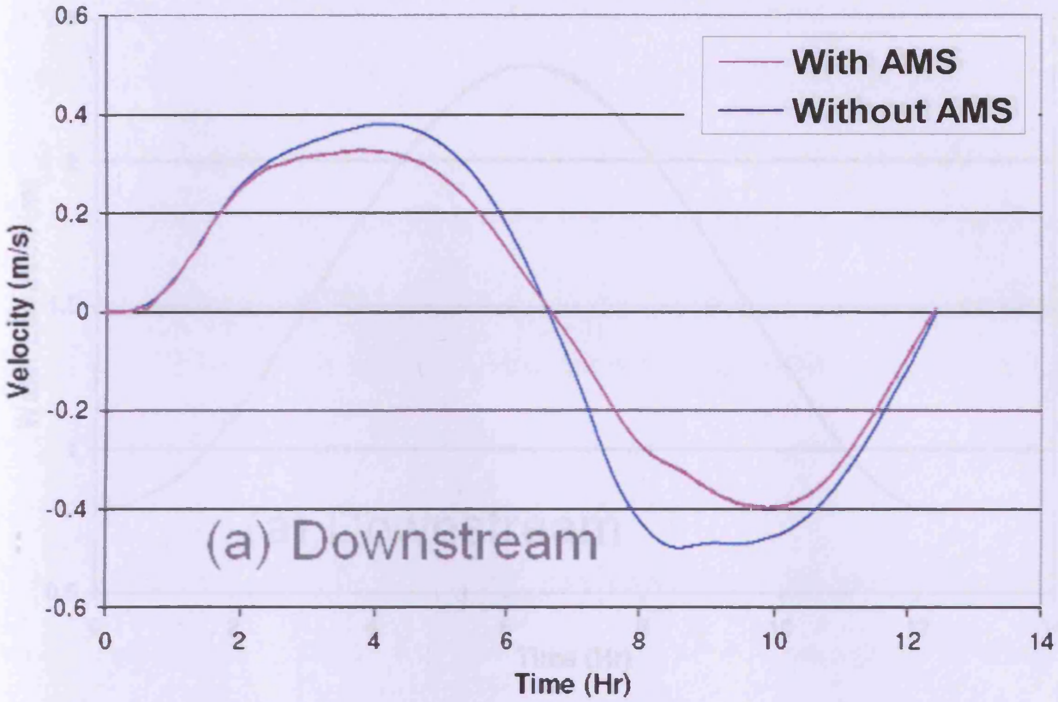
4.7.2 Hydrodynamic Modelling of Artificial Mangrove Shelter

Although research on hydro-environmental impact of mangroves has made good progress in recent years, there are still major uncertainties concerning the establishment of seedlings and innovative solutions for sustainable restoration and rehabilitation of mangroves. An improved understanding of such problems and solutions is crucial for better management procedures of the long term sustainable use of mangroves as natural resources. For that reason, numerical model are now employed to provide some of the useful findings to these problems.

Thus, this section will use the same numerical model as described previously, to study the hydrodynamics of AMS along the floodplains, particularly on: (i) the influence regard to the AMS on the tidal flow structure, and (ii) the consequential impacts of these changes on tsunami currents. In order to investigate these effects of AMS along the floodplains, an idealised case study was considered with circular cylinders being distributed along the whole length of a channel, of rectangular shape (see Figure 4.7 for details). The idealised channel width was set to 550 m, with a length of 2,450 m. In the model a mesh of 22 × 94 grid squares was used with a uniform grid size of 25 m.

Firstly, the model was set up and applied to simulate the hydrodynamic processes of the tidal flow structure in the AMS. At the open seaward boundary a sinusoidal wave was assumed, with the tidal range being set to 1.5 m, with low water at 0.8 m and high water at 2.4 m and a time step being set to 12 s. Simulations were undertaken for this tidal wave condition for the cases with and without the AMS. Comparisons of the velocity profiles and water elevations for both of these cases were undertaken to provide a good knowledge of the effects of the AMS on the tidal flow structure. Time series plots of velocities and water elevations at two selected locations of the idealised channel are observed as shown in Figures 4.16 and 4.17.

(a)



(b)

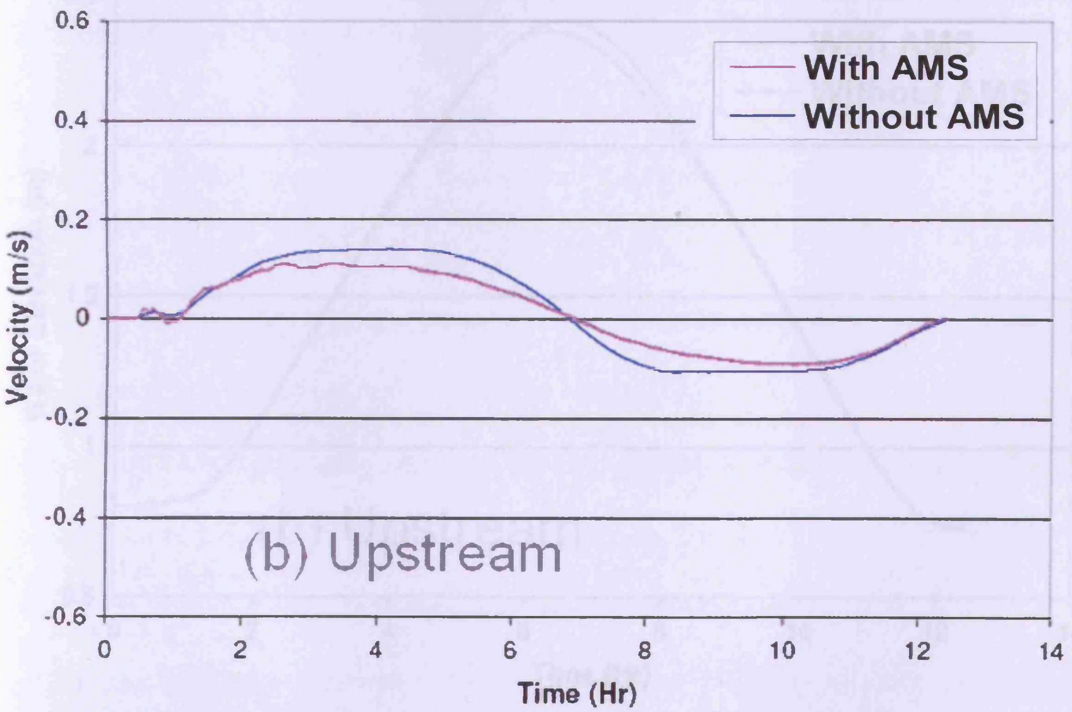
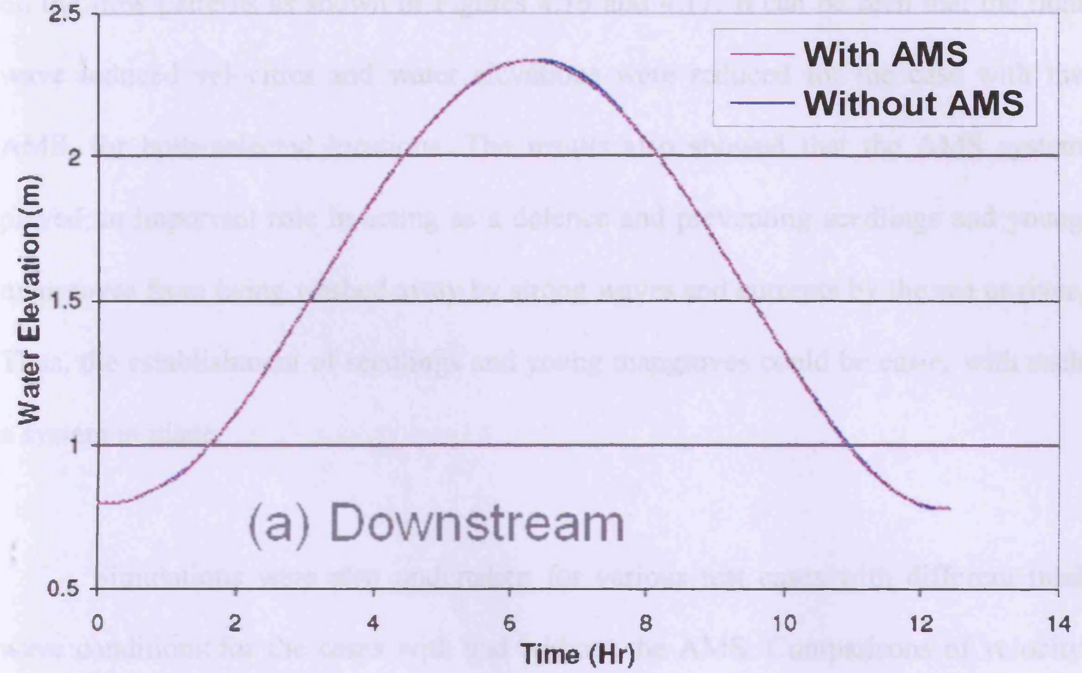


Figure 4.16 Time series of velocities at selected locations of (a) the downstream and (b) upstream of the channel

(a)



(b)

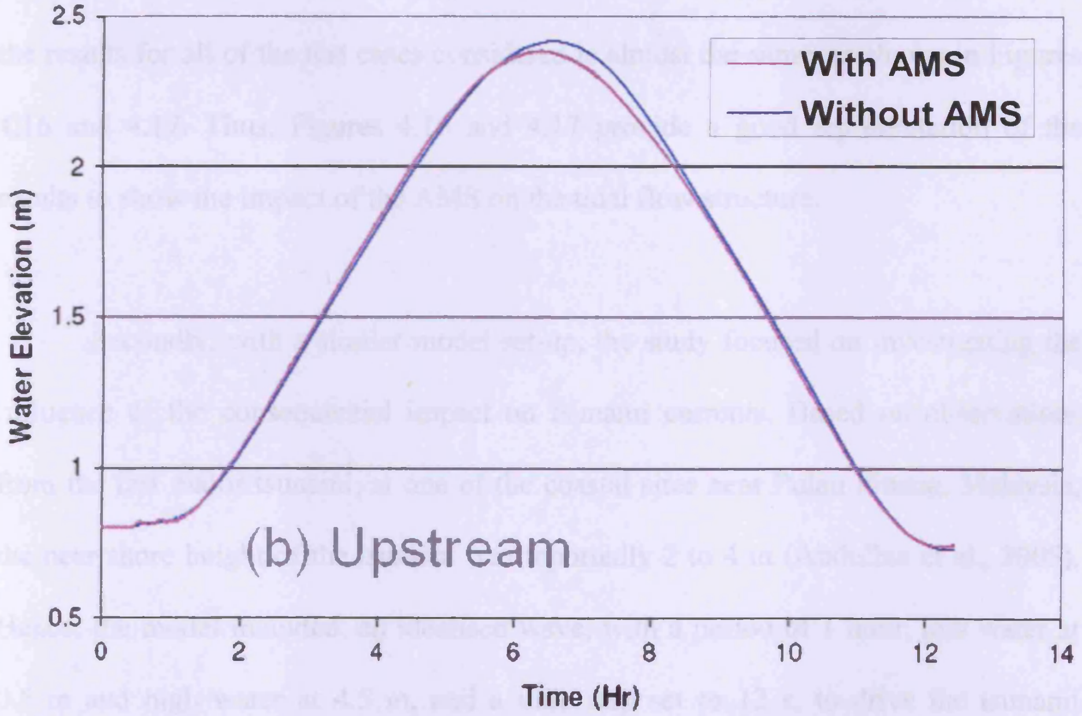


Figure 4.17 Time series of water elevations at selected locations of (a) the downstream and (b) upstream of the channel

Based on the observations, it was found that the AMS had a significant impact on the flow patterns as shown in Figures 4.16 and 4.17. It can be seen that the tidal wave induced velocities and water elevations were reduced for the case with the AMS, for both selected locations. The results also showed that the AMS system played an important role in acting as a defence and preventing seedlings and young mangroves from being washed away by strong waves and currents by the sea or river. Thus, the establishment of seedlings and young mangroves could be easier with such a system in place.

Simulations were also undertaken for various test cases with different tidal wave conditions for the cases with and without the AMS. Comparisons of velocity profiles and water elevations for all of these cases were undertaken. Based on the findings for test cases with different tidal wave conditions, generally, the tendency of the results for all of the test cases considered is almost the same, as shown in Figures 4.16 and 4.17. Thus, Figures 4.16 and 4.17 provide a good representation of the results to show the impact of the AMS on the tidal flow structure.

Secondly, with a similar model set-up, the study focused on investigating the influence of the consequential impact on tsunami currents. Based on observations from the last major tsunami, at one of the coastal sites near Pulau Pinang, Malaysia, the near shore height of the tsunami was reportedly 2 to 4 m (Abdullah et al., 2005). Hence, the model included: an idealised wave, with a period of 1 hour, low water at 0.5 m and high water at 4.5 m, and a time step set to 12 s, to drive the tsunami currents. Simulations have been undertaken for various conditions of the AMS with different porosities (i.e. different diameters and densities), and compared to the case without the AMS.

Comparisons of velocity profiles and water elevations for all of these cases were undertaken to study the capability of the AMS, particularly with influence regard to the AMS on tsunami currents. Figure 4.18 illustrates time series plots of the velocity profiles and water elevations for various cases with different porosities of the AMS. From these results, it can be seen that the tsunami induced velocities and water elevations were significantly reduced for the case with the AMS. For the condition with the AMS, the velocities were reduced by up to 1.2 m/s from the condition without the AMS, as shown in Figure 4.18 (a).

These results showed that the drag force induced by the AMS greatly affected the tsunami induced flow structure. The findings also implied that the blockage effect of the AMS would make a contribution to the velocity profile due to a considerable fraction of the flow volume being taken up by the AMS. It was found that the AMS had a significant impact on the hydrodynamic characteristics of the tsunami currents. The study has thus shown that the AMS also play a key role as natural mangrove shelter in wave attenuation and in slowing down tsunami currents.

It can be seen in Figure 4.18 (a), the smaller the porosity of the AMS, or the closer the trees were located to one another (i.e. the higher density) and the bigger the trees (i.e. the bigger the diameter), then the greater was the reduction in the wave energy. The findings again confirm that the AMS can play the same roles as natural mangrove shelters for coastal protection and preventing young mangroves from being washed away by strong waves and currents, or even tsunamis. Thus, the AMS should be widely promoted as an innovative solution to provide better management practices for the long term sustainable use of mangroves as natural resources, eventually for the effective management of floodplains.

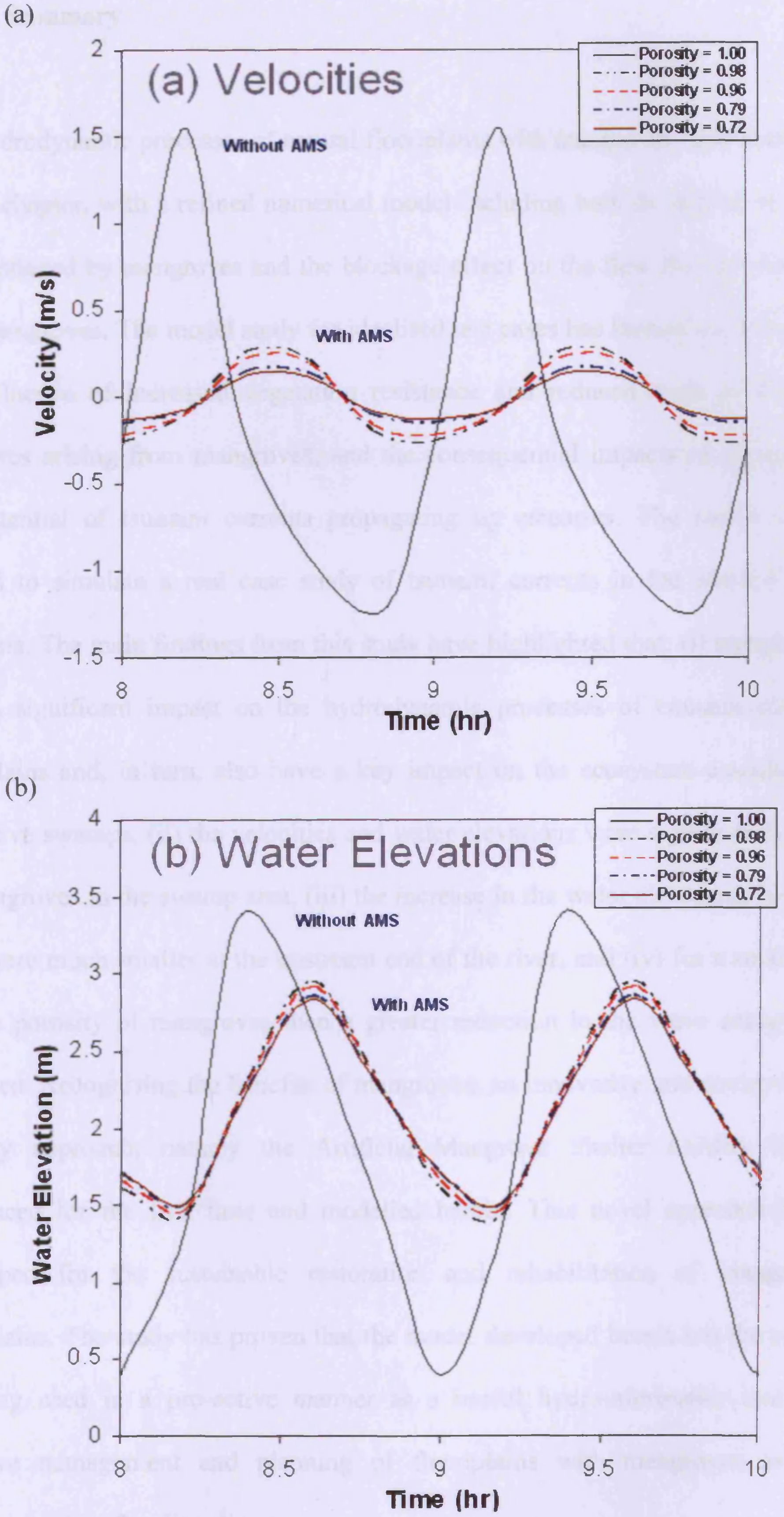


Figure 4.18 Time series of (a) velocities and (b) water elevations for the AMS with different porosities

4.8 Summary

The hydrodynamic processes of natural floodplains with mangroves have been studied in this chapter, with a refined numerical model including both the effects of the drag force induced by mangroves and the blockage effect on the flow through floodplains with mangroves. The model study for idealised test cases has focused on investigating the influence of increased vegetation resistance and reduced areas of flood flow structures arising from mangroves, and the consequential impacts of mangroves on the potential of tsunami currents propagating up estuaries. The model has been applied to simulate a real case study of tsunami currents in the Merbok estuary, Malaysia. The main findings from this study have highlighted that: (i) mangroves can have a significant impact on the hydrodynamic processes of tsunami currents in floodplains and, in turn, also have a key impact on the ecosystem associated with mangrove swamps, (ii) the velocities and water elevations were significantly reduced by mangroves in the swamp area, (iii) the increase in the water elevations in the main river were much smaller at the upstream end of the river, and (iv) for a smaller value for the porosity of mangroves then a greater reduction in the wave energy can be observed. Recognising the benefits of mangroves, an innovative and environmentally friendly approach, namely the Artificial Mangrove Shelter (AMS), has been introduced for the first time and modelled herein. This novel approach has been developed for the sustainable restoration and rehabilitation of mangroves in floodplains. The study has proven that the model developed herein has the capability of being used in a pro-active manner as a useful hydroinformatics tool for the effective management and planning of floodplains with mangroves as natural defences against flooding disasters.

CHAPTER 5

HYDRODYNAMICS OF URBAN FLOODPLAINS WITH VEHICLES

5.1 Introduction

The primary focus of this chapter is directed to floodplains in urban environments. As highlighted earlier, floodwater flows through urban floodplains with storm water systems are often inadequate during extreme storm events and/or when the river flood inundation extent becomes extreme. Such flows may cause potential hazard risks to humans and their properties along the floodplains. Recently, flood hazards relating to vehicles have become more noticeable and it is vital to investigate the hydraulic behaviour of vehicles on urban floodplains. Therefore, this chapter outlines a study of the theoretical and experimental aspects of the hydrodynamics of floodwater flows over urban floodplains with vehicles.

Firstly, a theoretical background study is discussed to establish an understanding of the hydrodynamics of floodwater flows over urban floodplains with vehicles; a condition which can be very important for extreme storm events, or even moderate storm events, when the storm water system is insufficient to drain away the surface runoff. The relationship between floods and floodplains with vehicles is briefly discussed to provide an outline of the fundamentals for further investigation into the details of this topic. Subsequently, there is an obvious need for a better understanding of all potential forces acting on a flooded vehicle in order to develop an accurate physical model and eventually for a theoretical analysis and numerical modelling purposes.

Secondly, a series of laboratory experiments have been conducted in a small hydraulics flume (i.e. 0.3 m wide) using three different types of stationary scaled die cast model vehicles, with two scales being tested for each type of vehicle for their threshold conditions of instability. At an early stage of the experiment, each vehicle was placed at an orientation where the rear of the model vehicle was facing the flow instead of a smooth curve and the aerodynamic front end of the vehicle. The experimental results obtained for the smaller scale model vehicles were first scaled up using the theory of hydraulic similarity to the larger scale and the accuracy of these scaled up predictions were then validated using the experimental results obtained for the same scale of model vehicles. Similarly, the experiment results were scaled up to the idealised prototype conditions, to develop a clearer fundamental understanding of the influence of floodwater flows, particularly on hydraulic stability of vehicles in urban floodplains.

Thirdly, focusing on the same types of stationary model vehicles, the effects of different vehicle orientations to the flow were investigated in order to identify the critical threshold conditions of the vehicle instability, according to the mechanical condition of sliding balance. This investigation has been undertaken by conducting a series of experiments in the same flume as before. Throughout the tests, the critical (or lower) value of the threshold condition that affects the instability of each vehicle in the orientation of flow was determined. This orientation set up for the vehicles was selected for further investigation as the critical condition for instability. Subsequently, these experiments also provided the investigation of the relationship of the drag force and blockage effects on different vehicles, with different orientations, in order to provide an appropriate understanding for future hydrodynamic modelling. Further investigations were also undertaken to examine the effects of ground surface gradients on flow conditions during instability of vehicles. These investigations were conducted to see how vehicles begin to move under different ground surface conditions.

Fourthly, this study investigated the critical conditions of floodwater discharge, including flow velocity and floodwater depth at the threshold of vehicle instability in the same hydraulics flume. This part of the study focused on the stationary small scaled model vehicles at the specific orientation relative to the flow as recommended in previous experiments. These experimental results were then interpreted and scaled up to the idealised prototype conditions. Scaling results obtained in the flume up to idealised prototype conditions were provided, giving relationships between flood conditions in urban floodplains and vehicle stability. A straightforward envelope curve has been developed based on these scaled up results. Referring to this envelope curve, a novel innovative approach has been first introduced herein, known as the Traffic Light of Hydraulic Stability (TLHS). This envelope curve can be easily used as a useful guide or procedure to evaluate the degree of hydraulic stability for vehicles.

Finally, the results for all the test cases have been analysed to investigate the effects of vehicles on floodwater flow propagation over urban floodplains and, on the other hand, the influence of the floodwater flows on the stability of model vehicles. The two principal factors of hazards (i.e. the floodwater depth and flow velocity) that affect the stability of vehicles in urban floodplains have been identified to confirm the significant impact of hydrodynamic processes in urban floodplains with vehicles. All experiments undertaken so far have only looked into the conditions under which the vehicles begin to be moved. So far observations have been made from the theory studied and experiments conducted to systematically look into the hydraulic behaviour of vehicles in urban floodplains.

5.2 Urban Floodplains with Vehicles

Over the past few centuries many of the major towns and cities worldwide have been developed along floodplains due to their rich natural resources. Continuing development along such floodplains are completely altering the surface profiles, by increasing impermeable urban areas due to road pavements, built structures and parking lots, etc. (see Figure 5.1). These typical urban infrastructures have tended to replace natural vegetation, which originally helped to absorb water, prevent erosion, etc. As impervious surface areas have increased, consequently less water has infiltrated into the ground, and more and more water runoff has been transferred from the natural to urban surface areas (as shown in Figure 5.2); this has meant that more floods have tended to occur.

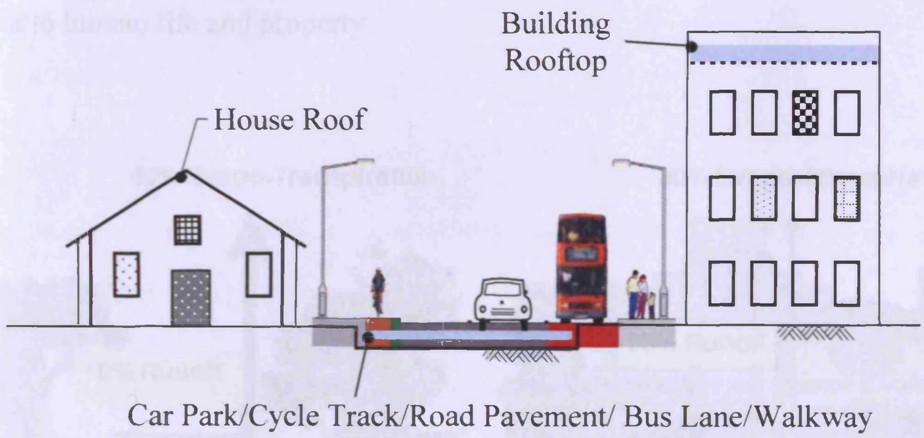


Figure 5.1 Typical impervious surfaces of urban areas

By considering the potential hazard risks, as highlighted in these floodplains, and disregarding the presence of buildings, bridge structures and road pavements in urban floodplains which have been widely researched over the past, this chapter primarily focuses on floodplains with vehicles (see Figure 5.3 for typical commercial and private vehicles on roads). Most of commercial vehicles (i.e. lorries, trucks, buses, and vans) are heavy and generally remain stable and stationary during floods, and hence less attention will be focused on these vehicles in this study.

Typically in an urban area, in particular private vehicles (i.e. saloon cars) are relatively light in weight, moveable and commonly found in large numbers on road sides and at parking lots along floodplains, where high hydraulic hazards may be expected. These vehicles that are stationary or parked along urban floodplains form the main focus consideration in this study. In general, these vehicles were not designed to withstand water forces in floodwaters. Accordingly such vehicles along floodplains are at significant flood hazard risk in comparison with other infrastructure, which are heavier and fixed permanently in one place or some even designed to stand with hydraulic forces. This consideration highlights a real concern of instability of the vehicles and safety of the passengers, prior to being inundated, which poses a genuine threat to human life and property.

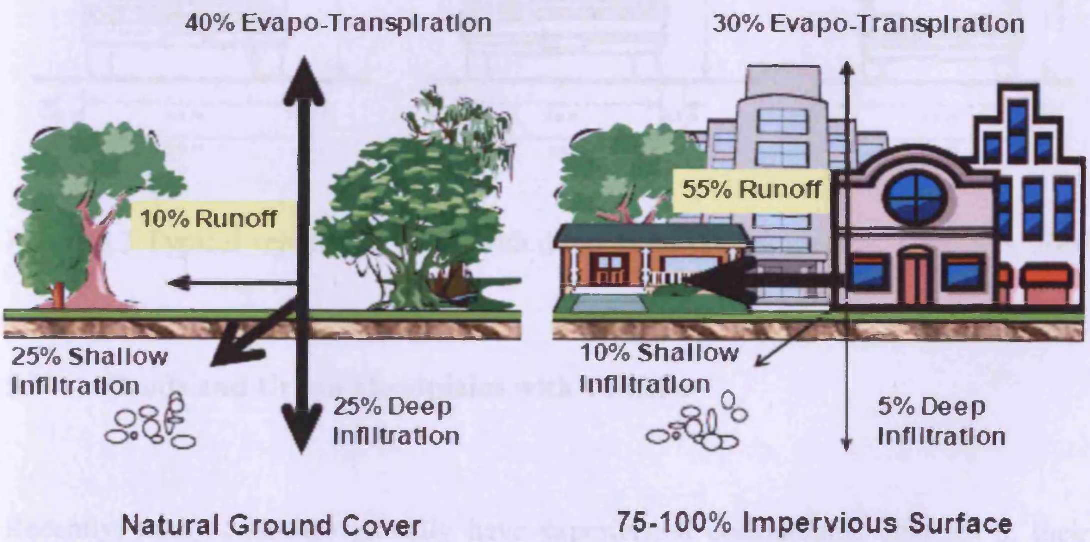


Figure 5.2 Comparison of natural and urban surface areas (OEHHA, 2006)

This hazard also presents a number of potential consequences, "the primary consequence is the injury or death of a person resulting from them being trapped in the vehicle when it loses stability and also due to insufficient time to evacuate. The likelihood of this occurring relates to the behaviour of that person, since it is often the case that people underestimate the velocity or depth of the floodwater and attempt to drive through it when it is in fact unsafe. If the person is trapped in a vehicle in floodwater they are vulnerable to a range of risks e.g. drowning and injury or death caused by debris impact on the vehicle or the vehicle crashing into a structure" (Environment Agency, 2004). With regard to this latter risk, this type of consequence for vehicles on the move will be not considered in this preliminary stage of study.

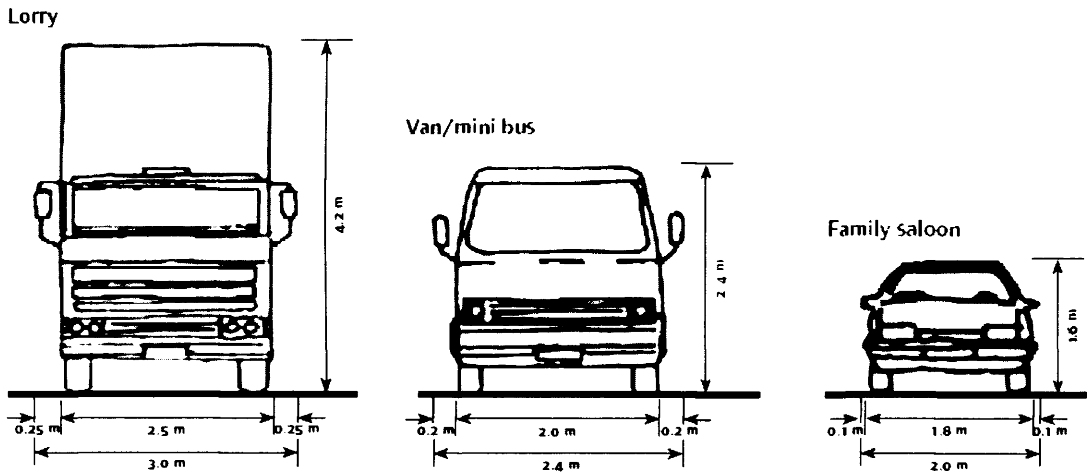


Figure 5.3 Typical vehicles on roads with dimensions (Department of Transport, 2007)

5.3 Floods and Urban Floodplains with Vehicles

Recently, many countries globally have experienced considerable changes in their climatic and meteorological conditions, leading to increased flooding, more pronounced inundation extent and increased frequency in flooding. The problems arising range from minor impacts, such as frequent flash flooding on urban areas, to major incidents, where larger impervious urban floodplains are inundated for several days after an extreme storm event. In particular, flash floods propagate rapidly, which can cause significant risks to human life and properties. These flood situations are becoming more common due to a number of factors that are not related to the estimation of the magnitude and frequency of flooding.

Over spilling and flowing of flood flow over these urban areas becomes a serious problem, where it causes potential risk to human life, health and much damage to property. This flood flow can seriously disrupt public and private transportation by cutting off road and railway networks, as well as leading to floating debris, including vehicles parked along floodplains and large vegetation, such as trees. Rapid movement of this large debris by floodwaters with a seaward flow (i.e. rivers discharge flooding), landward flow (i.e. tsunami and tidal current flooding) and localised overland flow (i.e. flash flooding) after exceptional events have different potential risks to human life and property. This large debris can be washed away by floodwaters, causing damage by colliding with property and causing loss of human life through collision. Often the effects of flooding are made worse due to this debris being transported and blocking flow paths at the downstream end of a river or channel.

On Monday 16th August 2004, a small picturesque town along the UK North Cornwall coast, namely Boscastle, was struck by a devastating flash flood. This flood took place over a short river basin reach, with a steep terrain and a flat urban surface set up. It was caused by heavy rainfall of up to 200 mm in a period of 5 hours, which the small river valley just could not handle. This is one of the best recorded extreme flood events in UK with trans-critical flows. What makes Boscastle so relevant to this study is the number of vehicles that were swept away. The Environment Agency

(2004) and North Cornwall District Council (2005) reported millions of pounds of damage (as shown in Figure 5.4) were caused as the waters inundated buildings, destroyed bridges and an estimated 115 vehicles were washed out to the harbour. In this case, some of the vehicles and other debris were floated and swept off by the floodwater, and were then caught under the local bridge, blocking the flow path and finally causing the bridge to collapse under the stress.

Figure 5.4 Boscastle flood on Monday 16th August 2004 (Photographs courtesy of North Cornwall District Council, 2005)

Some other vehicles and debris were washed straight out into the sea, without any obstructions to the flow, other than delaying the upstream waters reaching the sea. At this point, the Boscastle flood highlights the problems caused by this large debris movement and its effect on floodwater flows. Thus, further research studies are needed to acquire a better understanding of the hydrodynamics of such floodwater flows over urban floodplains with vehicles, and also the influence of typical floodwater flows on the stability of vehicles particularly on threshold conditions. Flooding, such as that occurring in Boscastle, cannot easily be prevented; however, with an improved understanding of the impact of vehicles and debris on floodwater flows then possible disastrous consequences can be reduced or ideally eliminated.

In the recent years, there have been numerous studies and increasing interests of engineers and researchers on urban flooding and floodplains, inline with recent developments in the application of floods on bridges, built structures, roads and subway networks. Some of these experimental studies were undertaken only for steady flow conditions. Nanía et al. (2004) conducted an experimental study of the dividing flow in steep street crossings. Some similar studies were investigated by Shabayek et al. (2002), Soares-Frazão and Zech (2002) and, Rivière and Perkins (2004). Ishigaki et al. (2003) studied the flood propagation both through streets and subway networks for an urban area. Soares-Frazão and Zech (2007) presented an experimental study of dam break flow against an isolated structure. On the other hand, some of the researchers have modelled urban flooding with numerical approaches. Mark et al. (2004) outlined a modelling approach and principle for analyses of urban flooding using a one dimensional hydrodynamic model. Liang et al. (2007) modelled supercritical flow past buildings in urban environments, Boonya-Aroonnet et al. (2002), Mark et al. (2001), Ishikawa et al. (2002), Kolsky et al. (1999), Holder et al.

(2002), and Schmitt et al. (2002) have all further studied the modelling of urban flooding for different applications.

To the knowledge of the author, not much previous work has been reported for floodwater flows over urban areas with vehicles. Existing studies on the stability limit of motor vehicles in floodwaters is also limited. In 1967, Bonham and Hattersley studied the hydraulic model testing of the stability of vehicles on flooded crossings. Subsequently Gordon and Stone (1973) studied experimentally the stability of a Morris Mini car on flooded roads with the two back wheels being locked against movement. The vehicle stability condition was obtained when the horizontal force was just balanced by the product of the measured vertical reaction force and the coefficient of friction. In this approach it was proposed that it was important to estimate the appropriate value of the coefficient of friction. These corresponding studies were then applied in Australia with reference to the Floodplain Development Manual by the New South Wales Government (1986) and the Australian Rainfall and Runoff by Institution of Engineers, Australia (1987).

In addition to these research studies, other studies by Keller and Mitsch (1992, 1993) included a mathematical analysis to investigate the stability of vehicles on flooded roadways for idealised Suzuki Swifts, Ford Lasers and Toyota Corollas. This analysis provides a simple method for estimating the forces exerted on stationary vehicles in floodwaters, with the analysis including the vehicle mass and dimensions, buoyancy and drag forces, which resulted in the corresponding incipient velocity formula for a partially submerged vehicle. Based on this work, the Environment Agency/DEFRA (2006) has highlighted a flood hazard matrix for vehicles in their report of flood risks in the UK. However, this referenced work was limited to computer simulations without any validation by hydraulic testing or experimental studies. Also, in considering the significant advancements made over the past couple of years to vehicle design and the materials used, it could be argued that the earlier studies have been applied well beyond their limits. Thus, additional research studies, especially using physical experimental configurations, are urgently needed to address these deficiencies and particularly for the nature and scale of the flood threat.

Also, for existing experimental studies of the stability condition of flooded vehicles, it has usually been assumed that: (i) a model vehicle in a flume experiment was water tight and would float as the incoming water depth exceeded the height of the vehicle; (ii) the coefficient of friction, and drag, was often set at a constant value; and (iii) the results obtained were only applicable to partially submerged vehicles, and the stability threshold for fully submerged vehicles was not taken into account. According to the author's recent observation of flooded vehicles, it has been found that a completely water tight vehicle is too idealised in a real event of urban flooding and the coefficients of friction and drag usually change with the incoming water depth. Therefore, it was deemed necessary to conduct further studies to get more accurate predictions of the stability threshold of flooded vehicles. All of these observations and the more recent design of vehicles have been taken into consideration for further investigation in this chapter.

5.4 Background Theory and Governing Equations

In the first instance, the background theory and governing equations used to describe the floodwater flow over floodplains with vehicles will be introduced and discussed here to provide a clear understanding for further study in this chapter.

5.4.1 Hydrodynamic Forces

Moving water particularly flood flows create hydrodynamic forces which can move vehicles on urban floodplains. An understanding of the relevant forces involved is necessary to attempt to characterise the stability threshold of vehicles in floodwater flows and the relationship of the gravitation force (vehicle weight), buoyancy force, friction force, and drag force due to the water flow. Figure 5.5 shows the main forces acting on the vehicle in a flood condition.

Referring to the forces acting on a vehicle in the horizontal and vertical directions, Gordon and Stone (1973) defined the limit of vehicle stability as:

$$H / \mu R = 1 \tag{5.1}$$

where H is the measured horizontal force; μ is the friction coefficient; and R is the measured vertical force reaction.

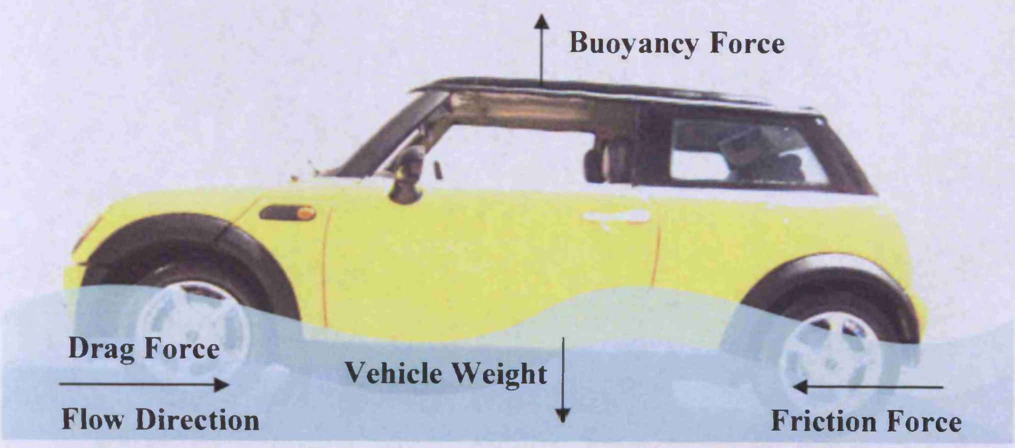


Figure 5.5 Forces acting on the vehicle in a flood condition

5.4.1.1 Buoyancy Force

Keller and Mitsch (1993) studied the forces acting on a stationary vehicle in flowing water with a simple theoretical approach. For the forces in the vertical direction, the vehicle will be carried by the flow when the buoyancy force is greater than the vehicle weight. This buoyancy force is given by:

$$F_B = \rho \, g \, V \tag{5.2}$$

where ρ is the density of water; g is the acceleration due to gravity; and V is the submerged volume.

5.4.1.2 Drag Force

For the forces in the horizontal direction, Keller and Mitsch (1993) stated that the instability of a vehicle occurs when the drag force at an axle is equal to the restoring force due to the axle load. As the floodwater passes through a vehicle, a frictional surface force is exerted on its surface. If the flow intensity is relatively low, then the surface friction is the main force acting on the vehicle as a drag force. If it is relatively high, then separation of the streamlines in the form of a small wake occurs behind the top edge of the vehicle and vortexes form. Hence, a pressure difference develops between the front and rear of the vehicle, which causes the form resistance. The resultant of the surface resistance and form resistance can be called the drag force (Chien and Wan 1999).

The drag force, in general, is made up of two components, including: the pressure (or form) drag and the surface (or skin friction) drag. This mechanical drag force is generated by the interaction between the water flow and the vehicle shape, and is given by:

$$F_D = \frac{1}{2} \rho C_D A v^2 \qquad (5.3)$$

where C_D is the drag coefficient, which is related to the flow pattern and the vehicle dimensions; A is the submerged area projected normal to the flow; and v is the velocity of flow.

5.4.1.3 Friction Force

The primary hydrodynamic force on the vehicle in the longitudinal direction is the restoring force on the axle, namely the friction force, acting between the vehicle tyres and the floodplain surface, which leads to the vehicle being lifted off the bed and swept downstream. It is assumed that the wheels of a vehicle are all locked against any movement as it parks on a floodplain, thus a frictional force will be produced to resist the vehicle sliding on the floodplain surface instead of rolling. The frictional force preventing the vehicle from sliding is the total resistance acted on the four wheels by the floodplain surfaces, and is given as:

$$F_R = \mu N \qquad (5.4)$$

where μ is the friction coefficient, set at 0.3 after Bonham and Hattersley (1967), while Gordon and Stone (1973) implied that the friction coefficient ranges from 0.3 to

1.0, and Cox and Ball (2001) commented that the value of friction coefficient is dependant upon the conditions of tyres and the contact surface; and N is the axle load in wet conditions (also the axle load in dry conditions minus the buoyancy force on the vehicle, distributed on the front and rear axles according to the centre of buoyancy location). As shown in Equation 5.4, the coefficient of friction does not relate to the mass of the object or the contact surface area, it is simply a material property specific to the two bodies involved. Guidelines can be found for these coefficient values between the two materials; however the true values are best determined experimentally. In general, the magnitude of the friction force is governed by the magnitude of the normal force. There is no friction force once the vehicle is lifted off from the surface.

5.4.2 Instability Threshold Values

Vehicles on floodplains can start to move by sliding, rolling or jumping under the action of floodwater according to the intensity of the incoming flow, with the distribution of the velocity and water depth around the vehicles being very complicated. For simplification of the current analysis, the instability threshold of a stationary vehicle is considered only for the first motion pattern in this study.

As the partially or fully submerged vehicle starts to slide along a surface, the frictional force preventing the vehicle from sliding is just balanced by the drag force induced by the incoming flow, thus the corresponding criterion of instability threshold is given by:

$$F_R = F_D \tag{5.5}$$

Substituting Equations 5.3 and 5.4, the velocity at the threshold of instability of each vehicle can be expressed as:

$$v = 2\,[\,F_R\,/\,(\,\rho\,C_D A\,)\,]^{1/2} \tag{5.6}$$

where C_D, the drag coefficient, is set at 1.1 if the water level is below the vehicle chassis and 1.15 if it is above the chassis (Keller and Mitsch, 1993). This velocity caused a parked vehicle to slide and is measured in m/s. In general, the faster the water moves, the more the hydrodynamic pressure on the vehicle. While the velocity is one of the key factors in determining the potential impact of floods on vehicle stability, the total impact of moving water is also related to the depth of flooding. These two principal factors of hazard (i.e. the floodwater depth and flow velocity) combine to affect the threshold of vehicle instability in urban floodplains and this study focuses on understanding the impact of the hydrodynamic processes involving both parameters.

5.4.3 Hydraulic Similarity

Hydraulic similarity is the relationship between the properties of the model and the prototype. There are three types of hydraulic similarity to consider herewith: geometric (shape), kinematic (motion), and dynamic (force). Unfortunately it is generally impossible to satisfy all three types of similarity with a scaled down model. Therefore, the dominant forces must be identified and correctly reproduced, at the expense of other less dominant forces. As gravitational forces are dominant in this study, the homogeneity will be based solely upon the Froude number as it is more applicable. Thus, the Froude number in the model and prototype (subscripts *M* and *P*) will be best constant as given by:

$$F_M = F_P \tag{5.7}$$

or, substituting for Froude numbers, gives:

$$\left[\frac{v}{(gL)^{1/2}}\right]_M = \left[\frac{v}{(gL)^{1/2}}\right]_P \Rightarrow \left[\frac{v_M}{(gL_M)^{1/2}}\right] = \left[\frac{v_P}{(gL_P)^{1/2}}\right] \tag{5.8}$$

where v is a characteristic velocity; L is a characteristic length; and g is acceleration due to gravity. Since gravity is the same for both the model and the prototype then it cancels out giving:

$$\frac{v_M}{v_P} = \left(\frac{L_M}{L_P}\right)^{1/2} \tag{5.9}$$

For an undistorted model the ratio $\frac{L_M}{L_P}$ is known as the scale factor of the model giving:

$$\therefore \frac{L_M}{L_P} = \frac{1}{X} \tag{5.10}$$

where X represents the geometric scale used. Combining Equations 5.9 and 5.10 gives:

$$\frac{v_M}{v_P} = \left(\frac{1}{X^{1/2}}\right) \Rightarrow v_M = \frac{v_P}{X^{1/2}} \tag{5.11}$$

5.5 Laboratory Experimental Study

Prior to the effective development of hydrodynamic models, physical experimental studies were extensively used in many engineering projects to gain insight into the complex hydrodynamic features associated with such potential projects. Such laboratory experiments offer an opportunity for calibration and validation of the hydrodynamic models, which are developed for more complex investigations of various aspects of hydraulic and environmental engineering. With the design and construction of an experimental study, which could then be used to validate the hydrodynamic model, this has been the main objective of this study to understand the processes of floodwater flow, particularly on the hydrodynamic processes over floodplains with vehicles. It is also important to undertake a laboratory study of these flow processes, so the fundamental qualitative data could be acquired through observation of the flow characteristics for this type of flow condition. The scope of this laboratory analysis was not to recreate a particular case study at scale; therefore it was not considered that a distorted scale model would be required at this stage. In fact this part of the study was simply to create a scaled model version of a single stationary vehicle for the purposes of a hydrodynamic analysis with real life conditions.

5.5.1 Laboratory Flumes

The investigations on the hydrodynamic processes of urban floodplains with vehicles were conducted in the Hydraulics Laboratory of the School of Engineering at Cardiff University, UK. Numerous investigations were planned and undertaken by conducting a series of experimental studies on scaled die cast model vehicles including: a

Mitsubishi Pajero, BMW M5, Mini Cooper, and a Ford Escort, in two hydraulics recirculation flumes, i.e. a small and a wide laboratory flume.

5.5.1.1 Small Laboratory Flume

A small laboratory flume was first selected for the initial stage of the experimental studies to validate the accuracy of the scaled up prediction, with the theory of hydraulic similarity, in order to understand the influence of floodwater flows particularly on the stability of prototype vehicles in real floodplains. The experiment flume was 10.0 m long, 0.30 m deep and 0.30 m wide, with a horizontal bed made of a rough surface and two side glass walls (as shown in Figure 5.6).

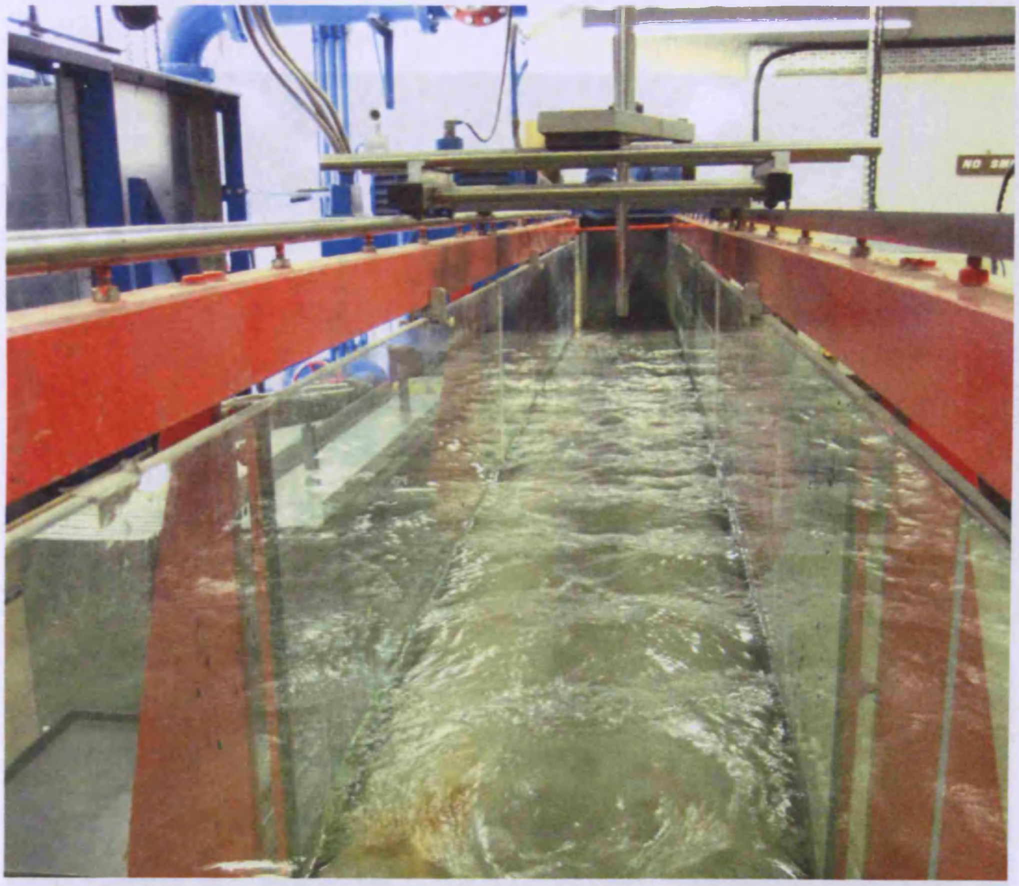


Figure 5.6 View of the small laboratory flume

The flume compromised a rectangular channel section with inlet and discharge tanks at either end. The end weir and the bed slope of the flume were adjusted manually for a series of test cases. The discharge flows were controlled electronically and there was a digital display to show the flow rates.

5.5.1.2 Wide Laboratory Flume

With consideration of the possible hydraulic effects of side walls in the small flume, particularly with large scaled model vehicles, a wide flume was selected to further investigate the critical values of the threshold conditions that affect the instability of vehicles in urban floodplains. This wide flume had a length of 10.0 m, a depth of 0.3 m and a width of 1.2 m, as shown in Figure 5.7.

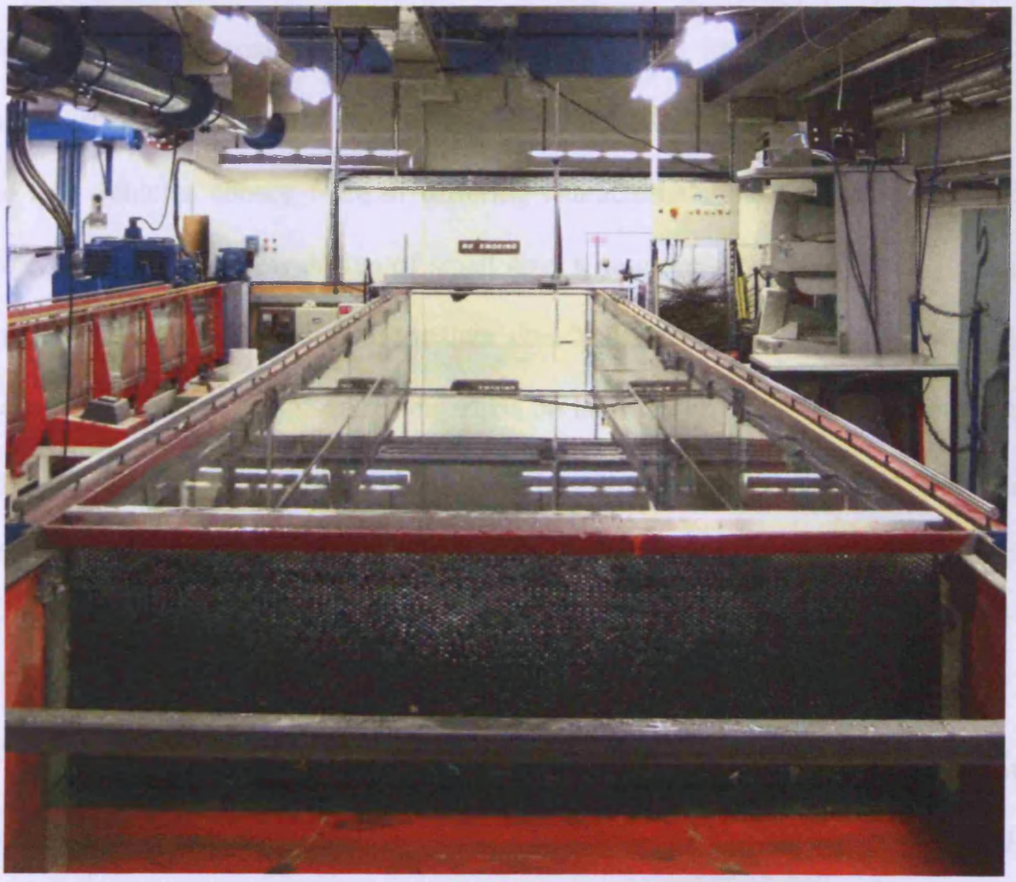


Figure 5.7 View of the wide laboratory flume

The flume was constructed of glass sides and a rough surface bed. It was equipped with measuring gauge pressure centred along the flume sections. The water was first pumped through a delivery pipe underneath the flume, through a grill and into the inlet reservoir at the upstream end of the flume. The water was then passed through a honeycomb baffle to reduce non-uniformities in the flow structure before entering the flume. An adjustable steel thin plate weir was designed and constructed at the downstream end to provide the control for the flow regimes and depths throughout the experiment. This was manually operated through a range of elevations from 0 to 330 mm above the bed. The water flow was adjusted manually and was measured through a calibrated flow meter attached to a flow computer.

5.5.2 Scaled Model Vehicles

The four types of scaled model vehicles used in this investigation were: a Mini Cooper, BMW M5, Mitsubishi Pajero, and a Ford Escort (as shown in Figure 5.8). The four vehicles chosen were of differing characteristics in terms of size, design, shape, and weight: a new design of small size, a new design of medium size, a large size vehicle, and an old design of medium size. This range of vehicles was considered to provide a good coverage and comparison on how the size (i.e. small, medium, and large), design shape (i.e. new and old with aerodynamic considerations) and weight (i.e. light and heavy) of vehicles would affect the conditions needed for the threshold of vehicle instability in urban floodplains.

Small size and light weight vehicles are generally less stable under the circumstance of flooded surfaces, and thus attention was focused initially on the Mini Cooper. Today's vehicles on roads are different in design from the past, where new improvements in these vehicle design have taken into consideration aerodynamic design, although these concerns are not as strong as they may be in a sports car.

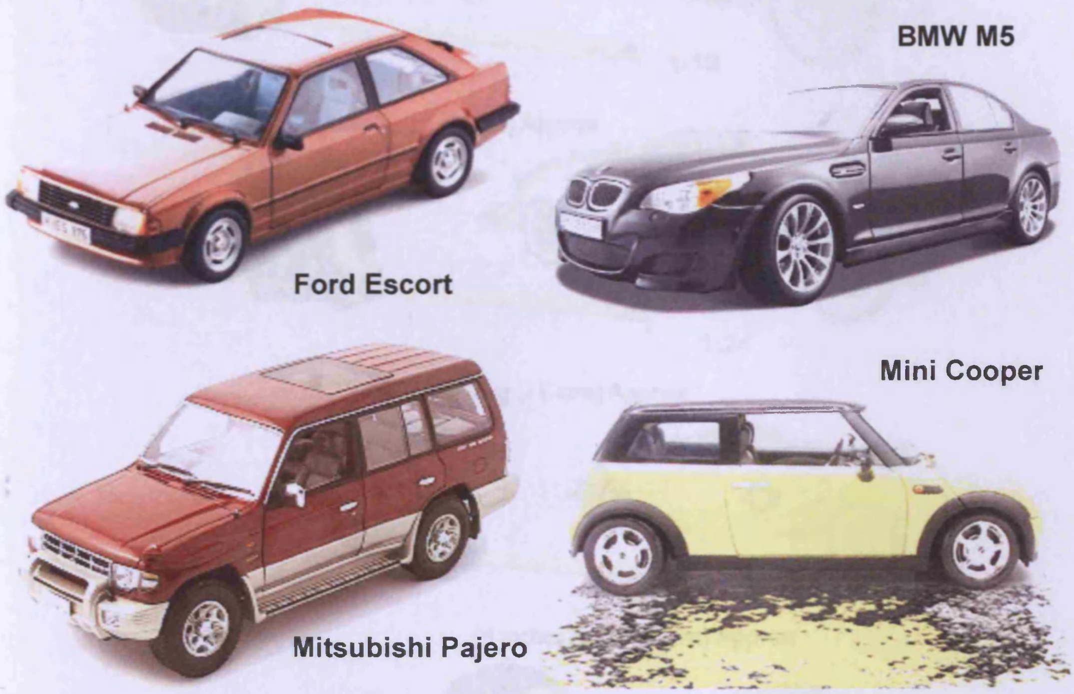


Figure 5.8 Model vehicles used

In the current study, the physical model vehicles provide a good comparison on how the vehicle's size, design shape, and weight can affect the threshold of instability in flooded waters. Figure 5.9 shows typical scales of die cast model vehicles which were available for this experiment. Ensuring that the models used were of the appropriate scale was important to provide adequate results. Thus, two sets of different models with the scales of 1:43 (e.g. smaller scale) and 1:18 (e.g. larger scale) were adopted, where these scales were best fitted with several requirements for this study. The die cast models were produced by manufacturers to an exact geometric scale, meaning that as well as every length being scaled correctly, all angles were also equal in the model and prototype; that fulfilled, the geometric similarity for a scaled model was satisfied.

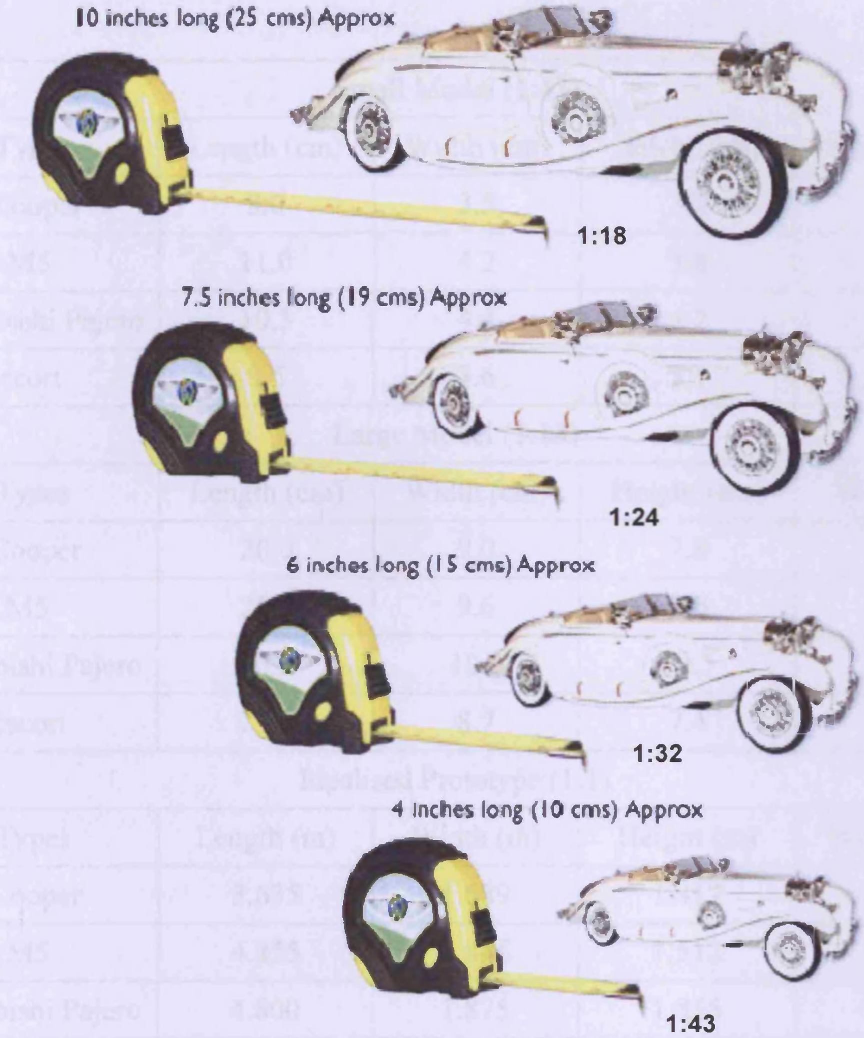


Figure 5.9 Typical scales of die cast model vehicles (Photograph courtesy of Model Car World)

On inspection the tyres of each vehicle appeared to be made from the same material. Each of the model and idealised prototype vehicles varied in dimensions, detailed vehicle specifications are listed in Table 5.1. Vehicles of the type under study were generally built to be as stable as possible with a centre of gravity as close to the centre of the car as possible. It appeared that the Mitsubishi Pajero was the most stable vehicle, with the biggest size and heaviest weight among the vehicles investigated.

Table 5.1 Specifications of scaled model and idealised prototype vehicles

Small Model (1:43)				
Types	Length (cm)	Width (cm)	Height (cm)	Weight (g)
Mini Cooper	8.0	3.5	3.2	53.8
BMW M5	11.0	4.2	3.8	82.8
Mitsubishi Pajero	10.5	4.4	4.2	76.6
Fort Escort	9.5	3.6	3.1	65.0
Large Model (1:18)				
Types	Length (cm)	Width (cm)	Height (cm)	Weight (g)
Mini Cooper	20.0	9.0	7.8	650
BMW M5	25.5	9.6	8.0	710
Mitsubishi Pajero	26.5	10.0	10.5	920
Ford Escort	23.0	8.7	7.4	760
Idealised Prototype (1:1)				
Types	Length (m)	Width (m)	Height (m)	Weight (kg)
Mini Cooper	3.635	1.689	1.417	1132
BMW M5	4.855	1.846	1.512	1830
Mitsubishi Pajero	4.800	1.875	1.855	2300
Ford Escort	4.148	1.563	1.335	1900

To simulate the handbrake being left on, then the wheels of the model were glued so that they would not rotate freely. Three of the models were without front windows, so plastic tape was attached and glued around the edges to make the model vehicle initially water tight.

5.5.3 Experimental Measurements

Focusing on the stationary scaled model vehicle, this work investigated the critical conditions of floodwater discharge, flow velocity and floodwater depth at the threshold of vehicle instability. The case without model vehicles in the flume was also studied to compare the results for no obstruction to the flow and for the purposes of experiment control. The water discharge flows in the flumes were measured through a calibrated flow meter attached to a flow computer. Water depth measurements were made through the use of a simple pointer depth gauge device, which had a millimetre scale attached. The scale of gauge was first zeroed against the bed of the flume and the water depth was measured by moving the pointer to the water surface. This relied heavily upon visual observations, but was considered accurate enough for the purposes of this study with average results being recorded.

Flow velocity meters commonly used in laboratory flumes include the following types: propeller, electromagnetic, Pivot tube, hot-film anemometer, laser-Doppler anemometer, and acoustic-Doppler anemometer. In this laboratory study the propeller type velocity meter was used, where the number of revolutions of the propeller is proportional to the flow speed parallel to propeller axis. The reasons to choose propeller, referred to herein as the Nixon Streamflo velocity meter (see Figure 5.10), are because it is the advantage of being robust, capable of recording the very low velocities occurring in this study, and a completely portable system with digital indicator requiring no mains electricity supply. This was ideal for carrying around from one measuring point to the next. The system was highly sensitive with an accuracy of ± 2% and a read frequency of over 1 to 10 seconds, responding to velocities as low as 5 cm/s and up to 300 cm/s.

The propeller measuring head, with a cage approximately 15 mm diameter, enabled readings to be taken in confined spaces, thus accurate measurements of velocity were possible for the hydraulic model. This propeller was small in order to minimise flow interference and allow deployment close to the bed and banks to provide sufficient readings for the lowest flow in shallow waters; but a small meter was more susceptible to damage and fouling, where several precaution are steps had to be considered.

The experiments were carried out under carefully controlled conditions with occasional examination of the probe tip being undertaken to ensure complete cleanliness, where some foreign matter, particularly fine hair may some times foul the rotor spindle. This will normally be apparent by a serious and unexpected drop in indicated frequencies of complete stoppage of the rotor. Although these meters undoubtedly may modify the flow around them, calibration is fairly straightforward and was carried out every time before the start of a new experiment.

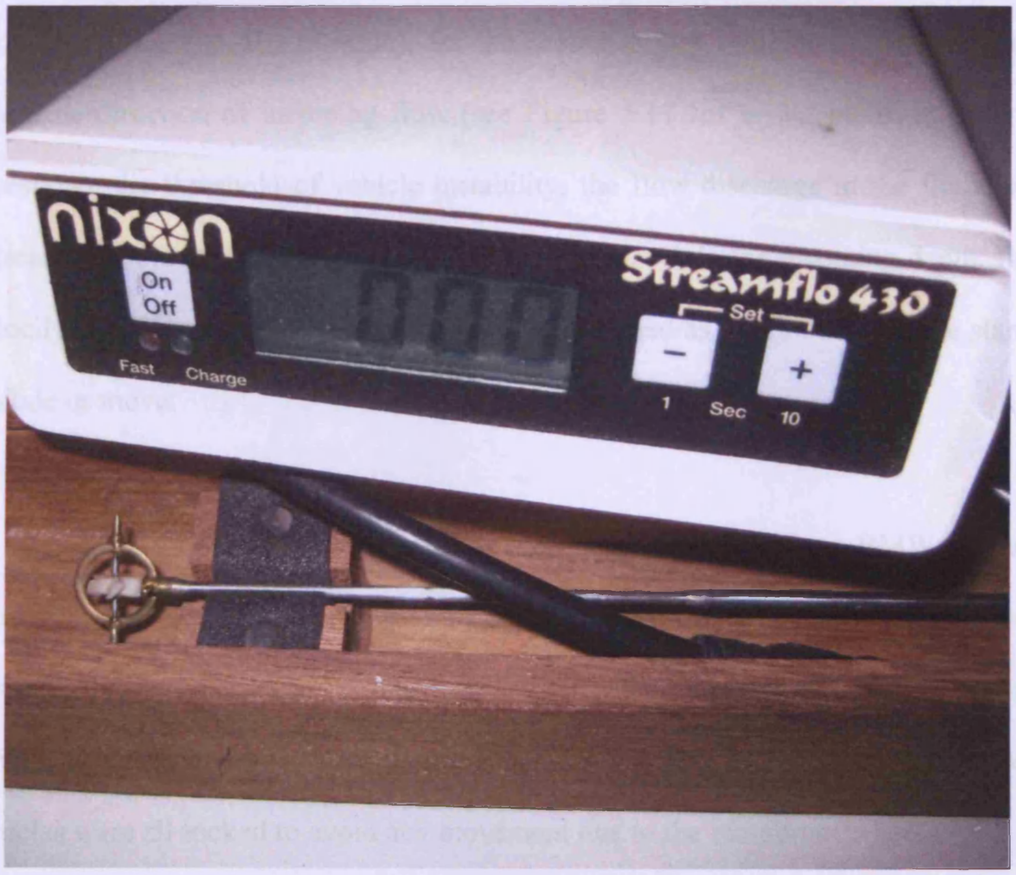


Figure 5.10 Velocity meter

5.5.4 Experimental Procedures

Extensive investigations of the hydrodynamics of urban floodplains with vehicles were undertaken by conducting a series of experimental studies on the scaled model vehicles in the hydraulic laboratory flumes. A series of experimental studies were carried out following the procedures as discussed herewith on: the threshold of vehicle instability, the effects of vehicles orientation and ground surface gradient, the vehicle stability on urban floodplains, and the influence of vehicles on floodwater flows.

5.5.4.1 Threshold of Vehicle Instability

In the initial stage of the current study, the experiments were undertaken in the small hydraulic flume (i.e. 0.3 m wide), for the scaled model vehicles with the rear end faced the direction of incoming flow (see Figure 5.11 for layout plan). In order to investigate the threshold of vehicle instability, the flow discharge in the flume was increased gradually to a steady value of increments, while the incoming depth, flow velocity and the corresponding discharge were recorded as the flooded vehicle started to slide or move.

Three types of the model vehicles (i.e. the Mitsubishi Pajero, BMW M5, and Mini Cooper), with two scales of a smaller (i.e. 1:43) and larger (i.e. 1:18), were considered to provide a good comparison and for validation purposes. Considering the vehicles are stationary or parked along the floodplains, the wheels of the model vehicles were all locked to avoid any movement due to the rotation of wheels.

The experimental results obtained for the smaller scale model vehicles were first scaled up using the theory of hydraulic similarity to the larger scale and the accuracy of this scaled up prediction was then validated using the experimental results obtained for the same scale of model vehicle. Similarly, the experiment results were scaled up to the idealised prototype conditions.

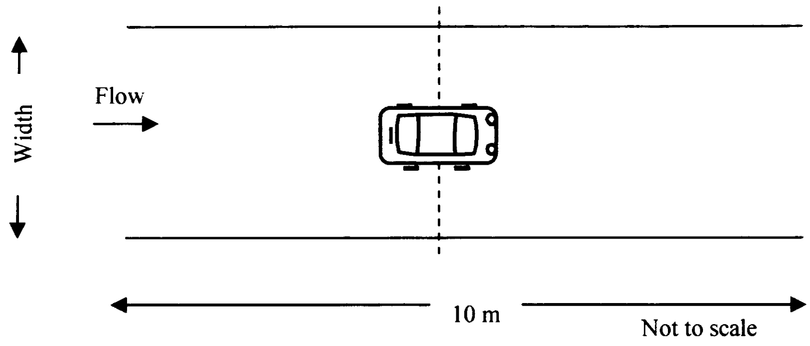


Figure 5.11 Layout plan for the small flume, showing the rear end of the vehicle facing the flow

5.5.4.2 Effects of Vehicle Orientation

The effects of the vehicles at different orientations to the flow were investigated in this study, accordingly to the condition of sliding balance. The investigation was undertaken in the small hydraulics flume (i.e. 0.3 m wide) for a flat bed, where the gradient of the flume was set to zero. Focusing on the same type of small scaled stationary model vehicles, with the same procedures as discussed previously, the experiment study was repeated by turning around the rear or front ends of model vehicles for the different orientations of 0^{o}, 15^{o}, 30^{o}, 45^{o}, 60^{o}, 75^{o}, and 90^{o} relative to the flow (as shown in Figure 5.12). The model vehicles were ideally placed at the same location in the flume for every test, with different orientations to the flow, in order to reduce inconsistencies in the experimental results.

Throughout the study, as the lowest threshold values obtained, the specific orientation relative to the flow was identified for the critical threshold conditions that affected the instability of each vehicle. Vehicles in this specific orientation to the flow were generally less stable under condition of flooding, and thus attention was focused in the current study, where this orientation will be selected for all the investigations after this as one of the critical condition to threshold the instability of vehicles.

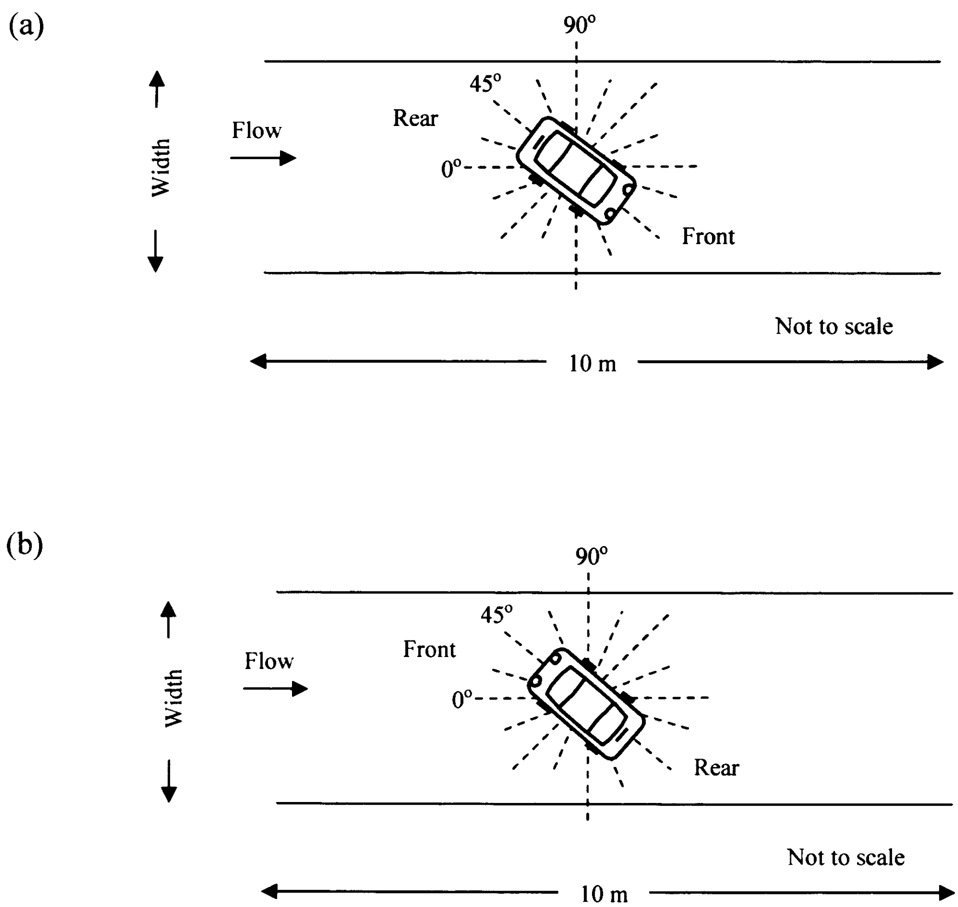


Figure 5.12 Layout plan for the small flume, showing: (a) rear and (b) front ends of vehicle for different orientations relative to the flow

5.5.4.3 Effects of Ground Surface Gradient

Further investigations were also undertaken to see how vehicles begin to move in different ground surface gradients for the critical threshold conditions of instability.

The surface gradient indicated that the ground surface's inclination from the normal was significant for current study. The experiments were first tested for the 1:43 scaled model vehicles in the small hydraulic flume, with previous recommended orientation to the flow, at four different surface gradients of 1:100, 1:200, 1:300, and 1:1000 (see Figure 5.13).

Again the discharge was increased gradually to a steady value of increments until movement occurred. The water depth and the flow velocity were recorded at the time of triggered movement. On the other hand, each of the processes was repeated with the 1:18 scaled models in the wide flume (i.e. 1.2 m wide) for results comparison. These experiments were eventually undertaken to show the effects of ground surface gradient on the forces needed at the threshold of vehicle instability.

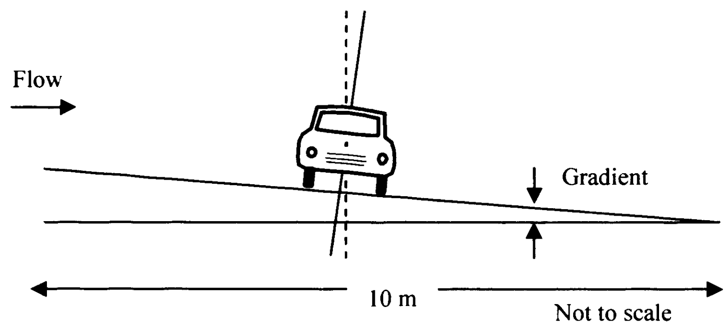


Figure 5.13 Sketch of a model vehicle in the flume with ground surface gradient

5.5.4.4 Vehicle Stability in Urban Floodplains

In order to study the vehicle stability in critical threshold conditions, model vehicles in a specific orientation to the incoming flow was selected based on the recommendation in previous experiments (layout plan as shown in Figure 5.14). This experiment study focused on three stationary small scaled model vehicles (i.e. the

Mitsubishi Pajero, BMW M5, and Mini Cooper) in the small hydraulics flume. Experiments were conducted separately for each vehicle at a starting flow, and then the flow was constantly increased until the threshold of stability of the vehicle was achieved. The critical values of the corresponding flow velocity and floodwater depth that triggered the movement of the vehicles in flooded urban surfaces were recorded. This was repeated at least three times until the results were found to be consistent. The critical threshold values from the experiments were then scaled up with the theory of hydraulic similarity, as in Equations 5.10 and 5.11, to interpret to the idealised prototype conditions.

All experiments undertaken so far were only looked for critical conditions, under which the vehicle begins to be moved with a recommended orientation of vehicle to the flow. This experiment is very important for the studies relating to flood risk management since it provides useful guidelines and procedures for the evaluation of the critical conditions for vehicle stability on floodwater flows. It is also helpful for assessing the flood hazard of vehicles in urban floodplains, particularly in terms of estimating of the principal factors of hazards (i.e. the floodwater depth and flow velocity).

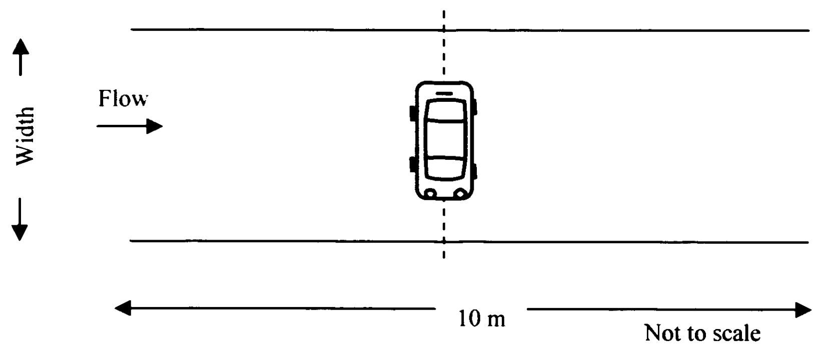


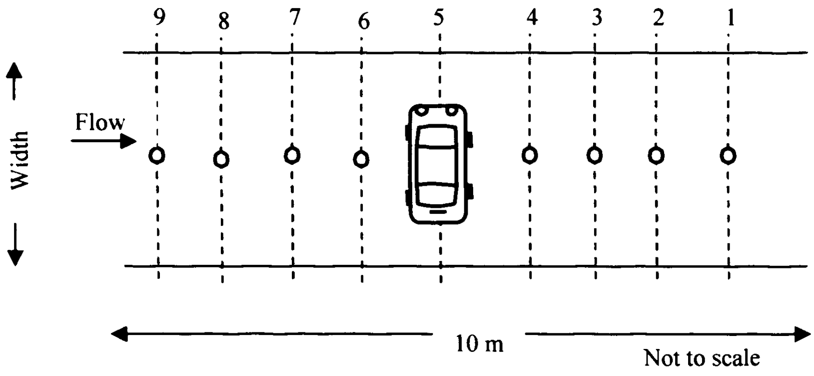
Figure 5.14 Layout plan for the wide flume, showing side of vehicle facing flow

5.5.4.5 Influence of Vehicles on Flood Flows

In order to understand the influence of vehicles on flood flows during the critical conditions of the threshold of instability, it is ideally necessary to be able to determine how the flow velocity vector, water depth, and the elevations of the bed and water surface vary in space and time. To investigate this influence for critical conditions, a recommended orientation of the vehicle to the flow was selected based on the earlier findings.

The experiments were carried out in the wide hydraulics flume for four types of 1:18 scaled model vehicles (i.e. the Mitsubishi Pajero, BMW M5, Mini Cooper, and the Ford Escort) using starting flows of 5.0 l/s and then separate repeated experiments for flows increased in increments of 1.5 l/s until the threshold of stability of the vehicle was achieved. When this threshold condition occurred, the value of the flow was recorded, and the water depths and velocities were measured at eight points along the centre of the flume (as shown in Figure 5.15). This method was repeated at least three times to get an average value for the flow, velocity and depth.

Figure 5.15 shows the measurement points (i.e. points 9, 8 and 7: incident or transmitted points before the model; point 6: front end of the model; point 5: rear end of the model; and points 3, 2 and 1: transmitted points after the model). The case without the vehicles in the flume was also studied, with the same procedures allowing comparisons of the results for the case with no obstruction to the flow. All of the results for this case were recorded and analysed with the same methods.



Points	9	8	7	6	5	4	3	2	1
Locations (m)	9.25	8.25	6.75	5.75	5.00	4.25	3.25	1.75	0.75

Figure 5.15 Layout plan for the wide flume, showing locations of the measurement points

5.6 Experimental Results and Discussions

The hydrodynamics of urban floodplains with vehicles has been systematically studied with the laboratory experiments as discussed. The study has aimed at addressing the deficiencies in the data and developing proper procedures or guidelines to enable an assessment of the flood hazard, especially with regard to the hydrodynamic impact of vehicles in urban floodplains. Therefore, the experimental results and discussions herewith have enabled the establishment of an understanding of the effects of these vehicles on the hydrodynamics of floodwater flows over urban floodplains and, on the other hand, the influence of the floodwater flows on the stability of vehicles. The discussions have also focused on investigating the critical conditions of hazard factors (i.e. floodwater depths and flow velocities) at the threshold of instability for different types of stationary scaled die cast model vehicles in hydraulics flumes, eventually for the application to prototype conditions.

5.6.1 Threshold of Vehicle Instability

In order to investigate the threshold of vehicle instability, detailed experiments for vehicle models at two different scales have been conducted to record the incoming water depth, flow velocity and the corresponding discharge as the flooded vehicles started to move or slide. For the case of small scaled model vehicles, the results are shown in Table 5.2 and Figure 5.16. As an example of the results for the model vehicle of Pajero, the incoming water depths changed from 1.8 to 10.5 cm, with the flow velocities changed from 0.362 to 1.148 m/s, while the corresponding discharges required to threshold movement for the Pajero varied from 6.2 to 17.5 l/s, and the values of the Froude number for different incoming depths ranged from 0.50 to 2.7. The results showed that at very high water depths then a low threshold velocity was needed, while at very shallow depths then a very high velocity was necessary.

Based on the results in Table 5.2, Figure 5.16 shows the incoming depths and corresponding velocities for three different vehicles with the rear end facing the flow. Firstly, it can be seen that for the case where incoming water depth (h_i) is greater than the height of a vehicle (h_v = 0.032 to 0.042 m), the Pajero requires the least threshold velocity. This is due to the aerodynamic streamlining of the vehicle and also the surface area presented to the flow when the vehicle is fully submerged. The Pajero is easily the least aerodynamic vehicle and also presents the largest surface area at the rear of any of the vehicles. This causes the largest pressure drag and therefore the resultant force on the Pajero is much larger than for the other vehicles as given in the Equation 5.3. As both the projected area of the vehicle and the drag coefficient will be larger, a smaller threshold velocity will be needed to create a drag force which is great enough to overcome the friction force.

Table 5.2 Threshold for instability of 1:43 scaled model vehicles

Vehicle 1 = PAJERO						
Runs	Discharge (l/s)	Depth (m)	Velocity (m/s)	Q (m^2/s)	Froude number	Status*
1	17.50	0.105	0.556	0.058	0.547	1
2	13.60	0.093	0.487	0.045	0.510	1
3	11.70	0.080	0.488	0.039	0.550	1
4	10.55	0.077	0.457	0.035	0.525	1
5	9.41	0.069	0.455	0.031	0.553	1
6	8.57	0.065	0.439	0.029	0.550	1
7	7.20	0.061	0.393	0.024	0.509	1
8	6.33	0.055	0.384	0.021	0.522	1
9	5.75	0.053	0.362	0.019	0.502	1
10	5.38	0.048	0.374	0.018	0.544	1
11	7.50	0.040	0.625	0.025	0.998	2
12	8.70	0.030	0.967	0.029	1.782	2
13	7.50	0.024	1.042	0.025	2.147	2
14	6.20	0.018	1.148	0.021	2.732	2
Vehicle 2 = BMW						
Runs	Discharge (l/s)	Depth (m)	Velocity (m/s)	Q (m^2/s)	Froude number	Status*
1	21	0.105	0.667	0.070	0.657	1
2	18.00	0.098	0.612	0.060	0.624	1
3	11.50	0.070	0.548	0.038	0.661	1
4	8.10	0.050	0.540	0.027	0.771	1
5	7.70	0.040	0.642	0.026	1.024	1
6	6.75	0.030	0.750	0.023	1.383	2
7	6.50	0.025	0.867	0.022	1.750	2
8	5.92	0.020	0.987	0.020	2.228	2
9	4.90	0.015	1.089	0.016	2.839	2
Vehicle 3 = MINI						
Runs	Discharge (l/s)	Depth (m)	Velocity (m/s)	Q (m^2/s)	Froude number	Status*
1	22.00	0.112	0.655	0.073	0.625	1
2	16.50	0.092	0.598	0.055	0.629	1
3	11.50	0.065	0.590	0.038	0.739	1
4	8.60	0.050	0.573	0.029	0.819	1
5	6.80	0.040	0.567	0.023	0.905	1
6	7.00	0.030	0.778	0.023	1.434	2
7	6.48	0.025	0.864	0.022	1.745	2
8	5.45	0.015	1.211	0.018	3.157	2
* Status 1 = Fully Submerged; Status 2 = Partially Submerged						

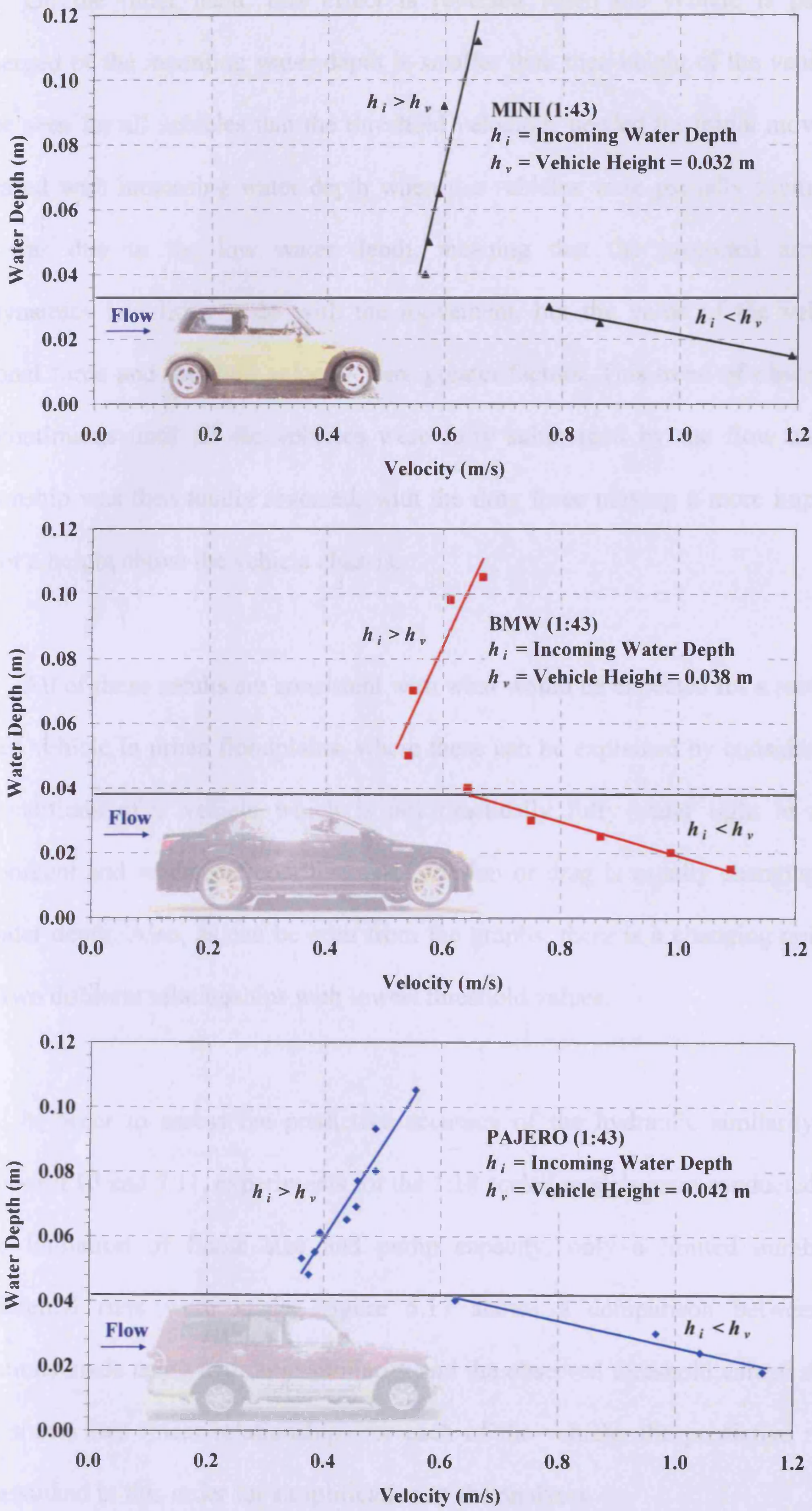


Figure 5.16 Threshold values for model vehicles with rear end facing the flow

On the other hand, this effect is reversed when the vehicle is partially submerged or the incoming water depth is smaller than then height of the vehicle. It can be seen for all vehicles that the threshold velocities needed for initial movement decreased with increasing water depth when the vehicles were partially submerged. This was due to the low water depth, meaning that the projected area and aerodynamics had little to do with the movement, but the value of the vehicle's frictional force and the fluid velocity were greater factors. This trend of observation was continuous until all the vehicles were fully submerged by the flow and this relationship was then totally reversed, with the drag force playing a more important role for a height above the vehicle chassis.

All of these results are consistent with what would be expected for a prototype flooded vehicle in urban floodplains, where these can be explained by considering at the conditions of a vehicle which is not practically fully water tight in a real environment and where the coefficients of friction or drag is usually changing with the water depth. Also, as can be seen from the graphs, there is a changing point for these two different relationships with lowest threshold values.

In order to assess the predictive accuracy of the hydraulic similarity with Equations 5.10 and 5.11, experiments for the 1:18 scaled models were conducted. Due to the limitation of flume size and pump capacity, only a limited number of experimental runs were made. Figure 5.17 shows a comparison between the predictions made using hydraulic similarity and the observed threshold values. As the graph shows two linear relationships for each of the vehicle, the predictive results were assumed in this order for simplification of the analysis.

It can be seen that: (i) as the incoming water depth (h_i) is greater than the height of a vehicle (h_v), the predicted values agree to some extent with the corresponding values for all of the model vehicles; (ii) as a flooded vehicle is partially submerged where incoming water depth is lower than approximately 0.1 m, its threshold value is predicted less accurately due to the complex flow structure around this vehicle.

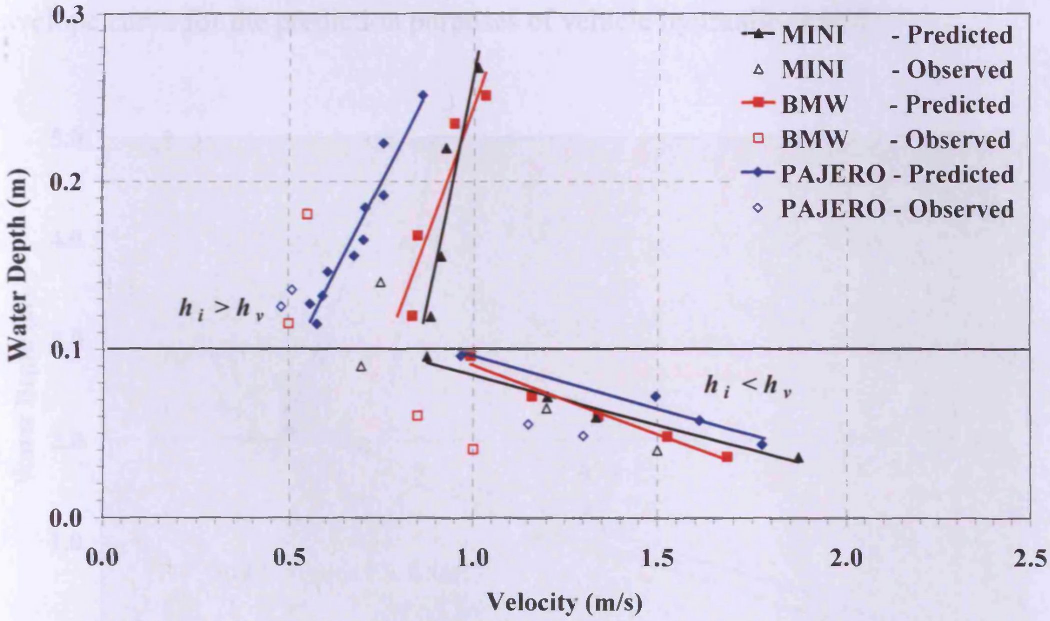


Figure 5.17 Validation of predicted results with observed data for 1:18 scaled models

Although the threshold values for all of the models were overestimated, it is still in a range of acceptability for this early stage of study. The trends of predicted values are in general agreement with the trends of observed data for all types of vehicle models. Therefore, the hydraulic similarity is still capable of estimating the threshold values for the larger scale vehicles and eventually for the estimation of prototype vehicles. In the current stage, hydraulic similarity with Equations of 5.10 and 5.11 has been applied to predict the threshold velocities for three types of vehicles with their idealised prototypes.

Figure 5.18 shows the predicted relationships between the incoming water depths and corresponding threshold velocities for the idealised prototype vehicles. Two set of linear relationships were observed for each type of vehicle for the conditions of fully and partially submerged conditions. These two linear relationships were significantly contrasted with each other in term of gradient, with this significant change being the height of the vehicle at approximately 2.0 m. The graphs have also been easily extrapolated from the linear relationships with the development of an envelope curve for the prediction purposes of vehicle hydraulic stability.

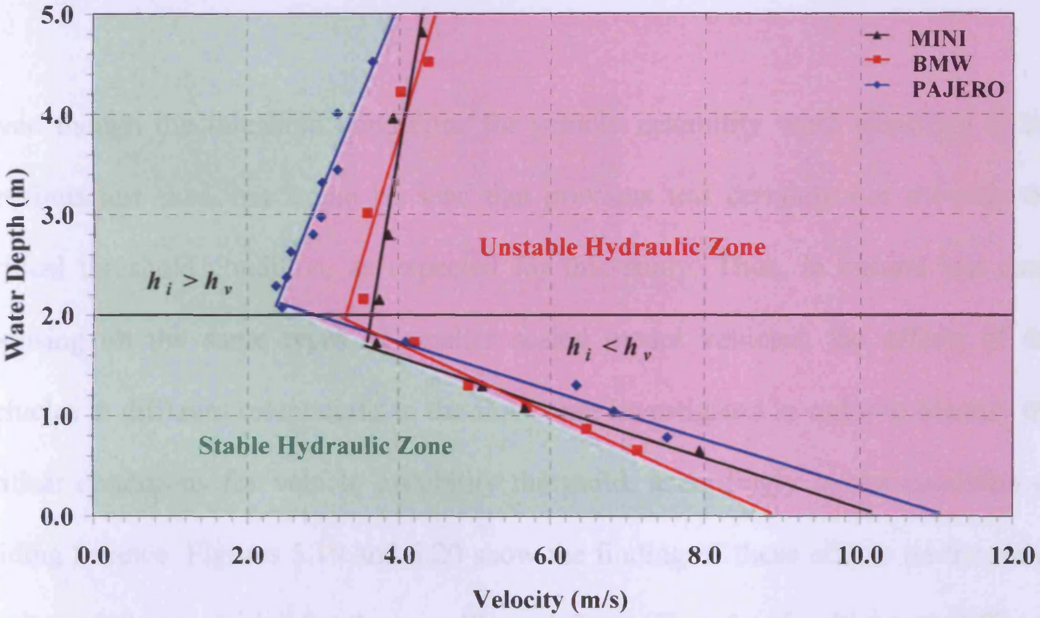


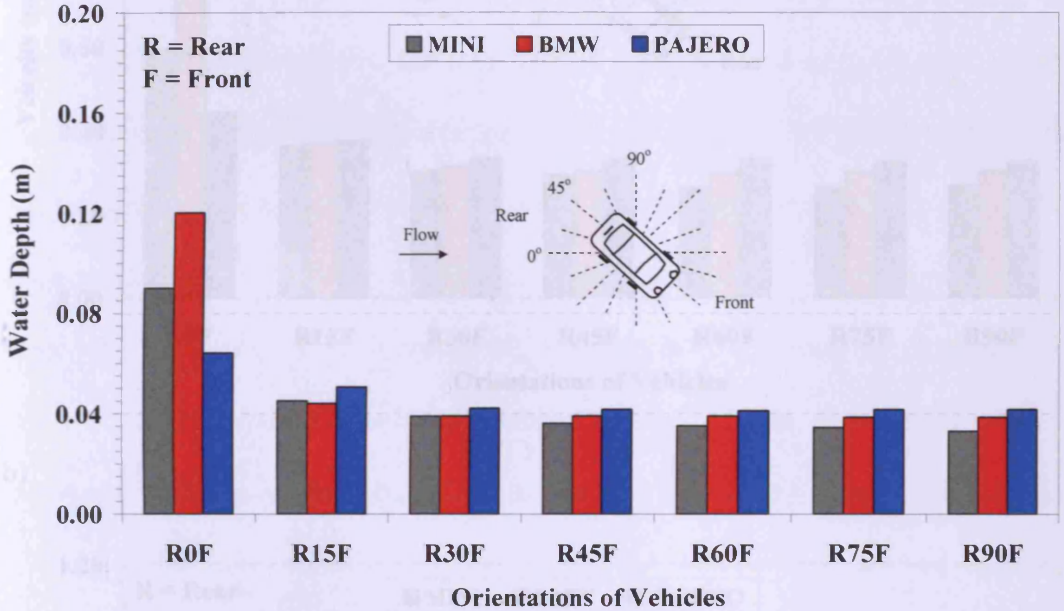
Figure 5.18 Predicted threshold values and stability zones of idealised vehicles

It also can be seen from Figure 5.18 that: (i) the threshold velocity for each fully submerged state, the range is from 2.0 to 4.0 m/s; while for the vehicle in the partially submerged state, the range is from 2.0 to 11.0 m/s; (ii) zones of hydraulic stability for each vehicle were differentiated with colours, where stable zones are shown in green and unstable zones in red; (iii) studies have also shown that deep water depths and high velocities can cause as much hazard as shallow water depths and low velocities. Thus, a simple envelope curve developed in Figure 5.18 can be easily used as a useful guide to evaluate the degree of hydraulic stability for vehicles, and it is also useful for assessing the flood hazard of vehicles in urban floodplains, although it is not a critical case as expected for this stage. All of these findings have provided a fundamental understanding on the threshold conditions of vehicle instability, eventually to support further studies on the critical conditions of vehicles with more confidence.

5.6.2 Effects of Vehicle Orientation

Even though the threshold conditions for vehicle instability were identified in the previous test case, but it can be seen that previous test certainly not showing the critical threshold condition, as expected for this study. Thus, in current test case, focusing on the same types of smaller scaled model vehicles, the effects of the vehicles at different orientations to the flow were investigated in order to identify the critical conditions for vehicle instability threshold, accordingly to the condition of sliding balance. Figures 5.19 and 5.20 show the finding of these effects on the water depth and flow velocity for the rear (R) and front (F) ends of vehicles at different orientations to the flow. Based on the finding, it can be seen that the actual front and rear ends of the vehicles facing flows (i.e. R0F and F0R) resulted in higher values for both the water depth and flow velocity for the threshold of instability. It is not surprising to find that a smooth and continuous curve for an aerodynamic front or rear end of the vehicles were not threshold the movement in the earliest. As a matter of fact, although the aerodynamic design of these vehicles plays a prominent role in hydraulic drag reduction, the smoothing front and rear ends of these vehicles facing flows reduces the extent and intensity of the high pressure. As a result, vehicles at these orientations to the flow required a longer time, and higher values for water depth and/or flow velocity, to threshold the vehicle instability.

(a)



(b)

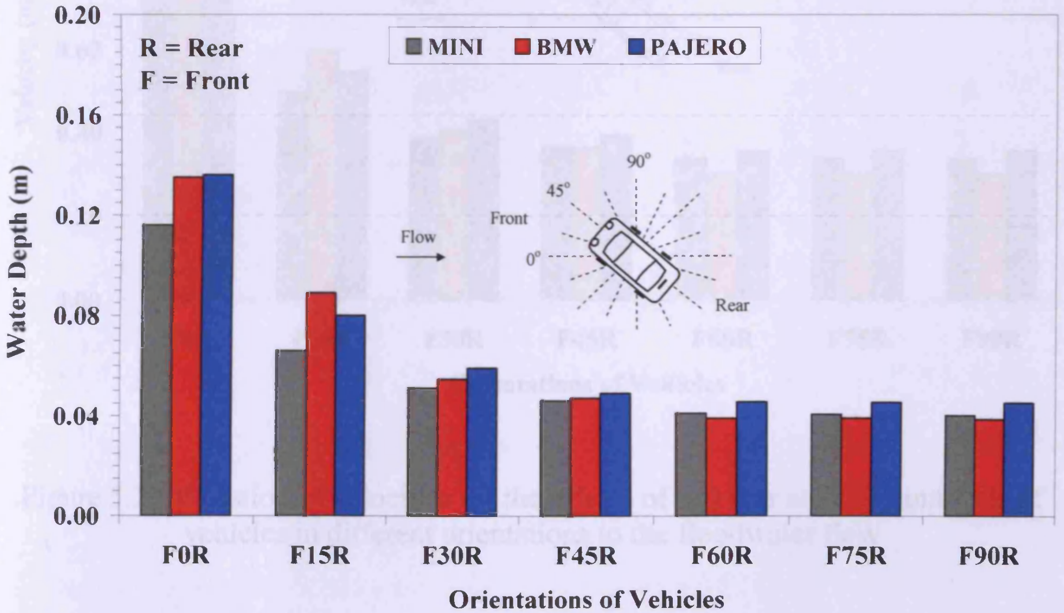
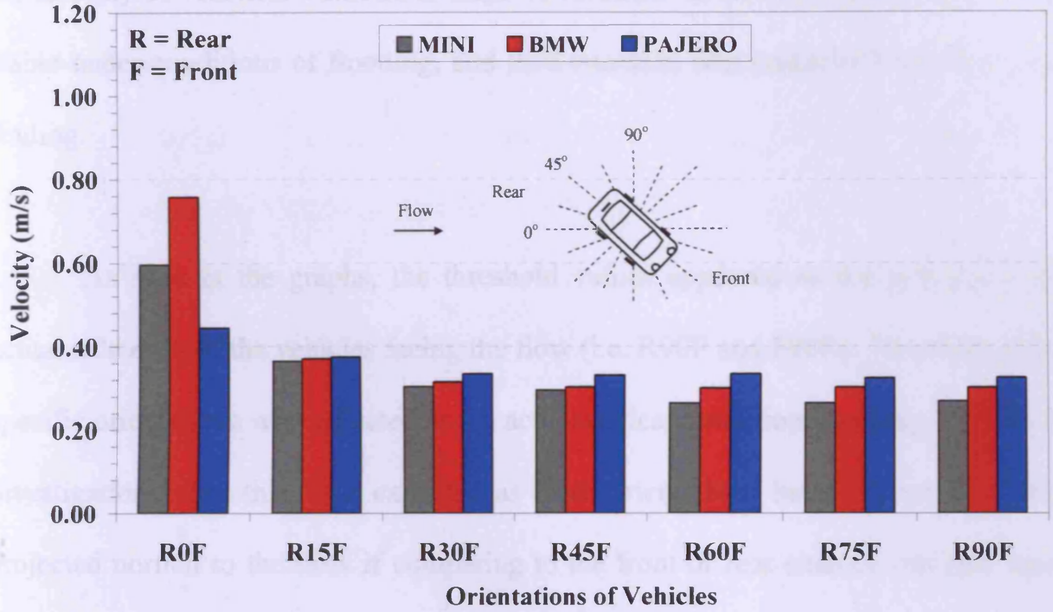


Figure 5.19 Variation of water depths for the effects of: (a) rear and (b) front ends of vehicles in different orientations to the floodwater flow

(a)



(b)

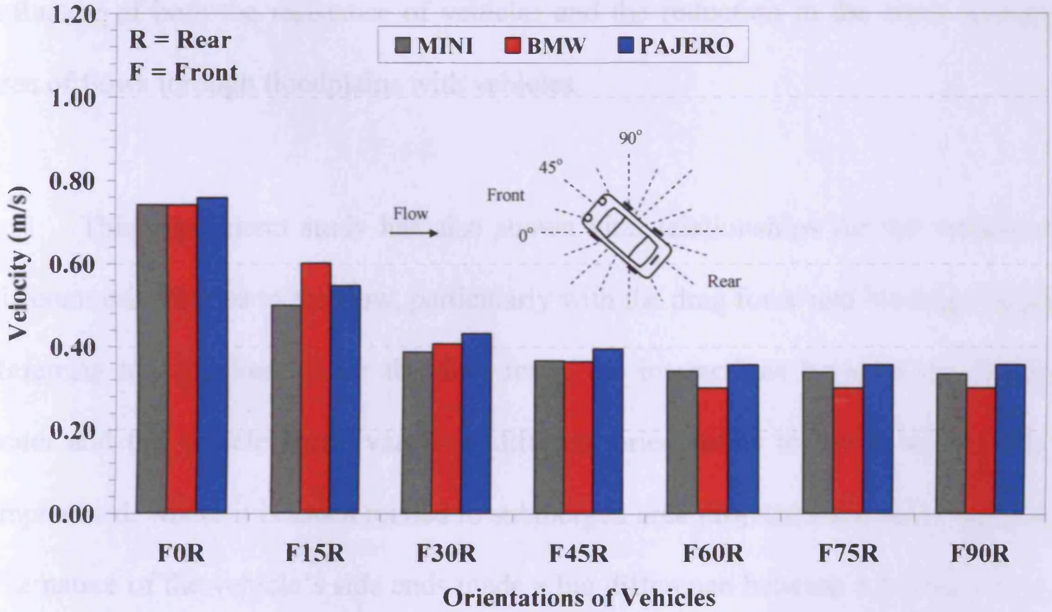


Figure 5.20 Variation of velocities for the effects of: (a) rear and (b) front ends of vehicles in different orientations to the floodwater flow

On the other hand, the orientations for the side ends of vehicles facing the flow (i.e. R60F to R90F and F60R to F90R) required smaller threshold values. These orientations were recognised as one of the potential critical conditions to first trigger the stability of vehicles. Vehicles in these orientations to the flow were generally less stable under conditions of flooding, and thus attention was primarily focused on this finding.

As seen in the graphs, the threshold values appeared as the lowest for the actual side ends of the vehicles facing the flow (i.e. R90F and F90R). Therefore, these specific orientations were selected as the actual critical conditions to apply in all other investigations after this. It is expected as these orientations have a large bluff area projected normal to the flow if comparing to the front or rear ends of vehicles, thus, the cross sectional area of flow through vehicles were reduced, and subsequently the drag forces and blockage effects were increased. As a result, this has created the influence of both the resistance of vehicles and the reduction in the cross sectional area of flows through floodplains with vehicles.

This experiment study has also shown vital relationships for the vehicles at different orientations to the flow, particularly with the drag force and blockage effects. Referring to Equation 5.3 for the drag force, the interactions between the flowing water and the vehicle shape varied in different orientations to the flow have been emphasised, where it is much related to submerged area projected normal to the flow. The nature of the vehicle's side ends made a big difference between a low and a high coefficient of drag. Hence, the finding shows that the vehicles at different orientations to the flow created a big difference in pressure between the two surfaces of the vehicle, and consequently caused a large resistance of drag and blockage to the flow.

5.6.3 Effects of Ground Surface Gradient

Figure 5.21 shows the effects of different ground surface gradients on the threshold of instability for flooded vehicles. The results show the comparisons for all of the smaller scaled model vehicles with side ends facing the flow at four different surface slopes of 1:100, 1:200, 1:300, and 1:1000 respectively in the small flume. It can be seen for all of the partially submerged model vehicles that the threshold velocity needed for initial movement increased with increasing surface gradients. This result is consistent with expectations and can be explained by Equation 5.4 for friction forces.

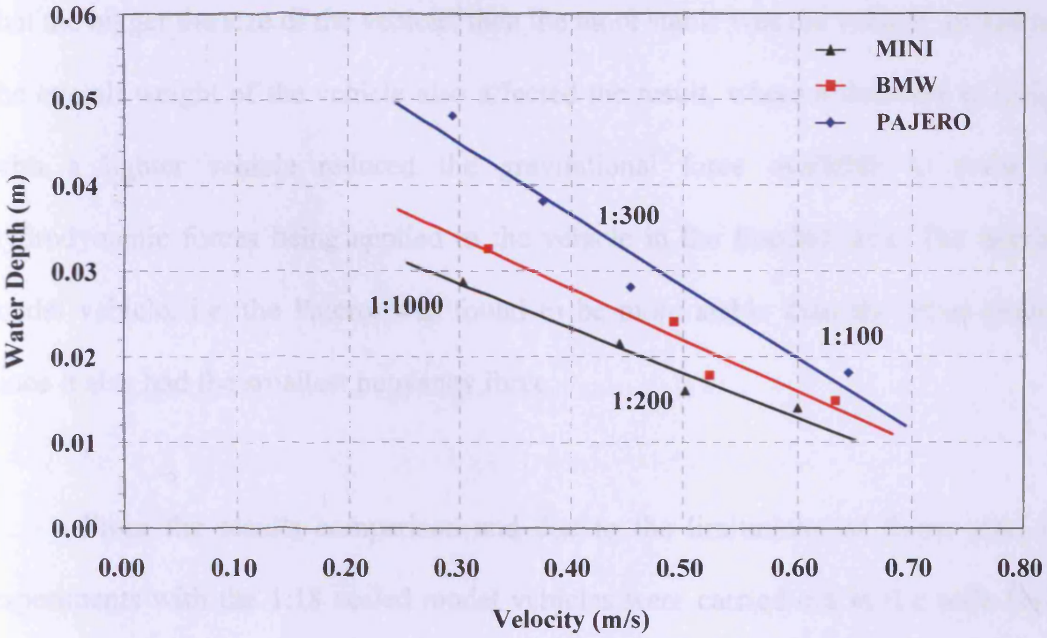


Figure 5.21 Effects of ground surface gradients on 1:43 scaled model vehicles

When the vehicle is on a flat slope the friction force is the normal force, which is equal to the weight of the vehicle. On the other hand, when the surface gradient is at an angle though, the normal force becomes less and as a consequence reduces the value of the friction force. The gravitational force now has a transverse component, which is added to the drag force. Therefore it is expected that the critical conditions for movement would be affected. This occurred for all of the cases considered, where the results showed that as the surface slope increased, then the water depth decreased and the velocity increased at the critical condition for the threshold of vehicle instability. The findings show the effects of the ground surface gradient on the threshold of instability for the 1:43 scaled model vehicles during their critical conditions.

For the 1:43 scaled model vehicles tested in the small flume with the conditions of partially submerged, the least stable was found to be the Mini and the most stable was the Pajero. This observation, shown in Figure 5.21, clearly indicated that the bigger the size of the vehicle, then the more stable was the vehicle. In addition, the overall weight of the vehicle also affected the result, where a decrease in weight with a lighter vehicle reduced the gravitational force available to resist the hydrodynamic forces being applied to the vehicle in the flooded area. The heaviest model vehicle, i.e. the Pajero, was found to be more stable than the other models, since it also had the smallest buoyancy force.

From the results comparison and due to the limitations of flume size, the experiments with the 1:18 scaled model vehicles were carried out in the wide flume (i.e. width = 1.2 m). Figure 5.22 shows the critical conditions during the threshold of instability for four larger model vehicles, with side ends facing the flow at three different surface slopes (i.e. 1:100, 1:200, and 1:300). These results suggest the same trends as for the experiments of the 1:43 scaled models with the small flume. The findings again showed the effects of the ground surface gradients on the threshold of vehicle instability for the critical conditions.

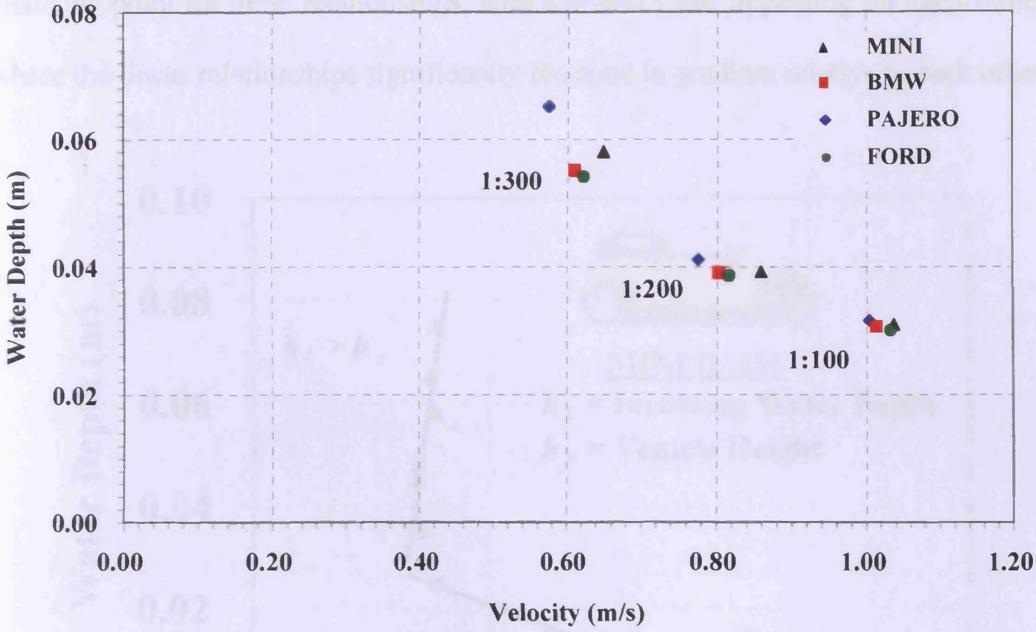


Figure 5.22 Effects of ground surface gradients on 1:18 scaled model vehicles

5.6.4 Vehicle Stability in Urban Floodplains

As mentioned previously, the floodwater depth is an important parameter in determining the criteria for the governing of the hydraulic stability for a vehicle. The other principal hazard factor is the water velocity, which is also a key parameter in estimating the flood damage extent resulting from the instability of vehicles in urban floodplains. Figures 5.23 to 5.25 show the incoming depths and corresponding velocities for three types of model vehicles, with side ends facing the flow in order to perform the critical threshold conditions, which is the main aim of this chapter. It can be seen that the results followed the same trends as discussed previously for the experiment on the threshold of vehicle instability, but with the lowest values being shown for the current critical case. Again, as can be seen from the graphs, two obvious relationships for each of the vehicle were observed. Eventually, there is a changing point for these relationships, with a lowest value appearing for each vehicle, where the linear relationships significantly changed in gradient relative to each other.

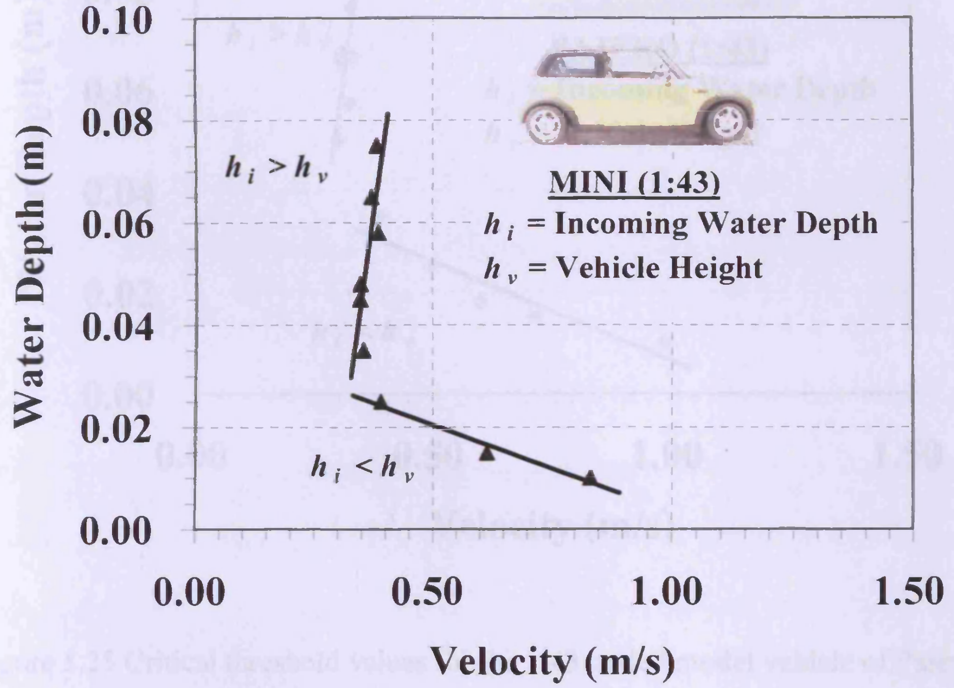


Figure 5.23 Critical threshold values for the 1:43 scaled model vehicle of Mini

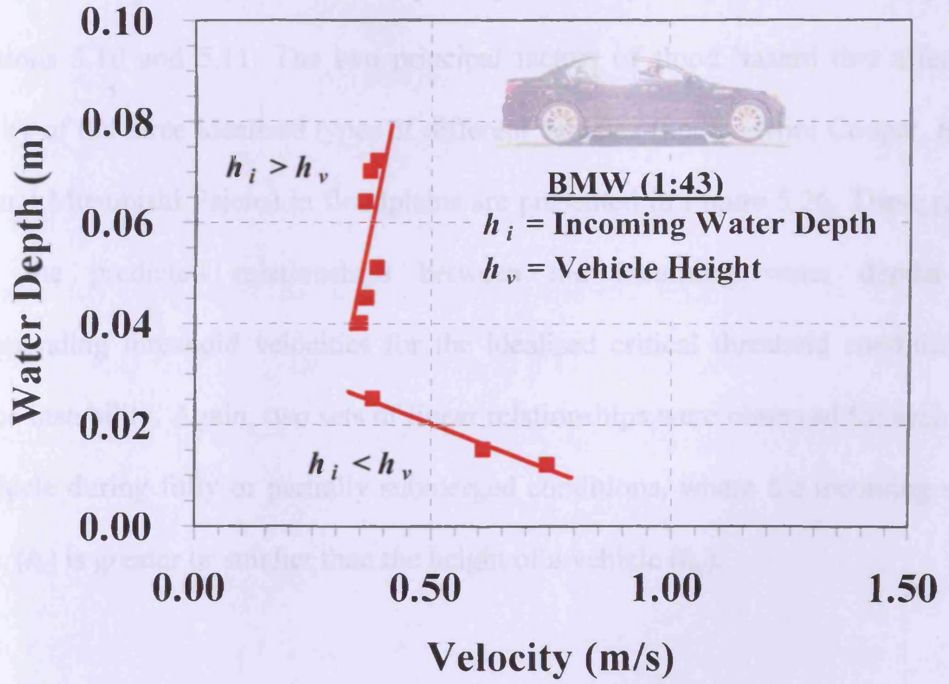


Figure 5.24 Critical threshold values for the 1:43 scaled model vehicle of BMW

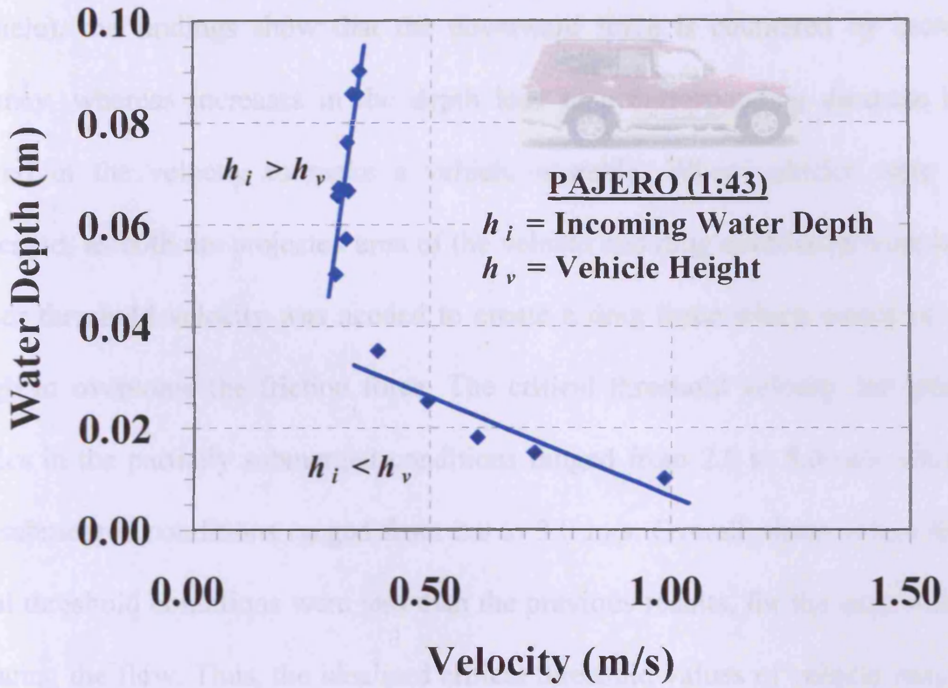


Figure 5.25 Critical threshold values for the 1:43 scaled model vehicle of Pajero

The results from the experimental study were again interpreted and scaled up to the idealised prototype conditions by using the theory of hydraulic similarity using Equations 5.10 and 5.11. The two principal factors of flood hazard that affect the stability of the three idealised types of different vehicles (i.e. the Mini Cooper, BMW M5, and Mitsubishi Pajero) in floodplains are presented in Figure 5.26. These results show the predicted relationships between the incoming water depths and corresponding threshold velocities for the idealised critical threshold conditions of vehicle instability. Again, two sets of linear relationships were observed for each type of vehicle during fully or partially submerged conditions, where the incoming water depth, (h_i) is greater or smaller than the height of a vehicle (h_v).

As highlighted previously, the graphs have shown clearly two contrasting relationships, with reference to the height of the vehicles. For the idealised vehicles when partially submerged (i.e. the incoming water depth is smaller than the height of a vehicle), the findings show that the downward force is countered by increased buoyancy, whereas increases in the depth lead to a corresponding decrease being required in the velocity to make a vehicle unstable. When vehicles were fully submerged, as both the projected area of the vehicle and drag coefficient were larger, a lesser threshold velocity was needed to create a drag force which would be great enough to overcome the friction force. The critical threshold velocity for idealised vehicles in the partially submerged conditions ranged from 2.0 to 8.0 m/s, while for fully submerged conditions ranged from 2.0 to 3.0 m/s. Overall, these values for the critical threshold conditions were less than the previous results, for the case with rear end facing the flow. Thus, the idealised critical threshold values of vehicle instability in floodplains have been identified and partially fulfilled the aim of this study. These findings have provided a better understanding on the critical threshold conditions of vehicle instability in flood flows.

Also, it can be seen from Figure 5.26 that deep water and low velocities can cause as much damage as shallow water and high velocities. All of these findings have been previously discussed and similar trends to these results were obtained. The main difference is that the current results have shown critical or lower values instead of others. The graphs have also been simply extrapolated from the linear relationships with the development of an envelope curve to predict idealised critical conditions of hydraulic stability for each type of vehicle. Referring to the envelope curves that have been developed, with three colour zones (i.e. green, yellow, and red) based, a novel innovative approach has been first introduced herein as the Traffic Light of Hydraulic Stability (TLHS) system. Through this innovation, zones of hydraulic stability for each idealised vehicle were easily identified by colour with the stable zone in green, the transition zone in yellow and the unstable zone in red. Thus, a straightforward envelope curve developed in Figure 5.26 can be ideally used as a useful guide or procedure to evaluate the degree of hydraulic stability for vehicles, and it is also very useful for assessing the flood hazard of vehicles in urban floodplains. On the other hand, predictions for the real prototype vehicles were recommended to further study with the mathematical formula derived by Xia et al. (2010) from the same experiment results found in this thesis.

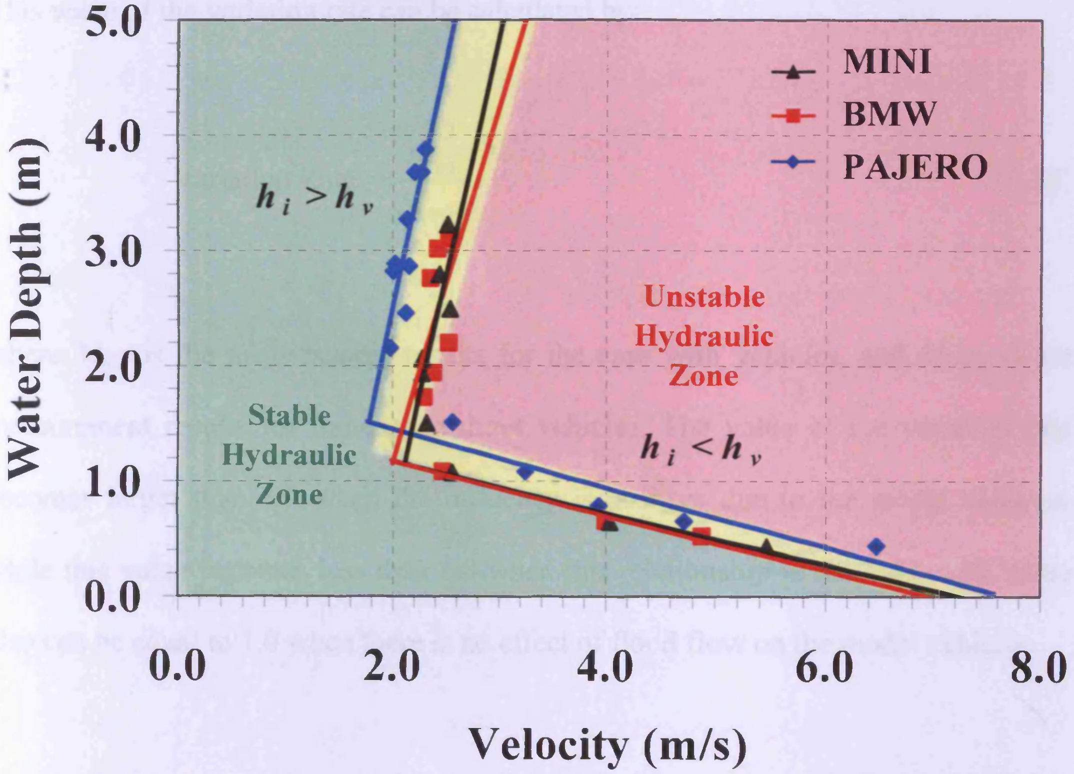


Figure 5.26 Critical threshold values of hydraulic instability for idealised vehicles

5.6.5 Influence of Vehicles on Flood Flows

Results for all of cases have been analysed to investigate the effects of model vehicles on flow propagation over floodplains at critical conditions, i.e. at the threshold of vehicle instability. To investigate these conditions, the side of the vehicle facing the flow of water was selected, as recommended in previous experiments, instead of a smooth curve and aerodynamic front or rear end of a vehicle. In order to examine this effect, the variation rate of the critical values of the water depth and velocity for the cases with and without vehicles were considered and measurements were taken at four relatively important points, which are the incident or transmitted point before the model (point 7), at the front side of the model (point 6), at the rear side of the model (point 4) and at the transmitted point after the model (point 3) as shown in Figure 5.15. This value of the variation rate can be calculated by:

$$\text{Variation Rate} = \frac{M_{WV}}{M_{WOV}} \tag{5.13}$$

where M_{WV} is the measurement results for the case with vehicles, and M_{WOV} is the measurement results for the case without vehicles. The value of the variation rate becomes larger than 1.0 when the influence is positive due to the model vehicles, while this value becomes less than 1.0 when this relationship is reversed. This value also can be equal to 1.0 when there is no effect of flood flow on the model vehicles.

The changes in the variation rate for all models are shown in Figures 5.27 and 5.28. The experimental results give a good understanding of the flow behaviour for floodplains with vehicles. These results suggest that model vehicles have a significant impact on the floodwater flow propagation and the hydrodynamic processes along floodplains. Since the model characteristics are almost the same, then the tendency of the variation rate for all the models becomes almost the same. By comparing all of the model vehicles, the Pajero has the largest influence on the flow characteristics along the flume, with the Mini having the smallest impact, while the BMW and Ford are in between.

The findings also show comparisons of the further investigative results of all models for three different surface slopes of 1:100, 1:200 and 1:300 respectively. These results show the effects of ground surface gradients on the hydrodynamic processes and flow conditions for different vehicles, located along floodplains. The findings suggest that the influence of model vehicles on floodwater flows is larger and potentially more significant at the front of model vehicles (i.e. the upstream end) when the floodplain surface is almost flat; while this relationship is reversed at the rear of the model vehicles at the downstream end.

The effect of model vehicles on the critical water depth are transmitted and extend further to the front of models at point 7, as shown in Figure 5.27, with the variation rates for this point being equal to, or larger than, 1.0 for all of the models. The transmitted water depth increased at the front of the models and decreased at the rear end by reflection of the models, which was common result for all of the model vehicles when the surface slope was flatter. Hence, model vehicles for these conditions have created a pressure difference between the two surfaces of the model vehicle, which cause the form resistance of drag and blockage to the flows. Typically, this drag and blockage is caused by the high pressure just upstream of the vehicle. This observation suggested that the area at the front side of model vehicles becomes more of a hazard than that at the rear side of end.

On the other hand, Figure 5.28 shows the variation rate of velocity for all of the models. Through reflection of model vehicles, the largest reduction effect of the velocity was observed at the front end of the models. The flow pattern at the rear end of the models was deemed to be more complex and there was more influence on the velocity in this threshold condition of vehicle instability.

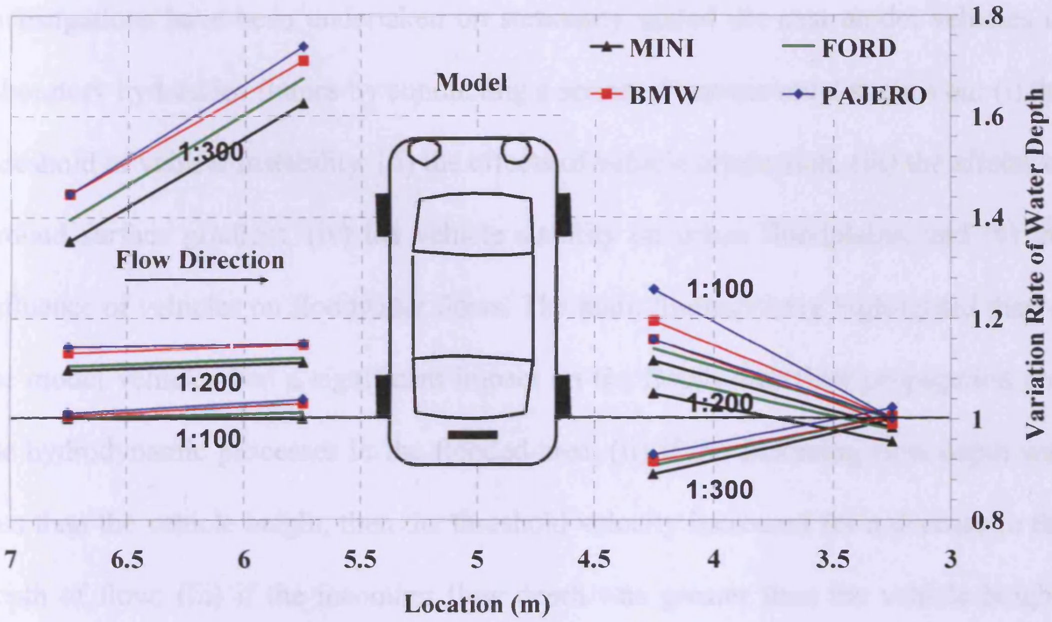


Figure 5.27 Variation rates of water depths for model vehicle instability threshold

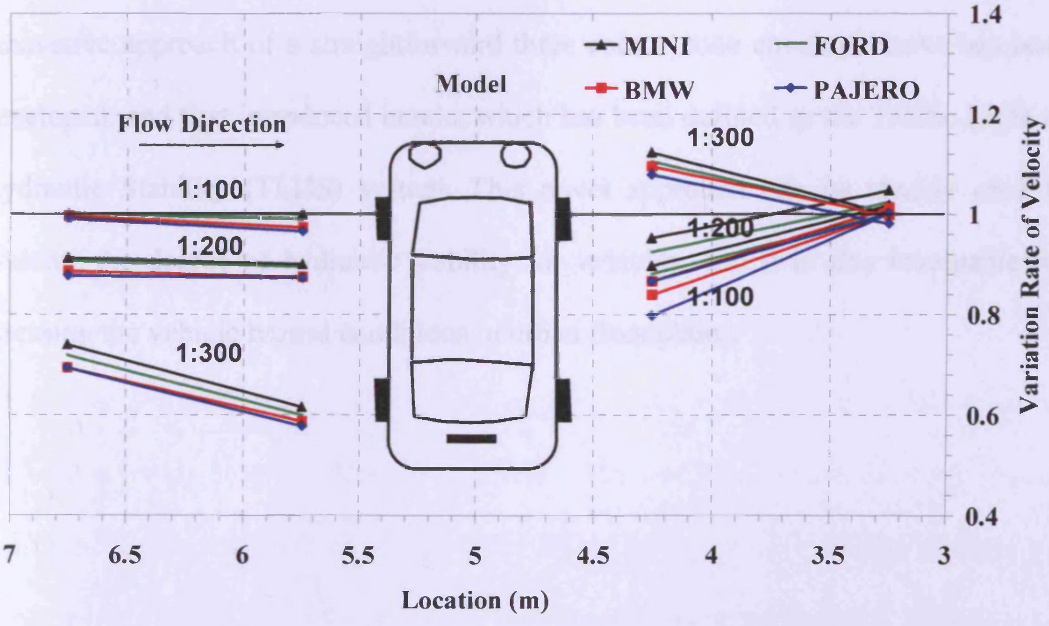


Figure 5.28 Variation rates of velocities for model vehicle instability threshold

5.7 Summary

This chapter has outlined a study of the theoretical and experimental aspects of the hydrodynamics of flood flows over urban floodplains with vehicles. Extensive investigations have been undertaken on stationary scaled die cast model vehicles in laboratory hydraulics flumes by conducting a series of experimental studies on: (i) the threshold of vehicle instability, (ii) the effects of vehicle orientation, (iii) the effects of ground surface gradient, (iv) the vehicle stability on urban floodplains, and (v) the influence of vehicles on floodwater flows. The main findings have highlighted that: (i) the model vehicles had a significant impact on the floodwater flow propagation and the hydrodynamic processes in the flooded area, (ii) if the incoming flow depth was less than the vehicle height, then the threshold velocity increased for a decease in the depth of flow; (iii) if the incoming flow depth was greater than the vehicle height, then the threshold velocity would rise with an increase in the depth of flow, and (iv) a flooded vehicle was more likely to move if the incoming depth just approached the vehicle chassis height due to the buoyancy effects. Based on these findings, an innovative approach of a straightforward three colour zone envelope curve has been developed, and first introduced herein, which has been defined as the Traffic Light of Hydraulic Stability (TLHS) system. This novel approach can be readily used to evaluate the degree of hydraulic stability for vehicles, and it is also invaluable for assessing the vehicle hazard conditions in urban floodplains.

CHAPTER 6

HYDRODYNAMICS OF FLOODPLAINS WITH VEHICLES AND BRIDGES

6.1 Introduction

Most rivers carry some amount of large natural debris, which can consist of rocks, trees, trash, etc. and consequently these debris can inundate floodplains during extreme flood events. As discussed in the previous chapter for urban floodplains, depending on the depth and velocity of floodwater flows, large debris such as vehicles and even houses can be carried downstream by floodwaters into rivers and these floating debris can build up in front of bridge structures, etc. The situation can become severe when water impinges on the superstructure of bridges as large debris blocks the flow path and strikes the actual bridge structure, rather than just the pier or abutment, and finally causes failure of the bridge under such stress.

In general, it is well understood that bridges on floodplains are often subjected to hydrodynamic forces of various forms and intensities, to mention but a few were investigated by Naudascher and Medlarz (1983), Malavasi and Guadagnini (2003), and Palermo and Nistor (2008). The most dramatic forces are those due to extreme events such as tsunamis, storm surges, flash floods, etc. and furthermore when the impacts are intensified by large debris creating blockages. Recently, flood hazard relating to such extreme flows over floodplains and the consequential hydraulic impact of flooded vehicles causing a water elevation build up in front of bridges has become more noticeable but to the knowledge of the author there is still no systematic research study of this hydrodynamics reported in the literature. Therefore, in this chapter, investigations have been pioneered to understand the hydraulic response of floodplains with vehicles blocking bridges.

Progressing from the earlier chapters on the topics of hydrodynamic processes in natural and urban floodplains, the primary focus in this chapter has been directed to the interaction of floodplains with vehicles blocking bridges. The earlier chapters have provided the foundations for the current chapter in the form of a good understanding of the hydrodynamic processes of floodplains and in particular on: (i) the hydraulic interactions of a group of natural mangrove trees with extreme flood events, and (ii) the influence of urban floodwater flows on critical instability threshold conditions of a single vehicle. Thus, this chapter takes into account the concept of the hydraulic blockages and drag forces of a group of mangrove trees and equates this to a group of vehicles for the condition blocking the front of a bridge during flood events. Apparently, the concept of natural and urban developments on floodplains has a good link to complement each other for effective floodplain management, which is in accordance with the main aim of this study.

Before investigating fully the background of this research area it is worth recapping the objectives of this particular study, and how they were to be achieved. With the design and construction of a laboratory physical model, which could then be used to understand the hydrodynamic processes involved, this has been the main objective of this study to investigate the floodwater flow over floodplains with vehicles blocking bridges. This study can be very important for extreme flood events, where the physics of the corresponding hydrodynamic processes along floodplains usually are very complex in nature and difficult to model analytically. It was also vital to undertake laboratory studies so that fundamental quantitative data could be acquired through observations of the flow characteristics for this type of complex flow condition, in order to interpret the data to similar conditions to real environments. The scope of this laboratory model analysis was to recreate a particular case study at scale for a similar typical cross section of floodplains that were typical of Valency, near Boscastle and the Klang river basins.

Overall this chapter covers the other aspects of the hydrodynamics of floodplains, with obstructions being further discussed as follows: (i) briefly describing the physical characteristic of floodplains with bridges and potential vehicle blockages, (ii) discussing the occurrence of floods and the consequential impact of floodplains with vehicles blocking bridges, (iii) summarising the background and governing theory of the hydrodynamic processes involved, (iv) presenting the physical modelling studies with a series of laboratory experiments for the hydrodynamic interactions of floodplains with vehicles blocking the flow at bridges, and (v) providing a discussion on the experimental results and findings from the development of comprehensive physical experimental studies.

6.2 Floodplains with Vehicle Blockages at Bridges

Floodplains or low lying areas along rivers are always a good place to develop and settle where townships and infrastructures are built, as shown in Figure 6.1 for a typical urban floodplain. Typically these floodplains consist of buildings, houses, bridges, hydraulic structures, roads, parking lots for vehicles, etc. By disregarding the presence of buildings, hydraulic structures, and roads in these floodplains which have been widely researched over the past (such as by Liang et al., 2007; Soares-Frazão and Zech, 2007; etc.), bridges and possible blockage of vehicles are the main focus to be further discussed in this chapter. As highlighted in the previous chapter, vehicles such as saloon cars are light in weight, moveable and commonly can be found in large numbers along floodplains, where flooding is expected when the drainage system is insufficient and these vehicles were not designed to withstand the corresponding water forces. Accordingly, vehicles along these floodplains are at significant risk from flooding as discussed in the last chapter and as the current chapter will highlight these vehicles potentially obstruct and block the normal flow through bridges.

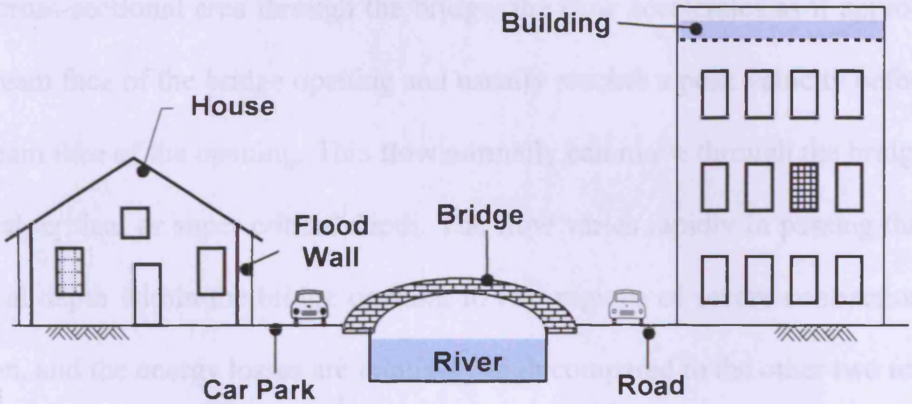


Figure 6.1 Typical cross section of an urban floodplain

On the other hand, bridges are usually found in most floodplains, where they are built mainly for the purpose of transportation. Bridges are constructed over rivers, resulting in the bridge structure and its elements, such as piers and abutments, being located within the water which may be subjected to significant hydrodynamic loading, and as well as obstructing the natural water flow along floodplains (French, 1994). In general, bridges are common hydraulic obstructions that must be addressed in the studies of floodplain hydrodynamics where this study is also concerned. Basically, bridges along these floodplains are intentionally designed to a certain degree to withstand the hydraulic forces exerted on them by the flow and other loads including the weight of vehicles, wind force, earthquake force, etc. (Hamill, 1999). Some bridges are even designed to take account of adverse effects on upstream flows and the impact of large debris build up.

It is well acknowledged that flows through bridges along floodplains have been conceptualised as having four regions: accretion, contraction, expansion, and abstraction (Laursen, 1970). Figure 6.2 displays this movement of flow in an idealised sense, along with these region reaches through the bridge. Apparently, due to the smaller cross-sectional area through the bridge, the flow accelerates as it approaches the upstream face of the bridge opening and usually reaches a peak velocity before the downstream face of the opening. This flow normally can move through the bridge at a subcritical, critical or super critical depth. The flow varies rapidly in passing through the critical depth within the bridge opening in two regions of severe contraction and expansion, and the energy losses are relatively high compared to the other two regions (USACE, 1993). Subsequently, downstream of the bridge, this fast moving flow expands into the wider valley cross-section of the floodplain and results in a decrease in the velocity. Accordingly, energy is lost through the bridge and the water surface may be significantly higher at the upstream end of the bridge than downstream.

Flow through a bridge is usually classified as low and high flow, depending on the depth of water flow (Chow, 1959). In a low flow condition, the elevation of the water surface is below the low chord of the bridge. This type of flow is the most common condition expected for the design of a normal bridge. During an extreme flood event, when the elevation of the water surface exceeds the maximum elevation of the upstream low chord of the bridge, the flow is classified as high. High flow through the bridge may occur under pressure flow conditions, with the bridge opening becoming submerged and acting as either a sluice gate or as an orifice, under weir flow conditions, or under energy conditions for highly submerged bridges, or under a combination of these conditions (USACE, 1993).

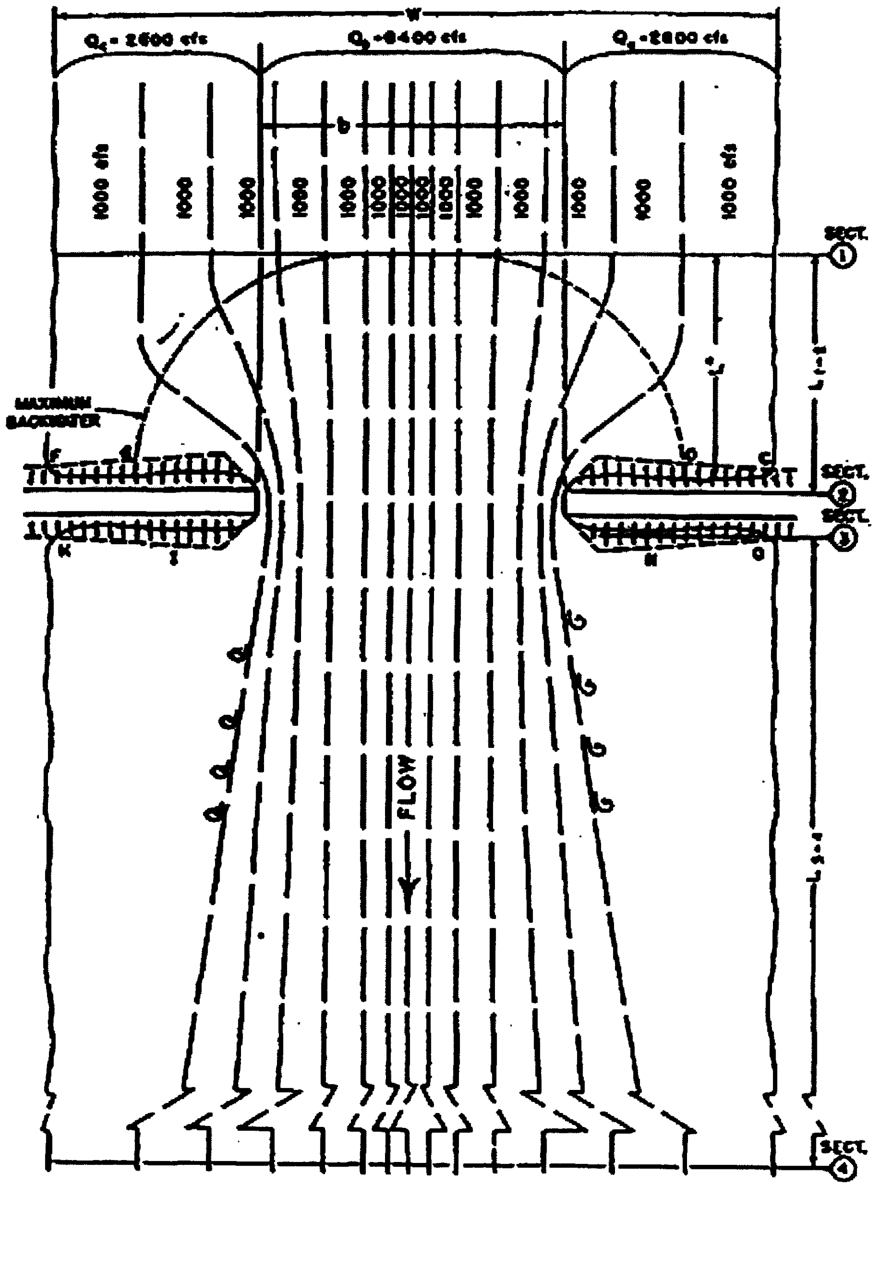


Figure 6.2 Flow lines for a typical bridge crossing (USACE, 1993)

6.3 Floods and Floodplains with Vehicle Blockages at Bridges

As has been highlighted previously, flood hazards relating to over spilling and flowing of excess water over floodplains, with large debris such as rocks, trees, trash, etc. are a serious problem and have became more prevalent in recent years. Often the effects of flooding are made worse due to large debris being transported and blocking flow paths at the downstream end of rivers and accordingly caught under bridges, etc. In this case, vehicles swept into rivers can also be part of the debris load, carried by rivers during large floods. Indeed, some recent flooding events due to vehicles blocking the flow, particularly in front of bridges, have highlighted significant rise on flood levels and consequential impact to floodplains. For example, and as previously discussed in detail, Boscastle was struck by a devastating flash flood in 2004 (see photographs as shown in Figure 6.3 for comparison of the scenario during and after the event) which was caused by heavy rainfall (Brigandi et al., 2007) as the waters inundated buildings, damaged about 115 vehicles, and destroyed several bridges (Environment Agency, 2004 and North Cornwall District Council, 2005). At this point, the 2004 Boscastle flood highlights the major problems caused by large debris flow including numerous vehicles that were carried with the flow and blocked bridges exacerbating inundation upstream.

During the flood event, some vehicles and large debris were floated and swept away by the floodwater, and then caught under the local bridge, blocking the flow path and finally causing the main bridge to collapse under the stress (as vividly demonstrated by Figure 6.4). Most bridges were overtopped and an extraordinarily high flow continued to pass through the severely throttled bridge and large debris blockage, resulting in more flow paths which made the hydrodynamic processes more complex. In this case the blockage of large debris build up acted as a temporary dam, with the main bridge opening serving as a low flow conduit and consequently cause a large backwater effect, extending far upstream of the bridges location. Furthermore, these floodwater flows and the large debris build up add a significant hydrodynamic load on the bridges, resulting in possible shearing of the bridge deck and consequential failure of the bridge superstructures.

Figure 6.3 Boscastle, UK: (a) flood on 16 August 2004 with bridge being blocked by vehicles and debris, and (b) after the event (Photographs courtesy of BBC News)

Figure 6.4 The Lower Bridge blocked by vehicles and other large debris during 2004 Boscastle flood (Photograph courtesy of www.tintagelweb.co.uk)

Following this extreme flood, the Environment Agency (2004) has carried out a full investigation into the storm, rainfall, and river events in the Boscastle and Crackington Haven catchments on 16 August 2004. Based on this expert study of the floods, undertaken by consultants HR Wallingford (2005) with technical support by Halcrow, the Centre for Ecology and Hydrology, the Met Office and the Royal Haskoning, a £4.5 million flood defence scheme has been proposed (as shown in Figure 6.5), which involved: (i) lowering and widening the river channel, (ii) a new main and overflow car parks, (iii) the Lower Bridge replacement, and (iv) a catchment management strategy.

Figure 6.6 shows the flood risk of the existing and new proposed design for the replacement of the Lower Bridge at Boscastle, based on the report of Environment Agency (2005a). Apparently, the old bridge obstructed floodwater flow more than the new proposed design. Thus, the replacement of the new bridge will significantly reduce the flood risk along floodplains and decrease the possibility of bridge blockage by large debris flow in the future. As highlighted here, it can be seen that it is important to define this type of flood risk in the earlier stages of engineering design for the best appreciation of floodplain management among engineers and researchers.

As far as this flood is concerned, it shows the need to further investigate and acquire a better understanding of the hydrodynamics of such an extreme flood flow over floodplains for a blockage caused by various vehicles in front of bridges. Flooding, such as that occurring in Boscastle, cannot easily be prevented; however, with an improved understanding of such knowledge then possible disastrous consequences may be reduced or ideally eliminated. Thus, this chapter will take into account the key issues mentioned previously for consideration in the future study.

(a)

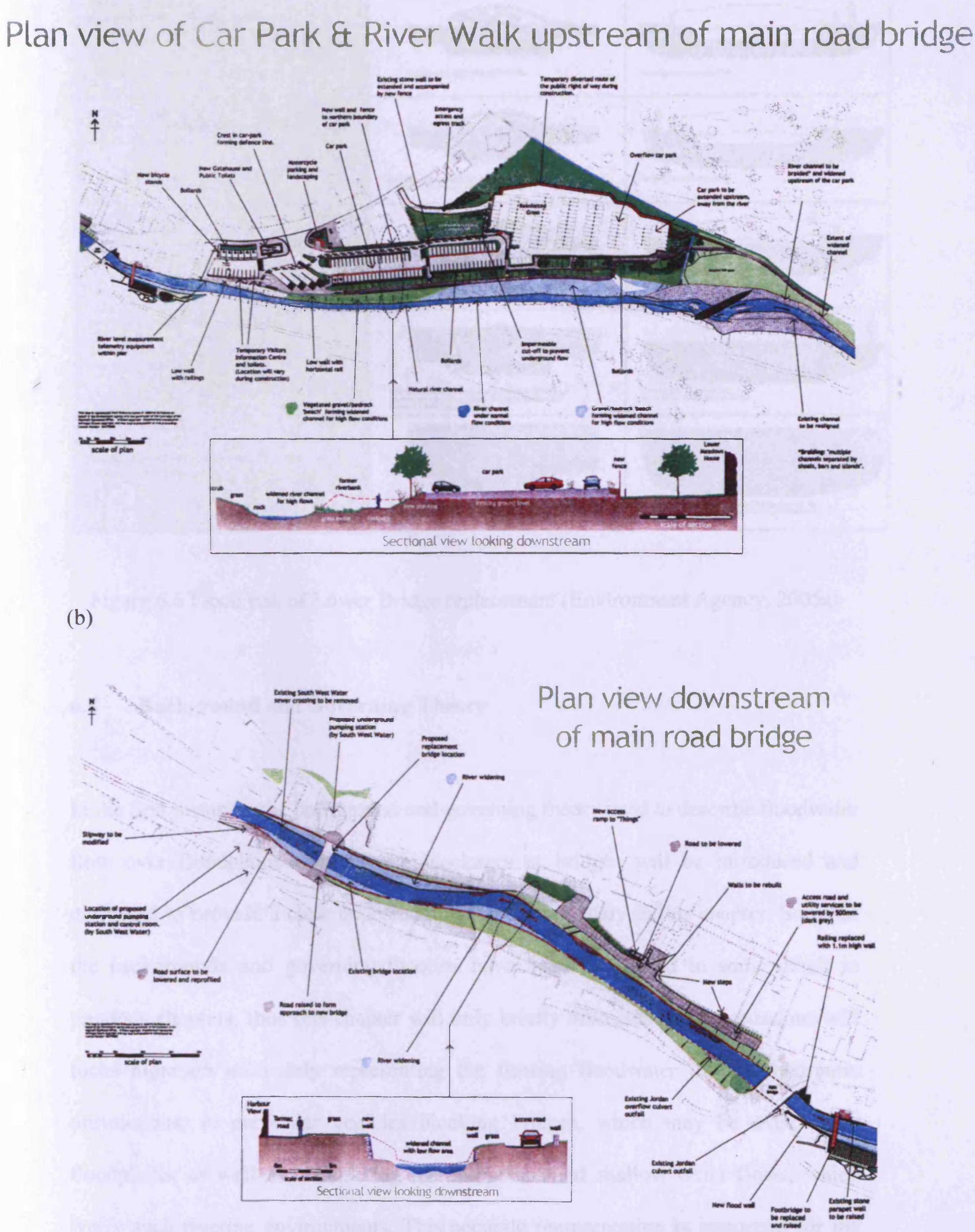


Figure 6.5 Proposed Boscastle - Valency Flood Defence Scheme: (a) upstream, and (b) downstream of main road bridge (Halcrow, 2005)

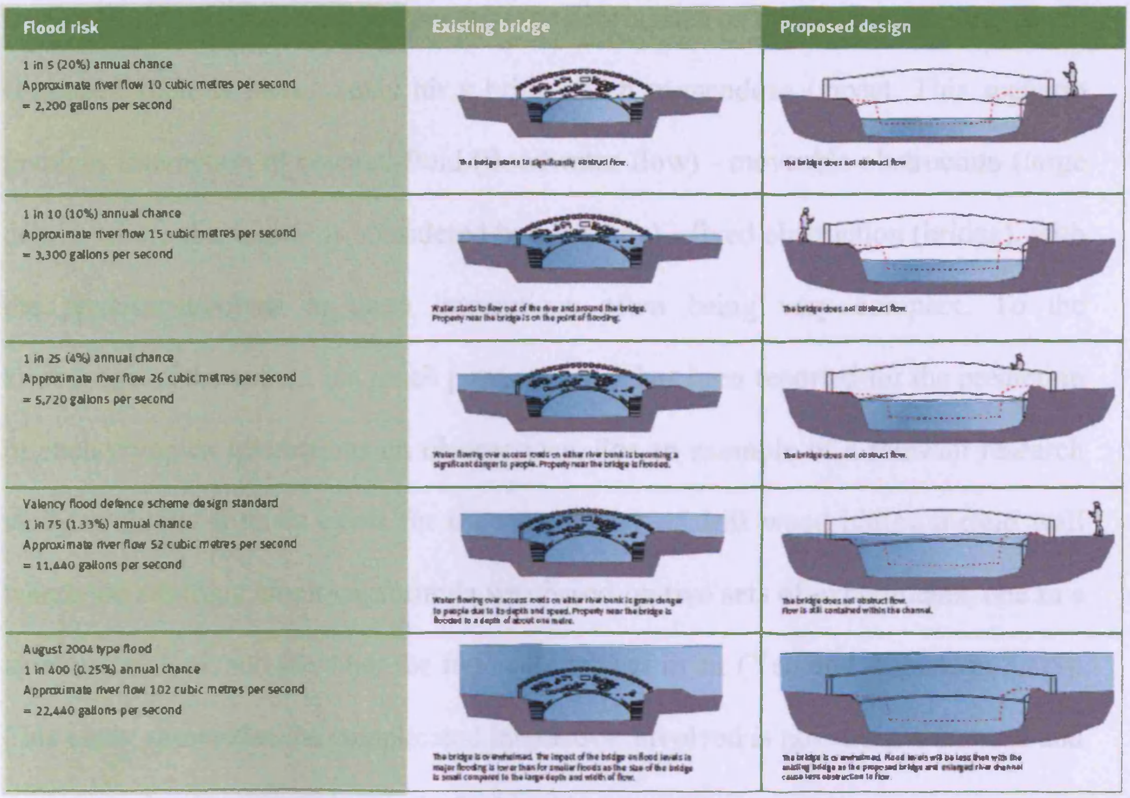


Figure 6.6 Flood risk of Lower Bridge replacement (Environment Agency, 2005a)

6.4 Background and Governing Theory

In the first instance, the background and governing theory used to describe floodwater flow over floodplains with vehicle blockages at bridges will be introduced and discussed to provide a clear understanding for further study in this chapter. Some of the backgrounds and governing theories have been introduced in some detail in previous chapters, thus this chapter will only briefly discussed. The discussions will focus more on accurately representing the flowing floodwater through hydraulic obstructions, in particular vehicles blocking bridges, which may be exist along floodplains, as well as considering the compound and shallow water flows, which typify such riverine environments. This accurate representation is important for the physical modelling studies hereafter to demonstrate a real environment of floodplains.

During an extreme flood event, large debris such as trees, vehicles, and part of structures such as houses, may hit a bridge with tremendous impact. This scenario involves interaction of coupled fluid (floodwater flow) - moveable obstruction (large debris, where the vehicle is considered in this study) - fixed obstruction (bridge), with the physics involved in these interactions often being very complex. To the knowledge of the author, not much previous work has been reported for the prediction of such complex interactions on obstructions. For an example of a relevant research study, a simple formula exists for the simple case of drift wood hitting a rigid wall where the resulting empirical formula was based on two sets of experiments, one in a small water tank and the other for full scale impact in air (Yeh and Robertson 2005). This study shows that the complicated interaction involved is not straight forward and further work was proposed to study further this scenario.

As mentioned previously, the complex interaction between water flow and obstructions has rarely been systematically investigated as an entity and generally the focus been biased towards one particular aspect, in addition most studies have been simplified to circular cylinders or similar, such as the investigations by Arntsen, 1996; Hoyt and Sellin, 2000; Zhu et al., 2000; Yeh, 2003; etc., or to rectangular blocks, such as the modelling work by Liang et al., 2007; Soares-Frazão and Zech, 2007; etc. It is clear from these studies that there is significant impact of the obstructed object's shape on the flow characteristics. Generally, streamlined objects have much less influence on the flowing water around them compared with the effect from blunt objects. Also as has been indentified previously, different geometries submerged by the flow have different flow fields and distributions of vortices along the surface of the obstruction, leading to the alterations of forces or the force coefficients with the change in the geometry.

In determining the hydrodynamic forces on obstructions, the properties of the flowing water that had the greatest impact were the height of the water and its velocity (French, 1994). As discussed in the previous chapter, the hydrodynamic and governing forces on a vehicle due to floodwater flows over floodplains consist of: gravity, buoyancy, friction, and drag force. Basically, primary responses to the flowing water through the vehicle blockages that stabilised in front of bridges (hereafter known as an entity of the obstruction) also have some similarity. The first two forces are the buoyancy (or lift force) and gravity (or weight of obstruction) which act vertically and perpendicular to the flow and can cause the obstruction to float (or rise). The other two forces are drag and friction, which act parallel to the flow and potentially affect the horizontal stability of the obstruction. Normally, these forces acting on an obstruction are evaluated through a non-dimensional coefficient.

Besides considering the flows through the obstructions and the corresponding hydrodynamic forces, the floodplain itself which typifies the environment is also important to be considered. During flood events, floodwater flows often overtop the main channel so as to fully use the wider carrying and storage capacity of the adjacent floodplains. Obstructions along floodplains may limit the effective conveyance until the depths are sufficiently large to cover the whole obstruction. Even in the absence of these obstructions, which may be present in each floodplain being considered, there is a significant increase in the complexity of the flow behaviour once overbank flow has occurred. As highlighted earlier, when over bank flow occur, a number of special considerations are required. For example, the proportion of flow between the sub areas, the difference in roughness between the main channel and the floodplain, the variation in the resistance parameters with depth and flow regimes, etc., all need to be considered (Shiono and Knight, 1991; Rhodes and Knight, 1994; and Knight, 2001).

6.5 Physical Modelling Study

In the current study, the physical modelling study was intended to provide a comprehensive facility to continue experiment studies commenced earlier and to create a model prototype floodplain for possible extreme flood events with vehicle blockages at bridges. The research study was conducted in the Hydraulics Laboratory of the School of Engineering, Cardiff University.

The study was focused on investigating the hydrodynamic processes of flow over floodplains, with vehicle blockages at bridges, as well as considering the compound shallow water flows, which typify the real environment of floodplains. As recommended earlier, a compound channel was considered for the experimental study to accurately represent the flows over floodplains. Accordingly, this study was investigated in a laboratory flume, with a newly built physical model of a straight compound channel, which consisted of a simplified replication of a main channel and two adjacent floodplains, based on a typical section of a prototype floodplain that similar to those found along the Valency, near Boscastle and Klang river basins or other floodplains with similarity.

To replicate the real floodplain set up, three different bridge designs were considered, which were typical of conditions found in the floodplains of Boscastle and the Klang. Each of the bridges was used for different floodplain configurations in different experimental studies. At the same time four different types of 1:18 die cast scaled model vehicles were used (i.e. the Mini Cooper, BMW M5, Mitsubishi Pajero, and the Ford Escort), which being similar to those used in previous experiment study. The model vehicles were placed in an idealised stable condition at the front of the bridge openings, either at the location of the floodplain or in main channel section. This physical experimental model set up, with the die cast scaled model vehicles, was thought to best represent the prototype environment for the current study, as has also been used in other studies such as by Bonham and Hattersley (1967), Gordon and Stone (1973), and Keller and Mitsch (1992).

Basically, the physical modelling study was designed to empirically determine the effect that vehicle blockages may potentially have in front of three different types of bridges with an upstream compound floodplain scenario. Accordingly, a series of laboratory experiments was carried out in different flow conditions to investigate the consequential impact of vehicles blocking bridges, in order to reproduce the real environment of a flood event. In this experimental study, different flow conditions were selected based on the experimental findings in previous chapter, for the critical conditions of vehicle instability threshold in floodwater flows, for the purpose to ensure that the selected flow conditions are big enough and able to threshold the vehicles to move and stable down or block in front of bridges.

In summary, the main purpose of undertaking a physical model study to investigate flows past vehicles blocking bridges was to obtain data that could be used: (i) to replicate a real flooding environment, (ii) to understand the complex hydrodynamic processes involved, and (iii) to provide data for future undertaking on the calibration and validation of numerical models. Full details of the design of the hydraulic flume and physical model of the floodplain, as well as the scaled model bridges and die cast scaled model vehicles used in the experiments are given as follows, along with details of the measuring procedures adopted.

6.5.1 Floodplain Physical Model

A floodplain physical model was designed and constructed for this study, with the aim of duplicating a straight compound channel, based on a typical section of a common prototype floodplain that can be found in many river basins, including parts of Boscastle and the Klang or some other floodplains. This physical model consists of a simplified replication of a straight compound channel (i.e. for a main channel with relatively shallow floodplains on either side), which mainly creates a basic environment for the investigation of flows over floodplains. At this preliminary stage of research on hydrodynamic interaction with the vehicle blockages at bridges, the model was designed to an undistorted scale, where it maintains the same scale in the horizontal and vertical planes for a straightforward interpretation of floodplains.

For the purposes of this study, a large laboratory flume with glass walls was used, with the rectangular flume having a cross section of 1.2 m width by 1.5 m depth, and an overall length of 17.0 m. The flume and the newly designed and built physical model of floodplains and channel are illustrated in Figures 6.7 and 6.8. The hydraulic flume was operated with a recirculation system, and the flow conditions were controlled by valves on the inlet pipes and an adjustable weir located at the downstream end of the flume. The discharge rate of the flow was obtained from the flow meter, attached to the inlet pipes. The bed slope of the flume was adjusted manually for a series of different test cases.

The simplified model of a straight main channel and shallow floodplains (see Figures 6.9 and 6.10 for details) was constructed with the Polyvinyl Chloride (PVC) blocks to form a compound section in the flume and to maintain a reasonably uniform roughness throughout the base, with the main channel base being regarded as the datum level for this study. The PVC blocks, of dimension 0.125 m thick, 0.4 m wide, and 0.5 m long, were constructed and filled with concrete to make them heavy enough to remain fixed with the water flow. 20 PVC blocks, as shown in Figure 6.11, were used along the base of the 10.0 m long floodplain, on both sides of the 0.4 m wide main channel.

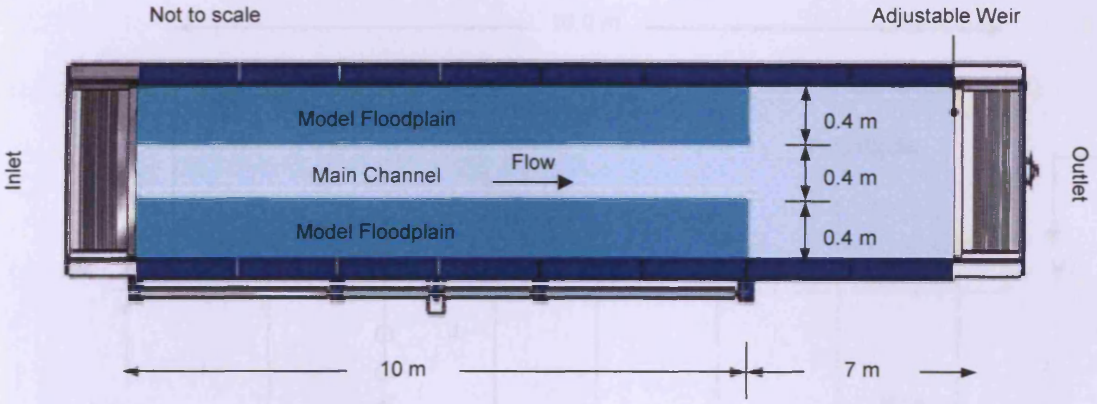


Figure 6.7 Schematic layout of laboratory flume and floodplain physical model

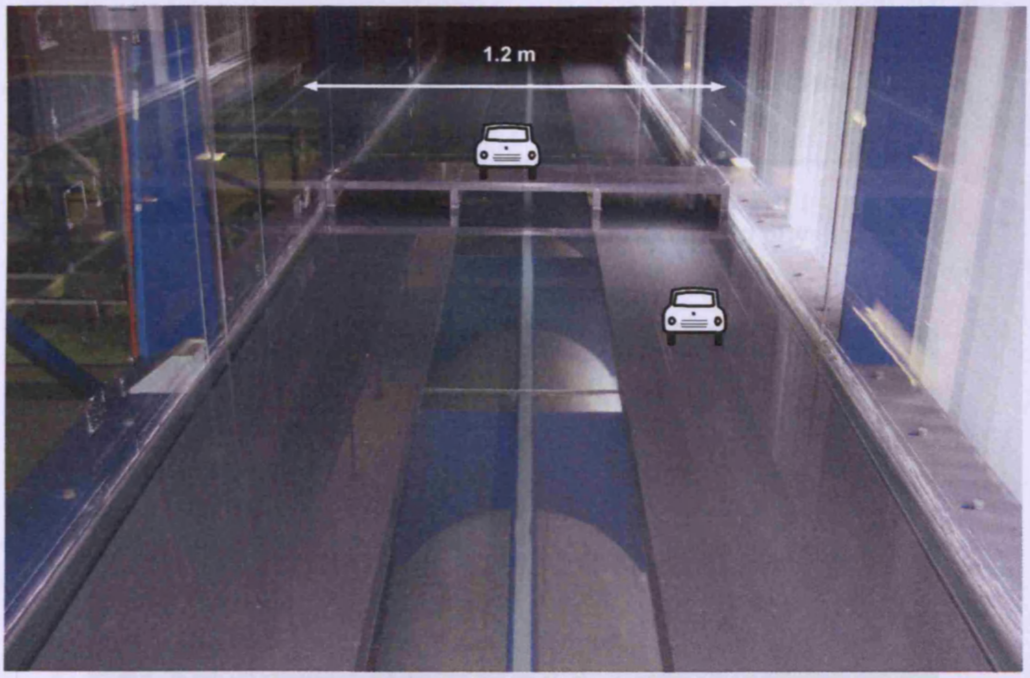


Figure 6.8 View of laboratory flume to accommodate the floodplain physical model with one of the design of scaled model bridge

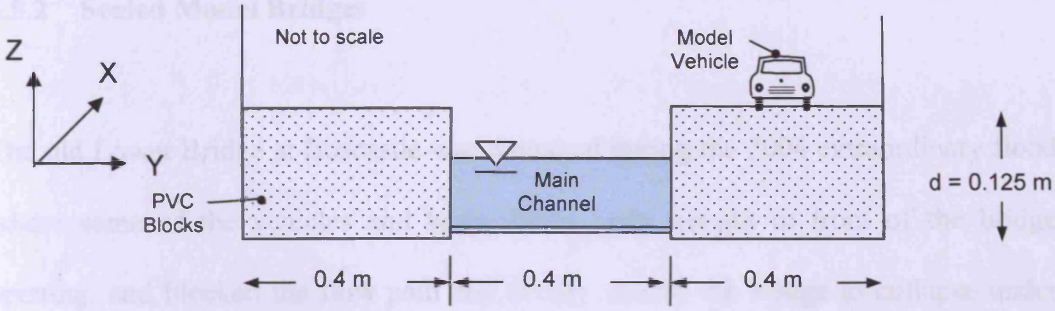


Figure 6.9 Typical cross section of floodplain physical model

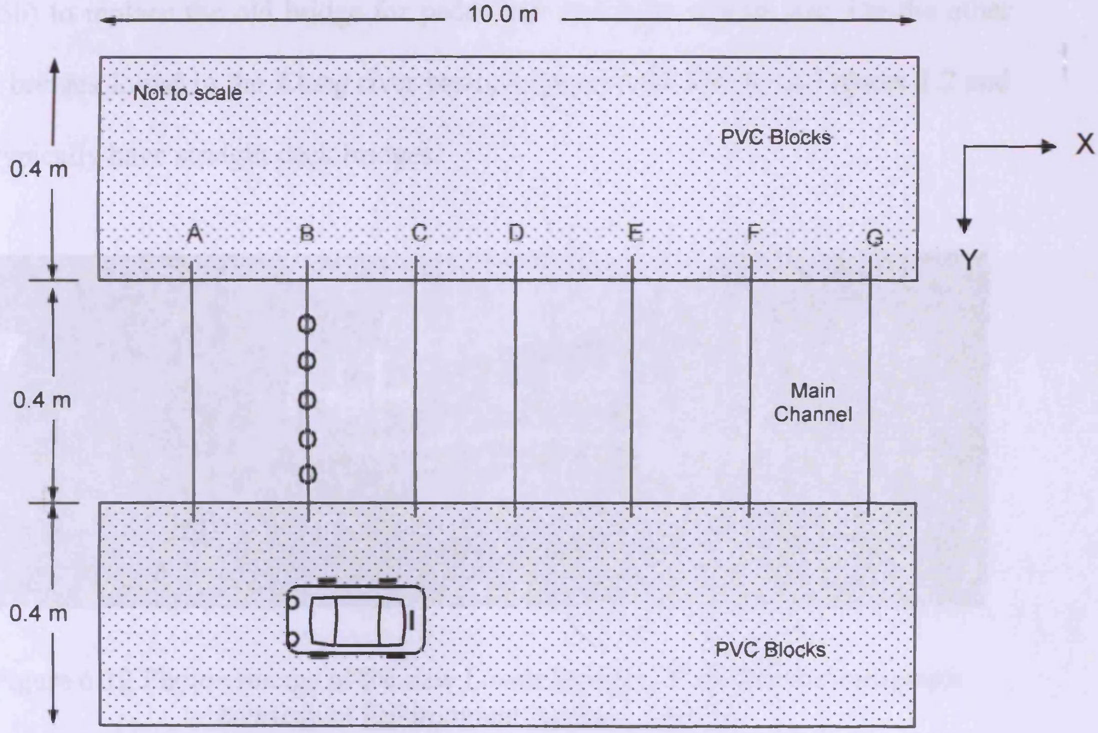


Figure 6.10 Typical longitudinal section of floodplain physical model

Figure 6.11 View of PVC Blocks used to construct floodplain physical model

6.5.2 Scaled Model Bridges

The old Lower Bridge at Boscastle was damaged during the 2004 extraordinary flood, where some of the vehicles and large debris were caught in front of the bridge opening, and blocked the flow path and finally caused the bridge to collapse under the stress (as previously discussed and shown in Figure 6.4). Consequently, the new arch bridge as shown in Figure 6.12 was commissioned by Environment Agency (2005b) to replace the old bridge for pedestrian and light vehicle use. On the other hand bridges found in the Klang river basin, as previously shown in Figures 1.2 and 1.9, typically have straight deck bridges.

Figure 6.12 Photomontage of the new Lower Bridge at Boscastle (Photograph courtesy of Environment Agency, 2005b)

For the purpose of physical modelling studies, the scaled model bridges were mainly intended to replicate the prototype system of bridges that may be found in the study areas at the Boscastle and Klang. Accordingly, three different types of model bridge designs were selected for the experimental studies, including: a single opening arch bridge model, a straight deck bridge model, and a three opening straight deck bridge model, as illustrated in Figures 6.13 and 6.14. Three bridges were eventually evaluated in the same laboratory flume and under the same experimental conditions in order to reduce the possible incurred error.

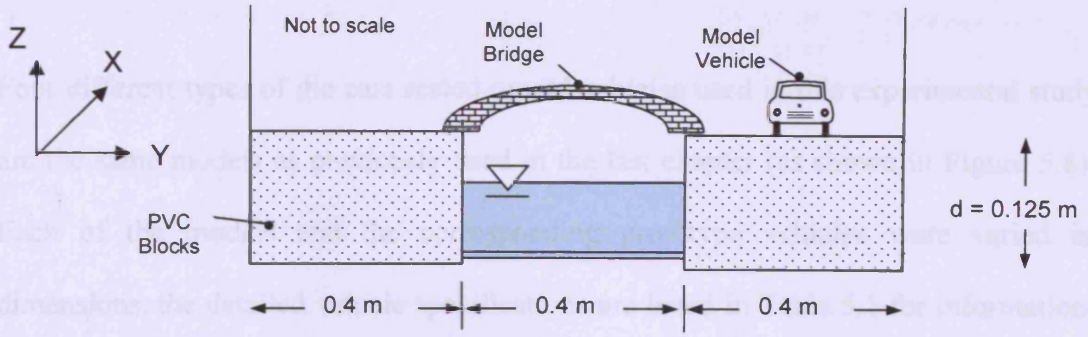
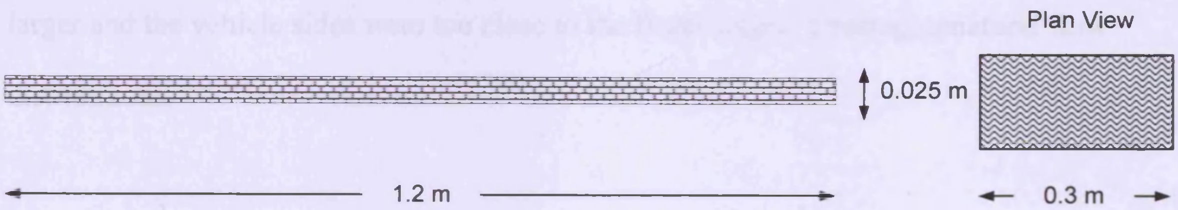


Figure 6.13 Typical cross section of physical model of floodplain with bridge

(a) Model design I - single opening arch bridge

(b) Model design II - straight deck bridge



(c) Model design III - three opening straight deck bridge

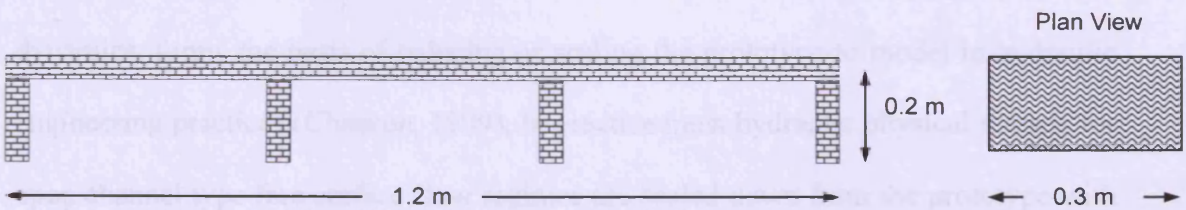


Figure 6.14 Design of scaled model bridges used in the study

6.5.3 Scaled Model Vehicles

Four different types of die cast scaled model vehicles used in this experimental study are the same models as previously used in the last chapter (as shown in Figure 5.8). Each of the models and the corresponding prototype vehicles were varied in dimensions, the detailed vehicle specifications are listed in Table 5.1 for information. All other details about these model vehicles were also provided in the previous chapter.

In this study, ensuring that the model vehicles used were of the appropriate scale was important to provide adequate results. Thus, the model vehicle with a larger scale of 1:18 was adopted, where this scale was best fitted with several requirements for the study. The dimensions of the experimental laboratory flume have primarily restricted the scale modelling. For example, a smaller scale was studied but the vehicles did not resist motion at the gentlest of conditions in the flume. A scale any larger and the vehicle sides were too close to the flume edges, creating unnatural flow distributions.

6.5.4 Dimensional Scale Modelling

In a physical modelling study, the similitude in geometry, motion, and force, or dynamics, forms the basis of reducing or scaling the prototype to model in hydraulic engineering practices (Chanson, 1999). In practice most hydraulic physical models for open channel type free surface flow regimes are scaled down from the prototype with a Froude similitude, where the gravitational force effects are dominant and the selected dimensionless number is the same for both model and prototype.

In the current study, as gravitational forces are dominant, the physical model was developed on the basis of dynamic similarity through the Froude law (as described in detail in the last chapter), in order to maintain similar characteristics of a real prototype flooding environment along the floodplains. Due to the nature of this study as previously discussed in the earlier chapter, it was highlighted why it was desirable to have some sort of appropriate scaling to the prototype. Ensuring that the physical model used is of the appropriate scale was important to provide adequate results for this study. Thus, a scaling factor of 1:18 was considered appropriate in the design and construction of the physical model. This scaling factor was selected to best fit with several requirements to be considered for this study, for example: the availability of scales for die cast model vehicles, exact dimension of the experimental flume, and minimum depth requirements for the operation of velocity measuring equipment were also restricted the scale modelling for a particular case.

Table 6.1 shows the dimensions of the scaled model and prototype parameters for the newly designed physical model, which consisted of a setting up of a main channel and two adjacent floodplains, with three bridges designs and four different types of die cast model vehicles. Three of the model bridges were constructed at a 1:18 geometrical reduction scale, based on the depths, widths and possible inundations in the experimental flume to make sure that the models were optimally sized to investigate a range of force values in flow conditions ranging from low to high flows. On the other hand, four different die cast model vehicles were produced by the manufacturers to an exact geometric scale of 1:18 to satisfy the real dimensions of prototype vehicles. That meant every length being scaled correctly and all angles were also equal to the prototype, where the model scaling also satisfied geometric similarity.

Table 6.1 Parameter of scaled model and prototype dimensions

Parameter	Model Dimension (m)	Prototype Dimension (m)
Vehicle Width	± 0.09	± 1.62
Vehicle Length	± 0.25	± 4.50
Vehicle Height	± 0.08	± 1.44
Flume Width	1.2	21.6
Channel Width	0.4	7.20
Floodplain Width	0.4	7.20
Floodplain Depth	0.125	2.25
All Bridge Width	0.3	5.40
Bridge I Span	0.4	7.20
Bridge II Span	1.2	21.6
Bridge III Span	1.2	21.6
Bridge I Height	0.15	2.70
Bridge II Height	0.125	2.25
Bridge III Height	0.325	5.85

6.5.5 Experimental Measurements

The measurement of spatial and temporal variations of water flow in real prototype floodplains is extremely difficult because of the limitations of measuring equipment and the ability to deploy it effectively, especially during key extreme flood events. Therefore, in this study, a straight compound channel in which a simplified main channel and two adjacent floodplains was constructed to investigate the flow discharge, velocity and water depth for the consequential impact of model vehicle blockages at three different types of bridges. The study also considered the case without model vehicles in the flume for the purpose of experimental control and to compare the results for no blockage at the bridges.

In current study, the measuring equipment was similar to that used in previous studies outlined in the last chapter on the hydrodynamics of floodplains with vehicles, thus, this chapter only describes briefly for information. Firstly, the water flow discharges in the flume were measured through a calibrated flow meter attached to a computer. The measurements were then recorded from the computer screen. Water depth measurements were recorded through the use of a simple pointer depth gauge device, which had a millimetre scale attached. The scale of the gauge was first zeroed against the bed of the flume and the water depth was then measured by moving the pointer to the water surface. This type of measurement relied heavily upon visual observations, but was considered accurate enough for the purpose of this study, with average values being considered for the turbulent water surface.

The flow meter used in this laboratory study was the propeller type referred to herein as the Nixon Streamflo velocity meter (as previously shown in Figure 5.10). Details about this type of flow meter were described in details in the previous chapter. This meter has the advantage of being robust, capable of recording the low velocities and suitable for the methods applied in this study, and completely portable with a digital indicator requiring no mains supply. Unfortunately, it has the minor limitation in operation of measuring a minimum depth, whereas some other flow meters also had an even higher depth requirement. Overall, this flow meter provided more advantages than disadvantage for the study.

The flow meter and other measuring equipments used in this study were calibrated before carrying out any measurements, in order to increase the accuracy of the results. In fact, for this study it was proposed that all measurements of the flow, velocity, and water depth were repeated at least three times to obtain the best average values.

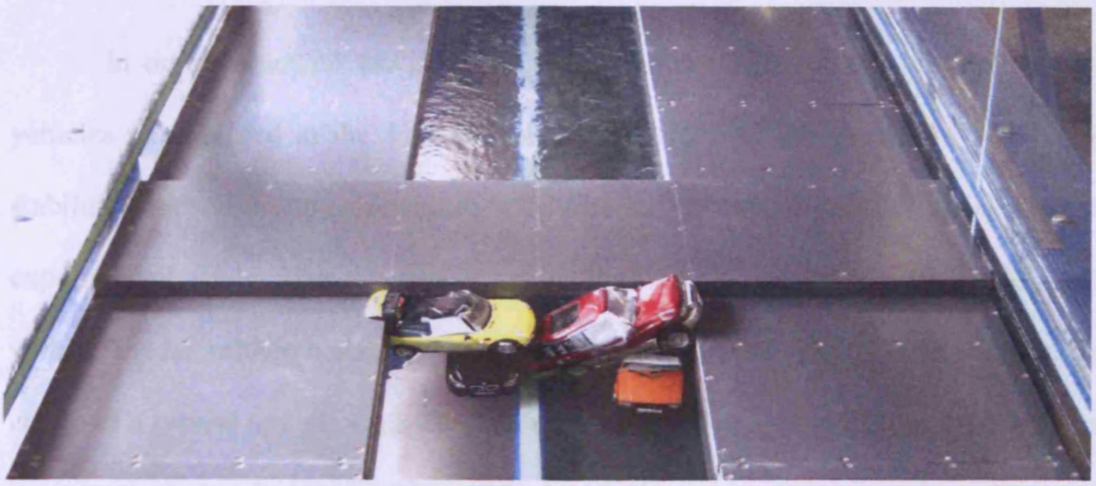
6.5.6 Experimental Procedures

Traditionally, most bridge designers and engineers are more confident in relying on expensive scaled experimental studies based on physical modelling studies in providing estimates of the water flow field and structural response on hydraulic loads. In this study, likewise others, extensive investigations on the hydrodynamics of floodplains with vehicle blockages at bridges were undertaken in this chapter by conducting a series of scaled experimental studies on the floodplains with model vehicles blocking three different designs of model bridges.

As discussed earlier in this chapter, these scaled experimental studies were conducted in a recirculation hydraulics flume to accommodate a replication of a simplified physical model of a straight compound channel, with relatively shallow floodplains on either side, and three designs of scaled model bridges, i.e. a single opening arch bridge model, a straight deck bridge model, and a three opening straight deck bridge model. Each bridge configuration was studied separately on different experiments, with the blockage of four scaled model vehicles. In this setting order, thus the physical model as shown in Figure 6.15 was ready for a series of experimental studies on floodplains.

(a) Model design I - single opening arch bridge

(b) Model design II - straight deck bridge



(c) Model design III - three opening straight deck bridge

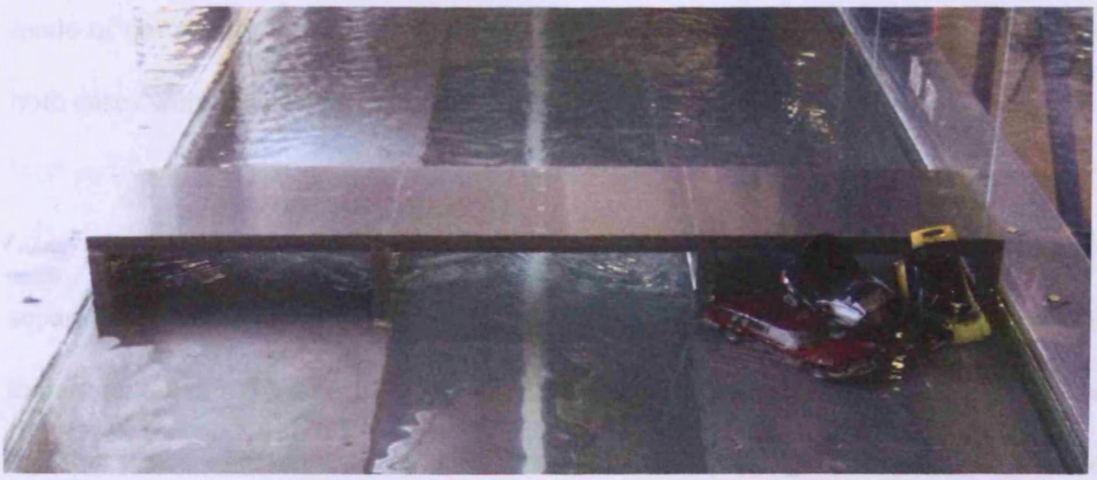


Figure 6.15 Physical model of floodplain with model vehicle blockages for three different designs of scaled model bridge

To begin the experimental studies, firstly, the bed surface of the physical model was maintained horizontal throughout the experiment. Flow discharge was distributed evenly through a horizontal plane at the inlet by passing the inflow through a layer of honeycomb baffle to reduce non-uniformities in the flow structure before entering the flume. The flume was also run for an hour before the start of any experiment to ensure steady conditions, and thereafter a near steady water temperature was held at about 18 °C. The origin of the coordinate system was set to datum of the flume at the centre of main channel bed level. Accordingly, all of the measurements were referred to this origin of coordinate system for consistency.

In order to set up the physical model for experimental studies, four model vehicles were placed at the front of the bridge based on an idealised condition of stability achieved as shown in Figure 6.15, whereas no movement occurred during the experimental study. The experiments were then conducted for the cases with and without model vehicle blockages for all three scaled model bridges being sited in the centre of a typical straight compound channel with a floodplain. The case without the model vehicle blockages was also studied with the same experimental conditions as for the case with the model vehicle blockages, in order to allow comparisons to be made of the results for the case with no obstruction to the flow. All of the results for both cases were recorded and analysed with the same methods.

In the current experimental study, three scaled model bridges were evaluated separately in the same laboratory flume for the same physical model set up and experimental conditions, in order to minimise the experimental error. All of the methods were also repeated for each of the model bridges, for the purpose of highlighting the difference in the results depending on the different bridges. The experimental study was also concerned with the submergence of the bridges and the blockage of the vehicles where they could be varied from partial submergence to complete overtopping of the bridges and/or vehicles.

In order to understand the influences of vehicle blockages at bridges on floodwater flows, it is ideally necessary to be able to determine the critical flow conditions to threshold the vehicle instability. In the current study, flow conditions were selected based on the experimental findings of the previous chapter on the critical conditions of vehicle instability threshold in floodwater flows. At this point, the critical values of the vehicle instability threshold were considered as the input to the current study, in order to make sure that the selected flow conditions were able to ensure that the vehicle instability was achieved, and possibly to move and build up at the front of the bridge during an idealised stable condition. In other words, flow conditions smaller than the critical instability threshold values are not possible to cause any movement of the vehicles, and possibly no blockage at the bridge.

To look into the influence of the vehicles blocking bridges on water depth, a longitudinal free surface profile was obtained along the centreline of the channel. Readings were taken at several cross sections with intervals varying from 1 m down to 0.05 m at the highest resolution required, particularly in the region of rapidly varying flow, downstream of the obstruction, in order to give the best spread of data and information on the progressive effects of the vehicle blockages being modelled and the corresponding hydraulic impacts. The measurement points along the centre of the channel included the location at the incident or transmitted points before the blockage, the front end points of the blockage, the rear end points of the blockage, and the transmitted points after the blockage.

On the other hand, based on Chow (1959) for integrating a logarithmic velocity profile, it can be shown that the mean velocity occurs at an elevation of approximately 60% of the water depth below the surface. As the study progressed it became apparent that it was necessary to investigate the vertical velocity profiles at several cross sections centred along the main channel, and in order to provide this information, so data were collected at a series of points at elevations of 25%, 40%, 50%, 60%, and 75% below the free surface. As a result, the velocity profiles achieved for each cross section, centred along the channel, provided a good understanding of the hydrodynamics processes of flow around the vehicle blockages at bridges.

6.6 Experimental Results and Discussions

The hydrodynamics of floodplains with vehicle blockages at bridges has been studied for the first time with laboratory experiments as discussed herein. The study aimed at addressing the limitations in the data and developing information to enable an assessment to be made of the hydrodynamic impact of vehicle blockages at bridges in floodplains. Therefore, the experimental results and discussions herewith have enabled the establishment of an understanding of the influence of the vehicles blocking bridges on the hydrodynamics of floodwater flows over floodplains, and the hydraulic impact of floodwater flows on vehicle blockages at bridges.

6.6.1 Influence of Vehicle Blockages at Bridges on Flood Flows

The results for all of test cases have been analysed to investigate the effects of the obstruction (i.e. the vehicle blockages at bridges) on flow propagation over floodplains and in the main channel. In order to examine these effects, the variation rates of water depths for the cases with and without vehicle blockages were considered, and measurements were taken at numerous key points at the upstream and downstream ends of the obstruction along the centreline of the flume. The value of the variation rate can be calculated using Equation 5.13 as described in detail in the previous chapter. The value of the variation rate becomes larger than 1.0 when the influence is positive, due to the obstruction, while this value becomes less than 1.0 when this relationship is reversed. This value will be equal to 1.0 when there is no effect of obstruction on the flood flow.

Figures 6.16 to 6.18 show the changes in the variation rates of water depths for the experiment on the physical model of floodplains with model vehicle blockages at three different designs of scaled model bridge. In term of the variation rates of water depths, the results show that the influences are positive at the upstream end of the obstruction, while this relationship is reversed at the downstream end of the obstruction for almost all of the test cases considered. The obstruction to the flow typically forces the water surface elevations at the upstream end to be higher than they would be if the obstruction weren't present. Generally, the tendency of the variation rates for all of the test cases considered is almost the same. The results give a clear understanding of the flow behaviour and show the influence of vehicle blockages at bridges. Accordingly, the results suggest that vehicle blockages at bridges have a significant impact on the flow propagation and the hydrodynamics along floodplains.

As also shown in Figures 6.16 to 6.18, the effects of the obstruction on the water depth was transmitted and extended far upstream for all cases. The transmitted water depth increased at the front of the obstruction and decreased at the rear end by reflection. Hence, the obstruction created a pressure different between the two surfaces in front of the bridge, which causes the form resistance of drag and blockage to the flow and it was also confirmed in the previous chapters by numerical and physical modelling. Typically, this drag and blockage caused a high pressure to occur just upstream of the obstruction, which was commonly observed for other types of obstructions such as the investigations by Hiraishi and Harada, 2003; and Struve et al., 2003; etc. As a result, this observation suggested that the area at the front side of the obstruction was more of a hazard than that at the rear of the bridge.

In this experimental study, four of the model vehicles were placed in a stable condition at the front of the scaled bridges in order to create an idealised case of a prototype environment for the study of flow characteristics. Generally, the main external flow characteristics around the obstruction for vehicle blockages at bridges were dependent on the shape of the whole body. As outlined in the previous chapter, obstructions with streamlined bodies have little influence on the flow around them as compared with the effect from blunt bodies. In this study, vehicle blockages at bridges were categorised as blunt bodies which have significant influence on the floodwater flow around them. Figures 6.16 to 6.18 show this relationship clearly, in particular when the flow discharge is increased. In fact, the large flow discharges generally have the biggest influence on the floodwater flow around the obstruction.

By comparing all of the bridges, the model designs I and II have the largest influence on the water depth along the centreline of the flume, with the case of the model design III having the smallest impact. The observations show that the model designs I and II only have a single opening at the front for both bridges, in addition to the vehicle blockages, which allow only relatively small volumes of water to pass through the blocked opening or act as a low flow conduit. On the other hand, model design III has three openings for the straight deck bridge, with only one being blocked by the vehicles. Based on these observations, the opening size allowing the water to flow through the obstruction also plays an important role in influencing the discharge rate and upstream elevation.

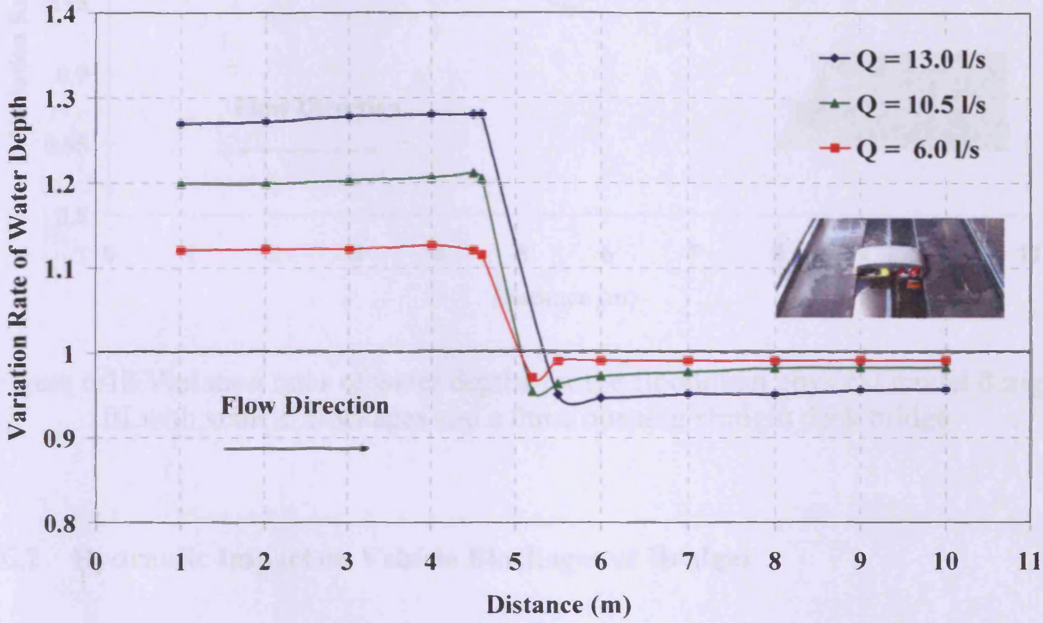


Figure 6.16 Variation rates of water depths for the floodplain physical model design I with vehicle blockages and a single opening arch bridge

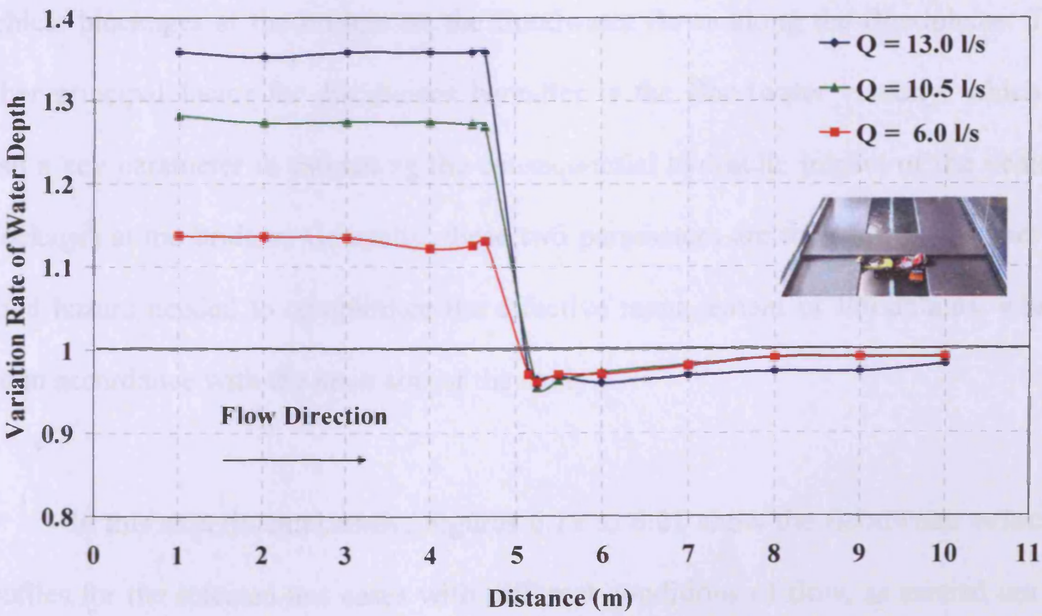


Figure 6.17 Variation rates of water depths for the floodplain physical model design II with vehicle blockages and a straight deck bridge

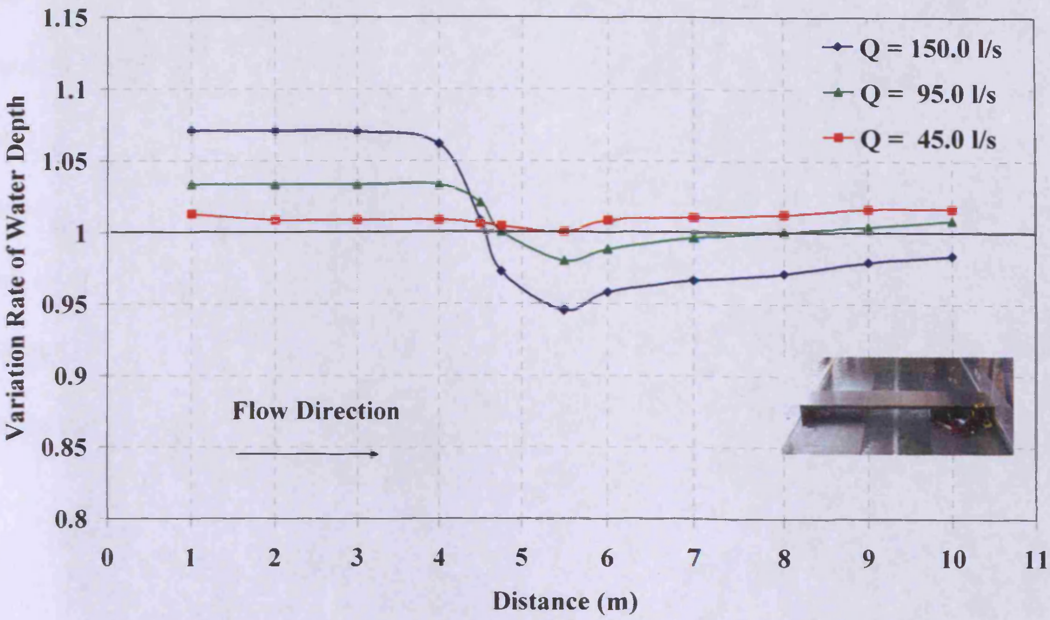


Figure 6.18 Variation rates of water depths for the floodplain physical model design III with vehicle blockages and a three opening straight deck bridge

6.6.2 Hydraulic Impact on Vehicle Blockages at Bridges

As mentioned previously, the floodwater depth is an important parameter in determining the influence of the governing hydrodynamics processes caused by the vehicle blockages at the bridges on the floodwater flows along the floodplains. The other principal factor for discussions hereafter is the floodwater velocity, which is also a key parameter in estimating the consequential hydraulic impact of the vehicle blockages at the bridges. Generally, these two parameters are the principal factors of flood hazard needed to compliment the effective management of floodplains, which are in accordance with the main aim of the study.

In this experimental study, Figures 6.19 to 6.21 show the floodwater velocity profiles for the selected test cases with different conditions of flow, as carried out in the physical model for three different designs of scaled bridge. Based on the graphs, it can be seen that almost all the results followed the same trends for each similar test case, with two obvious relationships being observed for the locations at the upstream and downstream ends of the obstruction. The transmitted velocity increased at the downstream end of the obstruction and decreased at the upstream end by reflection of the obstruction, which was common for all of the results. Through the reflection of the obstruction, the largest reduction effect of the velocity was observed at the upstream end of the obstruction.

On the other hand, the variation in the velocities just downstream after the obstruction were significantly increased in value and with the gradients also changed significantly. Eventually, this fast moving flow expanded further into the wider valley cross section of the floodplains, resulting in a decrease in the velocity further downstream. The flow pattern at the downstream end of the obstruction was deemed to be more complex and thus there was more influence on the velocity. The findings suggest that the influences on the velocities are larger and potentially more significant at the downstream end of the obstruction, while this relationship was reversed at the upstream end of the obstruction. Thus, alternative flood alleviation approaches, such as building flood fencing or a retaining wall along the floodplains may help to prevent flooded vehicles at bridge sites from being flushed into the river and creating a blockage. Figures 6.19 to 6.21 also clearly show that when the flow discharges are increased, then the water velocities were increased as well. As can be seen the larger flow discharges generally have the most significant influence on the floodwater flow around the obstruction. Furthermore, large flow discharges not only lead to increased flood risk and create the largest hydraulic impact on the obstruction of vehicle blockages at bridges, but they also cause the most serious threat to failure of the bridges.

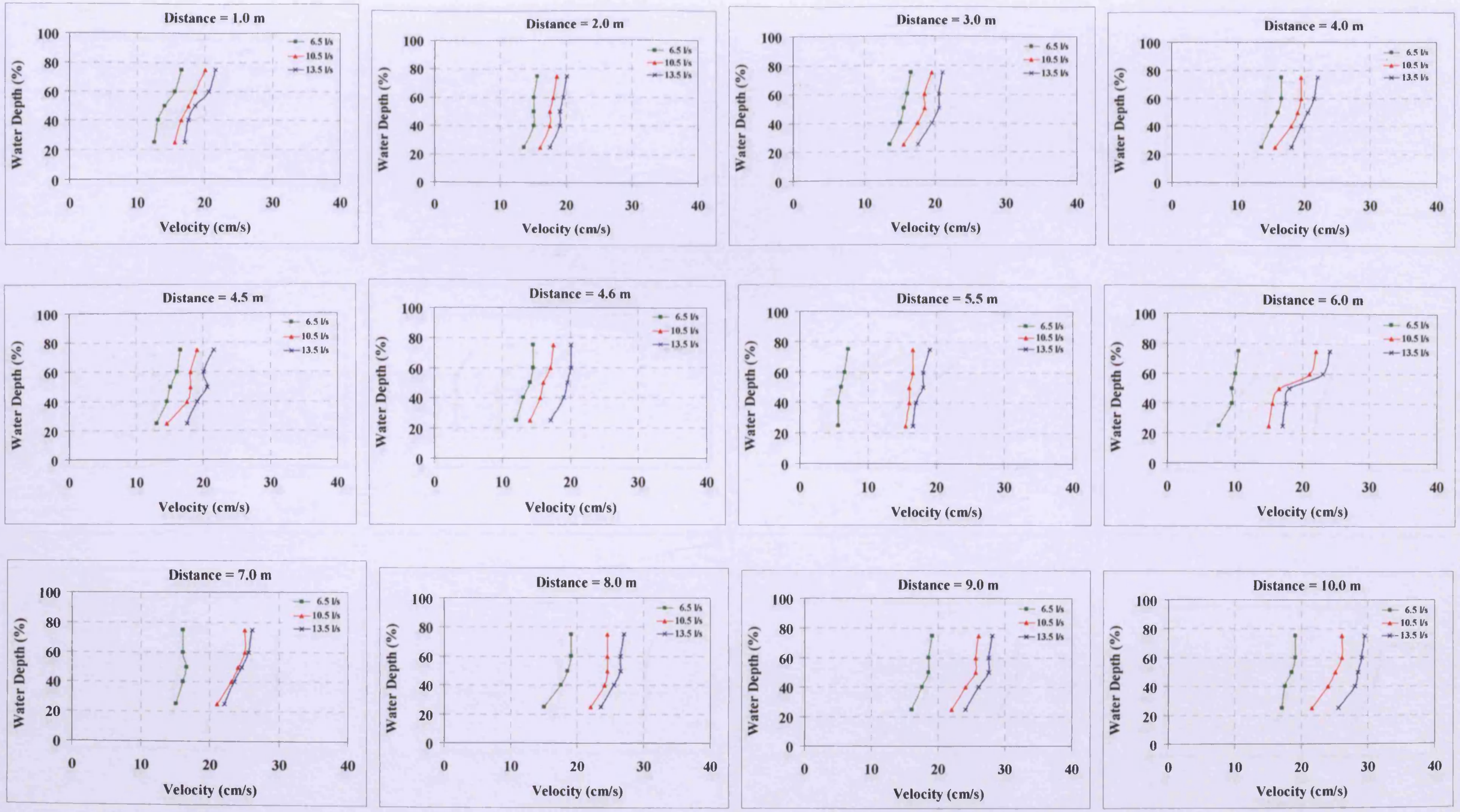


Figure 6.19 Variation of velocities for the hydraulic impacts on the model design I of vehicle blockages at bridge

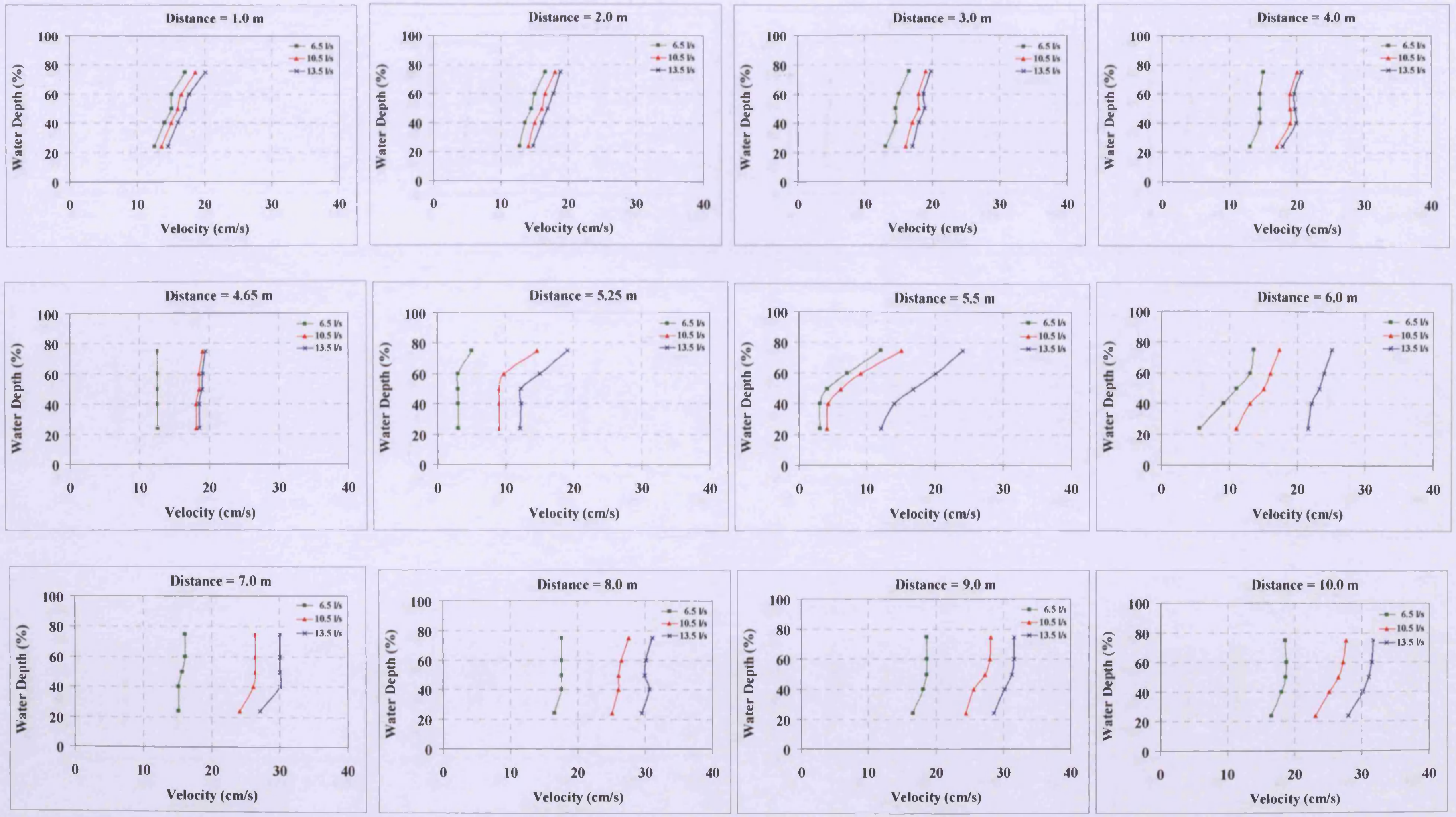


Figure 6.20 Variation of velocities for the hydraulic impacts on the model design II of vehicle blockages at bridge

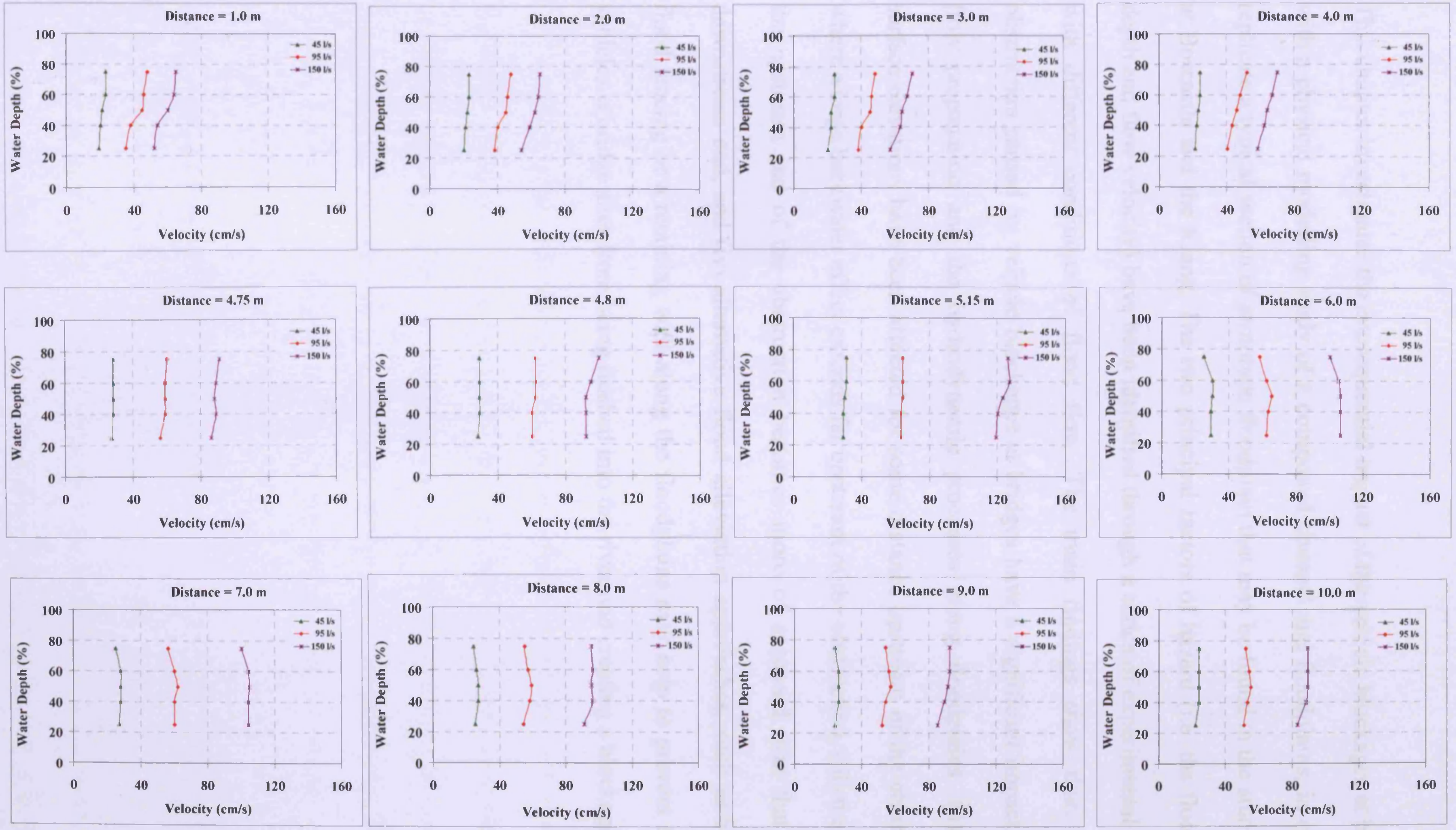


Figure 6.21 Variation of velocities for the hydraulic impacts on the model design III of vehicle blockages at bridge

6.7 Summary

This chapter investigates the consequential impact of the vehicle blockages at bridges, with a physical modelling study of a compound channel and floodplains, in order to replicate a typical section of prototype floodplain that may be found in the study areas at Boscastle and the Klang. The two principal factors of hazard (i.e. the floodwater depth and flow velocity) have been identified through a series of experimental studies with different conditions of flood flow. The main findings show that: (i) the obstruction caused by vehicle blockages at bridges have a significant impact on the flow propagation and the hydrodynamic processes along floodplains, (ii) water surface elevations have been affected for some distance upstream of the obstruction, where a large backwater effect extends far upstream of the obstruction, (iii) the area at the upstream end of the obstruction becomes more of a hazard than that at the downstream end, and (iv) alternative flood alleviation approaches, such as building flood fencing or a retaining wall along the floodplains may help to prevent flooded vehicles at bridge sites from being flushed into the river and creating a blockage.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

A considerable change in the climatic and meteorological conditions in recent years has directly or indirectly led to an increasing occurrence and probability of flooding, which is causing a significant increased risk to human life and property. Consequently, climate change and its variability will exacerbate vulnerability of water resources in the long term unless innovative management practices are implemented. In recognition of this need, the study of the hydrodynamics of river and floodplain flows undertaken in this thesis is an excellent example of an adaptation of innovative solutions to climate change, eventually for the effective management of rivers and floodplains.

In this thesis each chapter covers certain aspect of floodplain hydrodynamics, including in each perspective chapter: (i) an overview of floods and floodplains , (ii) modelling the hydrodynamics of floodplains, (iii) the hydrodynamics of natural floodplains with mangroves, (iv) the hydrodynamics of urban floodplains with vehicles, and (v) the hydrodynamics of floodplains with vehicles and bridges.

7.1.1 An Overview of Floods and Floodplains

An overview is given of the background relating to floods and the responses of floodplains, and the occupied development and encroachment activities, as well as the appropriate management practices. An understanding of the origins, causes, and conditions of floods, despite the hazards that may lead to damaging consequences, are fundamental to the preparation for detailed investigations as covered in the current study. The differences between the different types of flooding are summarised, as well as some of the common characteristics between them. Many terms and definitions are established, which have been used throughout this thesis.

A review is given on the nature and development of floodplains, in particular on the natural development and human encroachment activities (i.e. urban and rural developments) along floodplains. These development and encroachment activities on floodplains have often resulted in the removal of their existing functions as storage and conveyance capabilities of floodwaters, and the corresponding complex hydrodynamic flow interactions, with a wide range of hydraulic obstructions, such as vegetation, agricultural plants, infrastructure, bridge piers, buildings, vehicles on roads, etc., which form the primary focus of this thesis. An understanding of both developments on floodplains and their response to floodwaters provide the basic concepts for further investigation in subsequent chapters.

An introduction is also given into the current practices of floodplain management for their valuable natural resources and flood hazard risks to humans, as well as an outline of the need for appropriate strategies and tools for approaches to floodplain hydrodynamic modelling. In general, floodplain management is a decision making process that aims to achieve the wise use of the floodplains in reducing flood losses and protection of the natural resources and its functions.

7.1.2 Modelling the Hydrodynamics of Floodplains

In order to achieve an effective management for rivers and floodplains, modelling of the hydrodynamic processes has been widely researched over the past decades to assess flood hazards and natural resources. The background information of the corresponding research is covered, as well as with consideration being highlighted to the floodwater flows through selected obstructions and their complex interactions with floodplains. Natural and urban floodplains have been identified as the particular area of interest for this study, together with a detailed investigation to be addressed on modelling of hydrodynamic processes in each floodplain. Previous research studies and up to date views on the modelling of floodplain flows have been briefly reviewed. Both physical and numerical models have been incorporated in floodplain management and have been recognised of their potential to yield multiple benefits and innovative solutions for more sustainable floodplains. These potential benefits and innovative solutions will be further investigated in this study.

The governing equations and numerical methods used in the present study have been clarified in brief to provide a clear definition of the hydrodynamic processes considered in the current study. The hydrodynamic model has been refined from an existing two-dimensional depth integrated finite difference model, which was originally developed by Falconer (1986). The refined model is proceeded by describing the physical system of floodplains with a set of governing equations and conservation laws acting with the system. In this refined model, the assumption of a hydrostatic pressure distribution and a kinematic boundary condition at the free surface have been included in the three dimensional Reynolds averaged Navier-Stokes equations, to give the depth integrated equations of motion. The governing finite difference equations are then solved using the Alternating Direction Implicit method and formulated using a space staggered grid scheme.

7.1.3 Hydrodynamics of Natural Floodplains with Mangroves

The specific area of interest was to model the flood hydrodynamics through mangrove forests within natural floodplains. By extending the work of Struve (2000), Westwater (2001), and Wu et al. (2001) on the influence of increased vegetation resistance and reduced areas of flood flow structures arising from mangroves, the current study has focused on investigating the consequential impact of these changes on the dissipation of extreme flood events, particularly on tsunamis. The findings show that mangroves can have a significant impact on the hydrodynamic characteristics of tsunami currents in floodplains.

An idealised test case for studying the effects of mangroves, distributed along the whole channel, has been investigated to establish the significance of the effect of mangroves on the attenuation of tsunami currents, particularly at the head of a mangrove fringed estuary. It was found that the velocities and water elevations were significantly reduced by mangroves in the forested swamp and surrounding area. Consequently, the flood hazard to humans was decreased in these particular regions. The results also showed that for a smaller value for the porosity of mangroves, and then a greater reduction occurs in the wave energy. All of these findings showed that mangroves can play a key role in wave attenuation by slowing down tsunami currents and attenuating the wave height in swamp areas.

The model was also applied to study the tsunami currents in the Merbok estuary, Malaysia. Predictions were undertaken to study the effects of tsunami currents in floodplains, both with and without mangroves. These simulations were undertaken to investigate the effects of mangroves on the hydrodynamic and flushing processes in the floodplain. Due to the drag force and the blockage effect induced by mangrove trees, the increases in the water elevation in the main river were much smaller at the upstream end of the river. On the other hand, the velocities were significantly reduced in the swamp area. It is recognised that the storage of flood water on floodplains with mangroves can also reduce the flood magnitude downstream. These results showed that mangroves have a significant impact on the hydrodynamic processes of tsunami currents in a floodplain and, in turn, also have a key impact on the ecosystem associated with mangrove swamps.

Recognising the benefits of mangrove swamps, efforts have recently been made in many countries to re-establish mangrove forests. Working towards sustainable restoration and rehabilitation of mangroves, an innovative and environmentally friendly system, namely the Artificial Mangrove Shelter (AMS) has been proposed, designed and modelled in this study. Simulations have been undertaken for various conditions of the AMS with different porosities (i.e. different diameters and densities), and compared to the case without the AMS. Comparisons of velocity profiles and water elevations for both cases have also been carried out. The results have shown that for a smaller porosity in the AMS then the greater the reduction in the wave energy. The results suggest that the AMS can also have a significant impact on the hydrodynamic processes and, in turn, have a key impact on the natural ecosystem of mangrove swamps from the threat of flooding. The findings confirm that the AMS can play the same roles as natural mangrove shelters for coastal protection and preventing seedlings or young mangroves from being washed away by strong waves and currents, or even tsunamis, located by the sea or large rivers. An improved understanding of the response of the AMS, through this study, has provided a better management procedure for the long term sustainable use of mangroves as natural resources. Modern numerical hydro-environmental modelling tools provide much scope for the future design and application of the AMS.

The most useful tool to become increasingly important in many aspects of water resources and environmental engineering in recent decades has been the development of computational models. Numerical modelling tools in this study hold great promise for future applications in effective floodplain management. The study has also proven that the model developed herein has the capability of being used in a pro-active manner as a useful hydroinformatics tool for the management and planning of floodplains with mangroves as natural defences against natural flooding disasters.

7.1.4 Hydrodynamics of Urban Floodplains with Vehicles

With a change in the global climate predicted, the occurrence probability of urban flooding due to flash floods has increasing gradually in recent decades. Urban flooding caused by flash floods can often lead to the instability of vehicles being driven and/or parked along floodplains. If these vehicles block the flow passage, such as via a local bridge, then they can usually cause more significant damage to the flooded area. The extreme flood event that occurred in Boscastle highlighted the need for further studies to investigate the threshold of vehicle motion in flooded areas. Thus, an experimental study is outlined herein, which has been undertaken to establish an understanding of the hydrodynamics of floodwater flows over urban floodplains with vehicles.

As highlighted previously for the experimental study with floodplains, a compound or a two stage channel was recommended for this study, but current study focused mainly on a simplified one stage channel, with the assumption being most vehicles may be parked quite a distance from the main channel of a river, where the effects of a two stage channel may be reduced. The experimental study for this preliminary stage was therefore more focused on accurately representing the flow through an obstruction, which may be present in such floodplains being considered, as well as considering the relatively shallow water depths which typify these environments.

In order to study the threshold of vehicle motions, a series of flume experiments were conducted with stationary model vehicles in two scales (i.e. a small and a large scale). The experimental results obtained for the smaller scale model vehicles were first scaled up using the theory of hydraulic similarity to the larger scale and the accuracy of these scaled up predictions were then validated using the experimental results obtained for the same scale of model vehicles. Similarly, the experiment results were scaled up to the idealised prototype conditions, to develop a clearer fundamental understanding of the influence of flood flows, particularly on hydraulic stability of prototype vehicles in real floodplain environments.

Based on the observations, these predictions indicated that: (i) if the incoming flow depth was less than the vehicle height, then the threshold velocity increased for a decease in the depth of flow; (ii) if the incoming flow depth was greater than the vehicle height, then the threshold velocity would rise with an increase in the depth of flow, and (iii) a flooded vehicle was more likely to move if the incoming depth just approached the vehicle chassis height due to buoyancy effects. As a result, the findings from the current study can offer a preliminary quantified criterion of hazard level for vehicles parked on floodplains. The criterion for the vehicles on the move would be more complex and different from the current study. However, it should be pointed out that the results were based on relatively ideal circumstances in that the direction of the incoming flow was always facing one orientation of a vehicle and the channel bed was flat.

Throughout the model vehicle test, at different orientations to the flow, a critical condition that affects more in the stability of vehicles in urban floodplains has been identified. Vehicles in the orientation of the side end facing the flow are the one being recognised, generally less stable, and thus attention was mainly focused on this specific orientation as the critical condition to first occurrence of the threshold for vehicle instability. As a result, to investigate the critical conditions of the threshold of vehicle instability, the side end of the vehicle facing the flow of water was selected hereafter for the entire test case studies, instead of a smooth curve for the hydrodynamic front or rear end of a vehicle.

Further investigations were undertaken to examine the effects of ground surface gradients on flow conditions and the stability of vehicles. It was shown that the water depth decreased when the model vehicles were partially submerged, and the threshold velocities needed for initial movement increased with increasing surface gradients. The observations clearly indicated that the bigger the size of the vehicle, then the more stable was the vehicle. In addition, the overall weight of the vehicle also affected the result, where a decrease in weight with a lighter vehicle reduced the gravitational force available to resist the hydrodynamic forces being applied to the vehicle in the flooded area. The findings confirmed that the largest and heaviest vehicles were more stable than the smaller and lighter vehicles, in the flat bed surface.

For the investigation of critical conditions of floodwater discharge, flow velocity and floodwater depth at the threshold of vehicle instability, a series of experiments was undertaken using different types of stationary scaled die cast model vehicles in hydraulics flumes. The experiments were conducted by considering conditions of the vehicles which were not practically fully water tight as for real life conditions. The findings confirmed that the scaled model vehicles had a significant impact on the floodwater flow propagation and the hydrodynamic processes in the flooded area. The two principal hazard factors of the floodwater depth and flow velocity that affect the stability of vehicles in flooded urban areas were identified. The water depth increased at the front side of the model vehicles and decreased at the rear side by reflection for almost all the cases. This indicated that the area of the front side of the model became more hazardous than the rear side.

The experimental results were then extrapolated to the equivalent idealised prototype conditions with the theory of hydraulic similarity. A straightforward envelope curve has been first developed based on the scaled up results. Referring to this envelope curve, a novel innovative approach has been first introduced herein, identified as the Traffic Light of Hydraulic Stability (TLHS). Through this innovation, zones of hydraulic stability for each vehicle were identified by colour with the stable zone in green, the transition zone in yellow and the unstable zone in red. This envelope curve can be easily used as a flood risk management guide to evaluate the degree of hydraulic stability for vehicles, and it is also useful for assessing the vehicle hazard conditions in urban floodplains. By understanding the flood hazards, the study has resulted in recommendations being made for flood estimation and management plans, which, in turn, have a key impact on the reduction of flood risk. Further research is still needed to address the deficiencies in the data and develop proper procedures and guidelines to enable an assessment of flood hazard, especially with regard to the stability of flooded vehicles under real and more complex circumstances. With improvements in this knowledge, then possible disastrous consequences, such as Boscastle, could be reduced and prevented in the future.

7.1.5 Hydrodynamics of Floodplains with Vehicles and Bridges

Whilst extreme flood events are known to cause significant damage, the obstruction of vehicles moving with the flow have also been known frequently to exacerbate flooding by raising water elevations upstream. Firstly, the rapid movement of these large objects being washed away by the floodwater can cause damage to property and significant risk to human life through collisions, etc. Secondly, where obstructions block the flow conveyance at the downstream end of a channel and build up in front of bridges etc., then the upstream effects of flooding are frequently worsened. Thus, the current study has emphasized the need for more studies to be undertaken on representing the flows through such obstructions in the future.

This study investigates the consequential impacts of the vehicle blockages at bridges through experimental studies in a laboratory flume, with a newly built physical model of a straight compound channel, consisting of a simplified replication of a main channel and two adjacent shallow floodplains, based on a typical section of a prototype floodplain similar to conditions found along parts of the Boscastle and Klang river basins or other floodplains with similarity. The shallow floodplains with a compound channel were designed so that model vehicles could be built up to block the bridges for the investigation of flows through such obstructions, in order to replicate the real environment. The two principal hazard factors (i.e. the floodwater depth and flow velocity) were identified to confirm the consequential impact of the hydrodynamic processes in floodplains with vehicle blockages at bridges. All experiments undertaken so far have only looked into the scenarios under which the model vehicles were blocked at the front of the bridges in an idealised stabilised condition. So far observations have been made from the preliminary experiments conducted to systematically look into the hydraulic behaviour of vehicle blockages at bridges in floodplains.

The experimental results clearly acknowledged the flow behaviour and influence around vehicle blockages at bridges. The results confirmed that vehicle blockages at bridges have a significant impact on the flow propagation and the hydrodynamic processes on the upstream floodplains and a lesser impact on the downstream reach. Based on the results, the water surface elevations were affected for some distance upstream of the bridges, with a large backwater effect being measured to extend far upstream of the bridge location. This observation confirms that the area at the upstream end of bridges becomes much more of a hazard due to flooding when vehicles are blocked in bridges and from an engineering standpoint river reaches prove to vehicles being carried into rivers during extreme flood events should be fenced off to avoid cars, caravans, etc. being transported into the river by the flow. The findings eventually provided a good understanding of the hydraulic impacts of floodwater flows on the vehicle blockages at bridges along the floodplains.

7.2 Recommendations for Further Study

Following on from the studies reported herein some shortcomings were identified and a number of future research studies are recommended. These shortcomings and recommendations are summarised below:

- More numerical modelling studies are needed for the hydrodynamics of natural floodplains with mangroves, particularly on: (i) the development of an improved hydrodynamic representation of mangrove trees, by including other factors such as the influence of root and branch structures, which may also offer further resistance to the flow dynamics, (ii) further refinement of the momentum equations to include more accurate representation of the porosity terms, (iii) the representation of more extreme flood events for more complex circumstances, (iv) the application to more real floodplains, with real flood flow conditions, (v) model simulations with more pro-active test cases for the innovative approach of Artificial Mangrove Shelter (AMS) for the sustainable restoration and rehabilitation of mangroves.
- Further experimental studies are still needed to address the deficiencies in the data and develop proper procedures and guidelines to enable an assessment of flood hazards and investigations in the hydrodynamics of urban floodplains with vehicles, especially for situations with regard to: (i) the stability of flooded vehicles under real and more complex circumstances, and under extreme flood flow conditions, such as tsunamis, tidal waves, etc., (ii) the critical instability threshold conditions for greater range of vehicles, including lorries, buses, caravans, etc., all of which have larger cross-sectional areas of flow, (iii) the consideration of two compound channels, which typify real

floodplain environments, (iv) the application for vehicles on the move, which is the common situation in urban floodplains, (v) appropriate scaling to the prototype for good representation of the prototype environment, (vi) a mixture of numerous vehicles instead of a single vehicle, where normally a group of vehicles would be parked in a row along the floodplains, (vii) the validation of experimental results with numerical model simulations, and (viii) promotion of the innovative approach of Traffic Light of Hydraulic Stability (TLHS), with a more straightforward and accurate envelope curve.

- More detailed physical modelling studies are required to investigate hydrodynamics of floodplains with vehicle blockages at bridges and, in particular, for situations: (i) with more flood flow conditions to be considered, (ii) with a variety of vehicles blocking bridges, (iii) with different types of bridges as found in the real environment, (iv) with different stabilised conditions for vehicles to block and build up in front of bridges, (v) with validation of the experimental results against more numerical model simulations. In addition to the above the results in the experimental studies were accurate enough to give reasonable deductions, but there were some erroneous results due to human error; the accuracy of the readings could have been reduced due to the measuring of the depth, as the flow was turbulent and there was no flat level of water so measuring the depth could vary by several millimetres in either direction; and another cause of inaccuracies could have come from the measurement of the discharge, where the instrument used to measure the flow fluctuated at times and as the discharge was increased it was increasingly harder to check if the flow was accurate. Furthermore, the dimension of the laboratory flume was restricted due to scale modelling and an undistorted scale for integration over the depth should consider in future.

7.3 Achievements

The relevant publications and awards for this research study are listed below:

(i) Research Publications

Xia J.Q., Teo F.Y., Falconer R.A., and Lin B.L., Formula of Incipient Velocity for Flooded Vehicles, *Journal of the International Society for the Prevention and Mitigation of Natural Hazards, Natural Hazards*, Springer-Verlag, (2010), 1-14, ISSN: 1573-0840 (Print); 0921-030X (Online), DOI 10.1007/s11069-010-9639-x.

Teo F.Y., Falconer R.A., and Lin B.L., Model Simulations of an Artificial Mangrove Shelter for Coastal Protection, *Proceedings of the 5th International Conference on Asian and Pacific Coasts, Singapore*, Volume 4 (2009), 220-227, ISBN: 978-981-4287-94-4.

Teo F.Y., Falconer R.A., and Lin B.L., Hydraulic Model Studies on the Impact of Vehicles on Flooding in Urban Areas, *Proceedings of International Conference on Water Resources, Malaysia*, Paper ID 65 (2009), 1-7, ISBN: 983-42420-3-9.

Teo F.Y., Falconer R.A., and Lin B.L., Modelling Effects of Mangroves on Tsunamis, *Proceedings of Institution of Civil Engineers, Water Management*, Thomas Telford, London,162 WM1 (2009), 3-12, ISSN: 1741-7589 (Print); 1751-7729 (Online).

Teo F.Y., Mangroves: Natural Defences against Natural Disasters in Model Simulations, *Innovative Solutions for the Delta*, Royal Haskoning - DeltaCompetition, The Netherlands, (2008), 15-26, See http://www.deltacompetition.com/en-us/ Down loads/Lists/RHKDocuments/Attachments/25/Delta%20Book%2008.pdf.

Teo F.Y., Falconer R.A., and Lin B.L., Tsunami Currents in an Idealised Estuary with Mangroves, *Proceedings of 2nd international conference on managing rivers in the 21st century, Malaysia*, (2007), 218-226, ISBN: 978-983-3067-19-0.

(ii) Research Awards

Awarded First Prize of the International Delta Competition 2008, by the Royal Haskoning, the Netherland, for research paper on "Mangroves: Natural Defences against Natural Disasters in Model Simulations".

Awarded the David Douglas Award 2008, by the South Wales Institute of Engineers Educational Trust, Wales, for research paper on "Attenuation of Tsunami Currents in an Estuary with Mangroves".

Awarded First Prize of the UK Young Persons Paper Competition 2007, by the International Association of Hydraulic Engineering and Research, UK, for research paper on "Tsunami Currents in an Idealised Estuary with Mangroves".

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