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TWO-DIMENSIONAL FLOODPLAIN MODELLING THE CONCEPTS

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ABSTRACT

Numerical modelling of floodplains plays an important role in the overall process of floodplain management. It provides relatively easy and cost-effective description of flood behaviour and helps to analyse “what if” scenarios for various catchment management options. Numerous modelling tools are available for this purpose.

Two-dimensional modelling of floodplains has previously been limited in use due to excessive survey costs and lack of robustness and reliability of available modelling software. However more recently, cost-efficient survey techniques have become available and the modelling software has improved considerably to provide reliable and robust results. As such, two-dimensional floodplain modelling is gaining wider use.

Appreciation of floodplain modelling and its associated concepts has always been a challenge for floodplain managers, who traditionally are not adept in the modelling concepts. Two-dimensional modelling poses a greater challenge. For better understanding of floodplain processes, there is a need for the managers to understand the concepts and processes involved in the modelling of floodplains.

This paper provides the basic concepts of floodplain modelling with special emphasis on two-dimensional modelling. The data requirements for developing a two-dimensional model are presented and the approximations involved in the modelling and the limitations of terrain representation are discussed. Topographic grid generation process and the inherent approximations for the finite difference models are also presented.

Keywords: Floodplain, Hydraulic Modelling, Two-dimensional Hydraulic Modelling, Modelling Concepts.

1. INTRODUCTION

Floodplains present a formidable challenge to effective planning and management. Not only the flood risks to existing developments in the floodplain need to be managed, additional development pressure requires flood planning standards to be established. An essential component of the floodplain management is preserving biodiversity in the floodplains.

The floodplain management objectives can only be achieved if reasonably accurate flood behaviour is established for the floodplains. Data such as flood levels, discharge, velocity, hazard etc is required to define essential flood parameters for the floodplain. Only after such information is generated can the floodplain planning and management issues be addressed. Hydraulic modelling provides the required tool to generate this data.
Various hydraulic modelling techniques have been established over the last 30 years or so, with gradual improvements over time. Traditionally, floodplains have been modelled using a one-dimensional modelling approach, which has provided a reasonably accurate assessment of the floodplains. However, with growing awareness of floodplain management and increasing public participation, higher definition of flood behaviour has been sought by the management authorities.

High definition flooding analysis is increasingly being carried out using two-dimensional hydraulic models. Since two-dimensional modelling techniques are significantly different to traditional one-dimensional methods, there is a need for the floodplain managers to become adept with the latest techniques. This paper discusses the concepts underlying two-dimensional hydraulic modelling. Discussion is provided on data requirements and subsequent model development. Finally, the factors affecting the accuracy of modelling results are highlighted.

2. HYDRAULIC MODELLING

Assessment of flood prone areas for inundation can be undertaken by various methods. A simple method is to map the extent of large historic floods, which in the absence of detailed analysis, provides reasonable flood estimation. Another method is to construct a physical model of the floodplain on a laboratory scale and observe the flooding behaviour. However physical model building is a resource intensive process and is only justified where complexities of flood behaviour are not completely understood or are not amenable to mathematical modelling.

With advancements in numerical modelling techniques and growing computing power, mathematical modelling of floodplains is now an established norm. These computer models provide a reliable tool to assess flood behaviour and can be used to assess various management scenarios in the catchment.

Mathematical modelling aims to develop a better understanding of the hydraulic flow phenomenon active in the floodplain. Flood flow characteristics such as flood level, discharge and velocity are quantified to help floodplain managers in their decision making process.

The following discussion is related to mathematical modelling of the floodplains.

2.1 Model Types

Various classifications are possible for hydraulic models. A broad classification is based on the dimensionality of the model i.e., the number of flow dimensions, which are included in the modelling process. The classification is as follows:

2.1.1 Three-Dimensional (3D) Model

In a 3D model the water movement can be tracked in all three space dimensions. Hence the velocity and flow description is available everywhere in the mass of water body. Such models require large data sets to construct and need significant computer processing resources. 3D models are generally used for estuarine modelling where significant vertical movement is likely in the water body. As such they are useful for water quality modelling where pollutant dispersion can be modelled with higher degree of accuracy. Delft 3D, Mike3, RMA are examples of 3D modelling systems. 3D models are seldom used in floodplain modelling.
2.1.2 Two-Dimensional (2D) Model

2D models represent flow behaviour in two dimensions describing a horizontal plane. Such models assume vertically averaged flow, which can be visualised at a column of water with uniform velocity over the entire depth. However, the velocity can have different components along the horizontal plane. Historically 2D modelling systems have been developed to study the hydrodynamics of the estuarine environment. With increasing use of 2D modelling of floodplains, these modelling systems have been restructured to accommodate the dominant floodplain flow processes. Other models have specifically been developed for floodplain applications. 2D models can also be used for water quality modelling in addition to floodplain modelling.

Delft-FLS, Mike21, RMA2, FESWMS are examples of two-dimensional modelling systems.

2.1.3 One-Dimensional (1D) Model

As the name implies, 1D model determines flow parameters in a single dimension. The model assumes vertical and horizontal averaging of the flow. This is the simplest type of model, which is easiest to construct, but involves a number of hydraulic assumptions that may make the interpretation of results more difficult. Applications of 1D models include rivers, creeks and channels.

1D modelling is limited to flow analysis in pre-defined flowpaths and as such all flowpaths in the floodplain need to be identified a priori. The complex interaction between channel flow and the floodplain is also neglected in a combined channel and floodplain representation in a 1D model. In addition, losses at hydraulic structures that significantly constrict the floodplain are only approximately modelled and usually need calibration for accurate headloss assessment.

SOBEK, Mike 11, HEC-RAS, ISIS are a few examples of the vast array of 1D modelling systems currently available.

2.1.4 Quasi Two-Dimensional Model

Quasi two-dimensional modelling is a methodology where a 1D model is used to represent complex floodplain behaviour. The methodology involves constructing a 1D model that represents river/creek as a branch in the model with floodplain also approximated using one-dimensional branches. Prior to the introduction of 2D models, most floodplain analysis were carried out using quasi two-dimensional modelling.

2.1.5 Coupled One/Two-Dimensional (1D/2D) Model

The latest modelling approach is to combine 1D and 2D models to utilise the benefits of both types of modelling. The link between the two types of models is dynamic and hence a single model set-up can include both 1D and 2D components. Previously a combination of 1D and 2D models has been used whereby two separate models were constructed and results from 1D model were input to the 2D model. The process was cumbersome and involved flow approximations such as the flow in two-dimensional model being unable to return to the river/creek during the flood recession.

SOBEK 1D/2D, MikeFlood, Flo-2D are some of the currently available modelling systems.
3. TWO-DIMENSIONAL HYDRAULIC MODELLING

In the strictest sense, flood flow at any given place is three-dimensional in nature. However, in majority of the cases, simplification to two or one-dimensional flow is sufficient to define the flow behaviour. Relatively shallow flow over a wide flat area can be approximated in two dimensions by assuming uniform flow parameters over the depth of flow. Where the majority of the flow is confined to a single channel or flowpath, the flow can be assumed to be one-dimensional and a 1D mode would suffice.

Most floodplains are two-dimensional in nature and as such require two-dimensional models for flow assessment.

3.1 Governing Equations

Full three-dimensional flow is described by the Navier-Stokes Equations. Their simplification to two dimensions is generally referred to as the Shallow Water Equations, which when further simplified to one dimension become the St Venant Equations.

The governing equations are partial differential equations and are based on the principles of conservation of mass and momentum. The analytical solution of these equations is not available for the majority of practical applications and therefore numerical methods are used to develop approximate solution of these equations. The most commonly used numerical methods are the Finite Difference and the Finite Element methods. For each method various solution schemes have been developed that address numerical stability and robustness issues.
The following discussion is provided for the models utilizing the finite difference methods to solve the two-dimensional Shallow Water Equations.

### 3.2 Data Requirements

Various types of data are required for the development of a hydraulic model. The complexity of the required data increases with higher dimensional models. However, for any hydraulic model, the required data can be broadly classified into three types.

- **Topographic data** which represents the physical features of the modelled terrain. For one-dimensional models, cross-sections of the channel/flowpath are required whereas for a two-dimensional model, detailed terrain data is required in the form of a Digital Elevation Model (DEM). The cross-section data can be directly used in 1D models, but in the case of two-dimensional models, further processing is required. The processed data is in the form of a topographic grid with each grid cell representing an average ground level over the entire grid cell.

- **Hydraulic structures in the floodplain** such as culverts, bridges and weirs need to be surveyed and represented in the model.

- **Model boundary data** including flow data to be input to the model along with data to define the conditions at the boundaries of the model.

In addition some measure of the hydraulic roughness of the floodplain is required. The hydraulic roughness defines resistance to flow in various parts of the floodplain. In a 2D model, roughness related to various landuses in the floodplain can be incorporated in the model. A 2D roughness map of the floodplain is therefore prepared which has the same format as the topographic grid.

Another useful feature that has become available in 2D models more recently is the direct routing of rainfall within the two-dimensional hydraulic model (Rehman et al, 2003). As such, an additional input to the hydraulic model would be the rainfall data for the catchment.

#### 3.2.1 Acquisition of Topographic Data

Full exploitation of 2D modelling requires that an accurate representation of the floodplain is captured in the topographic data i.e a detailed Digital Terrain Model (DTM) is developed. Various hydraulic controls that are either ignored or coarsely modelled in a 1D model can be accurately included in a 2D model. This is especially true in an urban environment where even minor controls such as kerbs in a street can be represented.

Since a large number of survey data points (spot levels) are usually required for 2D grid generation, traditional ground survey techniques are usually not feasible. However use of ground survey can not be entirely precluded and may in some instances provide the required data that is sufficient to achieve the objectives of the study.

A more suitable and economical approach to the acquisition of this data is via the use of low level photogrammetry (aerial photography at less than 1:10,000). Although majority of data is obtained through this method, additional ground survey is required to capture major hydraulic controls and significant features of the floodplain. The accuracy of the aerial survey is usually limited to +/- 0.1 to 0.3 m depending on the scale of aerial photography. In dense vegetated areas, photogrammetric methods can not be used and the data for the DTM has to be augmented from ground survey.
Another option is to use air-borne laser scanning (ALS), which can provide very detailed ground survey. In this method a very high number of laser pulses are directed at the ground and the reflection of these pulses is processed to develop a DTM. A high density of survey points is achieved which requires filtering for errors, vegetation, buildings etc. In contrast to photogrammetry, ALS can capture ground data in dense vegetated areas after filtering the dataset. The information generated about the vegetation densities can also be used to define the hydraulic roughness of the floodplain (Verwey, 2001).

The topographic data acquired from the above methods is then utilised to develop a 2D topographic grid of the floodplain. The grid generation process is detailed in a following section.

### 3.2.2 Grid Spacing

Another important parameter to be considered in 2D modelling is the spacing of topographic grid. The grid provides a representative ground level for each grid cell. Thus a larger grid cell would result in greater variances in ground level over a larger area. In keeping with this grid property, there are a number of factors that determine the grid spacing:

- Features of the floodplain to be modelled. Broad rural floodplains can be well represented with a widely spaced grid. However, in dense urban catchments, a smaller grid spacing (2-10 m) is required. Although the catchment representation becomes better, smaller grid size results in a large model with intensive computational requirements.

- Available computation resources. Depending on the number of grid cells, model run time for models with small grid size can vary between several hours to several days. Generally, time is a limiting factor and models are developed to run in a few hours rather than a few days. With current computation power (Pentium 4, 3 GHz machines), an 80000-100000 grid cell model would require a few hours to run.

- Size of hydraulic structures. In pure 2D modelling, hydraulic structures need to be represented within the 2D grid. For such modelling applications, it is better to have smaller grid spacing to represent the hydraulic structure with as many grid cells as possible.

The above limitations have been addressed in many modelling systems whereby multiple grids with separate grid spacing can be used in a single model. Some modelling systems also facilitate placing of a smaller size grid on a coarse grid, usually referred to as parent-child grid combination.

### 3.3 Model Grid Generation

There are several methods for developing a 2D grid of the floodplain. The simplest method is to sample the terrain surface at the location of the grid cell such that the grid cell is a representation of the level at that point. For the purposes of floodplain modelling it is more appropriate to have a more sophisticated grid based on a Triangulated Irregular Network (TIN). A TIN is the most common DTM and is a network of triangular faces with the triangle sides formed by vectors joining the survey points.

There are many methods of developing a grid from a TIN. The method chosen will be determined by the DEM characteristics and the requirements of the model. Some of the more common Grid generation methods are:

- The TIN can be sampled at the centre of the grid cell to represent the DEM at that location.
- The level of the TIN can be averaged over the area of the grid cell.
- The highest level in the grid cell can be used to represent the grid cell
- The lowest level of the grid cell can be used to represent the grid cell

A further consideration to be given in the grid generation process is the alignment of the grid. A grid aligned in the direction of the primary flow paths will produce better results than a grid aligned at 45° to the flow path.

### 3.3.1 Grid Manipulation

After generating a grid there are features that will require checking and possibly modification. These are floodplain characteristics such as the top of weirs, road embankments, levees and the top of creeks that may require manual manipulation of the grid cell level.

Grids should be verified against the survey data used in their creation. A histogram showing the variance of the grid cell level from the survey data can be generated for the entire grid or specific features of the grid such as road embankments or levees.

### 3.4 Modelling of Hydraulic Structures

Hydraulic structures in a floodplain play an important role in defining the flood behaviour. Accurate representation of these structures is therefore vital for the development of a reliable and robust model. In urban areas the most commonly encountered structures are culverts, bridges, weirs and tidal gates whereas in rural areas additional structures such as regulators (sluice gates) may also be present. Operational management of the regulators influences the timing and peak of the flood at downstream areas and adds an additional dimension to floodplain management.

Modelling of structures varies in different modelling options. Some of the general approaches adopted for structure modelling are provided below:

#### 3.4.1 1D Modelling

The most accurate representation of structures is achieved in a 1D model. The standard structure formulae are used for estimating flood behaviour and replace the St Venant Equations in the solution scheme. Generally the headloss parameters for the structures can be adjusted to the likely losses for a particular structure variation. Eg culvert inlet losses vary for different inlet shapes and hence the model requires modification for inlet loss parameters.

Similarly bridges, weirs, regulators and other structures can be represented in a one-dimensional model. The vast array of structure definition available including user-defined structures provides flexibility to model most practical applications.

#### 3.4.2 2D Modelling

In pure 2D modelling, it is difficult to incorporate structure definition in the solution scheme. Thus only approximate representation is possible and flow behaviour for the 'structures' needs to be calibrated against more established modelling techniques or by desktop calculations. The structures are modelled by modifying the grid cells such that the required structure headloss is achieved.

For culvert/bridge representation, order of magnitude of structure width should be similar to grid size and if possible a number of grid cells should represent the structure. The flow behaviour of culvert/bridge flowing full or under inlet control results in further model assumptions.
Weirs however can be relatively easily represented and may actually provide a superior representation than possible in a 1D model. Levees, embankments, road tops and other similar structures can be represented in the 2D grid. Care needs to be taken to represent the correct crest level and width of weir along flow direction.

4. COUPLED 1D/2D MODELLING

The concept of coupling 1D and 2D models evolved from the need to draw upon the benefits of the two modelling types. The most significant advantage is the use of one-dimensional hydraulic structures in the model set-up. Another important benefit is that the channel/flowpath can be represented in a 1D model, which can sometimes be quite difficult to represent in a 2D grid unless the grid cell size is reduced. Thus the two-dimensional representation can be achieved with a coarser grid with coupled 1D/2D modelling than is possible with pure 2D modelling.

Various types of couplings are possible that provide various levels of modelling flexibility. Figure 2 provides a brief description of the coupling possibilities.

![Coupling Options Diagram]

Figure 2 - One and Two-Dimensional Model Coupling Options

4.1.1 Hydraulic Structure Modelling

Structure modelling is one of the key strengths of coupled 1D/2D modelling. All structure definitions possible in 1D modelling can be utilised in this type of modelling except the weir definition, which can be well represented in the two-dimensional component of the model.
5. ASSUMPTIONS AND ACCURACY

The most important aspect of any type of modelling is to understand the assumptions underlying the modelling process and to estimate the accuracy of the model results. Hydraulic modelling of any given flow phenomenon involves a number of assumptions and therefore the accuracy of the results is dependent on the assumptions made in the whole modelling process. The major assumptions and the impact of various processes involved in hydraulic modelling can be summarised below:

5.1 Topographic Survey

Survey data is the backbone of any hydraulic model. The accuracy of the survey would be directly reflected in the model results. For 2D modelling, survey is usually acquired through aerial photogrammetry or air-borne laser scanning. The accuracy of such data is seldom better than +/- 0.1 m and may generally be in the range of +/- 0.2 m. The accuracy of the modelled flood levels achieved from such data would roughly be the same, without considering any other error sources.

5.2 Two-dimensional Grid

A grid cell provides a representative ground level over the size of the cell. The size of grid cell therefore plays an important role in defining the accurate representation of floodplain. The model results provide a representative flood level for the grid cell that may or may not be accurate for a particular area within a grid cell. Thus the flood level would be underestimated for areas at a higher elevation then the representative grid cell level and overestimated for areas at a lower elevation.

5.3 Governing Equations

Natural flow is three-dimensional and its simplification to two or one dimension introduces some inaccuracy in the model. Such simplifications generally do not have a large impact on the model results provided that an appropriate model is selected.

5.4 Numerical Methods

Numerical methods are used to solve the partial differential equations of flow. The methods involve discretisation of these equations to simplified forms that can be easily solved. However the discretisation process results in a truncation error and the degree of truncation defines the order of the simplified equations. Most solution schemes use first or second order discretisation.

Additionally, the iterative solution of the simplified equations results in residual errors and usually some lower limit of acceptable error is specified to achieve the final solution of the equations.

Different solution schemes use different numerical processes as described above and hence impart different levels of inaccuracies to the model results.

5.5 Structure Modelling

The structure formulations used in one-dimensional models are based on laboratory experimentation and involve simplifications of natural three-dimensional flow usually present at structures.

If structure modelling is being carried out in a pure two-dimensional model, the results are usually approximate near the structure.
5.6 Other Assumptions

The input to hydraulic models is usually provided from the results of an external model. Usually a hydrological analysis is carried out that produces flood hydrographs as input to the model. Thus assumptions and inaccuracies inherent in hydrological analysis would be translated into the hydraulic model results.

6. CONCLUSIONS

Hydraulic modelling of floodplains provides relatively easy and cost-effective description of the flood behaviour. 2D hydraulic modelling is increasingly being used for this purpose. A brief description of the concepts related to this type of modelling has been presented.

2D modelling provides significant benefits over the traditional 1D modelling of the broad flat floodplains. The modelling is well suited to areas where flow patterns are poorly defined and where flow patterns are likely to change with stage. Important floodplain processes such as cross-catchment flows can be captured in a 2D model. Such processes may not be evident during the frequent flood and may only exist for extreme or large floods.

Another important benefit is the ability to represent the floodplain roughness in detail by specifying roughness values for varying landuses.

The results from 2D modelling can easily be presented in a plan and animations of the results provide an opportunity for general community to visualise the flood behaviour.

2D hydraulic modelling requires extensive survey data, which is generally acquired using aerial survey techniques. Aerial survey currently provides data with a lower accuracy than is generally achieved for 1D modelling using ground survey methods. 2D models are computationally intensive and require extensive computing resources.

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