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Linking direct rainfall hydrodynamic and fuzzy loss models for generating flood damage map

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ABSTRACT

This research work proposes a combined method for mapping flood loss in catchment scale in which direct rainfall modelling and fuzzy approach are linked. The direct rainfall modelling was carried out using HEC-RAS 2D in which rainfall event hyetograph was defined as the boundary condition, and infiltration layer and roughness layer were other main inputs of the model. The fuzzy loss model was developed to assess direct-tangible damages of the flood in which expert opinions were applied to generate verbal fuzzy rules of flood loss. In this model, depth and velocity are inputs and normalized flood loss (between 0 and 1) is output. The results of the direct rainfall model and the fuzzy loss model were combined to generate loss map using python scripting in geographical information system. The output of direct rainfall model was verified based on recorded depths at downstream hydrometric station in which the Nash–Sutcliffe efficiency (NSE) and root mean square error (RMSE) were applied as the evaluation indices. Due to acceptability of indices (NSE = 0.75, RMSE = 0.83 m), the direct rainfall model was reliable. Maximum flood loss was 0.91 in the case study. Using the proposed approach is recommendable for to improve flood damage assessment in the catchments.

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KEYWORDS
Flood loss map; hydrodynamic modelling; direct rainfall; Mamdani fuzzy approach; expert opinions

1. Introduction

Flood is one of the natural events, which could be disastrous and destructive. Hence, reducing the risk of floods has been reviewed in the literature from several decades ago (Lechowska 2018). Different aspects should be highlighted in flood studies, such as modelling, management and assessing impacts. Flood damage assessment or modelling is one of the key issues, which could be helpful before and after flood events (Wagenaar et al. 2018). Many previous studies have been published to assess flood risk or damage, which indicates the importance of this task for water resources engineers (e.g. Oubennaceur et al. 2019). The potential impact of a flood to the community and assets is defined as the vulnerability of the community to the flood. Hence, flood damage modelling is helpful for assessing vulnerability of the community to flood events. As the present study focuses on flood damage mapping of floodplains, it is required to review the available methods and prerequisites of flood loss modelling.

Using hydrological and hydraulic tools and models is a requirement in flood studies to assess flood flow characteristics. Generally, event-based or continuous hydrological models could be applied to simulate the hydrograph of a flood event, which has been extensively addressed in the literature (e.g. Natarajan and Radhakrishnan 2019; Zahmatkesh et al. 2019). Apart from assessing flood hydrograph, which is a main input for further assessments, it is required to simulate other flow characteristics, such as depth, velocity and extent of a flood. Hence, applying hydrodynamic model is popular in assessment of flood damage. One-dimensional (1D) hydraulic models were initially applied to simulate the hydraulic characteristics of a flood event in which governed equations would be solved along the main direction of river flow (Pathan and Agnihotri 2021). However, more studies demonstrated that 1D models might not be a good option for modelling flood events especially in floodplain areas where river flows two-dimensionally (2D, more details on 2D modeling are given by Wing et al. (2019)). Hence, 2D hydraulic models have been recommended in recent years (Ming et al. 2020). Many details should be considered for selecting an appropriate 2D model, including the purposes of simulations, available fund, accuracy requirements etc. More details regarding the capabilities, numerical schemes and methodology of available commercial and non-commercial models have been addressed in the literature (Teng et al. 2017). In recent years, hydrodynamic modelling approaches have been significantly improved which means using lumped runoff routing models to simulate flood hydrograph and using the results as the boundary condition are not the only available option. The newer commercial and non-commercial models are able to integrate the hydrological and hydrodynamic modelling of river basins which is advantageous technically. These 2D combined models solve the equations of flow motion on the available topographic model. In the present study, we highlight this recent approach to simulate flood extent and hydraulic characteristics combined with the flood loss model. This approach is called direct rainfall modelling in which one set-up will be developed to handle hydrological and hydrodynamic modelling. More details regarding direct rainfall approach have been addressed in the literature (David and Schmalz 2020; Hall 2015). Advantages/disadvantages of direct rainfall approach will be discussed in this study as well.

In the next step, we review how the flood damage could be defined in flood studies. According to the literature, the flood damage is defined in four categories:

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1 – direct-tangible impacts, 2 – indirect-tangible impacts, 3 – infrastructure damage and 4 – intangible damage (Romali et al. 2018). It should be noted that some variances might be seen for classifying flood damage in the literature. However, included damages are similar in all classifications. A brief review on the flood damage classes is helpful for the readers. The physical damages to the property and contents in the urban, industrial or agricultural areas are defined as the direct-tangible impacts of a flood event in which the flood impacts are easily observable. These impacts are major damages, and they have been studied in some previous research works, which means some classic methods of flood damage assessment have been established based on this type of impacts. For example, the depth-damage function is one of the known methods for flood damage assessment in which a direct relationship between depth of river flow and possible damages could be developed (Martínez-Gomariz et al. 2020). Another class of flood damage class is indirect-tangible impacts, which includes business interruptions, though some studies have distinguished them as an independent loss. Generally, business interruptions are defined as the indirect-tangible damage. Public service interruptions, production losses to companies outside the flooded area and post impacts of the flood such as tax revenue loss due to immigration of companies and business are defined as the indirect-tangible impacts of the floods (Romali et al. 2018). The urban areas might consist of telecommunications, transport service, power and many other infrastructures, which might be vulnerable to floods. Hence, damages to the infrastructures have been defined as another class of the flood damage in the literature. Finally, intangible impacts should be considered in flood studies, including health impacts, psychological distress, cultural heritage damage, impacts on the ecosystem and loss of trust (Lekuthai and Vongvisessomjai 2001). Many models have been proposed to assess flood damage including simple damage functions and advanced models, such as multiple linear regression, Bayesian network, artificial neural network and the random forest analysis. A general review on economic flood damage assessment has been addressed in the literature (Merz et al. 2010). Moreover, expert opinions are useful to assess potential damages because regional experts might have strong view on possible damages by observing or reviewing previous flood events. This study highlights a new method to apply expert opinions for mapping flood damage in floodplain areas.

It is required to mention the motivation of the study based on research gap as well as purpose and novelty of the present study. Using expert opinions by advanced models is one of the existing research gaps in flood studies. In other words, applying mathematical functions is not a perfect approach because damages could be changed consistently with the land use and economic activities. The regional experts have a better view on potential damages. However, the current methods of flood damage mapping are not able to integrate expert opinions in a flood damage model. Moreover, direct rainfall approach as an advanced hydrodynamic model has been rarely addressed to simulate flood damage. Due to this research gap as the motivation of the study, we develop a novel combined method to assess flood damage in floodplain area in which fuzzy approach model, with a focus on direct-tangible damage, linked with the direct rainfall modelling is used to generate a flood loss map. The Mamdani fuzzy loss model is able to consider depth and flow velocity as the key hydraulic characteristics of a flood event in which expert opinions are applied to develop membership functions and fuzzy rules. The proposed novel method can improve the flood loss assessment considerably. In fact, the main novelty of the present study is to develop a combined hydrodynamic-fuzzy model which is able to generate flood loss map in catchment scale considering expert opinions. More details regarding strengths of this method will be presented in the discussion.

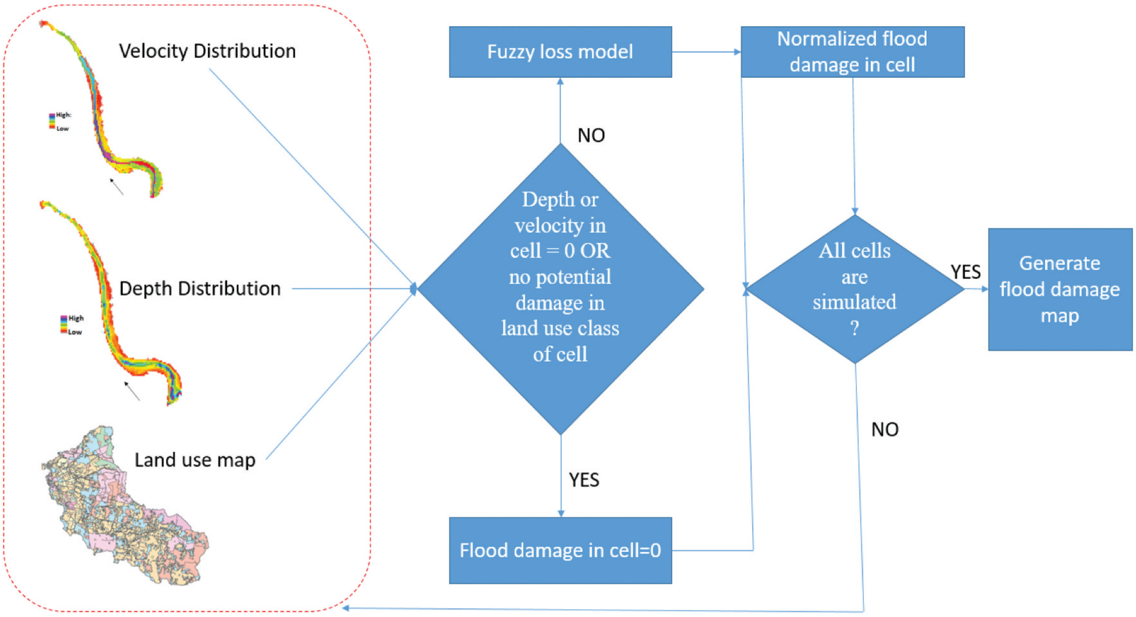


Figure 1. Workflow of the proposed method.

2. Methodology & case study

2.1. Overview on the method

Figure 1 shows the workflow of the proposed method in which three inputs should be used in the flood loss model, including depth and velocity distribution in the floodplain and land use map. Depth and velocity distributions are simulated using direct rainfall approach. It should be noted that direct rainfall approach is applied in catchment scale which means depth or velocity distribution map could be cropped for the selected region of flood loss modelling. Generally, land use map is available in catchment scale which could be cropped as well. After inserting inputs as the raster files, the model refines cells based on two technical considerations. First, if depth or velocity is 0 in a cell, no potential damage will be defined. In other words, flood damage will be defined as 0. Furthermore, if no direct-tangible damage is possible in the defined land use class, no potential damage will be considered in the cell as well. If two mentioned technical considerations are not satisfied, then flood loss in the cell will be simulated by the fuzzy loss model in which normalized flood damage in a cell (between 0 and 1) is the output of the model. Finally, flood damage map in the selected region is generated by simulating all available cells. In the next sections, case study and more details regarding simulation of the selected floodplain will be presented.

2.2. Case study

We utilized the proposed method to generate a flood loss map in the Macquarie River basin located in NSW, Australia. This river is one of the important rivers in this estate which has a significant role in supplying agricultural water demand. However, sequence of dry and wet years could be a threat for the communities in this basin. Remarkable flood events have been experienced during recent decades, implying flood modelling matters in terms of assessing potential flood damages. Macquarie River flows for 960 km which implies its basin is vast and many sub-basins are available. This catchment was selected for this study due to the following reasons:

1. Due to experience of some major flood events in previous years and drawbacks in the flood damage assessment, improving the flood damage studies was essential.
2. Regional water authorities have had serious focus on the flood damages in this catchment which means enough background and regional expert opinions were available to develop the fuzzy model.
3. There exist adequate data to verify the direct rainfall model.

In this study, we focus on one of the upstream sub-basins called Gulgong catchment where some rural and agricultural lands exist in the floodplain of the main river branch. Due to threats of floods, modelling potential damages is interesting for councils. Hence, the proposed method was applied to generate a flood damage map for the main river branch of the sub-basin. Figure 2 displays the location of the simulated sub-basin. Moreover, Figure 3 shows the digital elevation model (DEM) of the sub-basin and land use map which were utilized in the direct rainfall modelling of the catchment. Table 1 displays some key characteristics of the study area.

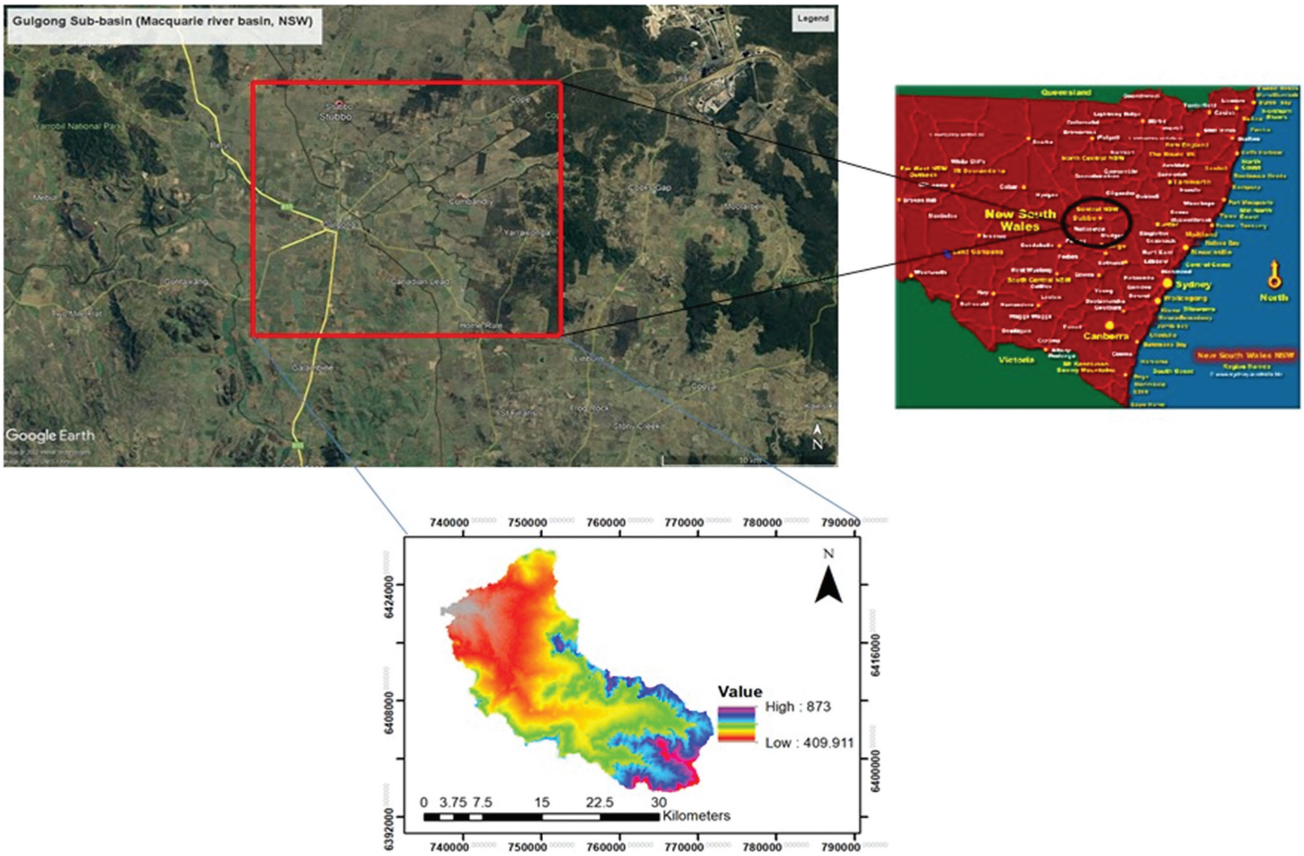


Figure 2. Location of the simulated sub-basin.

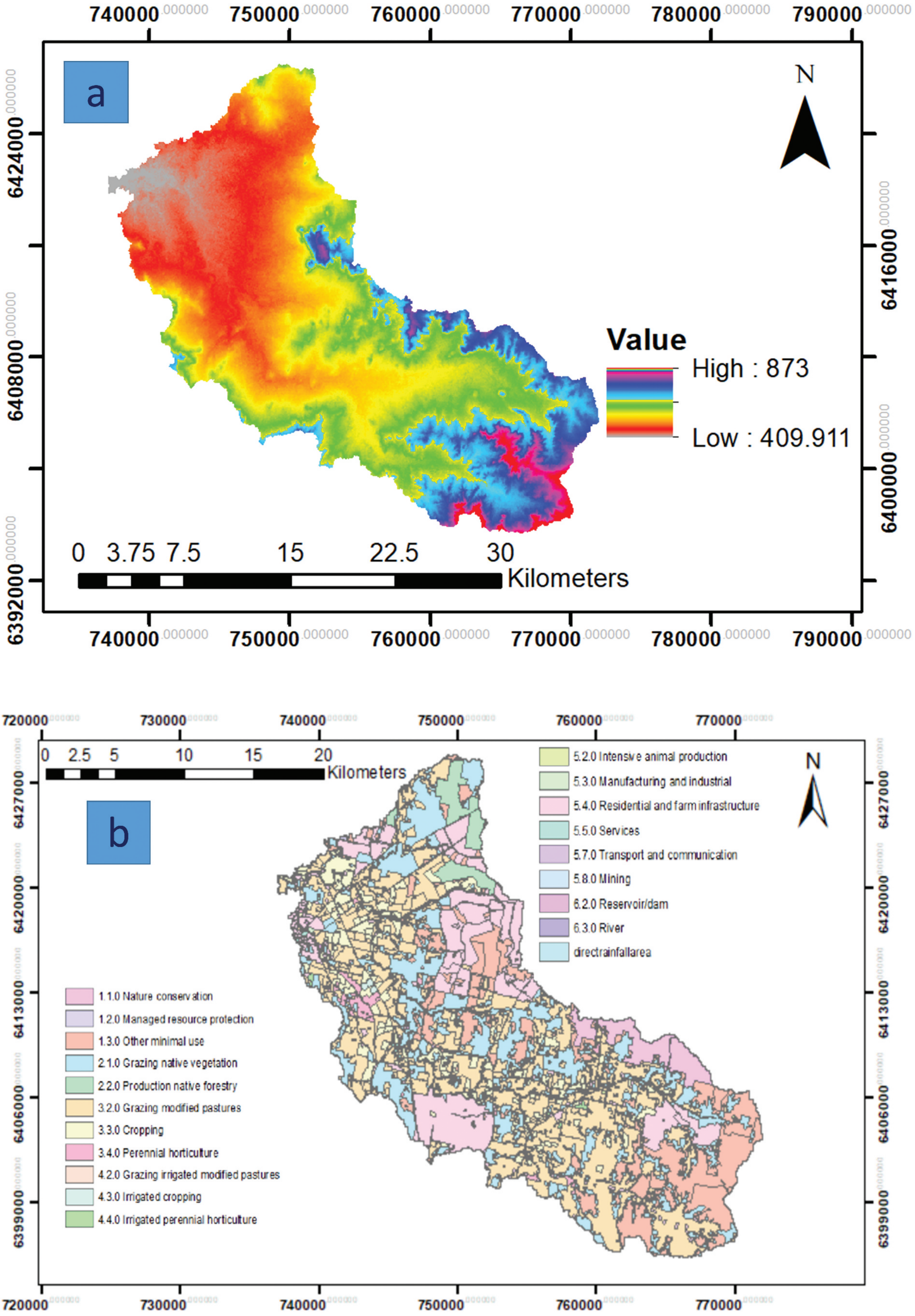


Figure 3. (a) DEM of the simulated sub-basin and (b) land use map of the simulated sub-basin.

2.3. Direct rainfall modelling

Figure 4 shows the flowchart of direct rainfall modelling in the present study. It should be noted that several commercial packages are available to implement direct rainfall modelling in a catchment. For example, HEC-RAS 2D, MIKE 21 and TUFLOW are known packages in this regard which have been improved in recent years for including direct rainfall modelling as a novel hydrodynamic approach (more details on TUFLOW are given by Huxley and Syme (2016) and more details on MIKE

Table 1. Some key characteristics of the simulated catchment.

Characteristic	Description
Latitude and longitude	738731.5 m E; 6,414,523.8 m S
Length of the main river reach	Approximately 32 km
Catchment area	457.2 km^2
Annual rainfall	278 mm
Climate	Warm humid summer, mild winter
Soil type	Various across the catchment, no main soil type is identifiable

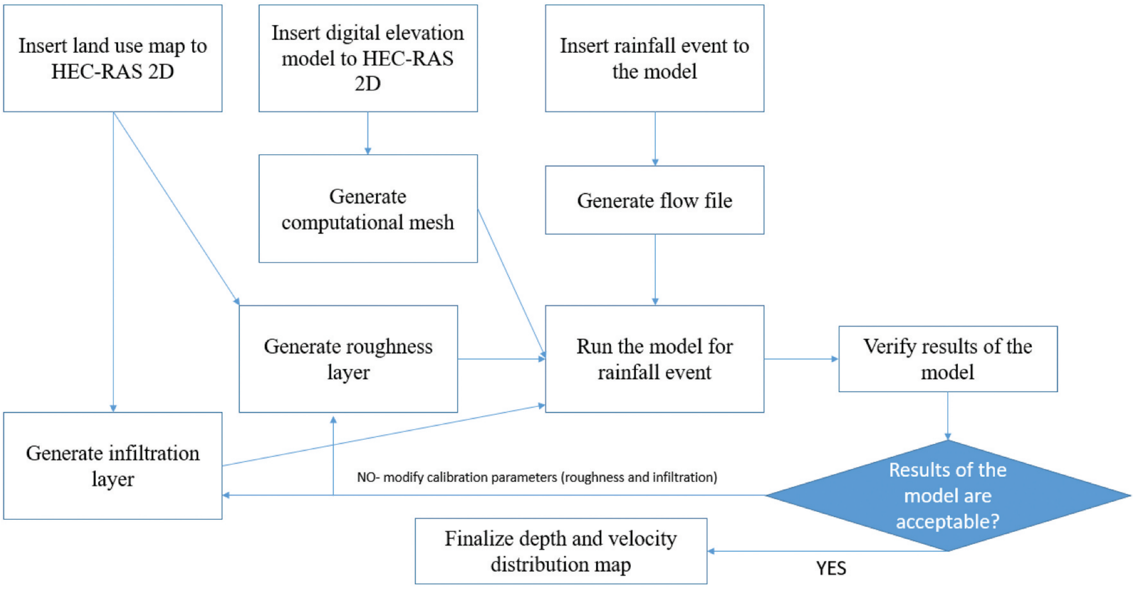


Figure 4. Flowchart of direct rainfall modelling in the present study by HEC-RAS 2D.

are given by Hall 2015). In the present study, we applied HEC-RAS 2D which has its own advantages for using in practical projects. First, this model is developed by the US Army Corps, known for being one of the developers of several hydrological and hydrodynamic models, which means it can be applied as a reliable model. Second, this model is free of charge which means a wide range of users can apply this model in the projects. Third, HEC-RAS has a user-friendly environment and graphical user interface. More details on used modelling approaches in HEC-RAS 2D including direct rainfall have been addressed in the literature (Costabile et al. 2020).

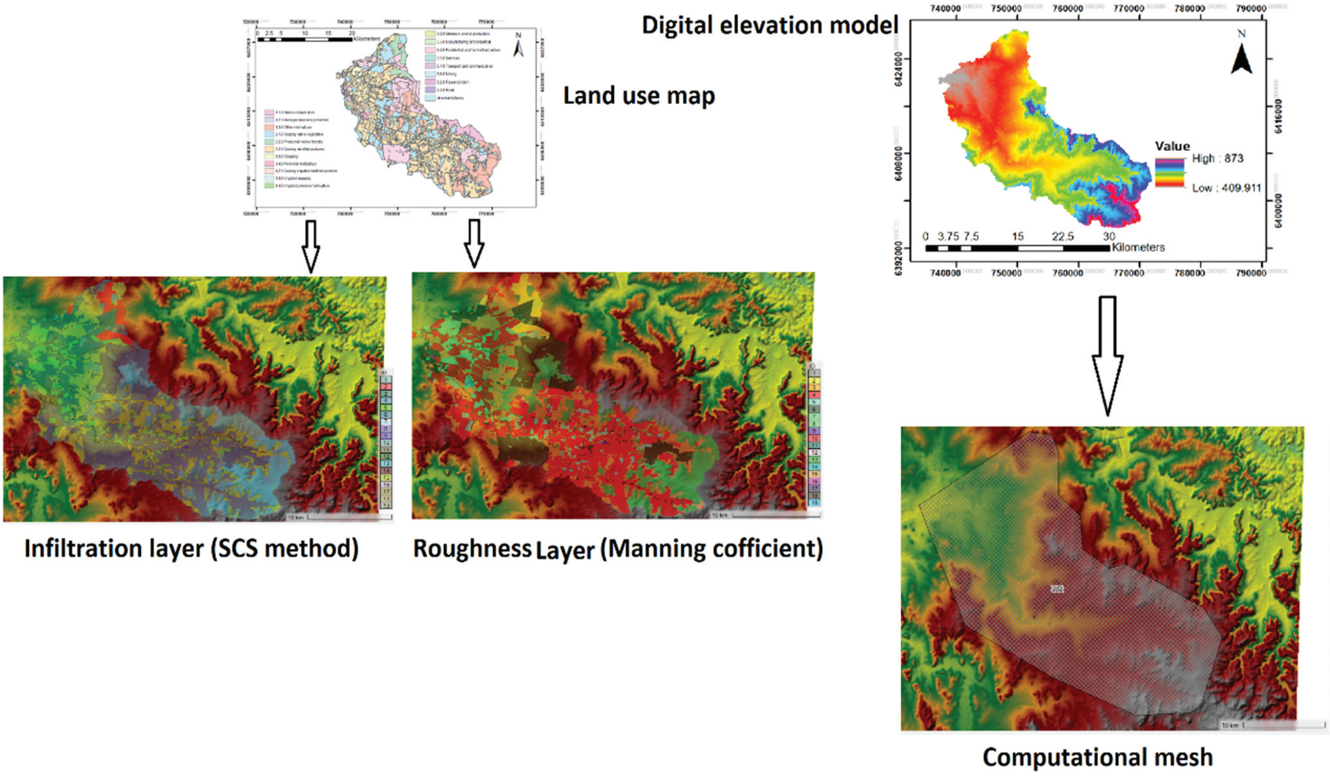


Figure 5. Geometry inputs of hydrodynamic model.

Table 2. More details on hydrodynamic direct rainfall model.

Initial condition (water level)	Defined as zero throughout the domain
Grid size	5 m × 5 m
Timing (simulated period)	A 6-h rainfall event (15-min intervals of rainfall depth (mm))
Time step	2 s
External forcing data (flow)	Rainfall depth in the simulated period (mm)
Verification procedure	Verified by a close rainfall event to AEP 1% in which river depth was recorded at downstream hydrometric station
Roughness	It is the calibration parameter consistent with the land use types defined in the range of 0.015–0.25
Infiltration	It is the calibration parameter consistent with the land use types defined in the range of 68–100 (SCS curve number method)

Based on the approach of HEC-RAS 2D for implementing direct rainfall model, roughness layer and infiltration layer could be developed considering land use map of the catchment. DEM file should be inserted to the model as well. Then, the model is able to generate computational mesh. In the next step, a rainfall event should be selected for simulating using direct rainfall modelling which means the flow file of the model should be generated in consistent with the hyetograph of the selected rainfall event. Then, user can run the model for the simulated period to generate depth and velocity distribution and extent of flood in the selected floodplain of the main river branch of the catchment. Figure 5 shows generated roughness layer, infiltration layer and computational mesh in the simulated sub-basin. Moreover, Table 2 displays more details regarding the developed hydrodynamic model.

It should be noted that spatial and temporal distributions of rainfall events have been studied across Australia which are available in some Australian hydrological models, such as RORB (more details are given by Laurenson and Mein (1995); Patel and Rahman (2015)). Figure 6 shows designed storm events in the case study which was applied in the direct rainfall modelling. Generally, 6-h rainfall events for 1% annual exceedance probability or 100 years return period is considered to assess flood damage. Hence, this rainfall event was selected as inserted to the flow file of direct rainfall model. However, other rainfall could be applied as well based on technical considerations of flood studies. It should be noted that we used a close real rainfall event to Annual Exceedance probability (AEP) 1% for verifying the rainfall model before main simulation of the selected storm in which recorded depths were available at downstream.

Two indices were applied to evaluate the performance of direct rainfall model in the verification process, including the Nash–Sutcliffe efficiency (NSE) and root mean square error (RMSE). NSE is a known index for measuring hydrological models. Moreover, RMSE is a general statistical index for measuring all types of models. More details regarding these indices have been addressed in the literature (Gupta and Kling 2011; Abbaspour et al. 2015). Furthermore, equations 1 and 2 show mathematical definition of these indices.

$$NSE = 1 - \frac{\sum_{t=1}^{T} (M_t - O_t)^2}{\sum_{t=1}^{T} (O_t - O_m)^2} \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{t=1}^{T} (M_t - O_t)^2}{T}} \quad (2)$$

where M_t is forecasted inflow by model in each time step, O_t is observed or recorded inflow in each time step and O_m is mean observed or recorded inflows in the simulated period. It should be noted that this index is one of the known indices for estimating robustness of the hydrologic models.

2.4. Flood loss modelling

We developed a Mamdani fuzzy approach to generate flood loss map in which depth and flow velocity are the hydraulic inputs of the loss model. Expert systems such as fuzzy inference system and expert panels have extensively been addressed in water resource management as the effective tools to improve management strategies

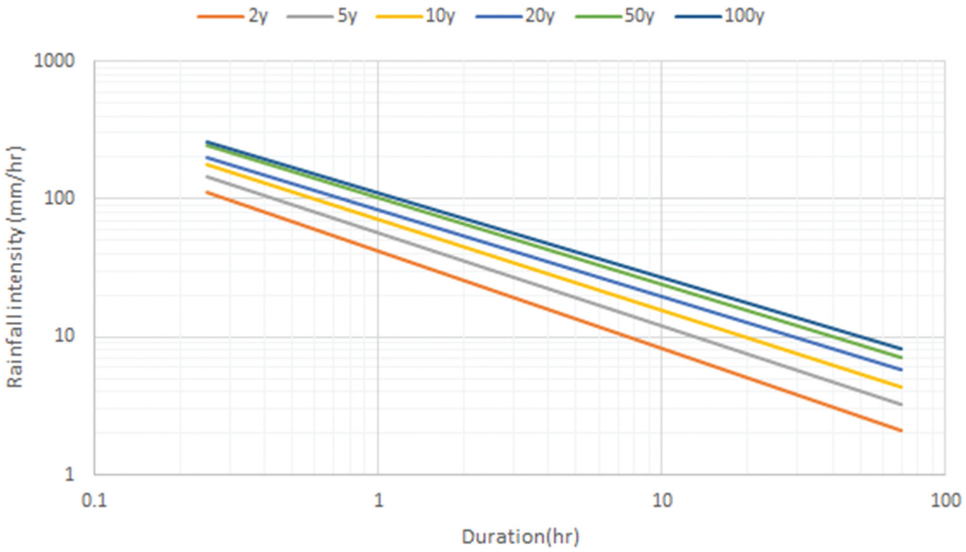
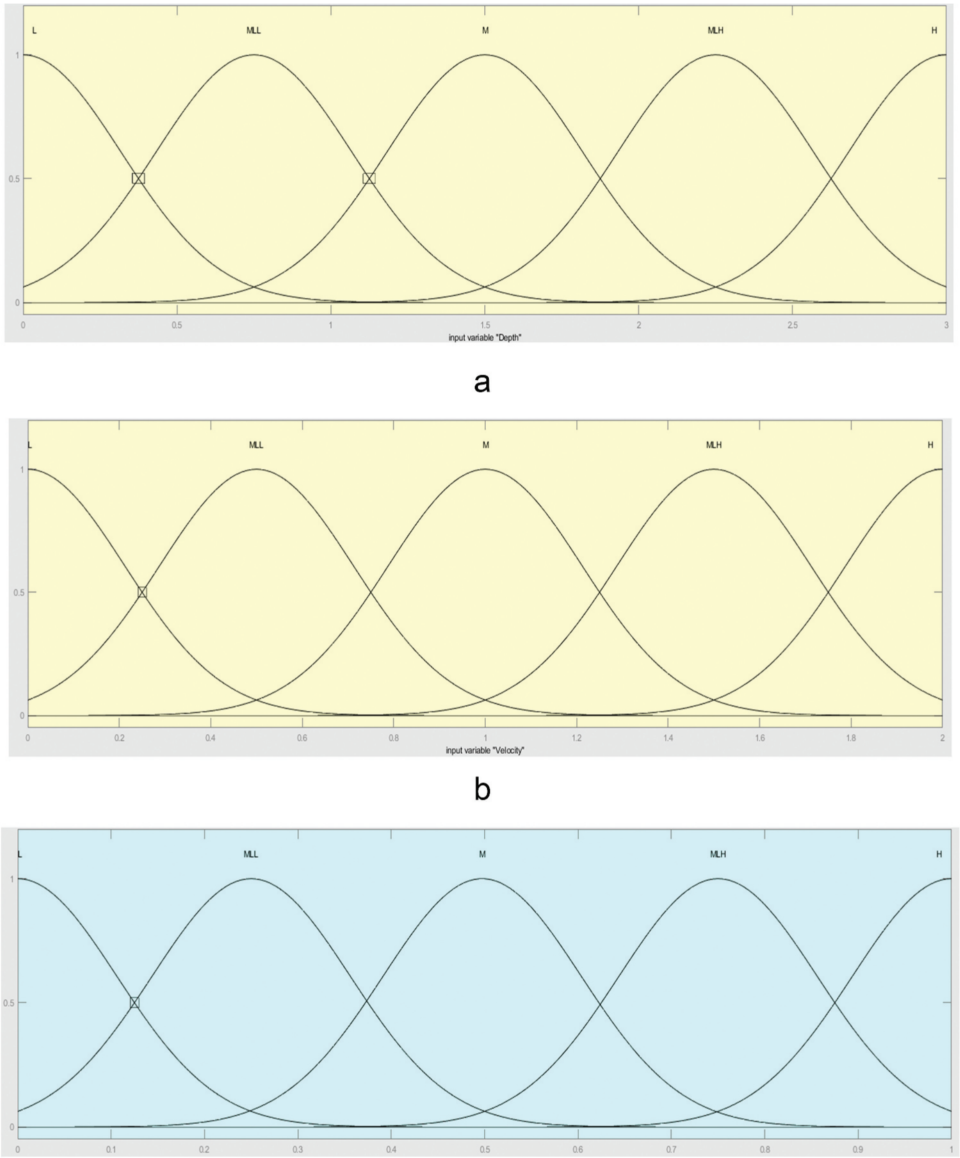


Figure 6. Designed storm events in the case study.

(Chen et al. 2020). We applied the Mamdani fuzzy approach to assess flood damage, which is a known fuzzy inference system used in many previous studies. This type of fuzzy inference system is capable to consider the expert opinions in development of rules as well as membership functions. Mamdani fuzzy system (MFIS) was originally developed as a method to provide a control system by combining verbal control rules created by experienced human operators. The proposed fuzzy inference systems in the present study are inspired from the control systems in which verbal rules are developed based on opinions by an expert panel. More details on structure and computational steps for the MFIS have been addressed in the literature Pourjavad and Mayorga (2019). The developed fuzzy inference system estimates direct-tangible losses in which depth and velocity are the inputs and flood loss (direct-tangible damage) is the output. Figure 7 displays membership functions for inputs, including depth and velocity, and output (flood damage). Moreover, verbal fuzzy rules were developed by an expert panel method which is shown in Figure 8. In the panel, verbal rules are developed and reviewed by a specific process and will be finalized by the chief of the panel. Finally, Python scripting in a geographical information system was applied to combine the outputs of the direct rainfall model and fuzzy loss model.

3. Results

In the first step, it is essential to present the fuzzy rules of flood damage developed by an expert panel method which are applied for mapping flood damage in the case study. Figure 9 shows pseudo-colour graph of the rules in which depth and velocity are the inputs of rules and changing colour means magnitude of normalized flood damage. In this graph, dark red means minimum damage (0) and yellow means maximum damage (1). Based on this figure, high depth causes significant damage even in low velocities. However, impact of high flow velocity on increasing damages in lower depth is not negligible.



a

b

c

Figure 7. Membership function of Mamdani fuzzy inference system: (A) depth, (B) flow velocity and (C) normalized flood damage between 0 and 1).

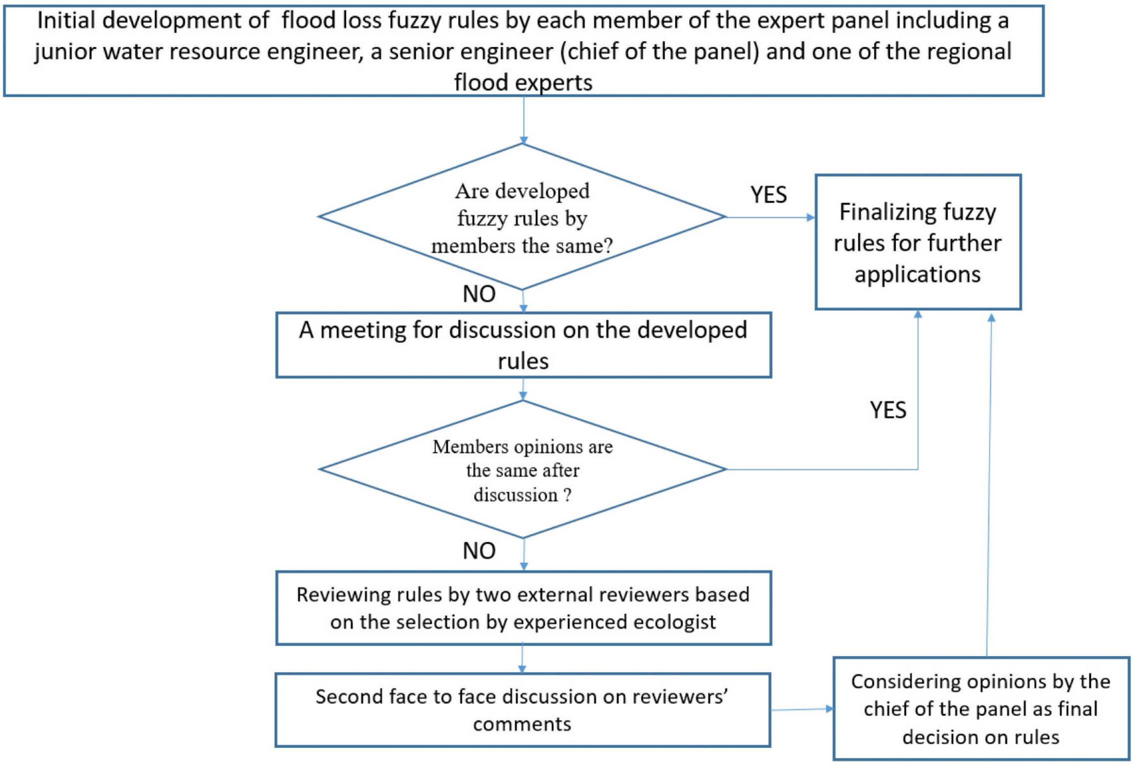


Figure 8. Workflow of expert panel method for developing verbal fuzzy rules. This panel defines the membership function with the similar approach prior definition of fuzzy rules.

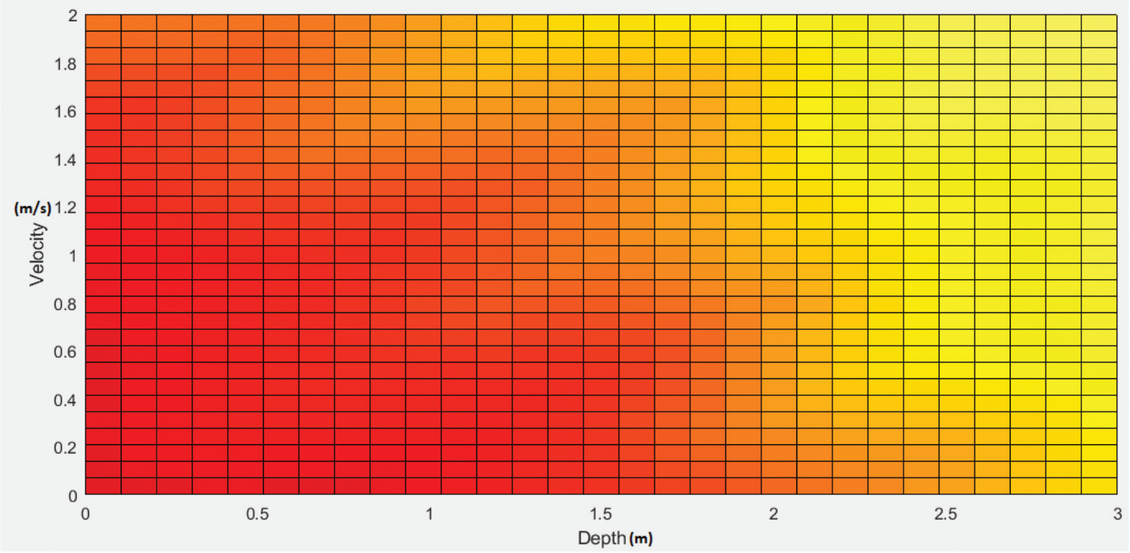


Figure 9. Pseudo-colour graph of verbal fuzzy rules of flood damage.

In the next step, results of direct rainfall modelling should be presented. One of the important challenges for developing hydrodynamic models is verification process of the model. In other words, the outcomes of a hydrodynamic model could not be acceptable if the model is not able to generate a real flood event with limited error. In the present study, we applied a designed storm event which is not available in real world. However, we simulated a real rainfall event close to designed storm event for verifying the model. Due to availability of a hydrometric station at downstream of simulated sub-basin, it was possible to verify the model by using recorded water level or depth in the station. Figure 10 displays changing of depth in one hour of flood peak which indicates the results of the model and recorded data are close. As mentioned, two indices were applied to evaluate the accuracy of the direct rainfall model, including NSE and RMSE. These indices are shown on this figure as well. According to the literature, maximum NSE is one which means the model is perfect. However, developing a perfect model is not possible practically. NSE more than 0.5 is a recommended value to accept the performance of a model. In the present study, NSE is 0.75 which corroborates the predictive ability of the model to simulate depth in the hydrometric station. Furthermore, RMSE is 0.83 m, which implies that the mean error of the model in generating actual depth during a flood event is deemed acceptable. Hence, the developed model is useful for selected designed storm event as well.

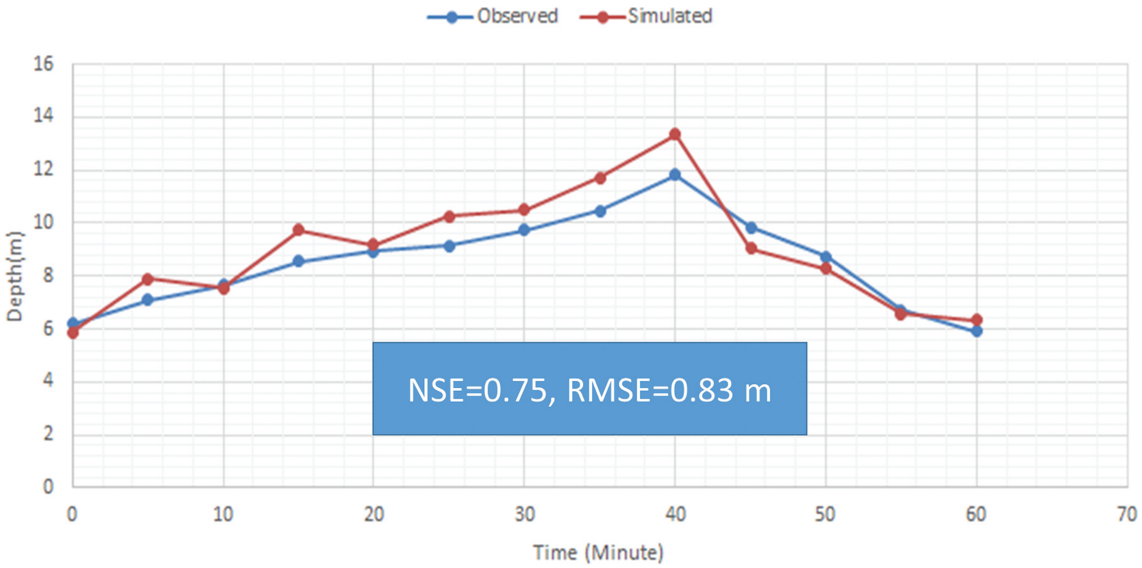


Figure 10. Direct rainfall model verification in one hour of flood peak at downstream hydrometric station.

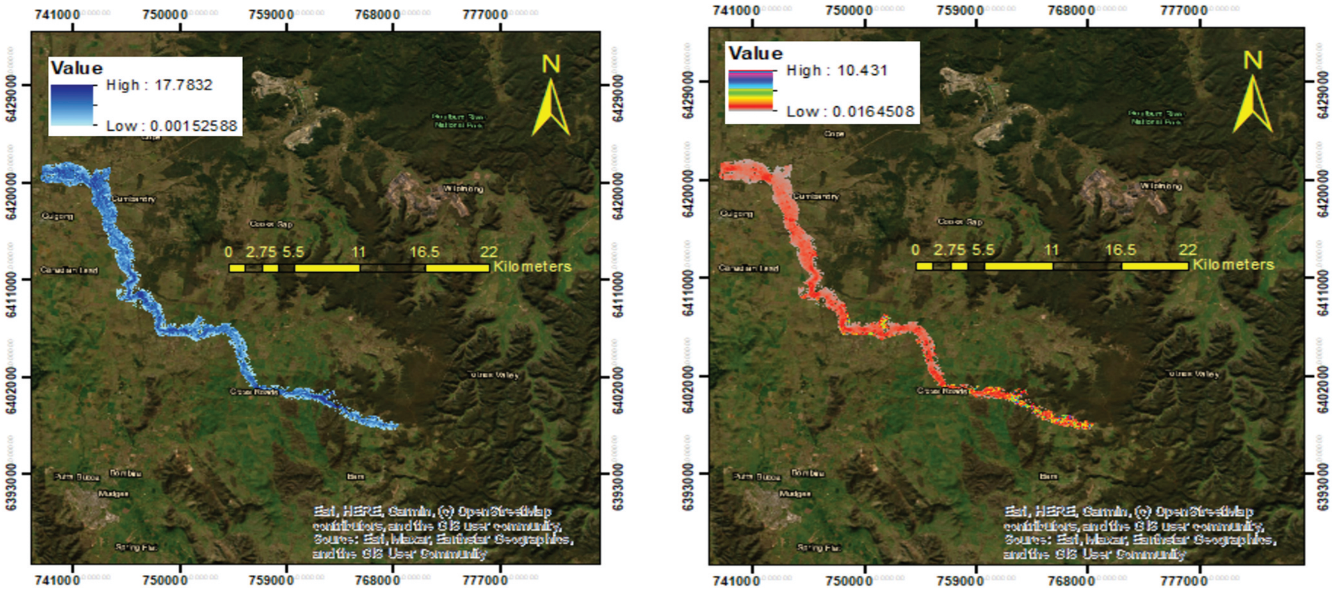


Figure 11. Flow characteristics of simulated storm event (up: depth (m), down: flow velocity (m/s)).

Figure 11 shows the depth and velocity distribution in the floodplain of the main river branch in which depth and velocity are altered in a wide range. The extent of flood is logically increased from upstream toward the downstream. Hence, downstream flood damage might be considerable. It should be noted very high depth or velocity such as depth more than 15 m is happened in the main channel of the river. In contrast, depth of flow in the floodplain is less than 3 m in most areas. Figure 12 shows the flood damage map in the study area in which normalized flood damage alters between 0 and 0.91. In some areas the flood damage is 0 due to minimal use of the lands, which means the model is able to exclude areas with no potential damage. Moreover, flood damage at downstream areas increased considerably due to the prevalence of more rural and agricultural lands. Figure 13 displays flood damage downstream of the simulated sub-basin for having a better view on the results of the model. It should be noted that the simulated sub-basin is a low population area in which some areas especially at downstream are rural or agricultural lands. Hence, flood damage of floodplain areas where land use is minimal or natural is 0. Finally, Table 3 shows the computational complexities in the case study. The direct rainfall model is a highly complex model due to considerable required time and memory for simulating even one rainfall event with the high resolution of computational mesh.

4. Discussion

A full discussion on technical and computational aspects of the proposed method is needed for better understanding of its applicability. Furthermore, it is required to discuss on the strengths and limitations of the proposed method. Comparing the proposed method with previous ones is helpful to investigate how this method is able to improve flood damage mapping as a critical task for water resources engineers.

Outcomes of this research work in the case study or other cases can be used in several aspects of flood studies. First, it can be applied for improving assessment process of flood insurance which is a vital need to compensate potential flood damages. We applied a hydrodynamic approach which can be utilized in

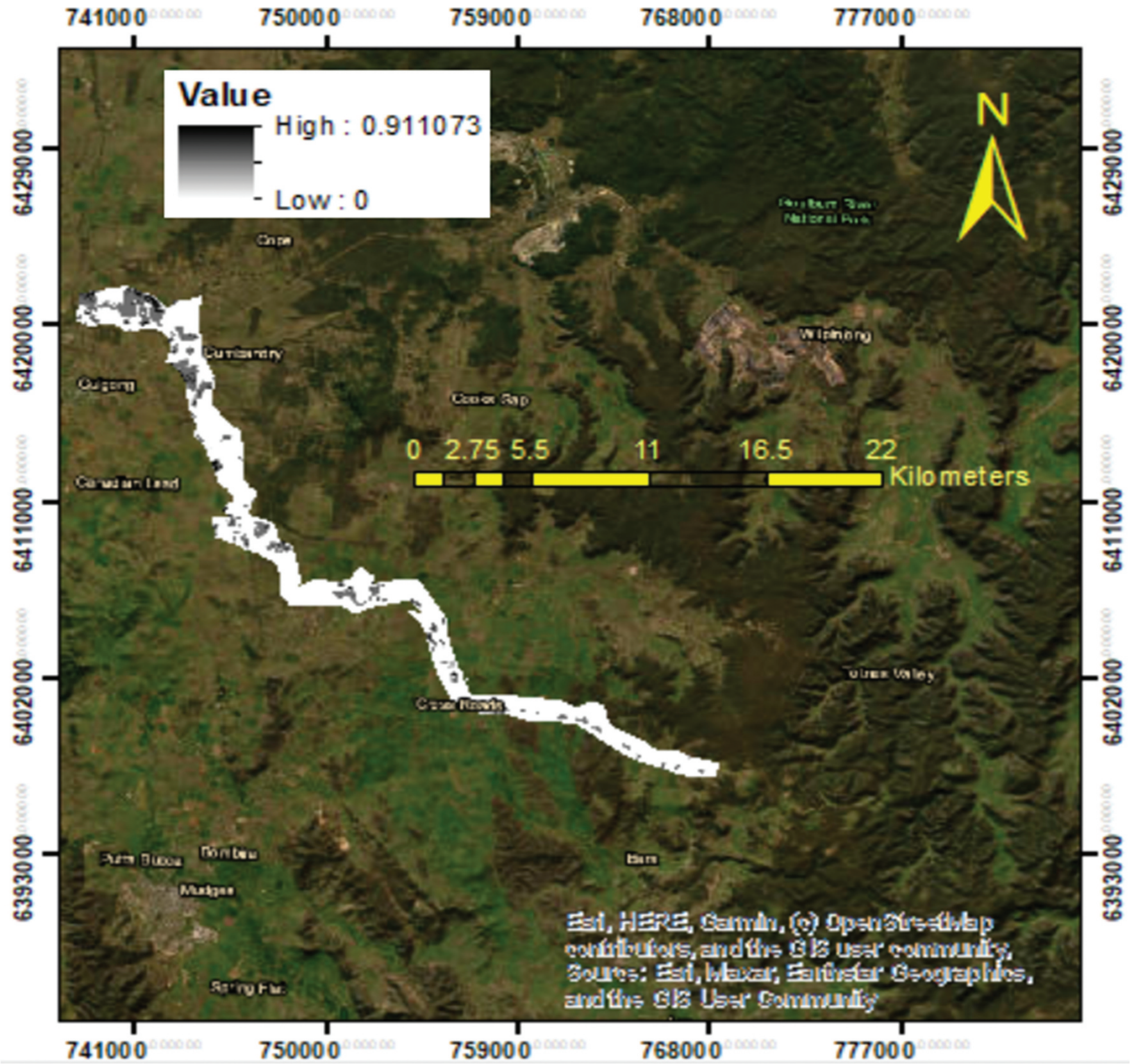


Figure 12. Flood loss map in the flood plain of main river branch.

the catchment scale. Hence, it is advantageous in terms of integrated flood damage assessment. In the present study, we only focused on the main river branch in the simulated sub-basin. However, the proposed method (due to using direct rainfall modelling) is able to generate flood damage map in the basin scale as well. For example, the proposed method can be applied in basin with dense urban areas where an integrated flood damage map is helpful for developing a comprehensive plan of flood mitigation or management.

It is required to discuss on technical and computational aspects of the direct rainfall approach. Conventionally, developing depth or velocity distribution map consists of two steps. First, a lumped runoff routing model is used to generate flood hydrograph. In other words, rainfall event and losses (initial loss and continuous loss) are the main inputs of the model to generate a flood hydrograph. Then, the outcome of the runoff model will be used as the boundary condition (generally upstream boundary condition) in the hydrodynamic model, and by adding downstream boundary condition, the hydrodynamic model simulates flood extent, depth and velocity distribution. The conventional approach has some advantages and drawbacks which should be reviewed. Hydrological models do not need considerable computational time which means many designed storm events could be simulated in a short time. Generally, run time of these models is less than several minutes which implies changing the model's parameters is possible and easy for having many tests to achieve the best results. In contrast, hydrodynamic model needs much more computational time to generate hydraulic characteristics. In fact, hydrodynamic modelling, especially when the modeller applies a fine computational mesh, needs much time to solve the shallow water equations in each cell. One of the drawbacks of the conventional method regarding hydrodynamic modelling is to develop a set up in the catchment scale. In other words, it is necessary to generate flood hydrographs in many locations of a big catchment as the boundary conditions of the hydrodynamic model. It should be noted that it is an arduous and complex task because several hydrological models should be developed to generate flood hydrographs. Currently, hydrodynamic models are usually being utilized in the river reach scale in which flood hydrograph is not remarkably changed from upstream to downstream of a river reach. Due to this drawback, developing several standalone hydrodynamic models in basins is usual to have better understanding on potential flood losses. In other words, several flood studies should be carried out to generate flood loss map in river basin scale. In contrast, direct rainfall approach could be used in river basin or sub-basin scale. One of the most important advantages of direct rainfall approach is to develop an integrated model and faster model setup time. Furthermore, this approach is helpful to investigate

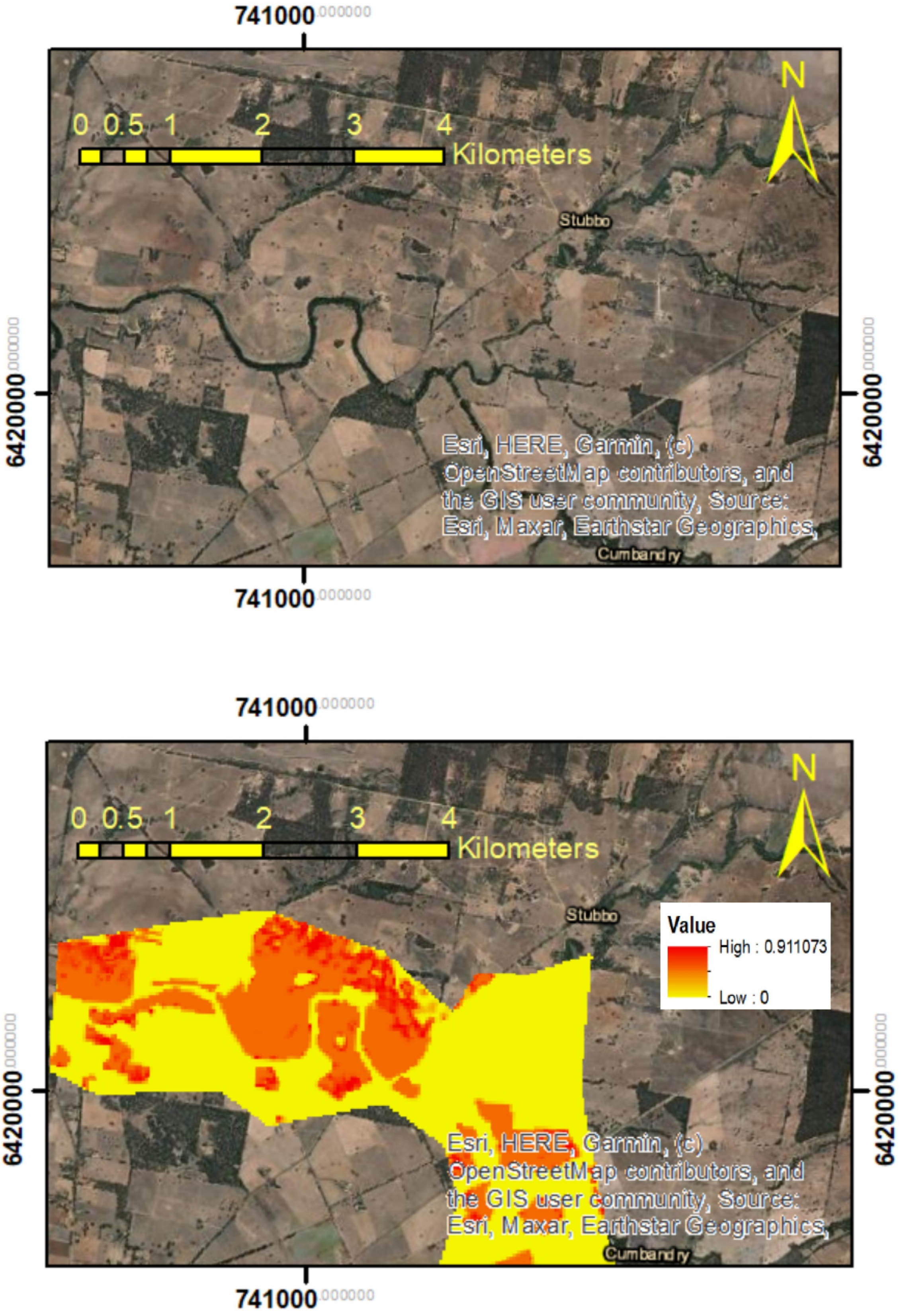


Figure 13. A close view on flood losses at downstream (up: base map, down: base map with loss layer).

Table 3. Computational complexities in the case study.

Type of computational complexities	Direct rainfall modelling in the case study (computational mesh: 5 × 5 m, rainfall: 1% AEP)	Generating flood damage map by linking output of direct rainfall model and fuzzy loss model
Computational time (hours)	12.67	0.11
Required memory (CPU usage %)	89%	48%

response of different regions to the flood events. In other words, direct rainfall approach can be applied for prioritizing sub-basins in terms of potential flood damage for better use of flood mitigation approaches. Direct rainfall model can be useful to simulate possible interventions for mitigating flood impacts. For example, any intervention at upstream would have impacts at downstream as well. Conventional method is only able to show the impact of intervention in a limited area. Conversely, direct rainfall approach is able to indicate how an intervention could be effective in all areas of a river basin. Another advantage of this approach is to visualize the results of flood modelling in an applicable scale especially for stakeholders who would like to have a whole picture of flood impacts in catchments. In other words, direct rainfall model is a golden tool to engage community in the flood mitigation projects. Currently, community engagement is one of the big challenges in many countries to reduce potential impacts of floods which means using the proposed method is helpful in this regard.

Computational challenges of using direct rainfall model might be however a hindrance to apply this approach practically. The computational time of this model is much more than combination of using a lumped runoff routing model and hydrodynamic model. In fact, this model uses hydrodynamic approach in all locations of a basin or sub-basin which means computational complexities are very high. According to the literature, computational complexities are defined as the required time and memory to obtain a solution by a code. Unfortunately, direct rainfall approach is weak in terms of computational complexities because it needs considerable memory and time to simulate flood maps. For example, the computational time was more than one day in the case study which demonstrates using this approach in real projects could be difficult. It should be noted that engineers those who apply these types of models in small and large river basins are not willing to apply complex approaches because they should use the models for several flood events or numerous simulations. Hence, lack of motivation for using this approach in consulting engineers due to high computational complexities is one of the challenges for future applications of the proposed method.

We developed a fuzzy approach to assess flood loss which should be discussed as well. Mamdani fuzzy approach is originally developed to include the operator's rules for managing control systems. Hence, expert opinions in different branches of engineering could be developed in the structure of control systems. In this study, this approach was used for developing flood loss model, which is advantageous in terms of technical aspects and community engagement. Hence, we discuss on the advantages of this method considering these aspects. Conventionally, mathematical functions are applied to assess flood loss in the projects. In other words, flow characteristics such as depth distribution can be converted to the loss map of a flood event. Utilizing depth-damage function is a common and classic method which is currently being applied in many countries. It should be noted that depth is not the only parameter which could be effective on flood damage. In many cases, flow velocity might rise flood damage remarkably. Thus, using both parameters is the first requirement for assessing flood damage. Some limited mathematical graphs and functions have been developed that consist of both depth and velocity in assessment of flood damage. However, all of these methods have a significant weakness to simulate flood loss which is lack of ability to consider regional considerations in flood damage assessment. In other words, flood damage could be changed case by case due to difference between land use, properties values and available businesses. Hence, using general mathematical function in the literature is an inaccurate or rough assessment of flood damage. It should be noted that developing regional functions is an arduous task because full quantified assessment on previous flood events is needed. However, many flood damage surveys have been carried out based on qualitative assessment which means regional experts have valuable opinions on how flood loss could be altered due to changing depth and flow velocity. Hence, using expert opinions based methods is highly recommendable for flood damage assessment. The proposed fuzzy approach is able to work based on opinions by experts which might have adequate information on potential flood damage by changing depth and velocity in case studies. Experts can contribute in two parts of developing fuzzy loss model, including developing membership functions of inputs and output and verbal fuzzy rules. We proposed an expert panel including three members to develop verbal fuzzy rules. It should be noted that we limited the number of members in the panel due to some technical considerations. First, available members in the panel are the main members for flood damage assessment which means each main member might have a network of experts or surveyors to receive feedback of flood damage in previous flood events. Moreover, having several members in the panel might make development of the rules much more difficult due to need for more time in meetings or conflicts among the experts. Hence, it is recommendable to select some effective experts in the main panel who can have a network of experts for developing verbal fuzzy rules of flood damage with the highest possible accuracy.

Another advantage regarding the proposed flood loss model is to enable the community to be engaged in the process of flood damage assessment. In fact, the main members especially chief of the panel could have close relationship with the regional communities who are vulnerable to the flood events and have experienced flood losses in the previous events. Regional surveys by the panel can be applied in development of verbal fuzzy rules. It is an important strength for developed method because one of the current challenges is how community could be engaged in flood studies effectively. For example, some communities in Australia complain regarding assessment of flood damage because they believe that available methods might underestimate potential damages by floods. As a consequence of this underestimation, governments might not allocate sufficient fund to compensate possible flood losses. The proposed method is potential to be improved in terms of community engagement in the flood damage assessment. For example, stakeholders' opinion could be directly used in the panel by adding some key stakeholders to the panel. Moreover, socio-economic indices could be included in development of verbal fuzzy rules as well. Thus, we recommend enhancing the panel-based method in future studies to have more accurate rules of flood losses.

We developed the flood loss model for direct-tangible damages. However, other possible damages, especially intangible damages, are challenging for assessing flood loss. One of the advantages of the proposed method is the capability to include intangible damages in the verbal fuzzy rules. For example, mental issues are difficult to be quantified in the assessment of flood damage. However, the proposed expert system is able to develop a standalone model for assessing mental impacts of flood on communities.

It is essential to discuss the limitations of the method as well. Apart from computational limitations of direct rainfall modelling, which has been discussed, fuzzy loss model has some inherent significant limitations. The most important limitation of the fuzzy loss model is a need to establish a strong panel. In other words, lack of experts in many regions for accurate regional assessment is a big problem, which might restrict the applicability of the proposed method. Furthermore, considerable conflicts among the members might weaken the acceptability of the model in the regional communities. Experts might overcome the latter limitation by improving the structure of the panel.

5. Conclusion

This study proposed a novel method for mapping flood losses in which direct rainfall model was linked with a fuzzy approach-based model.

Fuzzy approach is able to include expert opinions considering regional requirements in the flood loss mapping which enables communities to be engaged in accurate flood damage modelling effectively.

The computational complexities of direct rainfall modelling, such as computational time, are the main limitation of this approach.

It is recommendable to apply other types of fuzzy approaches such as Sugeno fuzzy inference system to compare the results with the proposed approach.

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Availability of data and materials

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