TUFLOW – Two & one-dimensional Unsteady FLOW Software for Rivers, Estuaries and Coastal Waters

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Summary: Once limited to coastal hydraulics, two-dimensional (2D) modelling of free-surface flows is today used for a broad range of investigations, from oceans to urban flooding. Computer technology is driving this expansion and software are evolving to meet the scientific and engineering challenges. The TUFLOW software continues to develop and evolve to meet the challenges, particularly in flood modelling. Its strengths are rapid wetting and drying, powerful 1D linking options, modelling of hydraulic structures, treatment of levees and embankments, effective data handling and quality control outputs. It is suited to modelling flooding in major rivers through to complex overland and piped urban flows, and estuarine and coastal hydraulics. TUFLOW uses GIS to manage, manipulate and present data.

1 NOTATION

1D/2D	One/Two-Dimensional
2D domain	Area covered by 2D solution
cell	A single "square" in the finite difference grid
channel	1D flow calculation line
$\mathbf{C_r}$	Courant Number
ESTRY	1D Hydrodynamic Software
GIS	Geographic Information System
grid	The mesh of **cells** making up the 2D model
node	1D water level calculation point
RMA	Finite Element Software (distributed by Ian King)
SMS	BOSS Surface Water Modelling System
TUFLOW	2D Hydrodynamic Software

2 INTRODUCTION

Once limited to coastal hydraulics, two-dimensional (2D) modelling of free-surface flows is today used for a broad range of investigations, from oceans to urban flood studies. Computer technology is driving this expansion and software are evolving to meet the scientific and engineering challenges. This paper provides a brief description of the TUFLOW software.

3 BACKGROUND

TUFLOW (Two-dimensional Unsteady FLOW) is the product of a research and development project jointly funded by WBM Pty Ltd and The University of Queensland. The objective was to develop a 2D modelling system with dynamic links to a 1D system. The project was completed in 1990.

The impetus for the project was the inability of 2D schemes to model estuarine systems flowing in and out of a coastal bay. Due to computer hardware limitations at the time, the coarse grids of the 2D models could not adequately represent estuarine flow behaviour. Coastal bay models were reliant on defining boundaries at estuarine entrances – a sometimes-difficult task.

The project was successful in its objectives and the resulting software extensively used for the next eight years in a range of applications, predominantly in the tidal hydraulics fields. Within its first year of application, over twenty models were developed by WBM for investigations ranging from large coastal bays to the effects of marina pontoons in a small estuary.

By 1998, WBM's TUFLOW applications to tidal hydraulics had diminished, being primarily replaced by the RMA software. There was also a major shift from UNIX based systems to Microsoft Windows. Whilst the TUFLOW computational engine was readily portable to a PC environment, the major investment in pre- and post-processing software (named TWOPRO), required a major overhaul to move to a Windows PC environment.

At this time, WBM and others were applying finite difference and finite element 2D models to complex floodplain flow cases. However, available software were deficient in different ways needing new features to model hydraulic structures; rapid wetting and drying and other characteristics required for floodplain modelling. In 1997, WBM initiated further research into a range of 2D schemes for modelling floodplains, as it was envisaged this field would be the next evolutionary step in flood modelling.

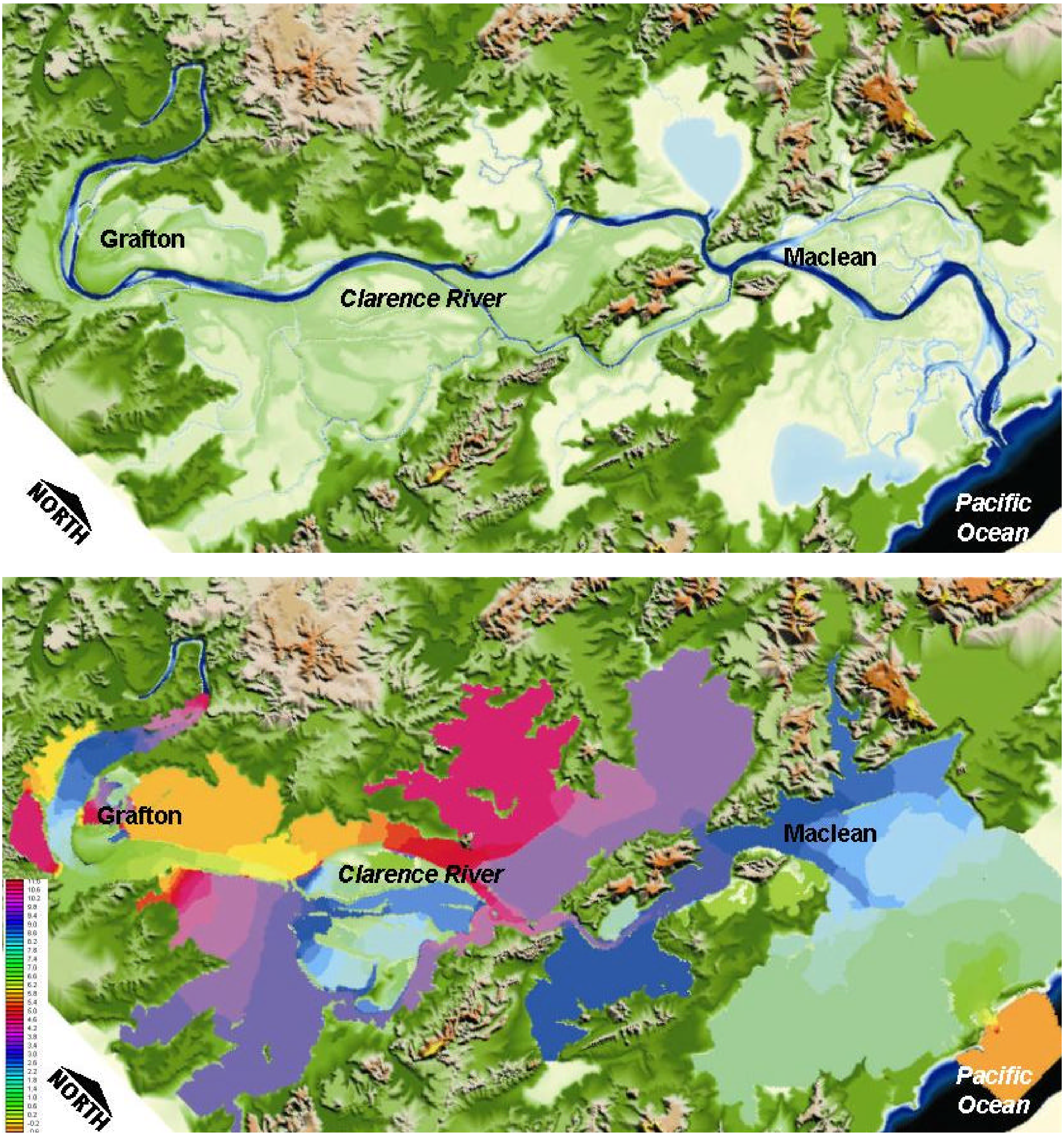
Upgrading TUFLOW was selected as the best option due to its strengths over finite element schemes in rapid wetting and drying, and its unique and flexible dynamic links with a 1D scheme. The pre and post data processing issues were resolved through the use of other software. Major, high profile studies were won and new features for floodplain modelling researched and developed.

TUFLOW now enjoys a renaissance as an excellent 2D/1D flood-modelling package.

4 SOLUTION SCHEMES

4.1 TUFLOW

TUFLOW is based on the solution scheme documented in Stelling (1984). It is an finite difference, altemating direction implicit (ADI) scheme solving the full 2D free surface flow equations. Additional features were incorporated by Syme (1991). For details on equations, solution methodology, term discretisation, testing and validation, refer to Stelling (1984) and Syme (1991).



The above images show the DTM and shaded flood level contours tor the Clarence River, NSW. This is a major2D model in size and flooding complexity. It has been calibrated to five flood events.

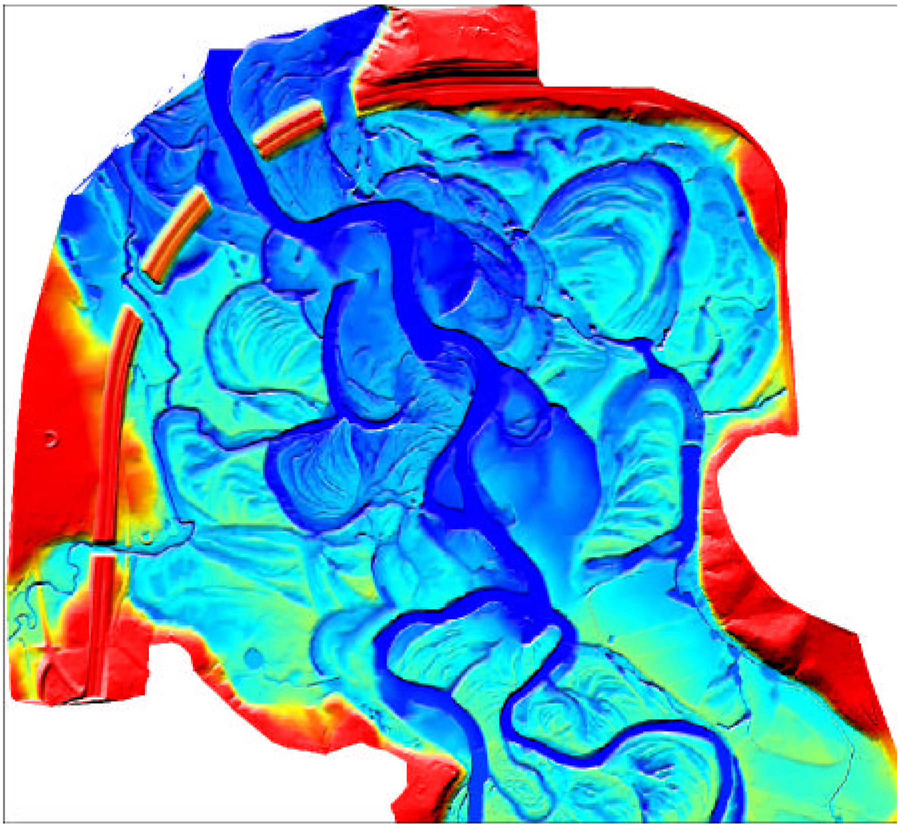
4.2 ESTRY

ESTRY is described in Morrison and Smith (1978). It is an explicit finite difference scheme solving the full 1D free surface flow equations. ESTRY is applied to a wide range of river and urban flood investigations and estuarine tidal studies since 1972.

5 TUFLOW / ESTRY DYNAMIC LINKS

5.1 General

The dynamic linking capability between TUFLOW and WBM's well established 1D software, ESTRY, is a major strength and considerable advantage since first applied in 1990. 1D models of estuaries were attached to 2D coastal models, or alternatively fine-scale 2D models were nested inside a broader-scale 1D model. The ability to orientate the 1D/2D interface at any angle to the 2D grid, allowing total flexibility in locating the interface, is also of significant note.



A high quality DTM is required for 2D modelling. The above is part of a DTM used in a TUFLOW flood study of the Goulburn River, Victoria. The road crossing in the top left is the Hume Highway.

Prior to widespread application in flooding investigations, the 1D link was relatively crude, but sufficient for the purpose intended. Links were located across waterways, along an alignment where the water level is essentially horizontal.

With the adaptation of TUFLOW to floodplain modelling, the need for more flexible and complex linking was identified. The advanced linking functions developed have been extensively applied to a range of flood models varying from major river systems to fine-scale urban flood models. The types of links available are described below.

5.2 Joining of 1D and 2D Models (External Links)

External 2D/1D links are applied along any part of the 2D domains's perimeter(s) of active cells. In its simplest form, the assumption is the water level along a link is horizontal. More complex linking allows sloping water surfaces based on interpolation between 1D nodes. External links can be at any orientation, start completely dry, and wet and dry during a simulation.

5.3 Nesting 1D Models Inside 2D Models (Internal Links)

Internal links are used to model flow that is within the 2D domain, but not represented by the 2D solution. This may be a small culvert through an embankment or a complex underground pipe network. This allows 2D overland flows and 1D "sub-surface" flows to be modelled simultaneously. The most common application is for modelling culverts through embankments where the size of the culvert is small relative to the cell size.

The 1D/2D connection can be a single cell through to a line or group of cells. 2D cells can start dry, and wet or dry at any time during a simulation.

5.4 Split 2D Model Links

An extension of the external links is the modelling of a waterway in 1D and overbank areas as 2D. This is useful where the drain, creek or river is too coarsely represented by the 2D cells and is better represented by 1D cross-sections. The 2D area is essentially split into two or more regions by a 1D network. As for the previous link types, 2D cells can wet and dry at any point during a simulation.

6 COMPUTATIONAL FEATURES

6.1 Wetting & Drying

TUFLOW uses the wetting and drying algorithm described in Syme (1991). It is referred to as the "free-overfall" method, although it is not a substitute for modelling upstream controlled weir flow (which is discussed later). The method offers significant stability during rapid wetting and drying, a major plus for modelling floodplains and large inter-tidal areas.

6.2 Bridges and Culverts

Where the hydraulic structure's dimensions are comparable or larger than the 2D cell size, it is recommended that the structure is modelled in 2D. 2D cells are adjusted in height (invert and/or obvert) and width to model the flow area.

Losses associated with bridge decks and box culvert soffits and walls are accounted for.

Structures that are small in comparison to the cell size are modelled in 1D. A typical example is a pipe through a road embankment.

Note that the 1D approach of specifying inlet and outlet losses associated with the contraction and expansion of fluid flow is not applicable within a 2D scheme. A 2D scheme inherently models the contraction and expansion process, and does not require the specification of head losses as would be applied in a 1D solution. However, a 2D solution does not represent losses in the third dimension and from fine-scale form losses. The resolution of the model mesh, the viscosity formulation and other factors also affect how a 2D scheme models a hydraulic structure.

It is therefore imperative that through testing and experience, the performance of a 2D scheme at hydraulic structures is understood and additional losses are applied to compensate for: effects not or poorly represented (eg. vena contracta, bridge pier losses, etc); mesh resolution and other factors. Research carried out indicates that for 2D box culverts, an additional loss of ~0.2 to 0.5 of a dynamic head is required where the culverts are modelled by a few cells, reducing to no additional losses where the same culverts are modelled by hundreds of cells. The opinion formed is that as the model resolution becomes finer, there is less need to apply additional losses as the flow patterns are more accurately modelled. Interestingly, similar testing using RMA2 has shown the opposite trend. This demonstrates how different solution schemes can exhibit different characteristics, thus highlighting the need to know your software.

6.3 Weirs

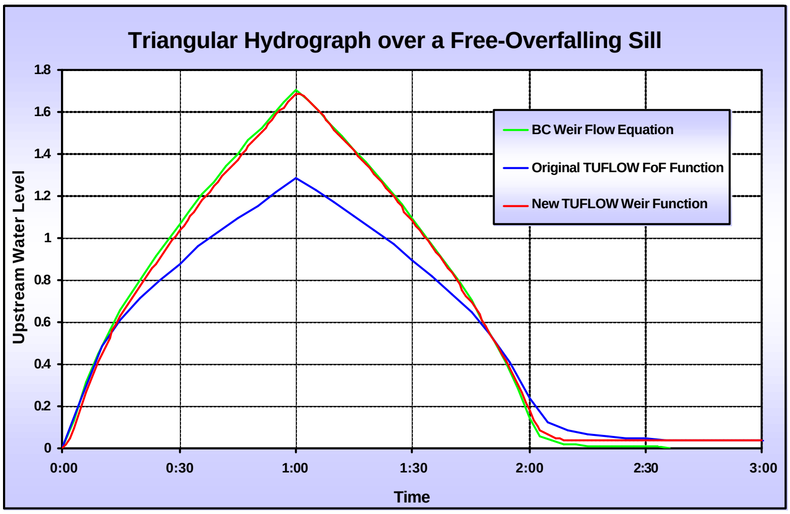
6.3.1 2D Flow Weirs in 2D Domain

This is a powerful feature for models containing weirs, levees, road/rail embankments or other features that may experience critical flow (upstream controlled flow) during a simulation. It is used for modelling complex floodplain flows that are influenced by levees and road/rail embankments.

Flow automatically switches in the 2D model between upstream and downstream controlled modes. The broad-crested weir formula is applied if the flow is upstream controlled. A weir "calibration" factor can be set globally or can vary spatially over the 2D domain. The factor adjusts the weir formula, which is useful where imperfect broad-crested weir flow occurs due to obstructions (eg. vegetation on a levee). Varying the weir factor is not recommended unless calibration data or other information exists. The weir flow option can be switched on or off on a spatial basis.

6.3.2 1D Flow Weirs in 2D Domain

1D weir channels are inserted into a 2D domain where, for example, a bridge is overtopped. If the flow through the bridge is modelled using the 2D equations, the flow over the bridge is modelled using a 1D weir channel. In these situations where multiple structure flows occur at one location, the ability to model a combination of structures is used.



Test results of automatic switching 2D weir flow function. The green line shows the theoretical curve, red line the 2D weir function and the blue line the "free-overfall" method, which is not correct.

6.4 Boundary Types

TUFLOW accepts a range of boundary types as listed below.

- Water level as: time-series; sinusoidal curves; and a function of discharge
- Flow or velocity as: time-series; constant rate; and a function of water level (flow only).
- Rainfall over the model and evaporation.

Boundaries can occur as a summation of several boundaries. For example, an ocean boundary may be the sum of two water level data sets: one for the tide elevation and one for the increase in ocean elevation from a storm surge.

6.5 Oblique Boundaries

2D model water level boundaries and 2D/1D links can be located at any location and orientation, and exhibit the same stability as boundaries aligned to the X and Y-axes. The method used is the "oblique boundary method" (Syme, 1991).

Without an oblique boundary method, instabilities can occur along oblique water level boundaries because boundary values follow a "jagged" line due to the fixed grid discretisation. This "jaggedness" typically causes instabilities, which the oblique boundary method overcomes.

6.6 Embankment Breaches

Changes in the 2D topography due to embankment breaches or other causes are modelled through adjustment of the topography over time. In conjunction with the automatic weir flow switching, breaches, etc are simulated.

This feature resulted after witnessing the part removal of a lake bund that was holding floodwaters back. The "excavator module" was developed, tested and applied to the event, rectifying an unsatisfactory model calibration!

6.7 Viscosity

Currently available viscosity formulations are: constant over the entire grid; constant value dependent on velocity; and the Smagorinsky formula.

It is not advisable to use high viscosity values to achieve model stability as this distorts results, especially through constrictions such as bridges (Syme et al (1998)).

6.8 External Forces (Wind, Waves, etc)

External forces from wind stress, wave radiation stresses, etc are applied over the 2D grid. The force field can vary spatially.

6.9 Model Stability

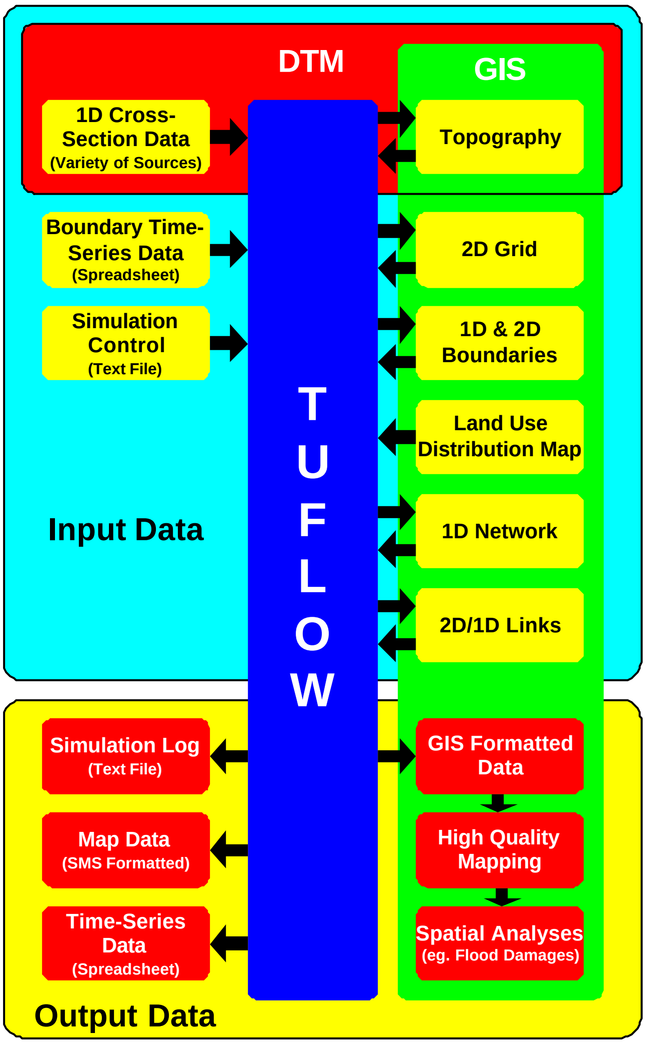
TUFLOW exhibits good stability and robustness, especially where rapid wetting and drying occurs. Most models are simulated at a C_r of around 5. It is not recommended using a C_r greater than 10 as distorted results may occur (this is a characteristic of implicit finite difference schemes). Varying the computational timestep is not known to affect results except possibly when the C_r becomes high (>10).

7 INPUT DATA

7.1 Input Data Structure

A fundamental difference to other software is TUFLOW's data input process. The bulk of data input for 2D and 1D model data are GIS formats. This offers several benefits including:

- the unparalleled power of GIS as a "work environment";
- the many GIS data management, manipulation and presentation tools;
- input data is geographically referenced, not grid referenced, allowing the cell size to be readily changed;
- substantial cost savings in not having to develop a specialised graphical interface;
- efficiency in producing high quality GIS based mapping for reports, brochures, plans and displays;
- handover to clients requiring data in GIS format; and
- better quality control.



The figure illustrates TUFLOW's input and output data process, showing how GIS based data plays a key role.

When a new model is being developed, TUFLOW writes "empty" GIS data layers based on the geographic location and orientation of the grid. A GIS system such as MapInfo or ArcView is used to set up, modify, thematically map and manage the data.

For time-series data and other non-geographically located data, spreadsheet software is used. Text files are used for controlling simulations and simulation parameters.

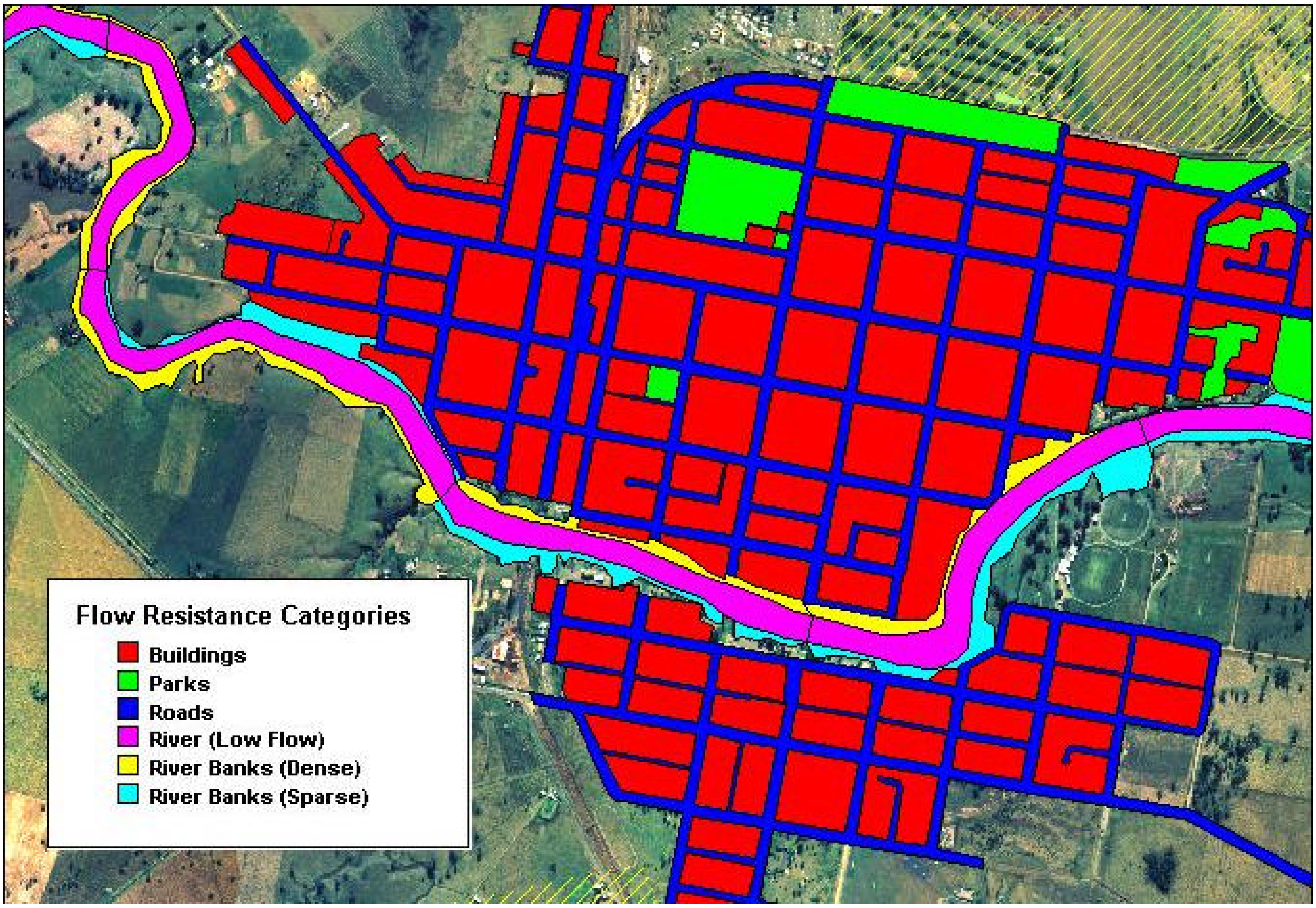
7.2 Text Files

Text files are used for directing inputs to the simulation and setting parameters. The style of input is very simple, free form commands, similar to writing down a series of instructions. This offers the most flexible and efficient system for experienced modellers. It is also easy for inexperienced users to learn.

7.3 GIS Input

The bulk of the data input is via GIS data layers. GIS data types include:

- 2D grid;



Flow resistance categories (material types) digitised in the GIS for input to TUFLOW. Red shades are urban areas, blue roads, green parks, etc.

- 2D topography (at cell mid-sides, corners and centres);
- land-use categories;
- model boundaries;
- hydraulic structure details;
- 1D network of nodes and channels;
- 2D/1D dynamic links;
- initial water level distribution;
- locations of time-series output.

TUFLOW GIS input is structured so that there is no limit on the number of different data sources. Input commands are repeated indefinitely to build a model from a variety of sources. For example, a model's topography may be built from more than one source, firstly a DTM defines the general topography, secondly 3D break-lines define the crest of a network of proposed levees and so on. The "build-a-model" approach offers unlimited flexibility and efficiency.

7.4 Data Validation

TUFLOW produces a range of check files for quality control. This is important as, for example, the final topography can result from more than one data source. Most check files are in the same GIS formats as the input data, so the modeller can easily visualise exactly what TUFLOW is using. Problems are quickly identified and solved by viewing the check files.

8 VIEWING RESULTS

As for the input data, TUFLOW is somewhat unusual in that it uses third-party software for viewing results. The primary software are SMS (Surface Water Modelling System), spreadsheet or other graphing software and GIS.

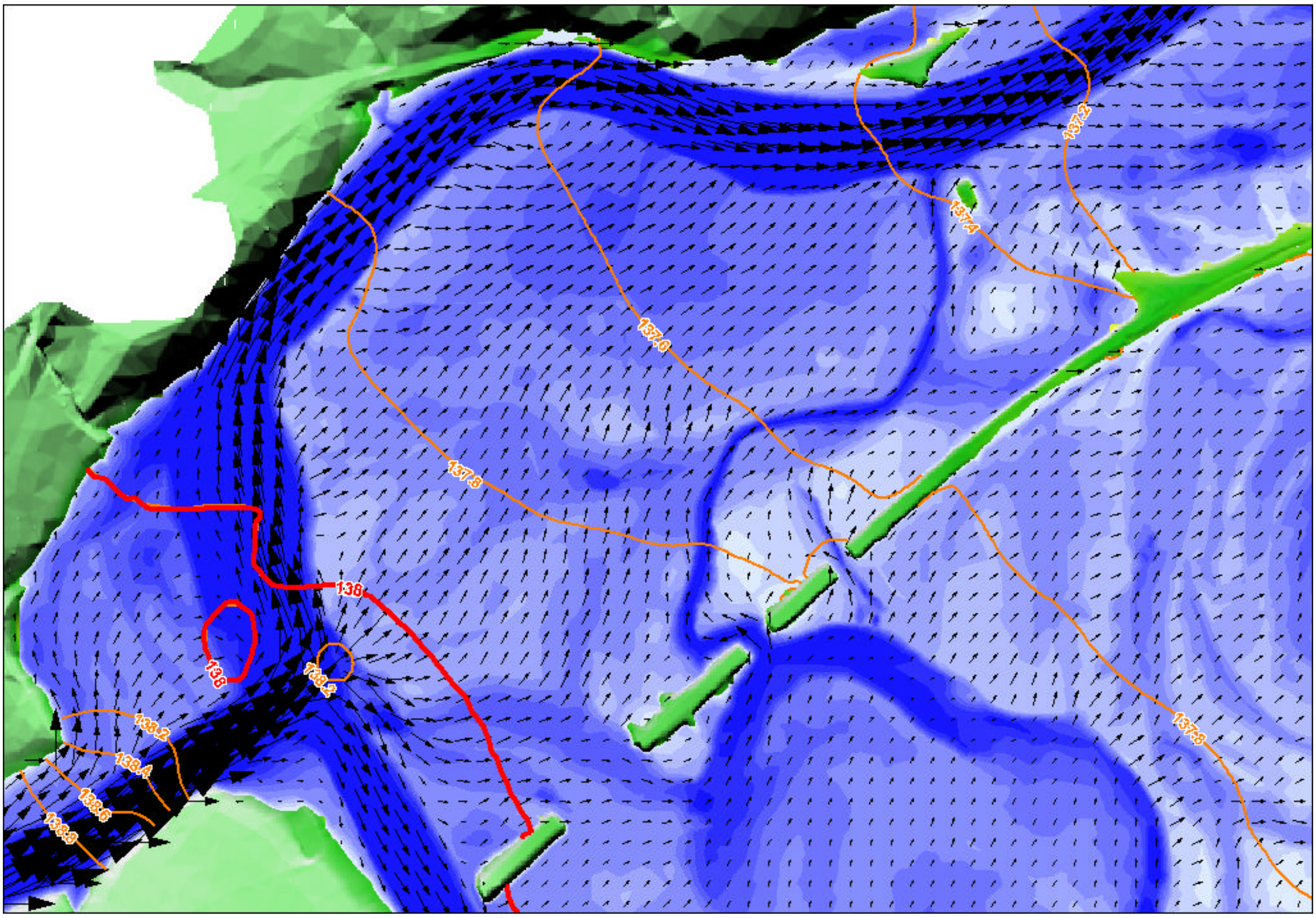
8.1 Text File Output

Simulation log files and some check files are text files. These provide reports on how the simulation progressed.

8.2 Map Output (SMS and GIS)

TUFLOW outputs SMS and GIS formatted files that are viewed in a variety of forms, such as water level contours, velocity vectors, depths, flood hazard and several other forms. DTMs, aerial photos and other GIS data are displayed in the background. Computer animations showing the rise and fall of the flood can be generated using SMS. High quality mapping for reporting, plans and public displays are produced using GIS.

SMS is a 2D modelling pre and post-processing interface developed by BOSS for the RMA2, FESWMS and other software. It is relatively inexpensive and can be used to view



Flood mapping of depths, flood level contours and velocity patterns of Sunday Creek floodwaters (on left) entering the Goulburn River west of Seymour, Victoria

results without a hardware lock. A hardware lock is required when saving files or printing.

8.3 Time-Series Data

Time-series output of water levels, flows, velocities, flow area, integral flow, depths, etc are available. GIS layers define the locations (as points or lines) of the time-series output.

Output files are in the standard comma delimited format (.csv), which are directly read by spreadsheet and other software. Tables, graphs and further analyses are produced. During model calibration experienced modellers set up spreadsheets with a variety of worksheets and charts to suit their style of operation. The latest results are pasted in, and the hopefully final(!) calibration is viewed.

8.4 Managing Instabilities

All software experience instabilities from time-to-time. Any TUFLOW instabilities are tracked and reported on in the simulation log file. The location of the instability is viewed using SMS or in a GIS. Like all modelling, fixing instabilities comes with experience. Seek and learn from the advice of an experienced modeller whenever in difficulty.

8.5 Result Integrity Checks

All models, of any software, should be checked for mass conservation. Flow lines at key locations throughout the model are digitised as a GIS layer. The flow time-series data should be viewed and mass conservation checked within the model and also compared with the boundary inflows.

9 MODEL CALIBRATION

Provided the topography is well defined and the boundary conditions are satisfactory, calibration is normally a straightforward process. Calibration of TUFLOW models is generally easier than 1D or quasi-2D models. 2D model topography and surface materials (bed resistance categories) are so well defined, there should be little or no need to make adjustments; while in a 1D model the modeller accounts for 2D flow paths and storage by selectively adjusting the topography (cross-sections and storage), and bed resistance (across a cross-section). Calibration requires adjustment of the bed resistance values (eg. Manning's n) and any additional form losses at hydraulic structures.

Most problems with model calibration are due to:

- poorly defined and/or inaccurate topography;
- inaccurate boundary conditions;

- inaccurate calibration data;
- poor grid resolution; and
- poor modelling of hydraulic structures.

Of note is that hydraulic controls such as levees and road/rail embankments must be correctly modelled by ensuring their crest elevation is assigned to the nearest mid-side or centre of a cell. 3D breaklines digitised in a GIS and read by TUFLOW ensures this occurs. No reliance can be made on a fixed grid model to automatically pick up the crest of a levee or embankment if directly sampling a DTM at the cell mid-sides and centres.

10 SUPPLEMENTARY ANALYSES

Results from TUFLOW are used for a variety of supplementary analyses such as flood damage assessments, advection-dispersion modelling, morphologic modelling, etc.

11 CONCLUSIONS

1. Continued advances in computer technology have seen 2D free surface flow software become feasible for a wider range of application.
2. The TUFLOW software has continued to develop and evolve to meet the challenges, particularly in flood modelling. Its strengths are rapid wetting and drying, powerful 1D linking options, modelling of hydraulic structures, treatment of levees and embankments, effective data handling and quality control outputs.
3. TUFLOW is applicable for modelling flooding in major rivers through to complex overland and piped urban flows, and estuarine and coastal hydraulics.
4. TUFLOW uses GIS as its primary method of data management, manipulation and presentation. It also uses the SMS package for viewing and analysing results, and producing animations.

TUFLOW is proudly Australian made and owned. For further enquiries please contact tuflow@wbmpl.com.au.

12 REFERENCES

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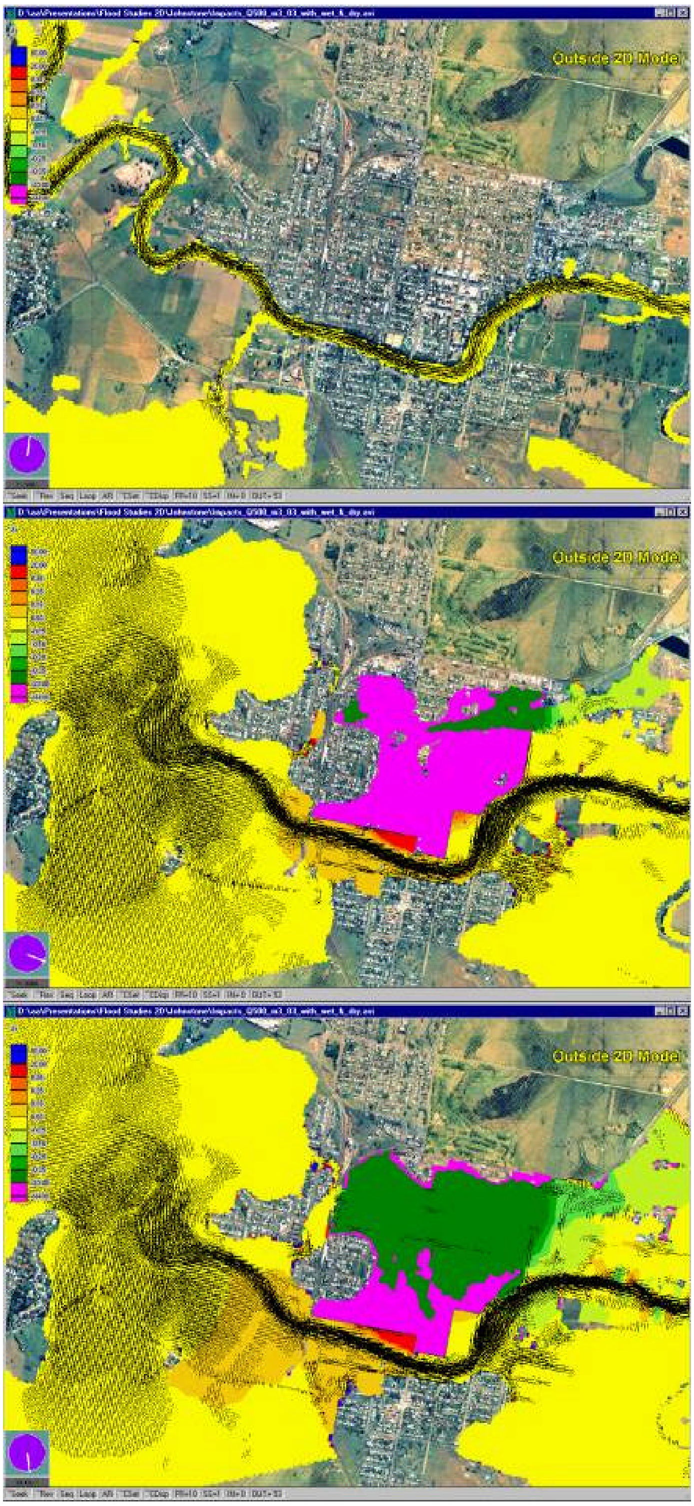

Computer animation stills showing the effect of a proposed levee for Casino, Richmond River, NSW.

Yellow indicates <5cm change in flood level, red shades indicate an increase in 10cm intervals and green shades a decrease. Pink areas were previously flooded, but are now flood-free if the levee is built.

The animation shows the rise and fall of the flood. The three stills shown above are at the start, before the peak and at the peak of the flood.