Enhancing the Capability of a Simple, Computationally Efficient, Conceptual Flood Inundation Model in Hydrologically Complex Terrain

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Abstract

The simple conceptual flood inundation model TVD (Teng-Vaze-Dutta) is more computationally efficient and cost-effective than traditional hydrodynamic models. It is especially useful for applications that do not require velocity output and have low demands on flood dynamic representation. In this study, we have addressed the main inherent limitations of the original TVD model including: the assumption that all the floodplain depressions connected to the river are instantly filled up to the in-stream water level at each time step; the lack of information sharing at the boundary of two modelling reaches; and insufficient soil moisture processes. All of these can affect the model's applicability and accuracy, especially in very flat and hydrologically complex floodplains. A number of improvements to the model structure have been implemented to address mass conservation, reach connectivity and water balance issues. The revised model was set up to simulate a number of flood events in Australia's lower Balonne River and Darling River to test for its enhanced capability. The modelled inundation extents before and after the improvements were assessed against remote sensing water maps. The model developments have improved the accuracy of modelled flood extent. Nevertheless, there are still remaining issues that require the model to be used with caution when simulating flood inundation in difficult-to-model topographies, largely, the demand for reliable input of overbank flow volume and the extrapolating issue with weighting schemes.

Keywords Flood modelling · Floodplain · Inundation · Antecedent soil moisture content

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1 Introduction

Flood inundation models are useful tools for flood risk assessment, flood forecasting, hydraulic engineering and water resources planning. In the past decade, collective efforts amongst research organisations, commercial companies, and government agencies have greatly improved the accuracy of flood inundation models, as well as extended their range of applications. As reviewed in Teng et al. (2017), most of these models are either based on observations (empirical models) (such as those reviewed by Smith 1997) or solving fluid motion equations (hydrodynamic models) (e.g. Brunner 2016; DHI 2012; Moulinec et al. 2011; Prakash et al. 2014; Vacondio et al. 2011), whilst in recent years, a group of simple conceptual models have been developed using simplified physical processes to provide rapid estimation of flood inundation (e.g. L'homme et al. 2008; Nobre et al. 2011). The latter models do not include prediction of velocities, nor representation of momentum conservation or force field, which limits their usage to applications where dynamic effects are insignificant in determining the direction of water flow. However, their run time is usually orders of magnitudes shorter than traditional hydrodynamic models making them particularly suitable for large study areas and/or stochastic modelling that requires numerous runs.

The TVD model (Teng et al. 2015) is one of these simple conceptual flood inundation models. It was designed initially to account for overbank losses on the floodplain in order to close the water balance in a river system model (Dutta et al. 2013). It was developed further as a stand-alone model to be used in flood risk and environmental benefit assessment. It derives the flood extent by intersecting a series of planes at fine intervals with a high resolution DEM, determines the connectivity between the river and the floodplain storages, and links the water stage/volume measured at upstream gauges with the flood extent. It has been shown (Teng et al. 2015) to produce predictions of inundation extent that compare well in cell-to-cell comparison with water maps derived from Landsat TM imageries, in situations where clear flow paths across the floodplain exist. However, the comparisons diverge for very flat and more complex topographies such as multiple anabranches and braided channels. The possible cause for this divergence has been an intriguing research question, leading to a rethink of the model structure.

In this paper, we address inherent limitations of the original TVD model and present its latest development with a focus on the enhancement of its capability in hydrologically complex terrains. A number of modules in the model were implemented to address mass conservation, reach connectivity and water balance issues. The model (before and after the improvement) was set up to simulate several major flood events on various sections of the lower Balonne River and Darling River. The study area and data used in the modelling are introduced in Section 2. In Section 3, a number of inherent limitations of the model are identified in the process and corresponding improvements to the model were implemented in an attempt to overcome these limitations. Rainfall, evapotranspiration and infiltration representations were introduced into the modelling process to maintain the water balance on the floodplain; in particular, the antecedent soil moisture condition, which has major effects on the spread of the flood, was included in the model. In the results section (Section 4), the modelled inundation extents were assessed against remote sensing water maps on cell-to-cell bases. In Section 5 the model's strengths and weaknesses in modelling flood inundation on difficult-to-model topographies are discussed, and our main findings are summarised in Section 6.

2 Study Area and Data

The study area is situated at the border of the New South Wales and Queensland states in eastern Australia. The river reaches and floodplains modelled are in the lower Balonne River and the upper and middle Darling River region (Fig. 1). The landscape of both river basin systems are mostly flat plains, which have an average gradient of just 16 mm per kilometre. This factor alone makes predicting flood inundation particularly challenging for any model. The topography of the region is complex with many braided channels, anabranches and

Fig. 1 Study area in the lower Balonne River and Darling River region, Australia. The flow direction is from northeast to southwest

agricultural structures. The climate of the region is semi-arid and highly variable, making the soil moisture of the river basin very low most of the time. The soil type and land use vary wildly across the floodplains of both river basin systems.

In this study, the TVD model was run in the region where a LiDAR DEM is available. Only selected areas (highlighted in red boxes in Fig. 1) are shown in this paper to illustrate and discuss our findings. The data were collected from various sources for the modelling experiments. A 5 m DEM derived from the 1 m LiDAR DEM obtained from the Murray-Darling Basin Authority was the main input to the TVD model. Other input data include: flow measurements from several gauging stations with water level and volume; daily rainfall time series aggregated from the gridded climate dataset of the Australian Water Availability Project (AWAP) (Jones et al. 2009); Potential Evapotranspiration (PET) time series calculated from AWAP temperature, radiation and relative humidity using Morton's wet environment or equilibrium evaporation formulation (Chiew and McMahon 1991); the soil properties estimated from CSIRO digital soil mapping (TERN) (McKenzie and Gallant 2006). Selected pedotransfer functions (Vaze et al. 2016) were applied to determine the averaged infiltration parameters across the modelling domain.

A total of 107 water maps, derived from Landsat imageries, of paths 92, 93, 94, 95 and rows 80, 81, 82 with a time span from 1988 to 2012, were used as observations to validate the modelled flood extents. The water maps were derived by invoking the Normalized Difference Water Index (NDWI) (McFeeters 1996; Frazier and Page 2000) using the method described in Ticehurst et al. (2015). It should be noted that the Landsat water maps have a coarser resolution (30 m). They are also subject to limitations and uncertainty despite being considered useful in model validation (Schumann et al. 2009; Smith 1997).

3 Method

3.1 The Original Version of the TVD Model

The original TVD model is a simplified conceptual model that is based on the theory of the so-called "planar method" or "bathtub method". It derives the flood extent by intersecting a series of planes at fine intervals with a high resolution DEM and linking the water stage/volume with the flood extent (Teng et al. 2015). Building on the planar approximation, this model adjusts the DEM to reduce computational cost by removing the general downstream slope instead of inserting sloped planes. It builds a database by intersecting the adjusted DEM with water surface planes at each centimetre rise of river stage in order to establish a relationship between river stage, overbank flow volume, and inundation area (H-V-A). It identifies floodplain storages based on their connectivity to the river network. The major steps involved in this methodology are shown in Fig. 2 as blue blocks.

In this study, we investigated inherent limitations of the model and implemented modules to address them. Four areas of improvement (shown as orange blocks in Fig. 2) are elaborated below. In the following sub-sections, each underlying problem that could lead to unsatisfactory performance is explained, followed by a proposed solution.

Fig. 2 The flow chart showing the TVD modelling steps. The blue blocks are components of the original model and the orange blocks are the additional functions discussed in this paper

3.2 Mass Conservation

The original TVD model works on the assumption that all the depressions in the floodplain that are connected to the river with the elevation lower than the in-stream water level, will be instantly filled at that time step. This assumption is valid where the river channel is well defined and the water cannot escape too far from the river even in a relatively large flood event. However, it can cause significant over-estimation in areas that are flat and have complex topography, as i) there may not be enough water to fill all the depressions; and ii) the travel time for water to get to the depressions further away from the channel may be longer than a time step. This type of over-estimation is illustrated in Fig. 3 in which the Landsat derived flood extent, treated as observations here, is shown in blue and the TVD modelling result is overlaid in red with 50% transparency (the overlapping area appears to be purple). Three metrics were calculated for quantitative evaluation:

i)

$$M1 = \frac{A_{obs} \cap A_{mod}}{A_{obs}};$$

ii)

$$M2 = \frac{A_{mod} \setminus A_{obs}}{A_{obs}};$$

iii)

$$M3 = \frac{A_{obs} \cap A_{mod}}{A_{obs} \cup A_{mod}};$$

Fig. 3 The original TVD result (in red with 50% transparency) before considering mass conservation compared to the Landsat water map (in blue) with the two evaluation metrics shown in the lower right corner

where A_{obs} denotes the flooded cells in the Landsat derived water map, and A_{mod} denotes the flooded cells estimated by the TVD model. M1 is the accuracy indicator, M2 is the over-estimation indicator and M3 is the overall performance indicator. The best possible performance by the model is achieved if M1 = 1, M2 = 0 and M3 = 1. In the case shown in Fig. 3, the cell-to-cell comparison reveals that, although the ratio of correctly identifying flooded cells as flooded is relatively high with M1 = 0.75, there is a large over-estimation (indicated by M2 = 1.44) due to the flat floodplain, which brings M3 to 0.31.

To overcome this issue, the concept of mass conservation was implemented within the model to constrain where the water can travel based on the available volume for any time step. Instead of assuming the volume is equal to the floodplain storage capacity, it is more reasonable to distribute the volume based on how likely water would be present in the area. Three weighting schemes were tested in this study based on: 1) the closeness to the nearest drainage with all types of drainage treated equally; 2) the closeness to the nearest drainage with the main channel given a higher priority; 3) the record of historical flooding. The first two schemes start by generating a drainage network from the DEM and prioritise the water distribution based on the closeness to the nearest drainage. The third scheme overlays all available Landsat water maps to obtain a count of water occurrence for every grid cell from

historical records. Water is then distributed to the areas based on these weighting rasters starting from the highest value until the available water volume is exhausted.

3.3 Reach Connectivity

3.3.1 Reach Connectivity at the Boundary of Any Two Modelling Zones

No matter how computationally efficient a model is, there is a physical limit for what can be held in the memory of the computing platform at a given time. Thus it is a common practice to split a river into sections (reaches) when it comes to high resolution inundation modelling. Traditionally, hydrodynamic models use boundary conditions to transfer information between adjacent reaches and constrain the modelling results. The original TVD model operates on a reach by reach basis and does not share information between reaches, which can cause discontinuous flood extents. The TVD model delineates the depressions on the floodplain and identifies the flood extent based on whether the depressions intersect with the river network. On a reach-by-reach basis, it is possible to omit depressions that are connected to the river outside the current modelling zone, such as those depressions that are not directly connected to the river network in the current modelling extent but are connected to the river in the upstream or downstream reaches. To avoid such discontinuities in flood extent, the model needs to be able to identify all depressions that are connected to the river even when the connection point is outside the modelling zone.

The TVD model groups all depressions that are connected to each other into one and gives it a unique identification number, which made it possible to create a mapping network to store the connectivity between any depressions, even at the border of two modelling zones. We took advantage of the Python library NetworkX, which is a tool providing network construction and analysis functions, for this purpose. When the model is seeking to locate the depressions that are connected to the river, it first spatially detects the connectivity between each floodplain depression and the river channel, recording the status in the connectivity network. Then it searches through the connectivity network to decide whether the depression is in any way connected to the river through chains of adjacent depressions. Using this method, not only the depressions that intersect the river in the next modelling region, but also those that connect to the river in zones far away from the current modelling zone (where data are available and the pre-processing has been done) can be identified.

3.3.2 Reach Connectivity When Flow Direction Is Changing

Ideally, the delineation of a modelling zone should be defined as a reach where the slope is constant and the direction of the river does not change (the river is suitably straight). We tend to divide the river into such modelling zones when the river is meandering. This division makes it easier for slope adjustment but can cause problems when attempting to join the results from two zones together. It is particularly problematic when the river changes direction sharply, for instance due to obstructions or a marked change in the slope aspect. The TVD model adjusts the general slope in the DEM by adding a gradient raster to the original DEM. When different modelling zones are considered separately, the difference in the direction of the general slopes from the two zones causes a mismatch at the junction of the two zones. Such a mismatch leads to unevenness at the border of the adjusted DEM and consequently, dis-connectivity in the modelled flood extents. The model needs to be modified to make a smooth

transition between the modelling zones. This smoothing can be made using thin-plate spline interpolation. The gradient rasters used to adjust the DEM before and after smoothing are illustrated in Fig. 4. The new gradient raster shows a gradual change at the junction of the two modelling zones, opposed to the one without smoothing that shows an abrupt change at the junction. Using this gradient raster to adjust the DEM can avoid discontinuity in the modelling results.

3.4 Water Balance on Floodplains

It is well accepted in hydrology that antecedent soil moisture content has a very significant effect on flow responses on the floodplain during overland flooding (Zhang et al. 2011). Local rainfall, evapotranspiration and infiltration all have a substantial impact on the spreading of the flood. Most flood inundation models do not consider these effects or under-represent the processes, which can cause unrealistic predictions of flood inundation. In the TVD model we have incorporated a module to capture these processes, taking into account rainfall, evapotranspiration and infiltration. The soil moisture content is now continuously updated throughout the modelling period. An empirical method – the Horton Model (Horton 1941) – is used to relate infiltration rate to elapsed time modified by certain soil properties.

This empirical method, with three-parameters, was first presented by Horton (1941) and has since been widely used in hydrological modelling. The infiltration capacity f_p to time t relationship may be expressed as

$$f_p = f_c + (f_0 - f_c)e^{-\beta t}$$

where f_0 is the maximum infiltration rate at the beginning of a storm event and reduces to a low and approximately constant rate of f_c as the infiltration process continues and the soil becomes saturated. The parameter β controls the rate of decrease in the infiltration capacity. Horton's equation is applicable only when effective rainfall intensity is greater than f_c and parameters f_0 , f_c , and β must be evaluated using observed infiltration data (Maidment 1993). To satisfy these conditions in the TVD model, the infiltration equation is set to be effective only when the rainfall intensity is greater than f_c or when the grid cell is covered by flood water. The soil moisture is only affected by evaporation if none of the criteria are met.

Fig. 4 The map on the left shows the border of the gradient rasters from the original TVD model, which are used to adjust the slope of the DEMs, for two adjacent modelling zones with different flow directions. The map on the right shows the same area after smoothing at the border of the two modelling regions

Previously, application of the Horton model has been limited because the parameters are dependent on specific soil and moisture conditions and it is difficult to take the requisite site measurements for a large area. Now with the help of digital soil mapping, the spatial distribution of soil depth, soil type and the associated soil hydraulic properties can be estimated for the modelling domain and applied to model infiltration. Conversely the additional uncertainty in the spatial distribution of soils, the resulting hydraulic properties and their impact on the modelled infiltration and consequent inundation results should be subject to further scrutiny.

Instead of using a constant parameter f_0 , we made a modification to Horton's method by varying f_0 at each time step based on the soil moisture content. Considering that the grid cell may have been flooded on the earlier time steps other than the immediately previous one, the maximum infiltration rate f_0 becomes a function of the soil moisture content:

$$f_0 = C(S_0 - S_t) + f_c$$

where C is a constant, S_0 is the maximum soil moisture capacity and S_t is the modelled soil moisture content at the time step. This requires the soil moisture content S_t to be kept in memory throughout the computation. As the Horton model usually runs at an hourly time step, but the TVD model runs at a larger interval, typically at a daily time step, the infiltration needs to be accumulated for the actual time step using iterations or a cumulative summary function.

4 Results

4.1 Mass Conservation

To distribute the water based on how likely water would appear in each grid cell, the weighting rasters were calculated for the modelling zone depicted in Fig. 3. The weighting raster for the first weighting scheme is based on the distance to drainage lines with equal weighting, as shown in Fig. 5a. The values are between 0 and 1 with the furthest cells to a drainage assigned a weighting value of 1 and the closest cells (generally the cells that fall on streams) a value of 0. The TVD result using this weighting raster is presented in Fig. 5d. There is a reduction of 0.6 in over-estimation metric M2 (from 1.44 to 0.84) using this weighting scheme. The improvement was achieved at the cost of reduced accuracy as M1 dropped from 0.75 to 0.66. However, the overall performance has been improved as M3 increased from 0.31 to 0.36.

We experimented with the second weighting scheme that gives different weighting to the main channel and secondary drainages. Numerous combinations were tested and the best result was achieved by giving more weighting to the cells close to the main channels and less to the cells close to the secondary drainages at a 70% vs. 30% weighting as shown in Fig. 5b. Figure 5e shows that by invoking this method, the overall performance was further improved as seen by M3 increasing from 0.31 to 0.39. This is mainly due to substantially reduced over-estimation of flooded area (M2 from 1.44 to 0.56), with most of the flood water now distributed near the main channel and a considerably reduced overland inundation. But there is an accompanying reduction in accuracy with M1 decreasing by 0.14, suggesting that using this weighting scheme to distribute water can effectively reduce the over-estimation but can also adversely impact the accuracy of estimation, as seen in the north-eastern and southern part of the region.

Fig. 5 **a, b, c** Weighting rasters based on closeness to drainage at equal weight, closeness to drainage with 70% vs. 30% weighting given to main channel vs. small streams, and Landsat flood occurrence count respectively; **d, e, f** the corresponding TVD results from applying above weighting rules compared to Landsat water maps

To apply the third weighting scheme, which is based on the record of historical flooding, a weighting raster was calculated based on all available Landsat water maps (Fig. 5c). A value ranging from 0 to 1 is assigned to each cell based on the number of times that the Landsat water maps indicate presence of water (a value of 1 was given to the cells that were never flooded and 0 was given to the cells that were flooded the maximum number of times). Using this scheme yields by far the best result: $M3 = 0.56$ with least over-estimation ($M2 = 0.20$) and little compromise on correctly predicted wet cells ($M1 = 0.67$) (Fig. 5f). As the Landsat water map used to validate the result has also been included to calculate the weighting raster, we undertook a further experiment to test whether including or excluding a specific Landsat water map would have much impact on the final results. A weighting raster was implemented to exclude the validation Landsat water map, which happened to be the one with the largest flood extent. With $M1 = 0.67$, $M2 = 0.40$, and $M3 = 0.48$, the new result is less favourable than the previous one but is still better than that obtained by using the other two weighting schemes.

4.2 Reach Connectivity

An area near Dirranbandi (in the upper part of the study area shown in Fig. 1) was used to test the newly implemented reach connectivity functions. Figure 6 shows the results from the TVD model before and after the improvement. The reach was divided into two adjacent modelling zones as outlined in the figures. The original model does not exchange information between the modelling zones, which results in abrupt discontinuities in the flood extent at the boundary

Fig. 6 The map on the left shows the disconnected flood extent at the border of the two modelling zones modelled using the original TVD model. The right map shows the modelled flood extents after implementing the reach connectivity module

of the zones (north-west and south-east corners). The improved model is able to connect those depressions that are not directly linked to the river in one modelling zone and therefore provides more realistic and continuous results at the border of the modelling zones. However, this does not guarantee accuracy in the modelling results as the method only works when the water level stays the same across different zones, whereas this assumption might not always be true in a long river channel. This is discussed further in Section 5.

4.3 Water Balance on Floodplain

Using a case study we have evaluated how well the model estimates flood extent after incorporating the water balance component in the TVD model. The modelling zone is located downstream of Tilpa (towards the middle of the study area shown in Fig. 1). A flood event with two peaks after a dry spell was chosen and the modelled flood extents were compared with Landsat-derived water maps. On the rising limb of the first peak, the soil is relatively dry and the flood propagates slowly. However, on the rising limb of the second peak, the soil is almost saturated and therefore the flood propagates to a much larger extent.

The plot of the time series of water level measured at the upstream gauge and the modelled flood extent for four dates (2011-12-30, 2012-01-15, 2012-03-19 and 2012-04-04) is presented in the top panel in Fig. 7. The four dates were selected due to the availability of the corresponding Landsat water maps for validation. The modelled results compared with Landsat water maps with and without implementing the water balance module are shown side by side in Fig. 7. The evaluation metrics were calculated and are shown in the bottom right corner of each map.

The overall performance M3 is generally better after implementing the water balance module, except for the first date, where the difference in the results is small. Even after the improvement, the model performed relatively poorly in predicting flood extents at the beginning of the event with M3 equal to 0.48 and 0.42 for the first two dates. The agreement is higher for the third and fourth dates where M3 increased to 0.83 and 0.73 respectively. The improved model is able to reduce the over-estimation on all four dates, especially for the second date where a large over-estimation was significantly reduced.

Fig. 7 The daily time series of water levels for the case study flood event at Tilpa (shown in the top panel) and the TVD results for the four selected dates compared to Landsat water maps. The maps on the left show the results using the TVD model without the water balance module. The maps on the right shows the results using the TVD model with the water balance module

5 Discussion

The comparison with Landsat water maps shows that the new functions implemented in the TVD model did improve the modelling results. But modelling in areas with complex geography is still challenging and needs to be an on-going research focus. For mass conservation to work, one of the prerequisites is to accurately estimate overbank flow

Fig. 7 (continued)

volume. As the TVD model takes this input from a river system model, it is out of the scope of this study. Generally, this requires precise measurement of in-stream storage, which can be very demanding in a data sparse region (Marvanek et al. 2017).

Although using a weighting scheme to distribute the water can improve the agreement of the modelled flood extent with the corresponding Landsat water maps, the case study results also revealed that the model cannot reproduce realistic water depth at some places along the edges of the inundated area (with sudden drops of water depth from ~ 1 m to 0), due to the enforced cut-offs at the boundaries of the weighting raster.

Of the three weighting schemes tested, the weighting raster based on historical water occurrence yielded the best result. Similar to any observation based bias correction methods, it limits the flood extent to the maximum of the historical record, which can be potentially problematic under future conditions where the water level and flood extent could far exceed past records. Additionally, this weighting scheme made the model dependent on the availability, accuracy, and processing cost of the remote sensing water maps. This partly defies the main advantage of the TVD model: simple, fast and cost efficient. It should be recognised that iterating through the weighting values adds somewhat to the computational burden. Nevertheless, the new version of the TVD model is still orders of magnitude faster than most hydrodynamic models. For example, the flood event simulation for a modelling zone constituting more than 13 million grid cells takes 15 s to process a daily time step on a Xeon E5-2697 V3 (2.6 GHz) processor using

a maximum of 64 GB of RAM. This speed renders it feasible to model very large floodplains at a high resolution.

Considering the above-mentioned remaining issues, we recommend that the model still be used with caution when simulating flood events in challenging terrain. It is preferable to validate the model against hydrodynamic models using a selected number of simulated flood events if the model domain is hydrologically complex.

However, the TVD model can be used with confidence if the following conditions are met: 1) the river reach has a well-defined and even channel; 2) the length of the reach is less than or equal to the distance that water can travel in one time step; 3) there are reliable estimates of overbank flow volume available; and 4) there are daily or sub-daily remote sensing data and/or on-ground flood extent measurements for validation.

Furthermore, the model is capable of rapidly estimating maximum flood extent and water depth for a flood event, making it a useful tool for applications that do not require velocity output and have low demands on representation of flood dynamics.

6 Conclusions

The simple conceptual flood inundation model – the TVD model – has the advantage of low computational cost and can efficiently estimate the maximum or final flood extent in most conditions. However, increasing model accuracy in areas with hydrologically complex topography, without compromising model efficiency, is an on-going endeavour. Improvements to the model structure have been made to overcome its inherent limitations by implementing mass conservation, reach connectivity and maintaining water balance on the floodplain. These new modules improved model accuracy and reduced over-estimation of the modelled flood extent when compared to the Landsat water maps. Although the additional functions incorporated may increase the computational burden, the new version of the TVD model is still orders of magnitude faster than most of hydrodynamic models, making it a useful tool to model large floodplains, undertake sensitivity and uncertainty analyses, scenario modelling, or probability assessments that require a multitude of runs.

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Compliance with Ethical Standards

Conflict of Interest None.

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