

## ABSTRACT

This paper presents research undertaken to develop and implement a coupled hydrologic-hydraulic model which utilises remotely sensed data to improve flood forecasting skill in rural catchments subject to fluvial flooding. The discussion of literature reviews and subsequent knowledge gaps aids in the identification of key obstacles towards implementation. Collected data and modelling algorithms developed as part of the project are described before an overview of the progress towards implementation is given. To maximise the potential utilisation of this research end-users have been involved in providing data, setting up case studies, and defining research priorities and methods

# Improving flood forecasting skill using remotely sensed data

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## Introduction

Similar to many countries worldwide, Australia has witnessed the destruction caused by fluvial flooding. Sadly, there is no indication that floods will become less frequent or severe as our climate changes (Goodness 2013). Flood warning systems mitigate detrimental impacts and increase community resilience. Flood warning systems are comprised of in-situ and remotely sensed (RS) observation networks, weather and flood forecasting models, flood warning dissemination systems, and emergency response procedures (Sene 2008). Spatially distributed RS data offers additional ways to constrain and update the hydrologic and hydraulic models used for flood forecasting. Practical benefits of using RS data when generating flood warnings include longer lead times, a greater understanding of the uncertainty in streamflow forecasts, the monitoring of floodplain surface water and an improved modelling of floodplain inundation dynamics.

This project focuses on the improvement of flood forecasting skill by developing methods to optimally merge RS data and hydrological and hydraulic models. Throughout this paper skill is defined to represent the ability with which the model is able to replicate observed data. The hydrological models simulate critical rainfall-runoff processes which describe the loss of water to evapotranspiration, the subsequent partitioning of incident areal rainfall into overland and subsurface flows, catchment storage, and ultimately the discharge hydrograph. Research tasks aimed to improve the hydrological forecast skill are targeted at the optimal assimilation of RS soil moisture (SM) data into the hydrological model. The hydraulic model takes discharge hydrographs as input to simulate the flood wave routing and predict the inundation depth and velocity at each point on the floodplain. Research tasks aimed to improve the hydraulic modelling skill include constraining hydraulic models with RS water extent data and obtaining flood extent from observed Synthetic Aperture Radar (SAR) data. Unfortunately, the accuracy, precision and timeliness of forecasts are limited by the model capability given observations and computational requirements. To maximise skill improvements made possible by RS observations, potential errors and biases must be adequately accounted for.

Traditional hydrologic rainfall-runoff models are forced, calibrated to, and updated with in-situ measurements such as precipitation and streamflow. In conjunction with increased computational capabilities, significant increases in the temporal and spatial availability of RS precipitation and SM have spurred a new generation of flood forecasting, which involves rainfall runoff models that demonstrate skill improvement from being forced, calibrated to or updated with RS observations (Li et al. 2016). Benefits obtained from RS data include an increased understanding of model dynamics, representation of internal processes, ability to estimate model parameters, understanding of uncertainty, and the ability to deliver forecasts with greater lead times. These advances will provide critical improvements to flood warnings issued to emergency management services.

Inundation monitoring and hydraulic modelling capabilities have increasingly benefitted from recent technological improvements, new satellites and constellations of satellites.

Due to their synoptic view of the flooded area, RS observations can effectively support emergency services. Moreover, RS techniques provide spatially distributed information on inundation dynamics, which can solve the well-known issue of data scarcity for the constraint of floodplain inundation models (Bates et al. 1997; Horritt 2000; Bates 2004; and Werner et al. 2005).

As opposed to point-scale gauged data, two-dimensional information of flood extent and level has the potential to provide more comprehensive and effective ways to constrain the hydraulic model, thus leading to more accurate predictions of floodplain inundation dynamics.

The synoptic view provided by remote sensing data offers novel opportunities for model calibration, validation, and real time constraint; however, a number of practical hurdles have yet to be overcome to enable their routine use in an operational framework. First, remote sensing is a relatively recent technology; availability of historical observations is limited and hindcast analysis of extreme events is not always possible. Second, despite the fact that the number of satellites and the acquisition frequency is deemed to increase in the future, remote sensing observations are generally discrete in time. Moreover, acquisition is generally still opportunistic. Third, quantities used for model constraint (e.g. soil moisture, water depth) are derived from remote sensing observations, as opposed to direct measurements by gauge stations. This feature, combined with relatively low spatial resolution, sensor and catchment-related features lead to remote sensing data uncertainty. Hence, remote sensing data are affected by larger uncertainties than gauged data (at the point) and improved methodologies for uncertainty assessment are still required. Finally, the need to rely on different providers (due to the short time span of the satellite missions or their low acquisition frequency) requires a methodology for the appropriate merging of datasets. Consequently, further research and experience are strictly required to fully disclose the potential of two-dimensional remote sensing observations.

The final outcome of this project will be a coupled hydrologic-hydraulic model which improves flood forecasting skill in rural catchments subject to fluvial flooding through the use of RS data. Flash flooding as a result of severe rainfall is not able to be addressed by this research. This manuscript provides an overview of research conducted to date on the path to meeting this outcome.

The project is funded by the Bushfire and Natural Hazards Cooperative Research Centre (CRC) and it aims to investigate the optimal use of remote sensing observations for the provision of more accurate and timely flood forecasts through coupled hydrologic-hydraulic models. The project started on May 1st 2014 and it will end on June 30th 2020. Intermediate and final deliverables have been discussed with the Australian Bureau of Meteorology (BoM) and Geoscience Australia (GA). The Commonwealth Scientific and Industrial Research Organisation (CSIRO) has constantly provided active feedback on the research developed by this project.

The continuous hydrologic modelling approach constrained with soil moisture both integrates and complements the current event-based and gauged-based predictive protocols of

the BoM. The hydraulic model enables better understanding of floodplain inundation dynamics and the prediction of water depth and velocity in each point of the floodplain. Albeit, implementation of the coupled hydraulic model for any catchment in Australia is not feasible within the project timeframe, the methodologies developed within this project have the potential to enable floodplain inundation modelling in any Australian catchment. Specifically, this project will provide a roadmap for data collection, hydrologic data assimilation, model implementation, calibration, and constraint. Moreover, the results for the test sites can enable a better understanding of floodplain inundation dynamics in Australian catchments. Finally, this project is developing an algorithm for the detection and monitoring of floods using SAR data in vegetated areas. This capability will complement the existing GA protocols based on optical data.

## Literature review

### Application of RS data to improve hydrologic modelling skill

Precipitation and SM are the key hydrologic components that benefit from an increased availability of high-quality RS data. RS of precipitation can be used to force hydrological models when traditional in-situ measurements are not available or are inadequate. The blending of RS precipitation from ground and satellite-based radar is used to add value to precipitation estimates. Precipitation nowcasts and forecasts benefit from the assimilation of blended precipitation estimates. The potential for current uncertainties to propagate through models limit the usage of RS precipitation estimates to force current flood forecasts.

The RS of SM can aid flood forecasts by providing additional data for the constraint of hydrologic model parameters and model structural errors, as well as being used in data assimilation schemes to update flood forecasts as new observations become available. A review of the literature (Li et al. 2016) identified the following needs in the applications RS SN to flood forecasts:

- Ability of the modelled soil layer to represent the observed soil layer;
- Bias between the modelled and observed soil layer;
- Correct specification of the observed and modelled soil moisture errors; and
- Strategies to use multiple observations and products.

Further, it is noted that improvements in the ability to estimate the upper soil moisture layer will not necessarily lead to improvements in streamflow forecasts. This can occur as a result of a model's inability to concurrently simulate upper layer soil moisture and streamflow which are consistent with observations. The hydrologic modelling focus of this project was to use a model which aims to represent dominant hydrologic processes in the soil layer. Biases between modelled and observed soil layers were addressed through a joint SM and streamflow calibration scheme. The correct specification of observed and modelled soil layer errors in conjunction with strategies to use multiple observations is

being dealt with through the implementation of a dual Ensemble Kalman Smoother (EnKS) which adapts to modelled and observed error structures.

## Application of RS data to improve hydraulic modelling skill

The increasing availability of spatially distributed RS observations of flood extent and water level offers the opportunity for a comprehensive analysis of the predictive capabilities of two-dimensional hydraulic models. Nevertheless, such data availability requires a better understanding on how to effectively exploit the large amount of information offered by RS observations. An analysis of the state-of-the-art use of RS-derived observations of flood extent and water level to improve the accuracy of flood forecasting hydraulic models was presented in Grimaldi et al. (2016). The published literature have demonstrated that RS-derived observations of flood extent and water levels have the potential to improve floodplain inundation forecast accuracy.

Specifically, RS-derived observations can be used to constrain the parameters of the hydraulic model.

The low acquisition frequency and high uncertainty of RS observations are currently the main practical hurdles. Moreover, methodologies and protocols for the optimal comparison between RS-observations and model results are still under investigation. Consequently, RS-derived observations have so far been considered as a complement, not an alternative to field data for hydraulic model calibration/validation and real-time constraint.

Further research in the following areas is required to make full use of the new RS data sets:

- RS image processing algorithms;
- Optimal use of RS-derived information for the implementation of hydraulic models for flood forecasting;
- Definition of the most appropriate RS-derived observation (e.g. inundation extent and/or level) for the effective evaluation of the accuracy of modelled floodplain inundation dynamics; and
- Definition of RS-based protocols for the assessment of the parameter space of the hydraulic model to enable more accurate floodplain inundation predictions.

## Methodology

To aid in defining a project scope that maximises the potential for utilisation, the end users at the Bureau of Meteorology (BoM) Geoscience Australia (GA) and New South Wales State Emergency Service (NSW SES) have been engaged since the inception of the project. These end users continue to provide valuable input which helps shape the clearest path towards implementation of state-of-the-art fluvial flood forecasting processes driven by hydrologic and hydraulic models.

The state of the art in operational hydrologic and hydraulic flood forecasting that takes advantage of RS data was identified in the two aforementioned literature reviews (Grimaldi et al. 2016; Li et al. 2016). Knowledge gaps and

opportunities for development were identified therein. Data pertinent to the respective tasks were collected from responsible agencies. Two field campaigns were completed to measure river bathymetry at selected locations along the river systems. More specifically, the SonTek M9 HydroSurveyor Acoustic Doppler Profiler was used to obtain high resolution bathymetric data for approximately 20km and 16km in the Clarence River and Condamine-Balonne River, respectively.

The time and monetary expensive collection of bathymetric field data allowed the development of a high-resolution benchmarking dataset for the development of a low cost, data parsimonious methodology for the assessment of river bathymetry in data scarce catchments.

The next phase in the project involved undertaking various modelling tasks which addressed the identified knowledge gaps. As each modelling task reaches completion they are progressively rolled out for implementation.

## Data

The Condamine-Balonne and Clarence catchments were selected as case studies for this project. Both catchments have been subject to major floods during the study period beginning 2008 and ending 2014. Furthermore, good quality RS observations are available for both catchments.

Specifically, the area of the Condamine-Balonne catchment downstream of Chinchilla was selected as an example of a slow-moving meandering river system in which floods gradually rise over several days. In contrast, the Clarence River catchment shown in Figure 1 is an example of a fast-moving river system. Both catchments are susceptible to flash flooding from heavy rainfall.

The data collected for the catchments include hourly precipitation and streamflow observations (Bureau of Meteorology, 2019), monthly PET from AWAP (Raupach et al. 2012), SMOS RS SM, SRTM-derived DEM-H (Gallant et al. 2011), the Dynamic Land Cover of Australia (Lymburner et al. 2011), SAR images from different data providers (Cosmo SkyMed, ALOS-PALSAR, Radarsat2); optical images from satellite (LANDSAT5 and LANDSAT7, SPOT5 and SPOT6, ASTER) and airborne acquisitions. Further, the algorithms and tools developed within this project allow a certain flexibility for different data sources.

## Research components

The modelling tasks in this project cover three distinct, yet consequential topics, hydrologic modelling, interpretation of RS images, and hydraulic modelling.

### Hydrologic modelling

The hydrologic modelling research tasks were designed to address the identified knowledge gaps. For a flood forecasting model to benefit from RS SM observations it is imperative that the model soil layers adequately represent observed soil layers. Owing to data restrictions and computational capabilities, operational flood forecasting models are commonly conceptual in nature.

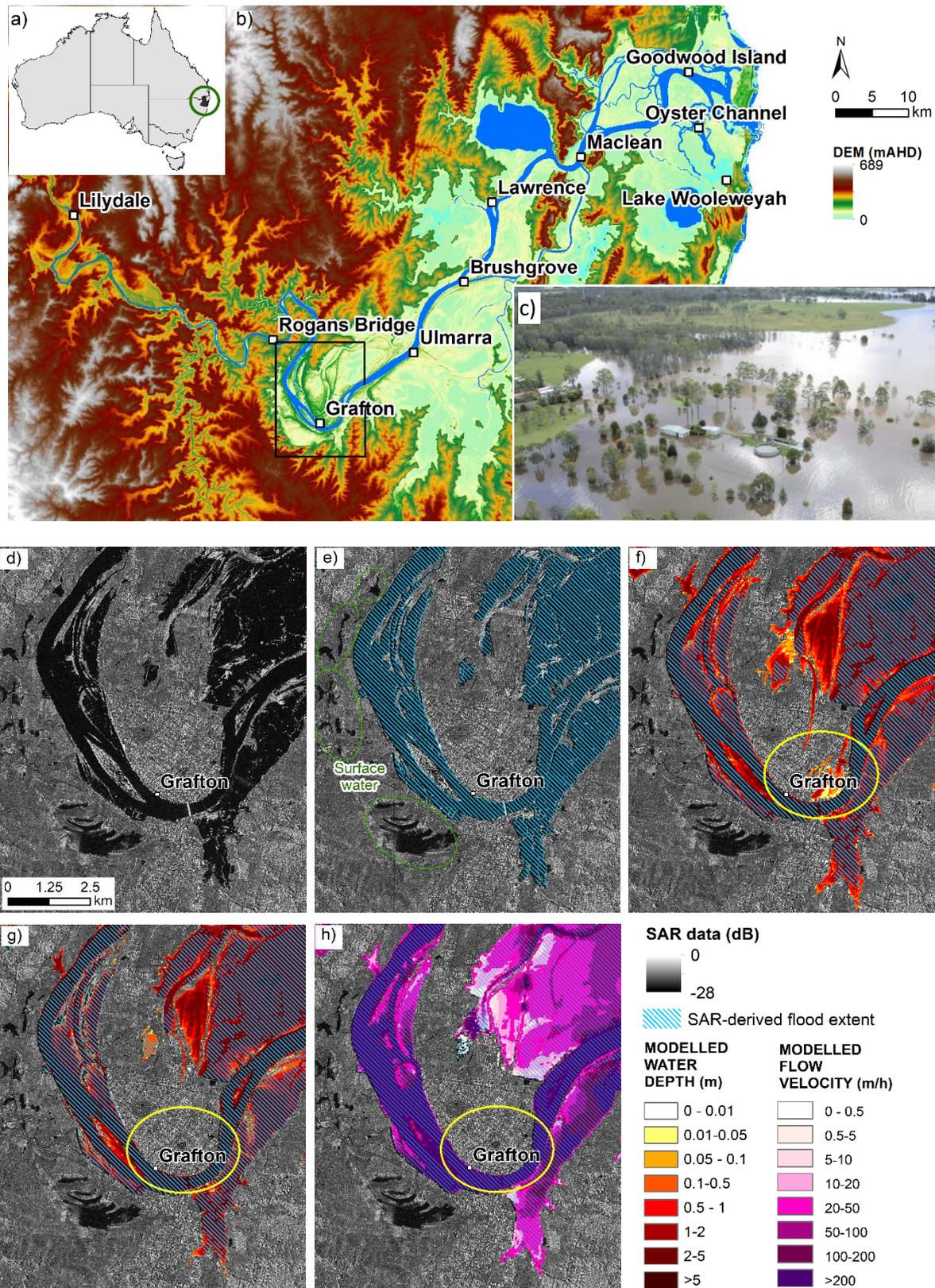


Figure 1: Panel a and b show the location of the Clarence catchment, and the Clarence catchment with the major towns, respectively; the black rectangle in panel b show the footprint of panels d, e, f, g, h. Panel c shows an aerial photography demonstrating the impact of flooding in the Clarence River (Photo supplied by NSW SES - Clarence Nambucca Region). Panel d shows the SAR data acquired during the 2011 flood (Cosmo SkyMed satellite); panel e shows the SAR-derived flood extent layer (green circles highlight surface water bodies not connected to the flooded area). Panel f shows the flood extent and depth values predicted by a preliminary model realization; the comparison with SAR-derived flood extent highlights false alarms in the townships of Grafton. Panel g and h show the improvement in modelled inundation extent and velocity obtained by using RS data for model evaluation.

Conceptual models represent salient rainfall-runoff dynamics and often represent complex rainfall-runoff dynamics with simplified assumptions that represent bulk catchment wide dynamics. Furthermore, it is common for conceptual models to yield similar skill in forecasting scenarios to more cumbersome physical models.

As RS SM becomes more accurate and readily available, it is often asked "how do we best include RS SM into our operational models"? One such answer involves the adaptation of a conceptual model such as GR4H (Perrin et al., 2003) to include a more physical representation of the soil layer. The hydrologic model GRKAL (Francois et al. 2003) does exactly this and is well suited to address the operational needs of a rainfall-runoff model that has the capability to benefit from RS SM observations.

Methods to deal with biases between modelled and observed SM are highly debated within the hydrologic community. If not treated appropriately biases between modelled and observed SM can lead to over or under-correction of states in data assimilation applications. The commonly used approach of cumulative distribution function (CDF) matching inappropriately assigns all of the bias to the observations and consequently results in a loss of information (Li et al. 2016). An alternative and less common approach of using SM observations in calibration has the advantage of retaining information (Li et al. 2016). This approach has been met with skepticism as it may degrade the ability of the model to simulate streamflow in the calibration, validation, and forecast periods. Research within this project has explored the impact of a joint calibration scheme that calibrates the GRKAL rainfall runoff model to both streamflow and SM. Results demonstrate that calibrating to SM and streamflow have a near-negligible influence on streamflow predictions and that internal ungauged gauged catchments observe improved streamflow predictions (Li et al. 2018). The influence of calibrating to SM and streamflow observations on data assimilation applications remains to be tested.

Assimilating streamflow into rainfall-runoff models for flood forecasting is the most widely adopted data assimilation approach to improve streamflow forecasts. The direct relationship between the streamflow observation and streamflow prediction ensures that assimilation of streamflow typically results in an improvement of the streamflow forecast. The updating of state variables such as SM with RS observations to improve flood forecasts has shown promising but mixed results (Li et al. 2016). Through the use of a conceptual model with a physically based soil layer and joint calibration scheme this project has begun to deal with some of the obstacles faced by improving flood forecasting skill in rainfall runoff models with RS SM observations. Strategies to correctly specify errors in observed and modelled soil layers for the dual assimilation of streamflow and RS SM are the focus of current research efforts. In the future, the outputs from the rainfall runoff models can be provided directly to emergency services or used as input to a hydraulic model to predict inundation depth and velocity at each point in the catchment.

## RS image interpretation

Observations of floodplain inundation provide pivotal information for emergency management and can enable

improved flood modelling capabilities. While sunlight and a clear sky are required for RS optical acquisitions, the 24-hour all-weather capability of SAR technology makes it a perfect choice for flood monitoring. A SAR is an active instrument that emits microwave pulses towards a target and measure the amount of microwave energy returned by backscattering off an object. Radar backscatter is mainly a function of surface roughness and the different response of smooth water surfaces and rough dry areas generally allows for flood mapping. However, the interpretation of the backscatter from flooded areas with emerging vegetation has been identified as one of the biggest challenges in SAR image analysis (Shen et al. 2019).

This project is developing an algorithm to automatically detect flooded vegetation using one single SAR acquisition and commonly available ancillary data (i.e. land cover, land use, and digital elevation models). The algorithm has been tested on three fine resolution images (one ALOS-PALSAR and two COSMO SkyMed) acquired during the January 2011 flood in the Condamine-Balonne catchment in Queensland, Australia. The results were validated using flood extent layers derived from high resolution optical images. In these case studies, state-of-the-art operational interpretation algorithms focusing solely on open water areas led to large omission errors with Overall Accuracy (OA) of 77 per cent, 65 per cent, and 75 per cent, respectively. Notwithstanding the difficulty to fully discriminate between dry vegetation backscatter heterogeneity and backscatter variation due to flooding using a single SAR image, the implementation of the proposed algorithm allowed the omission errors to be reduced thus achieving a final OA of 83.7 per cent, 81.5 per cent, and 85.7 per cent, respectively (Grimaldi et al. 2019). These results showed an overall accuracy larger than 80 per cent for all the test cases and hence encouraged the application of the proposed algorithm to other test cases and its extension to incorporate reference images and multi-polarised data in order to fully exploit the opportunities disclosed by recent satellite missions such as Sentinel-1 and NovaSAR.

## Hydraulic modelling

The 2-dimensional, raster based hydraulic model used in this project is based on LISFLOOD-FP (Bates et al. 2010) which solves the inertial formulation of the shallow water equations to simulate inundation depth and velocity in each point of the catchment. This project is investigating optimal ways to use RS data to support the implementation and the evaluation of flood forecasting hydraulic models. First, since systematic errors cannot be removed through calibration and data assimilation, the use of RS data for model set-up can be of paramount importance for accurate floodplain inundation modelling. Second, RS-derived information can be used to evaluate the predictive performances of the hydraulic model. Third, RS-based parameter assessment protocols can be designed for the delivery of more accurate floodplain inundation predictions. These three tasks are being investigated using the hydraulic model as a stand-alone component of the flood forecasting chain. In other words, gauged discharge and water level data have been used as input data to the hydraulic model in this phase of the project. This choice had the purpose to use an accurate input dataset. In a following phase of the project, coupling strategies between the hydrologic and the hydraulic model will be investigated. Each model implementation is affected by a

number of uncertainties and the cascading of these uncertainties has to be carefully evaluated. A preliminary analysis of the cascading of errors when coupling hydrologic and hydraulic models at the large scale was completed in Grimaldi et al. (2019). In this phase of the project, the hydraulic model was forced using measurements allowing investigation of the use of RS data in a simplified, controlled scenario.

The hydraulic model predicts the flood wave routing in the river system and, when the river capacity is exceeded, in the floodplain. Hence, accurate modelling of river flow dynamics is essential to simulate floodplain inundation. Bathymetric data are thus critical to the application of hydraulic models (Hilton et al. 2019; Wang et al. 2018). However, it is impossible to measure river bathymetry along the total river length, especially in large basins. Where the channel geometry is unknown, channel shape, depth, and roughness can be estimated through calibration, but different parameter sets can often map model predictions to the observed data generating an equifinality problem. Moreover, without the structural correction provided by an adequate geometrical representation, the sets of parameter values identified by calibration can lead to spurious nonphysical effects. Conversely, an approximated knowledge of river bathymetry can provide a more robust model setup (Neal et al. 2015). This project investigated the level of geometrical complexity required for the representation of river bathymetry in hydraulic flood forecasting models. More specifically, a numerical experiment was designed using the Clarence catchment as a case study to investigate an effective yet parsimonious representation of channel geometry that can be used for operational flood forecasting (Grimaldi et al. 2018). The analysis of a number of synthetic scenarios identified a rectangular, width-varying shape as the most effective simplified geometrical model. Width values can be derived from RS data while depth values can be assessed using a combination of global database and limited field data. Where river width data are not available, an exponential shape is recommended as the most viable solution. The proposed methodology for the preliminary assessment of river geometry has the purpose to support model implementation in data scarce catchments. Further, it has the potential to reduce the uncertainty of an ill-posed problem for RS-based model evaluation and constraint.

The use of RS-derived information for the evaluation of the accuracy of flood forecasting hydraulic models was then investigated using both the above described synthetic scenarios and real flood events as case studies. First, the numerical experiment based on the synthetic scenarios showed that distributed water levels derived from a synthetic RS observation, acquired as early as 24 hours before the flood peak at the input point of a short river reach, can enable the diagnosis of errors in the model implementation: flow propagation in low to increasing discharge conditions within the river strongly affects floodplain inundation dynamics with large discharge values (Grimaldi et al. 2018). Second, the modelling of the 2011 and 2013 flood events in the Clarence catchment showed that the combined use of RS-derived flood extent and RS-derived wet/dry boundary points enable an accurate evaluation of the predictive skill of the hydraulic model. Based on this analysis, a rapid methodology for the assessment of event-specific effective values of river roughness to enable more accurate representation of the flood event was formulated. More specifically, the comparison

between modelled and observed wet/dry boundary points can guide the constraint of river roughness values within the footprint of the RS acquisition. The comparison between modelled and RS-derived inundation extent can then be used to assess the roughness value outside of the footprint of the RS observation. Such a rapid RS-based methodology to constrain the distribution of effective river roughness values has the potential to lead to improved floodplain inundation predictions in both gauged and ungauged catchments while limiting the computational time.

Further testing is required to extrapolate the findings of these analyses to other catchments. Furthermore, in a real case scenario, the impact of uncertainties in RS-derived observations on the use of this data for the diagnosis of errors in model implementation has to be carefully evaluated. Nevertheless, this project shows (i) the importance of structural correction provided by an adequate representation of channel geometry, (ii) the use of RS data for model implementation, and (iii) the potential benefit RS-derived observations of flood extent and wet/dry boundary points to improve inundation modelling skill.

Finally, RS-aided improved predictions of the input discharge hydrographs developed within this project (hydrologic model) are expected to significantly enhance the accuracy of predicted floodplain inundation dynamics. To validate this statement, the final phase of this project will explore optimal ways to couple hydrological and hydraulic models (Grimaldi et al. 2019).

## Implementation

To facilitate the implementation of this research, the project team, the end-users and the CRC identified a number of key research outcomes that have strong ties to the end user objectives.

### Implementation of hydrologic modelling algorithms

This project is developing algorithms to effectively assimilate RS SM along with streamflow into hydrologic models for flood forecasting purposes. There is the potential for forecasts enhanced by assimilation of RS data to be delivered to emergency services or used as input to a hydraulic model for the prediction of inundation depth and velocity at each point of the river system and of the floodplain.

The dual observation calibration routine, rainfall gauge optimization routine, and single and dual observation EnKS routines are expected to be able to be applied to a broad variety of conceptual hydrologic models. Whilst the primary purpose is for flood forecasting it is expected that these routines can add value to 3-7 day streamflow forecasts. These 3-7 day forecasts are typically used to regulate environmental flows, dam releases, water allocations and reservoir storage levels.

Currently, the assimilation of RS SM improves forecast skill for catchments with larger times of concentration. As the acquisition of RS SM data becomes more frequent the ability for RS SM to improve flood forecasting skill in flashier catchments. The recent inclusion of GRKAL and future inclusions of dual observation calibration and assimilation

routines along with a rainfall gauge optimization routine in SWIFT2 will improve the BoM capability to forecast floods. A robust dual EnKS assimilation routine which includes calibration to RS SM and streamflow, optimization of rainfall gauge weighting, and allowance to update model and error structures will add value to flood forecasts by improving forecast skill and confidence. Greater confidence and forecast skill, leads to emergency services having more time to react to flood warnings.

## Implementation of a novel RS image interpretation scheme

This project is developing an algorithm for the retrieval of inundation extents from SAR images. The Water Observations from Space web-service developed and maintained by GA (<https://www.ga.gov.au/scientific-topics/earth-obs/case-studies/water-observations-from-space>; Mueller et al. 2016) makes use of optical sensors to provide information of historical surface water observations to allow better understanding of surface water availability and dynamics. The algorithm for the analysis of SAR data aims to complement the current capabilities for water monitoring from space by enabling the incorporation of information at night-time and in clouded conditions.

## Roadmap for the implementation of the hydraulic model

A comprehensive experience on the optimal use of RS observations to improve the implementation, evaluation, and calibration of hydraulic models for flood forecasts is being developed. While this project is focused on two specific case studies; the methodologies developed have made use of datasets available at the continental scale and thus have the potential to be used in a large number of Australian catchments. A roadmap for the optimal use of RS observations for the implementation and constraint of flood forecasting hydraulic models is being developed with the overarching aim to lead to the development of improved floodplain inundation prediction tools in many Australian catchments.

## Conclusion

This manuscript outlines the project life to date beginning with the early conceptual stages. The pathway to a coupled hydrological-hydraulic model which utilizes RS data is demonstrated via the discussion of literature reviews and identification of knowledge gaps which form key obstacles towards implementation. Collected data and developed modelling algorithms are described before presenting an overview on the implementation of research to date. To provide robust results the project continues to research the impact of joint calibration and estimation of catchment rainfall on hydrologic data assimilation. Further, an algorithm for the inversion of SAR data into flood extent maps is being developed. Moreover, novel methodologies for the optimal use of RS-derived flood extent and level to constrain the hydraulic model are being tested. Lastly the coupling of the hydrologic model and hydraulic model has yet to be completed. The continual involvement of research end-users

has been an integral component of implementing research to date.

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