2D Hydrodynamic Modelling: Mobile Beds, Vehicle Stability and Severn Estuary Barrage

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Statement of Use
This report is intended to be used by researchers, model developers and modellers who wish to understand and potentially use the advances in 2D modelling developed during WP1.1 of the FRMRC2. The report presents an enhanced approach to determining stability of vehicles during flooding. It also provides details of linked 2D hydraulics and sediment modelling and results from modelling of a potential barrage in the Severn Estuary.

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Summary

This report provides a summary of research undertaken in work package 1.1 of the FRMRC2. The focus is on aspects of 2D modelling of flooding and the report covers the following topics:

- Development of a 2D morphodynamic model in which the processes of flow routing, sediment transport and corresponding bed evolution are simulated using a coupled approach, with a refined wetting and drying approach.

- Development of incipient velocity formulas for flooded vehicles. Two incipient velocity formulae under different scenarios are proposed for assessing stability criteria of vehicles in floodwaters, and the accuracy of these formulas are validated using flume-based experimental data and observed data from real events.

- Development of an integrated numerical model for flood risk management. The developed model can be used to predict the inundation of flash floods and the corresponding flood hazards to people and property. The model was validated using observations obtained from three flash floods, which indicates the enhanced numerical model can be used as an approximate assessment tool to assist in flood risk management.

- Simulations of the impacts of a potential Severn Barrage on flood risk.
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1 Introduction

Work Package 1.1 of FRMRC2 was entitled “Hydrodynamic Modelling to Support Enhanced Flood Risk Estimation” and was conducted in the Hydro-environmental Research Centre, at Cardiff University, with Prof. Roger A. Falconer being the leader of this work package. This report provides a summary of the main outputs of the research – further information is published in a series of papers (as listed in Chapter 6).

This report includes the following sections:

- relevance of the research
- literature review
- summary of the key findings
- conclusions and recommendations
- list of publications
2 Relevance of the Research

The research conducted mainly covers three aspects of flood analysis: numerical methods for predicting flood routing over mobile beds, the stability criterion of flooded vehicles, and the effect of barrage construction on the coastal flooding in the Severn Estuary. The relevance of this research for each aspect is presented in this section.

2.1 Modelling of dam-break floods over mobile beds

Many numerical models pertaining to dam-break floods can be found in the literature, and they have been successfully used to predict the flood inundation extent and velocity distributions. However, the majority of these models are only applicable to dam-break floods over fixed beds. In some catastrophic flood events, flood flows have induced severe sediment movements in various forms: debris flows, mud flows, floating debris and sediment-laden currents. Due to the interaction between the sediment-laden flow and mobile bed, river channels, floodplains and other flood-prone areas undergo frequent morphological changes. For example, severe sediment deposition in a local reach caused by a dam-break flood would lead to reduced channel conveyance; in some extreme cases, the volume of entrained material could reach the same order of magnitude as the volume of water initially released from the failed dam, and this material usually includes large-size boulders, and even vehicles, which could block local hydraulic structures, such as bridges or culverts. For dam-break floods, the processes of flood wave propagation and associated bed evolution are usually very significant. In order to accurately predict these processes, it is necessary to develop a morphodynamic model using a sediment-water coupled approach to take into account the effects of bed level change and sediment contractions on the process of flood inundation.

2.2 Estimation of flood risk to people and vehicles in urban areas

The risk to vehicles and people caused by a flood varies both in time and place across a flood-prone area, and also changes with different body shapes and weights. The variation in the hazard degree for people in floodwaters needs to be understood by managers for urban floods. Therefore, it is important to assess the degree of people stability in floodwaters. Vehicles in urban areas usually tend to be unstable by losing their resistance (frictional instability) or becoming buoyant (floating) in flash floods, which further leads to various hazards, including causing injuries or mortality to passengers and bystanders, damage to buildings and infrastructure, and even exacerbation of a flood event by blocking local hydraulic structures, such as bridges or culverts. Therefore, it is necessary to investigate vehicle stability conditions in floodwaters and to develop appropriate formulations for engineers to estimate such conditions.

2.3 Estimation of future coastal flooding in the Severn Estuary

The Severn Estuary is an ideal site for tidal renewable energy projects, since this estuary has the third highest tidal range in the world. The UK Government recently considered many proposals for tidal renewable energy projects for the estuary. The Severn Barrage was one of the proposals submitted. If the barrage were to be built as proposed, the higher tide levels would be reduced significantly inside the barrage but the extent of reduction would depend on the mode of barrage operation. In order to prevent future coastal flooding in the basin, the barrage could also be
operated so as to reduce higher tide levels caused by storm surges. These disasters may cause great damage to life and properties along the estuary. Climate change is set to increase the potential impacts. An assessment of future coastal flood risk along the Severn Estuary needs to account for the effect of the potential barrage construction and various open seaward boundary scenarios.
3 Literature Review

3.1 Algorithms for 2D flood inundation modelling

For a flood induced dyke failure or dam break event, or a sudden opening of a sluice gate in a flood detention basin, a shock wave usually forms and then propagates forward on an initially dry bed. The processes of flood routing on dry beds caused by dam-break flows can usually be simulated by two-dimensional (2D) hydrodynamic models. Flood inundation studies based on 2D numerical model simulations and laboratory experiments for dam-break flows are one of the most widely studied topics in the current computational fluid dynamics research field (Bellos et al., 1992; Fraccarollo and Toro, 1995; Bradford and Sanders, 2002; Lin et al., 2003; Zhou et al., 2004; Yoon and Kang, 2004; Liao et al., 2007; Soares-Frazao, 2007; Liang et al., 2007). In the literature, many numerical methods are available for simulating dam-break flows. Zhao et al. (1996) presented a detailed review of a range of numerical methods developed for simulating dam-break flows, based on solving the 2D shallow water equations (SWEs). Bradford and Sanders (2002) presented a robust procedure for modelling urban floods and applied it to simulate the movement of a wetting and drying wave front. Among these numerical methods the finite volume method (FVM) with a total variation diminishing (TVD) scheme is considered to be one of the most successful methods for simulating the propagation of shock waves (Sleigh et al., 1998; Bradford and Sanders, 2002; Zhou et al., 2004; Liao et al., 2007). In a FVM solver, the depth-integrated 2D SWEs are solved in each computational cell with mass and momentum being automatically conserved, even in the presence of a discontinuity for some flow parameters. The normal fluxes across the cell faces are often evaluated using an approximate Riemann solver, instead of an exact Riemann solver. Such a method is computationally more efficient, yet it is still able to accurately capture shock wave fronts. In addition, numerical oscillations that sometimes occur at the flood wave front, including a hydraulic jump, can be suppressed by introducing a suitable flux limiter. For predicting dam-break flows it is necessary to employ a specific approach to simulating the evolution of wetting and drying fronts. In a practical study of flooding over a real topography or terrain, both positive and negative bed slopes generally exist, as well as different structures and obstacles, such as buildings, trees and roads, etc. The presence of steep bed slopes and/or sharp changes along the horizontal model boundary often results in challenging difficulties for numerical models, as an inaccurate treatment of wetting and drying fronts may lead to significant prediction errors. Therefore, it is necessary to propose an appropriate method to deal with the wetting and drying problem.

3.2 Modelling flash flood routing over mobile beds

Earlier studies on flood routing were primarily based on analytical solutions for idealised conditions. With the advancement of computer technology and numerical solution methods of the shallow water equations, hydrodynamic models based on one-dimensional (1D) and two-dimensional (2D) approaches are increasingly being used for predicting dam-break flows. Currently, numerical solutions of the shallow water equations type are one of the most active topics in the field of hydraulics research. Several numerical models pertaining to dam-break flows can be found in the literature, and they have been successfully used to predict flood inundation extent and velocity distributions. However, the majority of these models are only applicable to dam-break flows over fixed beds (Lin et al., 2003; Zhou et al., 2004; Liang et al., 2007). In some catastrophic flood events, particularly those caused by dam or dike failures, flood flows...
have induced severe sediment movements in various forms: debris flows, mud flows, floating debris and sediment-laden currents (Costa et al., 1988). Capart et al. (2001) pointed out that in some extreme cases, the volume of entrained material could reach the same order of magnitude as the volume of water initially released from the failed dam. It is thus often necessary to account for the process of morphological changes when simulating such severe dam-break flows. Currently, two approaches are often used to simulate the morphodynamic processes: uncoupled and coupled solutions (Zhang and Xie, 1993). In order to model the morphodynamic processes caused by dam-break flows, the second method may be more acceptable. This is due to the rate of bed evolution often being comparable to the rate of water depth variation. Early numerical models for simulating dam-break flows over mobile beds often adopted uncoupled solutions that did not account for the effects of sediment transport and bed deformation on the movement of flow (Ferreira and Leal, 1998; Fraccarollo and Armanini, 1998; Fagherazzi and Sun, 2003).

Although many 2D dam-break flow models over non-mobile, or fixed, beds have been developed over the past decade (Lin et al., 2003; Liao et al., 2007; Zhou et al., 2004; Liang et al., 2007; Begnudelli and Sanders, 2007; Gallegos et al., 2009; Fraccarollo and Toro, 1995; Zhao et al., 1996), 2D models for dam-break flows over mobile beds using the coupled solution are seldom reported due to the complexity of flow-sediment transport and bed evolution. Simpson and Castelltort (2006) extended an existing 1D coupled model of Cao et al. (2004) to a 2D model for the free surface flow, sediment transport and morphological evolution. This model used a Godunov-type method with a first-order approximate Riemann solver, and was verified by comparing the computed results with the documented solutions. As commented by Cao (2007), the first-order numerical scheme in solving the governing equations may have limitations in modelling water levels and sediment concentrations with gradient discontinuities. The model was applied to test cases with some idealized flat bed channels, without the need to consider the wetting and drying fronts. Therefore, it is necessary to develop a morphodynamic model for simulating dam-break flows over mobile beds with more advanced solution schemes and wider applicability.

### 3.3 Safety criteria of people and property in floodwaters

#### 3.3.1 Assessment method for people safety

Previous studies on the assessment method of people safety have been carried using two different approaches: (i) based on empirical or semi-quantitative criteria (NSWG, 2005; Penning-Rosswell et al., 2005; Defra and EA, 2006; Ishigaki et al., 2005, 2008), and (ii) based on formulae derived from mechanical principles, i.e. balance of forces, linked with experiments (Foster and Cox, 1973; Abt et al., 1989; Keller and Mitsch, 1992; Karvonen et al., 2000; Lind et al., 2004; Jonkman and Penning-Rosswell, 2008).

Empirical or semi-quantitative criteria were usually used to evaluate the degree of hazard to people by organisations of flood management or related departments of a government. Defra and the EA (2006) reported a simple method to determine the rating of flood hazard based on flow velocity, depth and the presence of debris. Formulae derived from a more mechanics-based experimental approach were obtained from studies by Abt et al. (1989) and Karvonen et al. (2000). Abt et al. (1989) reported experiments of human stability on one concrete monolith and 20 healthy, lightly dressed human subjects walking and standing in water of various depths. Karvonen et al. (2000) conducted further tests on people stability in the Rescdam project, in which seven people, age
ranging from 17 to 60 year old, were involved. Both these studies proposed a critical depth-velocity product, indicating that the combination of a certain depth and a corresponding velocity would lead to human instability. The empirical formula obtained is expressed as \( hU_c = f(m_p, h_p) \), where \( h \) is the depth of the incoming flow; \( U_c \) is the critical velocity for reaching human instability; and \( f(m_p, h_p) \) is an empirical function related to the height \( (h_p) \) and mass \( (m_p) \) of a person.

The studies on people safety in floodwaters by Foster and Cox (1973), Keller and Mitsch (1993), and Takahashi et al. (1992) adopted alternative criteria for people stability, and major differences between these studies in the methodologies used for developing the criteria exist (Cox and Ball, 2001). Foster and Cox (1973) based their criteria on physical tests in a laboratory flume, and presented the safe and unsafe flow conditions for standing children. Keller and Mitsch (1993) established a force balance equation for a person standing on a flooded street against sliding, linking the buoyant force, weight, frictional resistance and drag force due to flowing water. The formula is given by:

\[
U_c = \sqrt{2F_r / (\rho_f C_d A)}
\]

where \( \rho_f \) is the density of the flowing fluid; \( C_d \) is the drag coefficient; \( F_r \) is the restoring force due to the friction with \( F_r = \mu F_N \); \( F_N \) is the magnitude of the normal force acting on the surface; \( \mu \) is the friction coefficient; and \( A \) is the submerged area projected normal to the flow. This criterion of people stability (Keller and Mitsch, 1993) was based on a computational analysis of potential flow conditions, rather than on any laboratory experiments.

In this analysis, the dimensionless coefficient of friction between the child’s shoes and the road surface was assumed to be 0.30 under sliding, and a conservative value for \( C_d \) of 1.2 was adopted with the assumption that the body shape of a child was idealised to the shape of a vertical cylinder (Cox and Ball, 2001). According to Eq. (1), two curves were presented between the product of the flow velocity \( (U_c) \) and the incoming depth \( (h) \) at the point of human instability versus \( h \), for a five year old child with the height and weight of 1.11 m and 19 kg respectively and an adult, under the condition of sliding equilibrium. Fig. 1 shows the instability curves for a child and an adult in floodwaters, and it can be seen that there is a significant difference between the critical velocities for the child (0.5 m/s) and the adult (2.2 m/s) as the incoming depth is equal to 0.6 m. It
should be noted that whether a person standing in floodwaters is in danger or not depends on the objective condition (such as the local flow pattern, terrain and visibility) and the objective condition (such as the physical and psychological status of a person). Therefore, the curves in Fig. 1 just present a rough estimate of the risk to a generic person in floodwaters, and these curves have been used in the following numerical assessment of people stability in floodwaters.

### 3.3.2 Assessment method for vehicle safety

Existing studies on the stability criteria of vehicles in floodwaters are limited. Gordon and Stone (1973) investigated the stability of a Morris Mini car with the two back wheels being locked to prevent any 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 important to estimate the appropriate value of the friction coefficient for sliding. Bohham and Hattersley (1967) suggested a sliding friction value of 0.3, while Gordon and Stone (1973) indicated that the friction coefficient ranges from 0.3 to 1.0. Keller and Mitsch (1993) conducted a theoretical investigation into the stability conditions for idealised cars, and developed a simple method for estimating the forces exerted on a stationary vehicle in floodwaters and an incipient velocity formula for a partially submerged vehicle.

In the latest report by AR&R (Shand et al., 2010), existing guidelines and recommendations for the limits of vehicle stability were compared with experimental and analytical results, with a marked difference being obtained between these two sets of results. Therefore, interim criteria for stationary vehicle stability were proposed for three vehicle classes, including small passenger and large passenger vehicles, as well as 4WD (four wheel drive) vehicles. In the recent study conducted by the authors (Xia et al., 2011ab), all of the forces acting on a flooded vehicle were analysed and the corresponding expression for incipient velocity was derived for commonly used vehicles parking on flooded roads or streets. The proposed formulas can account for two scenarios: (i) the inside space of a vehicle would be filled by the floodwater; and (ii) the inside space would not be filled quickly by the flood water, and the vehicle would start to float for a relatively high depth. More details can be seen in section 4.

### 3.3.3 Estimation of flood risk to buildings

Buildings are potential places of refuge during floods and are frequently used by people in flood-prone areas. A partial or complete failure of buildings in which people might shelter to provide safe refuge is consequently a significant factor in determining the potential number of deaths resulting from flooding in extreme circumstances (Defra and EA, 2006). Buildings can collapse because of water pressure, scour of foundations, or a combination of these events. In addition, debris carried by a flood in the form of trees, boulders or vehicles, can cause severe damage to buildings. Kelman and Spence (2004) presented an overview of flood characteristics with respect to their applicability for estimating and analysing direct flood damage to buildings. Flood actions on buildings include: hydrostatic actions, hydrodynamic actions, and erosion actions, etc. However, the main flood actions are the depth difference between water levels outside and inside a building and the velocity near the building walls. Kelman (2002) proposed matrices for damage to buildings based on the maximum flood depth difference and the maximum flood velocity. Five potential levels of damage were assigned to different combinations of depth differences and velocities, from minor water contact and infiltration to irreparable
structural damage. However, such complex matrices for damage to buildings are not necessary in the initial assessment of flood risk.

Therefore, a simplified assessment matrix for the flood risk to buildings was presented by Defra and the EA (2006). This matrix adopted an average of hazard scale for each building type in each combination of depth difference and velocity (Kelman, 2002). The assessment matrix can also be approximately expressed by regression into a simple formula:

\[ HD = 0.7U^{0.14} \Delta h^{0.34} \]  

where \( U \) = velocity near the building walls; \( \Delta h \) = depth difference between water levels outside and inside a building; and \( HD \) = hazard degree of the building in floodwaters. The hazard degrees have been grouped into three damage categories, including some damage \(( HD \leq 0.5)\), severe damage \(( 0.5 < HD < 0.98)\) and irreparable damage \(( HD \geq 0.98)\). It should be pointed out that such a matrix is an indicative assessment of the damage that would occur to buildings in urban areas, and it can not include the effect of different types of building. However, it is often accepted for a preliminary assessment of flood risk in local organisations such as Environment Agency.

### 3.4 Flood risk associated with the proposed Severn Barrage

Coastal flooding is generally caused by a combination of high water levels, which may be caused by spring tides and storm surges, together with high waves (Townsend, 1981), which can lead to overtopping of coastal defences and inundation of low-lying areas, potentially causing damage to life and properties. Waves and storm surges are caused by storm events with high winds blowing over the adjacent sea. Tsunamis, caused by undersea earthquakes, landslides, volcanic eruptions and meteorites can also be important in causing coastal flooding in some parts of the world. Defra (2005) commissioned a study into the tsunami risk to the UK, which concluded that the risk of a tsunami higher than storm surge levels of 2 m could be extremely low and that although further study and upgrading of warning systems was recommended, no specific tsunami flood defences were required. The value of the UK’s assets at risk from flooding by the sea has significantly increased in recent years. In England and Wales alone, over 4 million people and properties valued at over £200 billion are at risk (Office of Science and Technology, 2004). The expected annual damage in England and Wales due to coastal flooding is predicted to increase from the current £0.5 billion to between £1.0 and £13.5 billion, depending on the scenario of climate and socio-economic changes (Hall et al., 2006). At the current stage it is difficult to predict the exact magnitude of sea level rise in a specified estuary in the future, and different values of sea level rise have been predicted by researchers. According to the prediction by Hansen (2007), a sea level rise of several meters will be a near certainty if greenhouse gas emissions keep increasing unchecked. Using results from the Hadley Centre’s HadCM3, Hulme et al. (2002) predicted that by the 2080s relative sea level may reach over 70 cm above the current level in Wales and southwest England in the case of high CO\(_2\) emissions scenario. Therefore, it is necessary to pay more attention to the changes of coastal flooding caused by future sea level rise due to climate change from global warming, or occurrence of extreme sea levels caused by meteorologic or geological disasters.

The hydrodynamic processes in the Bristol Channel and Severn Estuary are highly complex due to the irregular land boundaries and the extremely high tidal range, and the hydrodynamic processes of astronomic tides in the Severn Estuary have been studied extensively by researchers and organisations using numerical models (Uncles, 1983; Evans et al., 1990; Harris et al., 2004; DE et al., 1989). These models need to be refined.
further and can be then used to analyse the potential risk of coastal flood in case of extreme sea levels. Bates et al. (2005) applied a simple two-dimensional hydraulic model to assess the coastal flood risk due to sea level rise in various areas at different scales. Purvis et al. (2008) presented a methodology to estimate the probability of future coastal flooding given uncertainty over possible values of sea level rise, and applied this methodology to a 32 km coastal stretch of the Severn Estuary in South-West England. To simulate the tide propagation in an estuary caused by storm surges or tsunamis, it is necessary to incorporate additional terms into the governing equations defining the hydrodynamic processes. For example, the time evolution of the bottom displacement is usually included in the continuity equation of flow when simulating tsunami propagation, and the wind stress needs to be calculated and the corresponding term needs to be included in the momentum equations of flow when predicting the development of storm surges (Jain et al., 2006; Wolf, 2009).

3.5 References


4 Summary of the Key Findings

4.1 Modelling flood routing with the refined wetting and drying method

Significant refinements have been made to a two-dimensional hydrodynamic model, based on a TVD finite volume method, to predict rapid flood flows on initially dry beds. A Roe’s approximate Riemann solver, with the MUSCL scheme, has been used in this model. The scheme is second-order accurate in both time and space and is free from spurious oscillations. The model deploys unstructured triangular grids and adopts a refined wetting and drying approach originally developed for a regular grid finite difference model, DIVAST. This approach can be summarised as follows:

1. Firstly, each cell is checked at the start of each time step to decide its type. In this method, the computational cells are divided into three types. A cell is considered to be active and wet if the water depth at the cell centre $h_i$ is greater than a small value of water depth, $h_{min}$. A cell is considered dry with its velocity being set to zero, if $h_i$ is less than $h_{min}$. Further, a dry cell can be classified as an inactive dry one if all of the three surrounding cells are dry, and as an active dry cell if one of the three surrounding cells is wet. The inactive dry cells will be removed temporarily out of the computational domain, and this treatment can accordingly decrease the computer time in the case of lots of inactive dry cells.

2. Then, each wet cell or active dry cell is checked after each time step for possible drying. If the predicted depth at the end of each time level $h_i$ becomes less than $h_{min}$, then this cell is set as a dry cell. In addition, the cell $i$ is also treated as a dry cell, even if $h_i$ is greater than $h_{min}$ but the maximum water depth $\text{Max}(h_j)$ of the three surrounding cells, around the cell $i$, is less than $h_{set}$. Here $h_{set}$ is a preset small water depth, typically of a value of 2 - 2.5 $h_{min}$. However, the water elevation retained at this dry cell is set to the value at the previous timestep when the cell was still wet.

3. Finally, each inactive dry cell from step (1) is checked after each time step for possible wetting. An inactive dry cell $i$ is considered as being flooded and to be an active dry cell if the water level at a neighbouring wet cell $j$ around the dry cell is greater than both the bed elevation at the centre of cell $i$ and the midpoint bed elevation of the common edge of cells $i$ and $j$. An active dry cell will be returned to the computational domain at the start of the next time step. Outflow of flow flux is not permitted from an active dry cell, and the active dry cell can be re-introduced into a wet one only if one of the surrounding cells is wet, provided that the flow flux entering this dry cell is large enough.

The model has been applied to several cases, including the Glasgow flood in the UK and a flood event in the Yellow River in China. Numerical model tests were undertaken to investigate the sensitivity of model predictions to the value of a minimum depth as required for treating the wetting and drying fronts. It has been found that the selection of the minimum water depth has a significant impact on the speed of the flood wave propagation on an initially dry bed. For a given time step, an excessively large value of the minimum water depth will lead to inaccurate predictions of the wetting and drying wave fronts, but a very small value will result in numerical instability (Fig. 2).
4.2 Modelling of dam-break flows over mobile beds using a coupled approach

Dam-break flows usually propagate along rivers and floodplains, where the processes of fluid flow, sediment transport and morphological changes are closely linked. However, the majority of existing 2D models used for simulating dam-break flows are only applicable to a fixed bed. The hydrodynamic model described above has been extended to include sediment transport and bed level changes to enable the prediction of dam-break flows over mobile beds. In this model 2D shallow water equations are modified to account for the effects of sediment concentration and bed evolution on flood wave propagation, with the non-equilibrium transport equation for graded sediments being used to represent the sediment transport processes. In addition, the model can take account of the adjustment process of bed material composition during the morphological evolution process. The sediment transport equation is solved in a semi-implicit manner. The predictor-corrector scheme is used in time stepping, leading to a second-order accurate solution in both time and space.

(1) Governing equations for flow and sediment transport

The hydrodynamic governing equations used are based on the two-dimensional shallow water equations, but with additional terms being included to account for the sediment effects on the fluid density and bed level change. The shallow water governing equations of the 2D hydrodynamic model comprise the mass and momentum conservation equations for the water-sediment mixture flow. The modified continuity and momentum equations in the \( x \) and \( y \) directions can be expressed in detail as follows:

\[
\frac{\partial}{\partial t}(h) + \frac{\partial}{\partial x}(hu) + \frac{\partial}{\partial y}(hv) = -\frac{\partial Z_b}{\partial t} \tag{3}
\]

\[
\frac{\partial}{\partial t}(hu) + \frac{\partial}{\partial x}(hu^2 + \frac{1}{2}gh^2) + \frac{\partial}{\partial y}(huv) = gh(S_{w} - S_{b}) + hv\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - \frac{\Delta \rho g h^2}{\rho_m} \frac{\partial S}{\partial x} + \frac{\rho_v - \rho_s}{\rho_m} \frac{\partial \omega Z_b}{\partial t} \tag{4}
\]

\[
\frac{\partial}{\partial t}(hv) + \frac{\partial}{\partial x}(huv^2 + \frac{1}{2}gh^2) + \frac{\partial}{\partial y}(huv) = gh(S_{w} - S_{b}) + hv\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - \frac{\Delta \rho g h^2}{\rho_m} \frac{\partial S}{\partial y} + \frac{\rho_v - \rho_s}{\rho_m} \frac{\partial \omega Z_b}{\partial t} \tag{5}
\]

where \( t \) = time; \( h \) = water depth; \( u \) and \( v \) = velocity components in the \( x \) and \( y \) directions, respectively; \( g \) = gravitational acceleration; \( \nu_t \) = turbulent viscosity coefficient; \( \Delta \rho = \rho_v - \rho_s \), in which \( \rho_v \) = clear water density and \( \rho_s \) = sediment density;
\[ \rho_m = \text{density of water-sediment mixture} \]
\[ \rho_0 = (1 - \rho' / \rho_f) \rho_f + \rho' , \] in which \( \rho' \) is dry density of bed material; \( S = \text{total concentration of graded sediments} \). The bed slope terms (\( S_{h_x}, S_{h_y} \)) and friction slope terms (\( S_{f_x}, S_{f_y} \)) are written as \( S_{h_x} = -\partial Z_b / \partial x \), \( S_{h_y} = -\partial Z_b / \partial y \) and \( S_{f_x} = n^2 \sqrt{u'^2 + v'^2} / h^{4/3} \), \( S_{f_y} = n^2 \sqrt{u'^2 + v'^2} / h^{4/3} \), in the \( x, y \) directions, respectively, where \( Z_b = \text{bed elevation} \); \( n = \text{Manning’s roughness coefficient} \).

For the suspended load, the 2D non-equilibrium transport equation is given as:
\[ \frac{\partial}{\partial t} (hS_k) + \frac{\partial}{\partial x} (huS_k) + \frac{\partial}{\partial y} (hvS_k) = \frac{\partial}{\partial x} (he_x \frac{\partial S_k}{\partial x}) + \frac{\partial}{\partial y} (he_y \frac{\partial S_k}{\partial y}) - \alpha_s \omega_s (S_k - S_{k+1}) \] (6-1)

For the bed load, the 2D non-equilibrium transport equation is given as:
\[ \frac{\partial}{\partial t} (hq_{sk}) + \frac{\partial}{\partial x} (hq_{sk}u_{sk}) + \frac{\partial}{\partial y} (hq_{sk}v_{sk}) = -\alpha_b \omega_b (q_{sk} - q_{sk+1}) \] (6-2)

where \( E_s = \text{turbulent diffusion coefficient of sediment} \); subscript \( k \) represents the \( k \)-th sediment fraction; \( S_k, S_{k+1} \) represent, respectively, the sediment concentration, sediment transport capacity and effective settling velocity for the \( k \)-th fraction; \( \alpha_{sk} = \text{non-equilibrium adaptation coefficient of suspended load} \), which is an empirical coefficient associated with the rate of bed evolution. \( q_{sk} = \text{amount of bed load in a unit volume of water, in kg/m}^3 \); \( \omega_{sk} = \text{setting velocity of bed load} \); \( q_{sk+1} = \text{transport capacity of bed load in a unit volume of water, in kg/m}^3 \); and \( \alpha_{bk} = \text{non-equilibrium adaptation coefficient of bed load} \).

The equation used to represent the suspended load induced during bed evolution is written as:
\[ \rho' \frac{\Delta Z_{sk}}{\Delta t} = \alpha_{sk} \omega_s (S_k - S_{k+1}) \] (7-1)

The equation used to represent the bed load induced during bed evolution is written as:
\[ \rho' \frac{\Delta Z_{sk}}{\Delta t} = \alpha_{sk} \omega_b (q_{sk} - q_{sk+1}) \] (7-2)

where \( \Delta Z_{sk} \) and \( \Delta Z_{sk} = \text{thicknesses of bed deformation caused by suspended load and bed load, respectively, in one time step} \); and \( \Delta Z_i = \text{total thickness of bed evolution in one time step, given by:} \)
\[ \Delta Z_i = \sum_{k=1}^{N_f} \Delta Z_{sk} + \sum_{k=N_f+1}^{N_f} \Delta Z_{bk} \] (7-3)

in which \( N_f = \text{total number of fractions of non-uniform sediments} \); and \( N_f = \text{number of fractions of non-uniform suspended sediments} \). The model was used to study the influence of using different sediment size distributions on the flood flow and channel bed changes.

(2) Predicted results for a partial dam-breach flow in a mobile channel

Model studies were undertaken to investigate the differences in the speed of flood wave propagation over fixed and mobile beds. The model results indicate that there is a significant difference between dam-break flow simulations over fixed and mobile beds. For a dam-break induced flow at the initial stage, the rate of bed evolution is comparable...
to the rate of water depth variation near the dam site (Fig. 3). For mobile beds, the erosion extent over a bed made up of uniform sediment is less than that over a non-uniform sediment bed, while the maximum erosion depth obtained over the former is greater than that over the latter (Fig. 4). The planar shape of the scour hole is approximately elliptical over the uniform sediment bed and it is almost circular over the non-uniform sediment bed, which indicates an increase in the erosion extent in the lateral direction.

![Graph showing water level and bed level variations downstream of the dam for (a) P1 and (b) P2.](image)

**Fig. 3** Water level and bed level variations downstream of the dam for (a) P1 and (b) P2

![Graph showing contours of bed levels after 1h for (a) uniform sediment; and (b) non-uniform sediment.](image)

**Fig. 4** Contours of bed levels after 1h for (a) uniform sediment; and (b) non-uniform sediment

### 4.3 Incipient velocity formula for fully submerged vehicles

Flash floods propagate rapidly, which can lead to a significant hazard to human life and property. However, parked and unattended vehicles can also cause a hazard even in slowly propagating urban floods when they move as floating debris.

A formula has been derived to predict the incipient velocity of flooded vehicles according to the mechanical condition of sliding balance, with a key assumption being made that the inside space of a prototype vehicle would be filled quickly by the floodwater. A series of flume experiments were conducted using three types of scaled die-cast model vehicles, with two scales being tested for each type of vehicle (Fig. 5). More attention was focused on the case of fully submerged condition in these experiments. The experimental data obtained for the small-scale model vehicles were used to determine the two parameters in the derived formula (Fig. 6 and Table 1) and the prediction accuracy of this formula was validated using the experimental data obtained...
for the large-scale model vehicles (Fig. 7). Finally, the corresponding incipient velocities under various incoming depths were computed using this formula for these three prototype vehicles (Fig. 8). It is found that for a specified vehicle the value of incipient velocity reaches its minimum as the incoming flow depth approaches the height of the vehicle. The smaller and lighter the vehicle, the easier it to start sliding in floodwaters. The results can be used as a preliminary assessment to define the hazard to vehicles parking on flooded streets or roads.

Fig. 5 Fully and partially submerged vehicles in the flume

(1) Formula derivation and parameter determination

The incipient velocity formula for flooded vehicles has been derived, giving:

\[ U_c = \alpha \times \left( \frac{h_f}{h_c} \right)^{\beta} \times \sqrt{2g \left( \frac{\rho_c - \rho_f}{\rho_f} \right) h_c} \]  

(8)

in which \( h_f \) and \( h_c \) = water depth and vehicle height, respectively; \( \rho_c \) and \( \rho_f \) = densities of the vehicle and water, respectively; \( g \) = gravitational acceleration; and \( \alpha \) and \( \beta \) = parameters related to the shape of a vehicle, the type of its tyres and the roughness of road surface, which were determined in this study from flume experiments using die-cast model vehicles.

Table 1 Different parameter values in the formula of incipient velocity

<table>
<thead>
<tr>
<th>Flooding Degree</th>
<th>Partially Submerged</th>
<th>Fully Submerged</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>( \alpha )</td>
<td>( \beta )</td>
</tr>
<tr>
<td>Pajero Jeep</td>
<td>1.492</td>
<td>-0.731</td>
</tr>
<tr>
<td>BMW M5</td>
<td>1.116</td>
<td>-0.558</td>
</tr>
<tr>
<td>Mini Cooper</td>
<td>1.225</td>
<td>-0.708</td>
</tr>
</tbody>
</table>
Fig. 6 Incoming depths and corresponding incipient velocities of different vehicles
(For parameterisation)

(2) Formula validation and application
4.4 Incipient velocity formula for partially submerged vehicles

Vehicles parking in urban areas can often cause various degrees of hazard to people and buildings when they are swept away by flash floods. Therefore, it is necessary to investigate the appropriate criteria of vehicle stability in floodwaters, especially under partially submerged conditions.

In the present study different forces acting on partially submerged vehicles have been analysed, with the corresponding expressions for these forces being presented, to derive a mechanics-based formula of incipient velocity for partially submerged vehicles parking in urban areas, with an important assumption being made that the inside space of a prototype vehicle would not be filled quickly by floodwaters and the vehicle would start to float when the outside water depth exceeds a specified depth. About 100 runs of flume experiments were conducted to obtain the combinations water depth and the velocity when a vehicle is at the threshold of instability for three typical types of die-cast model vehicles of the same scale ratio of prototype-to-model dimensions (Fig. 9). The experimental data from these model vehicles studies were then used to determine two key parameters in the derived formula (Fig. 10, Fig. 11 and Table 2).

(1) Formula derivation and parameter determination
The formula of incipient velocity for partially submerged vehicles in floodwaters can be expressed as:

\[
U_c = \alpha \left( \frac{h_f}{h_c} \right)^\beta \sqrt{2g l_e \left( \frac{\rho_c}{\rho_f} \frac{h_c}{h_f} - R_f \right)}
\]  

(9)

where \( l_e \) = vehicle length; \( R_f = h_c \rho_c l_e (h_k \rho_f) \) in which \( h_k \) = critical water depth at which the vehicle starts to float. The values of \( \alpha \) and \( \beta \) are related to the shape of a vehicle, the tyre type and the roughness of the road surface, which are determined in this study by the experimental studies using die-cast model vehicles in a flume.

Fig. 9a Different vehicle orientation angles undertaken in the experiments

Fig. 9b Partially submerged model vehicles in flume
Fig. 10 Depth-incipient velocity relationships for partially submerged model vehicles
(For parameterisation)

Fig. 11 Comparison between the calculated and measured velocities for different model vehicles
(For parameterisation)
Table 2 Different parameter values for incipient velocity Formula Eq. (9)

<table>
<thead>
<tr>
<th>Vehicles</th>
<th>Parameters</th>
<th>$\alpha$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ford Focus</td>
<td></td>
<td>0.500</td>
<td>-0.178</td>
</tr>
<tr>
<td>Ford Transit</td>
<td></td>
<td>0.227</td>
<td>-0.764</td>
</tr>
<tr>
<td>Volvo XC90</td>
<td></td>
<td>0.394</td>
<td>-0.630</td>
</tr>
</tbody>
</table>

(2) Formula validation and application

The flow conditions were regarded as being similar to those in the prototype if the model displays similarity of form (geometric similarity), similarity of motion (kinematic similarity) and similarity of forces (dynamic similarity) (Shen 1979, Zhang and Xie 1993).

The size of the model vehicles were required to strictly follow geometric similarity, and three typical model vehicles were selected, therefore, with the same geometric scale ratio of 18. The tests were designed in an undistorted scale model, due to the use of vivid die-cast models, with the scale ratio of length $\lambda_L$ being equal to that of height $\lambda_H$, namely $\lambda_L = \lambda_H = 18$. According to the conditions for kinematic similarity, the scale ratio of the inertia force to gravity gives the relationship between the scale ratios of velocity $\lambda_U$ and length $\lambda_L$, which can be expressed by $\lambda_U = (\lambda_L)^{0.5}$.

Dynamic similarity implies that the ratios of the prototype to model forces are equal to the same scale ratio of $\lambda_F$, which is also equivalent to $(\lambda_L)^3$. Herein, the selected density of a model vehicle was nearly equal to that of the corresponding prototype, so that $\lambda_{Fg} = \lambda_F$ and $\lambda_{Fb} = \lambda_F$ were also satisfied. Although vivid die-cast model vehicles were used, the location of the model mass centre was likely to be different from that of a corresponding prototype vehicle. It was thus assumed that all of the wheels were locked, and only the motion pattern of vehicle sliding was considered. Therefore, the difference in the location of the centre of mass between the model and prototype vehicles was neglected. Furthermore, with such a scenario not being considered herein, then the uneven mass centre distribution over the axles could lead to the back of the vehicle becoming buoyant earlier and the frictional effect of the back wheels ceasing to contribute to stability. The stability criteria under these specific scenarios needs to be investigated in the future. With the relatively high values of the Reynolds number in the flume tests, the drag coefficient was considered constant for a specified shape (Chanson 2004), so that $C_d$ for the model was nearly equal to that of the prototype. The measured depth-averaged velocities mainly varied from 0.2 to 1.4 m/s, and the mean vehicle width was about 0.1 m, which led to larger Reynolds numbers $Re$, ranging from $2.0 \times 10^4$ to $1.4 \times 10^5$, where $Re = Ub_c/\nu$; and $\nu$ is the kinematic viscosity for water. Therefore, the similarity principle for the drag coefficient was guaranteed for all of the model and prototype vehicles used, resulting in $\lambda_{FD} = \lambda_F$.

The friction coefficient between the tyre and wet carpet for various model vehicles was measured in the flume. A model vehicle was put in the horizontal flume with the bed covered with a wet carpet, and with the vehicle then being pulled manually by a spring balance. The value of the force shown on the balance was recorded as the vehicle started to move. The value of the friction coefficient was equated to the ratio of the force recorded on the spring to the vehicle’s weight. The measured values of the friction
The friction coefficient were 0.39, 0.50 and 0.68 for the Ford Transit, Ford Focus and Volvo XC90, respectively. Therefore, the range of friction coefficients for the model vehicles corresponded well with the prototype ranges of between 0.25 and 0.75 (Kurtus 2005, Gerard 2006). It was concluded that the friction coefficients for the models were nearly equal to those for the prototypes, so that \( \lambda_{FR} = \lambda_F \).

Since these model experiments strictly followed the principles of geometric, kinematic and dynamic similarity, the incipient velocity obtained under a specified water depth for a model vehicle could be directly used to estimate the critical condition for the corresponding prototype vehicle according to the scale ratios. These scale ratios can be expressed by:

\[
h_{fp} = h_{fm} \times \lambda_L \quad \text{and} \quad U_{cp} = U_{cm} \times \sqrt{\lambda_L}
\]

(10)

where the subscripts \( p \) and \( m \) refer to prototype (full-scale) and model parameters respectively; and \( \lambda_L = \) scale ratio of length.

![Fig. 12 Comparisons between estimated incipient velocities for prototype vehicles using two different approaches](image)

Fig. 12 Comparisons between estimated incipient velocities for prototype vehicles using two different approaches (Sources of visually-observed data: BBC (2004). Dozens rescued from flash floods. BBC News <http://news.bbc.co.uk/2/hi/uk_news/england/cornwall/3570940.stm>; and BBC (2010). French flash flood toll up to 25. BBC News <http://www.bbc.co.uk/news/10337433>)

Incipient velocities for partially submerged prototype vehicles in floodwaters were estimated using two different approaches, including the predictions using the model scale ratios and computations based on the derived formula (Fig.12). These critical conditions in the prototype using the scale ratios compared well with the calculations using the derived formula, and the derived formula was also validated by the visually-observed data of swept vehicles in flash floods, which provided some degree of verification of the estimation reliability of the incipient velocity formulation derived for partially submerged prototype vehicles (Fig.12). Further details on the verification are available in Shu et al (2011).
4.5 2D modelling of flood hazard

Flash flooding often leads to extremely dangerous conditions due to its short timescale, giving limited opportunity for issuing warnings, and hence can result in deaths. Many past extreme flood events have been accompanied by flash floods, and they are one of the main sources of serious loss of human life among natural disasters. Flash floods can also cause heavy loss of property, such as the damage to a bridge and loss of vehicles in the 2004 Boscastle flood in the UK. Therefore, flash floods often lead to casualties and can cause damage to vehicles, especially in densely populated urban areas.

In flood risk management studies, it is desirable to be able to predict the degree of safety of people and vehicles during flash floods using a numerical model. In the current study, an algorithm for assessing the degree of safety of people and property has been linked with an existing two-dimensional hydrodynamic model capable of simulating flash floods, which comprises of a 2D integrated numerical model for flood risk management. In this algorithm, empirical functions relating water depths and corresponding critical velocities for children and adults, developed from previous studies, are used to assess the degree of people safety (Eq. (1) or Fig.1), and a new incipient velocity formula is used to evaluate the degree of vehicle safety (Eq. (8) or Fig. 8).

Fig. 13 Distributions of maximum hazard degrees for different people groups and vehicles

The refined model was then applied to three real case studies, including: the Glasgow and Boscastle floods in the UK, and the Malpasset dam-failure flood in France. According to model predictions, the following conclusions have been drawn: (i) model...
results for the Glasgow flood showed that children would be in danger of standing in the flooded streets in some areas (Fig. 13); (ii) for the Boscastle flood model results indicated that vehicles in the car park would be flushed away by the flow with a high velocity, which indirectly testified the predictive accuracy of the incipient velocity formula for vehicles (Fig. 14); and (iii) for the Malpasset dam-failure flood model results showed that the adopted method for the assessment of people safety was applicable, and some local people living below the dam would have been swept away, which corresponded well with the report of casualties. Therefore, the enhanced model can be used to evaluate the flood hazard degree of safety prediction for people and vehicles in flash floods.

4.6 Estimation of future coastal flood risk in the Severn Estuary

The Bristol Channel and Severn Estuary constitute a large, semi-enclosed body of water in the southwest part of the UK. Communities have settled in the coastal lowlands of this estuary for many centuries, and many of these lowlands and settlements have been subject to the risk of coastal flooding and have relied on the protection of artificial sea defences. According to the predicted future sea level rise and possible occurrence of extreme sea levels due to climate change and storm surge events, the probability of coastal flooding in the Severn Estuary will increase accordingly. On the other hand, the Severn Estuary is an ideal site for tidal renewable energy projects, since this estuary has the third highest tidal range in the world. Therefore, it is appropriate to predict the future status of coastal flooding in this estuary for various scenarios combining the effects of climate change and potential barrage construction. In this study, the finite volume algorithm hydrodynamic model was modified to predict the hydrodynamic processes associated with the operation of a tidal barrage. Three scenarios at the open seaward boundary were considered, including the observed time series of water level as the current baseline (Scenario I), the current level hydrograph plus a sea level rise of 1.0 m (Scenarios II) and the current level hydrograph in Scenario I with a surge height of 1.0 m (Scenarios III). Finally, the numerical model was used to simulate the hydrodynamic processes in the Severn Estuary using three seaward boundary scenarios for the conditions without and with the Severn Barrage (Fig. 15), and the flood risk in a small coastal floodplain was assessed with these predictions and documented data.

Model predictions show that: (i) without the barrage, the maximum water levels along the estuary could rise by 1.0-1.2 m due to sea level rise, and the effect of extreme sea levels on the maximum water level would be noticeable only in the outer estuary reach; (ii) with the barrage, the maximum water level could reduce by 0.5-1.2 m upstream.
of the barrage, even if a sea level rise of 1.0 m were to occur, and extreme sea levels could not influence the maximum water level upstream of the barrage; and (iii) the future flood risk in a small coastal floodplain would reach £6.5 M/yr due to sea level rise without the barrage, and such a coastal flood risk could be avoided completely if the barrage were to be built as proposed.
5 Conclusions and Recommendations

The research has developed:

- a morphodynamic model to simulate the processes of flood routing, sediment transport and corresponding bed evolution using a coupled approach, with a refined wetting and drying approach,
- incipient velocity formulae for flooded vehicles under different scenarios for assessing stability criteria of vehicles in floodwaters;
- an integrated numerical model to predict the inundation of flash floods and the corresponding flood hazards to people (including children and adults) and property (vehicles and buildings). The model was validated using some observations obtained from three flash floods, which indicates the enhanced numerical model can be used as an approximate assessment tool assist in flood risk management.

Concerning the stability criteria of vehicles in floodwaters, the research proposed two sets of incipient velocity formulae for different assumptions about the sealing capacity of inside space of a vehicle. It should be pointed out that the current study was based on relatively ideal circumstances that the direction of the incoming flow was always facing the rear or front side of a vehicle and the channel bed was flat. For the assessment of instability thresholds of flooded vehicles under real and more complex circumstances, further studies need to be conducted in order to enable a more practical application of the derived formulae, which should include: (i) the effect of different incoming flow directions; (ii) the effect of different bed slopes; and (iii) the potential prototype experiment with full-scale vehicles.

Concerning the integrated numerical model for predicting the flood risk to people and property in urban areas, the additional algorithm developed for hazard degree estimations is proposed as a valuable tool for flood risk managers responsible for planning and issuing flood warnings etc., associated with flash floods in urban and mountainous environments. However, a further calibration process is required in the
future to check the reliability of the integrated model as more observed data become available.
6 List of Publications

6.1 Peer-reviewed journal papers


6.2 Conference papers


[16] Falconer RA, Xia JQ and Lin BL (2010). The Severn Barrage Project: Modelling...


