IMPROVING FLOOD FORECAST SKILL USING REMOTE SENSING DATA

Final project report

Valentijn Pauwels, Jeffrey Walker, Stefania Grimaldi, Ashley Wright & Yuan Li

Monash University & Bushfire and Natural Hazards CRC

Version	Release history	Date
1.0	Initial release of document	10/12/2020

Australian Government
Department of Industry, Science, Energy and Resources

Business
Cooperative Research
Centres Program

Disclaimer:
Monash University and the Bushfire and Natural Hazards CRC advise that the information contained in this publication comprises general statements based on scientific research. The reader is advised and needs to be aware that such information may be incomplete or unable to be used in any specific situation. No reliance or actions must therefore be made on that information without seeking prior expert professional, scientific and technical advice. To the extent permitted by law, Monash University and the Bushfire and Natural Hazards CRC (including its employees and consultants) exclude all liability to any person for any consequences, including but not limited to all losses, damages, costs, expenses and any other compensation, arising directly or indirectly from using this publication (in part or in whole) and any information or material contained in it.

TABLE OF CONTENTS

ACKNOWLEDGMENTS

EXECUTIVE SUMMARY

Floods are among the most damaging natural disasters in Australia. Over the last 40 years, the average annual cost of floods was estimated to be $377 million per year. The 2010-2011 floods in Brisbane and South-East Queensland alone resulted in 35 confirmed deaths and $2.38 billion damage. The floods in June 2016 in Queensland, New South Wales, and Tasmania, resulted in five confirmed casualties. The Insurance Council of Australia stated on June 7, 2016 that about 14,500 claims totalling $56 million have been lodged from across the country. The floods in March-April 2017 in Queensland and New South Wales caused five confirmed casualties. Furthermore, according to the Insurance Council of Australia, 823,560 Queensland homes are still unprepared for flooding (March 11, 2018). The floods in North Queensland in January-February 2019 resulted in four confirmed fatalities and an estimated total direct cost of 1.3 billion dollars. In order to limit the personal and economic damage caused by floods, operational water and emergency managers rely on flood forecasting systems.

These systems consist of a hydrologic and a hydraulic model to predict the extent and level of floods. Using observed and predicted rainfall, the hydrologic model calculates the amount of water that is flowing through the river network, while the hydraulic model computes water depth and velocity in the river and in the floodplain. In recent decades, the accuracy and reliability of these flood forecasting systems has significantly improved. However, it remains difficult to provide accurate and precise flood warnings. This is a result of errors and/or uncertainties in model structures, model parameters, input data, and/or meteorological forcing (mainly rainfall). The hypothesis of this project is that remote sensing data can be used to improve modelled flood forecast skill and value.

More specifically, this project developed optimal ways to constrain and update the hydrologic model using remotely sensed soil moisture data. The significance of soil moisture is its direct impact on the partitioning of rainfall into surface runoff and infiltration. Second, this project proposed an algorithm for the monitoring of floods under vegetation. Finally, we investigated optimal ways to use remote sensing-derived inundation extent and level to implement and calibrate the hydraulic model. The results of this project enable improved predictions of flow depth, extent and velocity in the floodplain.

END-USER PROJECT IMPACT STATEMENT

Norman Mueller, *Geoscience Australia, Canberra, ACT.*

Digital Earth Australia (DEA) is working with Monash University to implement its flood mapping system in the Open Data Cube code. The intention is to use Monash's code to map water from Sentinel-1 SAR data and incorporate the water extents into DEA's Water Observations from Space (WOfS) product. Success of this work will allow the WOfS product to continue mapping water during cloudy periods, filling a large gap in the supply of water information to several agencies in Australia including the Murray Darling Basin Authority and the Commonwealth Environmental Water Office.

Karen Hudson, Chris Leahy, *Bureau of Meteorology, Melbourne, VIC.*

The Bureau of Meteorology has taken a keen interest in the work of the Monash University team regarding the Bushfire Natural Hazards CRC project "Improving flood forecast skill using remote sensing data". The project has clearly demonstrated the potential for remote sensing data to assist in real-time flood forecasting applications, as well as highlighting some of the challenges. Over the past few years, the Bureau of Meteorology has made opportunistic use of available satellite-derived flood extent data during flood events, for example use of MODIS imagery to help communicate flood extent in tweets and to track flood progression in remote areas with little ground data.

INTRODUCTION

Flood forecasting systems are useful tools that are used by operational water and emergency managers to reduce the impact of floods. Even though these systems have improved during recent decades, further research is needed to improve forecasting precision and accuracy.

The hypothesis of this project is that remote sensing is a helpful tool for operational flood forecasting. Consequently, remote sensing data are being utilised in two different ways. First, simulated soil moisture profiles from hydrologic models are improved through the optimal merging of simulated soil moisture states with remotely sensed surface soil moisture levels. This is expected to have a beneficial impact on modelled hydrographs. Second, estimated flood inundations and water levels from hydraulic models are improved through merging these model results with remote sensing-derived observations of flood inundations or water levels. This will improve the predictive capability of the hydraulic model. Overall, using remote sensing data in flood forecasting will lead to better early warning systems, management of floods, and post-processing of flood damages (for example for insurance companies).

In this project, the best methods to merge remote sensing data and hydrologic and hydraulic models have been investigated. After selecting the models, model-data fusion techniques were implemented and tested using a data base that has been developed as part of this project. A list of recommendations on how to best use remote sensing data for operational flood forecasting has been developed.

BACKGROUND

INTRODUCTION

The project investigated the following science questions:

1. How can satellite remote sensing data be best used to improve flood forecasting systems? How frequently are satellite acquisitions needed and how does this vary; do we need remote sensing data during the flood, or can remote sensing data acquired before the flood already provide sufficient information?

2. To what extent can we reduce the uncertainty in the flood predictions?

TEST SITE SELECTION

A first step in the project was the identification of two test sites, and the acquisition of required data to meet the project objectives. Criteria used in the catchment selection included:

- Representation of the diversity of Australian hydrologic regimes;

- The occurrence of floods in the recent past;

- The significance of the flood impact on communities;

- The availability of data to apply both hydrologic and hydraulic models;

- The availability of high resolution and accurate digital elevation data for one test site. This test site can be used as benchmark to assess the impact on flood forecasts of medium to low accuracy and resolution topographic data available at the continental scale.

MODEL SELECTION

A second step was the selection of the hydrologic and hydraulic models to be used in the study. Criteria were:

- Availability of the source code;

- Modularity of the model;

- Data requirements;

- Feasibility to incorporate remote sensing data;

- Ease to make operational;

- Documented model performance.

UNCERTAINTY ESTIMATION

A significantly important issue is the estimation of the uncertainty of the flood forecasts, which is the third part of the project. Rainfall forecasts are used in an ensemble mode, meaning that not one single value is used for a specific time and location, but a number of values. The spread in these ensemble members is

a measure of the uncertainty in the predictions. The calibrated hydrologic model is applied to each member of the rainfall ensemble, leading to an ensemble of hydrologic model discharge values. This will then be used by the hydraulic model, resulting in an ensemble of river water levels and flood extents. Similar as for the rainfall, the spread in the ensemble will be a measure of the uncertainty in the modelled water levels and flood extends.

MODEL-DATA FUSION

Uncertainty in the hydrologic model results is reduced through the merging with remotely sensed soil water content data and in-situ streamflow observations. More specifically, at each time step where an observation is available, a weighted average between the hydrologically modelled state variables and the observations is made. The weight of the model results and the observations is dependent on their level of uncertainty. Additionally, the errors in the modelled inundation extent, level, and velocity have been reduced by using remote sensing-derived flood extent and level to implement and calibrate the hydraulic model.

REMOTE SENSING

This project uses active microwave imagery from Synthetic Aperture Radar (SAR). The 24-hour all-weather capability of SAR technology makes it a perfect choice for routine flood inundation mapping to support flood management and response, for both gauged and ungauged catchments. An algorithm for the inversion of SAR imagery into maps of inundation extent has been proposed by this project.

METHOD OPTIMIZATION

The overall objective of the project was to aid operational flood forecasts through the use of remote sensing data. The analysis completed within this project led to the delivery of guidelines for the selection of remote sensing observations and their optimal use to implement and constrain hydrologic and hydraulic models.

RESEARCH APPROACH

HYDROLOGIC MODEL

Data collected for this sub-project include gauged rainfall, gauged streamflow, potential evapotranspiration (PET), SMOS RS-SM, and RS fractional vegetation cover (fc) for January 2010–June 2014. The rainfall data were obtained from the Australian Bureau of Meteorology. Streamflow data were obtained from the New South Wales Office of Water and Queensland Department Natural Resources and Mining. PET was extracted from the Australian Water Availability Project (AWAP) monthly PET product. SMOS data were obtained from the "Centre Aval de Traitement des Données SMOS" (CATDS), operated for the "Centre National d'Etudes Spatiales" (CNES, France) by IFREMER (Brest, France). MODIS vegetation cover data were obtained from National Computational Infrastructure (NCI).

The Short-term Water Information Forecast Tool (SWIFT) has consisted of numerous versions and since its inception has undergone major overhauls which include changes to the programming language. SWIFT can be considered a pre-release version and was developed using Fortran primarily for research purposes. A subsequent release, SWIFT2, was developed using C++ for ease of operations and integration into the BoM Hydrological Forecasting System (HyFS). SWIFT2 is commonly referred to as SWIFT. For this report the distinction between SWIFT and SWIFT2 will be kept.

Initial testing of hydrological models and development of data assimilation routines was conducted using SWIFT. The conceptual hydrologic models GRHUM and GRKAL were built into SWIFT. Eventually GRKAL was selected to be used to test Remote Sensing Soil Moisture (RS-SM) assimilation routines due to its advantage in propagating surface SM information into the root-zone. A schematic diagram of GRKAL was provided in the 2017 annual report. GRKAL has now been implemented into SWIFT2 and is available for operational and research purposes.

As part of the literature review (Li et al., 2016) conducted for this sub-project, methods to account for bias between SM observations and simulations were identified as critical components of further research to incorporate RS SM into flood forecasting models. Typically hydrologic modellers attribute all bias to the RS SM observation by matching the cumulative distribution function (CDF) of the RS SM observation to the CDF of the simulated soil moisture. Conversely, calibrating the parameters of the hydrologic model to simulate SM which represents the observed RS SM attributes all bias towards the model. Unfortunately, when RS SM observations are assimilated into the hydrologic model, neither method to account for biases has been able to consistently yield improved flood forecasting skill. The prevailing hypothesis is that the accuracy of rainfall forcing data hampers the consistent successful implementation of a RS SM data assimilation routine.

The quality control (QC) of rainfall data was shown to vastly improve streamflow simulation skill (Liu et al., 2018). However, there were rare occasions in which QC of rainfall data led to degraded streamflow simulations, suggesting that the process of gauge selection can be optimised.

To address the uncertainty in rainfall data being used to force the hydrological model a methodology (Wright et al., In preparation) to optimise the rainfall gauge weighting for streamflow simulation skill has been developed. Typically areal rainfall estimates are developed using the spatial distribution of gauges to an area. This methodology weights the rainfall gauges by determining the weightings which improve streamflow simulation skill the most. It is hypothesised that such a weighting of rainfall gauges is more likely to enable the hydrological model to simulate SM consistent with the RS SM. If this can be demonstrated then such a configuration is more likely to benefit from the assimilation of RS SM observations.

The ability to improve flood forecast skill by assimilating RS SM observations into GRKAL using models forced by traditional areal rainfall estimates and those retrieved from the optimization of gauge weights (OGW) methodology were compared. A fixed-lag joint ensemble Kalman smoother (EnKS) which simultaneously assimilates remotely sensed soil moisture observations and streamflow was developed and used. The joint EnKS provides improvements over the EnKS and ensemble Kalman filter (EnKF) by assimilation two observations types over a fixed window respectively. Translation of the code and testing are required to incorporate the joint EnKS into SWIFT 2.

Using the EnKF and the EnKS to assimilate RS SM observations and or streamflow into the GRKAL model a set of real data experiments were conducted to assess the impact each configuration had on forecasting skill. The experiments were conducted in the Condamine catchment upstream of Warwick. To assess the impact on forecasting skill known rainfall observations were used. Consequently results demonstrate hindcasting skill which are indicative of forecast skill when good rainfall forecasts are made. Figure 1 demonstrates that, prior to data assimilation occurring, optimising the rain gauge weighting can improve the ability of the hydrological model to forecast streamflow. Further benefits are observed when RS SM observations and streamflow observations are used in the data assimilation routines.
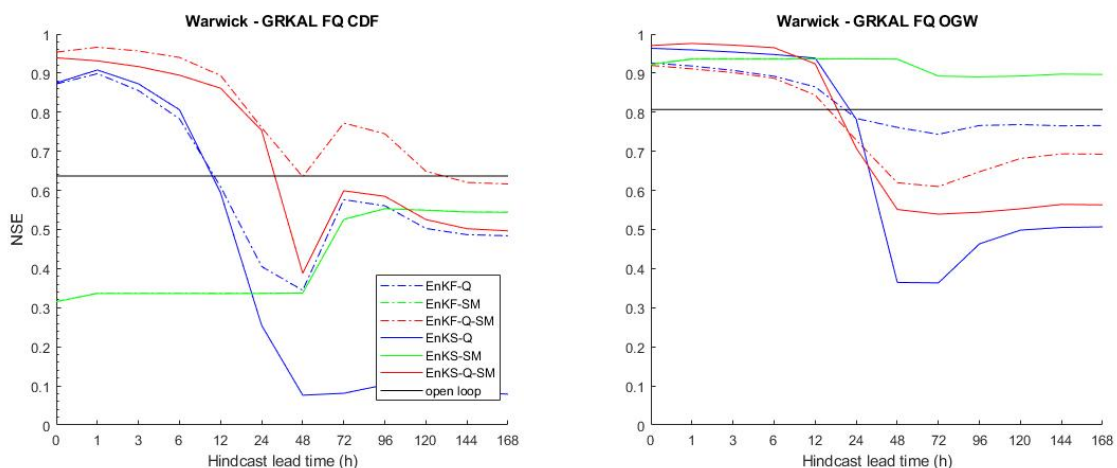

FIGURE 1: HINDCASTING PERFORMANCE USING TRADITIONAL (LEFT PANEL) AND OPTIMISED (RIGHT PANEL) AREAL RAINFALL ESTIMATES.

It should be noted that these results have been observed for the Warwick catchment and, due to rain gauge availability and quality, may not be broadly applicable. This could be a topic of further research.

REMOTE SENSING-DERIVED INUNDATION EXTENT AND LEVEL

Methods for the retrieval of inundation extent and level from satellite imagery are being developed. In particular, this project aims at improving flood detection and monitoring capabilities at the continental scale using active microwave imagery from synthetic aperture radar (SAR). The 24-hour all-weather capability of SAR technology makes it a perfect choice for routine flood inundation mapping to support flood management and response. SARs are active systems that emit microwave pulses at an oblique angle towards the target. The amount of microwave energy scattered off an object is primarily a function of its surface texture. Open water has a relatively smooth surface which causes radar radiation to be reflected away from the sensor, resulting in low backscatter. Rough terrestrial land surfaces, by contrast, reflect the energy in many directions, including back towards the sensor, and therefore appear as high backscatter zones. These differences allow flood extent to be mapped using a variety of techniques. A review is reported in Grimaldi et al. (2016).

However, a number of event-related and catchment-related factors can alter the backscatter characteristics and hinder accurate SAR image interpretations, particularly when the inundated areas have vegetation above the water. In these areas, the electromagnetic interaction phenomena between microwaves, horizontal and vertical surfaces are highly complex and detection of flooded vegetation has been identified as one of the biggest challenges for accurate flood mapping. Nevertheless, this is a frequent condition in many Australian dryland catchments where vegetation is common in the riparian zone. Existing image interpretation algorithms make use of detailed field data and reference image(s) to implement electromagnetic models or change detection techniques. However, field data are rare, and, despite the increasing availability of SAR acquisitions, adequate reference image or time series of reference images might not be readily available, especially for fine resolution images. To contribute to the current state-of-the-art, this project has developed an algorithm for automatic flood mapping in vegetated areas which makes use of single SAR acquisitions and commonly available ancillary data (i.e. land cover, land use, and digital elevation models).

The backscatter response of dry and flooded vegetation has been investigated using eleven SAR images (five COSMOSkyMed images and six Alos Palsar images) acquired over the Condamine-Balonne catchment and over the Clarence catchment during the flood events in January 2011. The analysis of backscatter response from vegetation has focused on the land cover classes defined by the National Dynamic Land Cover Dataset of Australia (Lymburner et al., 2011). This investigation has led to the definition of a method to distinguish between dry and flooded vegetation.

The proposed algorithm is described in detail in Grimaldi et al. (2020). The following paragraph presents a summary of the main concepts and results; the full demonstration, the flow chart showing the computational steps, and instructions to collect the ancillary data can be found in the above mentioned publication. Probability binning is used for the statistical analysis of the backscatter response of wet and dry vegetation for different land cover types. This analysis is then complemented with information on land use, morphology and context within a fuzzy logic approach. In a proof of concept study, the

algorithm was tested on three fine resolution images acquired during the January 2011 flood in the Condamine-Balonne catchment. Specifically, the analysed images were acquired by the L-band instrument on board ALOS-PALSAR and by the X-band instruments on board the COSMOSkyMed constellation. Albeit all the images had HH polarization, the use of SAR data retrieved using different wavelengths allowed for a preliminary test of the reliability of the proposed algorithm for the analysis of SAR images which have different characteristics. The SAR-derived flood extent layers were validated using inundation maps derived from high resolution (2 to 6 m pixel size) optical images. The optical-derived layers were provided by Geoscience Australia and the Queensland Department of Natural Resources and Mines, each optical-derived layer had undergone a quality control process by the providers: manual editing and use of historical information increased the information content of these layers, especially in areas with emerging vegetation. In these case studies, state-of-the-art operational interpretation algorithms focusing solely on open water areas led to large omission errors with the Producer's Accuracy (PA) for the class water as low as 10.1%, 33.3% and 16.5% and the Overall Accuracy (OA) of 77%, 65%, and 75%, respectively. The use of probability binning allowed the omission errors to be reduced and the PA for the class water to have an increase of +75.2%, +62.2%, and +115.1%, respectively. Finally, incorporation of land use, context, and morphological information allowed further refinement of the classification thus achieving a final OA of 83.7%, 81.5%, and 85.7%, respectively.

Notwithstanding the encouraging results of the proof of concept study, extensive testing is strictly required to investigate the trade-off between the characteristics of SAR data acquisitions (i.e. polarization, wavelength, and resolution), vegetation cover properties, and the accuracy of the methodology. By using both X and L-band acquisitions, the proof of concept study achieved a first analysis of the accuracy of the methodology for short and long wavelengths at HH polarization. To further analyse the reliability of the proposed methodology, the following phase of the project applied the algorithm to intermediate wavelengths and different polarizations. More specifically, the dual polarization (VV and VH) acquisitions made available free of charge by the 20 m spatial resolution C-band Sentinel-1 constellation (launched in 2016 by the European Space Agency) were selected for further testing. For this purpose, the algorithm was applied for the analysis of Sentinel-1 images acquired during the 2016-2017 floods in the Fitzroy catchment (WA).

VV and VH polarizations were analysed independently. The accuracy of the algorithm was evaluated by comparing the SAR-derived water layers with binary wet/dry maps retrieved from optical satellite images. More specifically, binary wet/dry maps were derived from Landsat and Sentinel-2 images (25 m pixel size) by Geoscience Australia. MODIS images (500 m pixel size) were used to complement this dataset and the Tasselled Cap Wetness Index was chosen for the computation of the MODIS-derived wet/dry maps. Figures 2 shows the SAR data, the wet/dry maps derived from the optical data, and the results of the analysis of the SAR data. It must be noted that these optical-derived flood extent layers were not subject to quality control or post-processing. Consequently, uncertainties and errors are likely to affect these optical-derived layers; an example of this issue can be seen in Figure 2B where scattered wet pixels are located at a considerable distance from the river network (this issue is highlighted

by the white ovals). Moreover, it must be remembered that detection of water under vegetation canopies using optical sensors is extremely difficult, especially when using medium (25 m pixel size) or low (500 m pixel size) spacial resolution. In Figure 2, yellow scribbles were used to facilitate the visual comparison between optical-derived (Figures 2B, 2E) and SAR-derived (Figures 2C, 2F) flood extent layers. A semi-quantitave analysis of the accuracy of the SAR-derived flood extent layers was then completed by focusing on the areas enclosed by the yellow scribbles. The results are explained in the next paragraph.

The semi-quantitave analysis of the accuracy of the SAR-derived flood extent layers was based on the computation of User's accuracy, Producer's accuracy for the classes dry and flooded, Overall accuracy and Cohen's kappa were computed for each SAR-derived water layer. Nevertheless, it must be noted that this analysis is affected by the above explained lack of accuracy of the optical-derived layers; consequently, the numerical results must be considered as indicative of the algorithm's performances rather than absolute quantitative evalutions. As an example, Table 1 lists the values of the performance metrics computed to assess the quality of the flood extent layer derived from the Sentinel 1A, VV polarization acquisition of February 23rd, 2017. An accurate detection of the dry and wet pixles would lead to performance values close to 1. It is here noted that the Producer's accuracy (PA) of the class water (listed in bold blue font) sensibly increases when adding the analysis of the flooded vegetation (i.e. when considering both FM1-OW and FM1-FV); a further increase of the performance metrics is then observed when adding the analysis of the empirical cumulative distribution function of the HAND (Height Above Nearest Drainage) index and DIST (distance) index to compute FM2.

A sensitivity analysis of the impact of the algorithm's parameters, inputs, and ancillary data on the accuracy of the results was performed; the results of the analysis are summarised below:

- The algorithm led to larger false alarms when applied to VH polarization data than to VV polarization data.
- The optimal trade-off between false alarms and omission errors for different footprints is achieved using slightly different definitions of the reference sample of dry vegetation. Use of both HAND index and information from Water Observations from Space (Mueller et al., 2016) allows the application of probability binning to a larger number of land cover classes than the use of the HAND index alone. Nevertheless, use of the first strategy can also increase the false alarms compared to the latter.
- The computation of the empirical cumulative distribution of the values of the HAND index for potentially wet areas could remove a slightly larger number of false alarms when compared to the use of a fixed HAND threshold value.
- For this catchment, use of the empirical cumulative distribution of the values of the DIST index did not improve the accuracy of the analysis; consequently, computation of the fuzzy membership function based on the DIST index is recommended only in areas with fields subject to flood irrigation.
- The analysis of adjacent footprints (same orbit number) allows using larger samples for the analysis of the backscatter response of each land cover and leads to more accurate analysis.
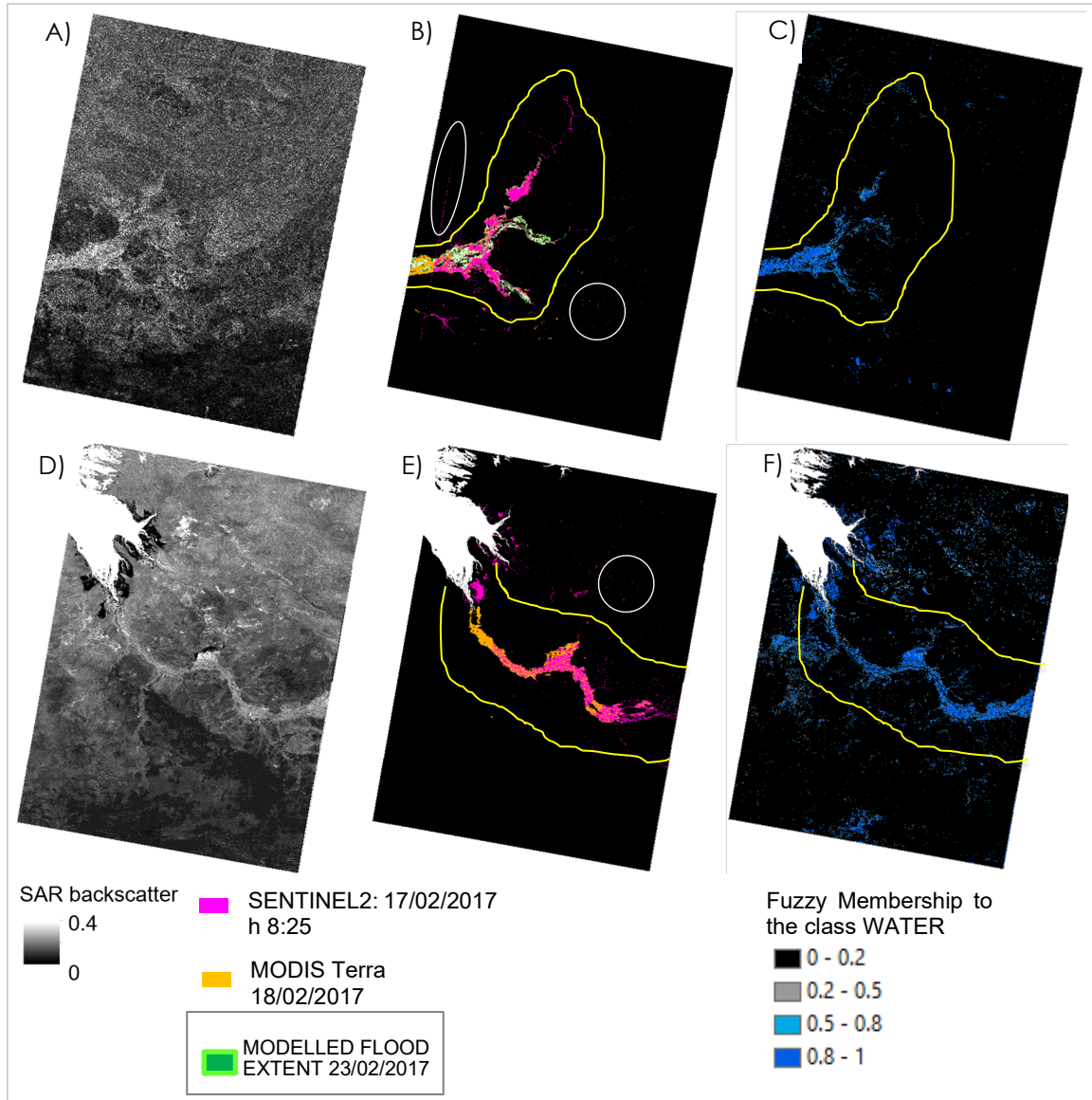
FIGURE 2 - (A) SAR BACKSCATTER ON FEBRUARY 23RD 2017, VV POLARIZATION; (B) WET/DRY FLOOD EXTENT REFERENCE LAYERS DERIVED FROM SENTINEL2 AND MODIS OPTICAL DATA; (C) FUZZY MEMBERSHIP TO THE CLASS WATER COMPUTED USING THE PROPOSED ALGORITHM. (D), (E) (F) SAME AS (A), (B), (C) BUT FOR THE SAR ACQUISTION ON FEBRUARY 28TH 2017. THE MODELLED FLOOD EXTENT IN FIGURE (B) WAS COMPUTED USING THE HYDRAULI MODEL (SECTION *HYDRAULIC MODE*), DARK GREEN INDICATES AREAS WITH MODELLED WATER DEPTH HIGHER THAN 10 cm, LIGHT GREEN INDICATES AREAS WITH MODELLED WATER DEPTH LOWER THAN 10 cm.

Optical image	Temporal lag between SAR and OPTICAL acquisitions (days)	% SAR footprint that could be evaluated	UA water	UA dry	PA water	PA dry	OA	Cohen's kappa
					FM1-OW			
SENTINE2 L 17/02/2017	6.5	24.1	0.874	0.963	0.007	1.000	0.963	0.012
MODIS Terra 17/02/2017	6.5	29.9	0.126	0.967	0.003	0.999	0.967	0.004
MODIS Terra 18/02/2017	5.5	14.5	0.358	0.892	0.002	1.000	0.892	0.003
MODIS Terra 23/02/2017	0.5	14.5	0.053	0.996	0.008	0.999	0.995	0.013

LANDSAT 22/02/2017	1.8	9.8	0.387	0.983	**0.011**	1.000	0.983	**0.021**
			FM1-OW and FM1-FV					
SENTINE2 L 17/02/2017	6.5	24.1	0.451	0.976	**0.363**	0.983	0.960	**0.382**
MODIS Terra 17/02/2017	6.5	29.9	0.449	0.982	**0.474**	0.980	0.964	**0.442**
MODIS Terra 18/02/2017	5.5	14.5	0.690	0.940	**0.483**	0.974	0.921	**0.526**
MODIS Terra 23/02/2017	0.5	14.5	0.031	0.998	**0.517**	0.927	0.925	**0.050**
LANDSAT 22/02/2017	1.8	9.8	0.170	0.992	**0.552**	0.953	0.946	**0.239**
			FM2 (HAND and DIST, ecdf)					
SENTINE2 L 17/02/2017	6.5	24.1	0.479	0.953	**0.373**	0.969	0.926	**0.381**
MODIS Terra 17/02/2017	6.5	29.9	0.479	0.967	**0.476**	0.968	0.939	**0.445**
MODIS Terra 18/02/2017	5.5	14.5	0.715	0.908	**0.487**	0.963	0.887	**0.516**
MODIS Terra 23/02/2017	0.5	14.5	0.032	0.996	**0.517**	0.894	0.891	**0.048**
LANDSAT 22/02/2017	1.8	9.8	0.177	0.988	**0.553**	0.933	0.923	**0.239**

TABLE 1: EVALUATION OF THE ACCURACY OF THE WATER LAYER DERIVED FROM SENTINEL1A, VV POLARIZATION, FEBRUARY 23RD, 2017. FM1-OW IS THE FUZZY MEMBERSHIP TO THE CLASS OPEN WATER; FM1-FV IS THE FUZZY MEMBERSHIP TO THE FLOODED VEGETATION; FM2 REFINES THE COMPUTATION OF FM1-OW AND FM1-FV BY ADDING THE ANALYSIS OF THE EMPIRICAL CUMULATIVE DISTRIBUTION FUNCTION (ecdf) OF THE DIST AND HAND INDICES.

The possibility to improve the accuracy of the proposed algorithm by adding further analysis and ancillary datasets was also investigated. More specifically, similarly to open water areas, dry bare areas result in low backscatter response and can then cause false alarms. Information from regolith data (Geoscience Australia, http://pid.geoscience.gov.au/dataset/ga/75626) and fractional cover (Geoscience Australia, https://www.ga.gov.au/dea/products/fc) were used to identify bare areas. This information was complemented with information of soil moisture at the time of acquisition of the SAR data. For this purpose, both modelled and remote sensing-derived datasets were tested. More specifically, the modelled soil moisture was retrieved from the AWRA (Australian Bureau of Meteorology, www.bom.gov.au/water/landscape/); remote sensing-derived soil moisture was retrieved from SMAP (SMAP Enhanced L3 Radiometer Global Daily 9 km EASE-Grid Soil Moisture, Version 3, NASA) and SMAP-Sentinel1 (SMAP/Sentinel-1 L2 Radiometer/Radar 1 km Soil Moisture, NASA, ESA). Information of surface cover, soil moisture, and backscatter analysis were combined to remove false alarms. Figure 3 shows an example of the detection of false alarms using either AWRA, or SMAP, orSMAP/Sentinel-1 ancillary dataset leading to similar results. Specifically, the false alarms identified by each one of the above listed ancillary dataset are highlighted by red pixels in the panels 3B, 3D, 3F.

Albeit further extensive testing is required, the analyses indicated that the proposed algorithm can positively contribute to the problem of automatically detecting flooded vegetation using readily available ancillary data.

In order to enable the testing of the proposed methodology, the numerical algorithm has been made available via GitHub under Apache 2.0 license at https://github.com/GeoscienceAustralia/dea-sar-flood-veg. The GitHub is the outcome of the collaboration with Geoscience Australia and it will be primarily used by Geoscience Australia to verify the reliability of the algorithm for the analysis of Sentinel-1 images acquired over many Australian catchments.
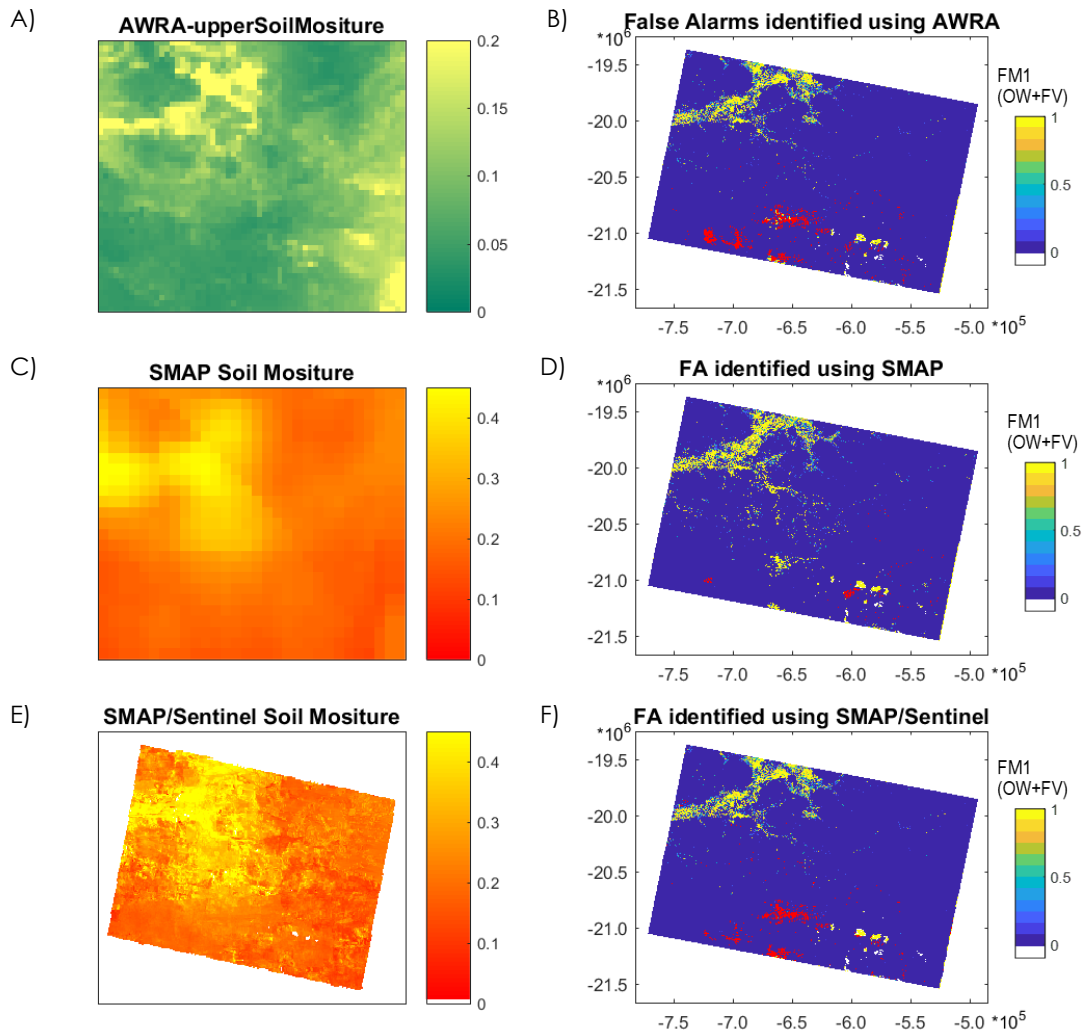
FIGURE 3 - JANUARY 18TH 2017 - (A) WETNESS FROM AWRA MODEL); (C) SOIL MOISTURE DERIVED FROM SMAP DATA; (E) SOIL MOISTURE DERIVED FROM SMAP/SENTINEL1 DATA. (B), (D), (F) FUZZY MEMBERSHIP TO THE CLASS WATER: FM1 IS UNION OF OPEN WATER AREAS (OW) AND FLOODED VEGETATION (FV); THE RED PIXELS INDICATE THE FALSE ALARMS HIGHLIGHTED USING AWRA MODELLED DATA, SMAP OBSERVATIONS, SMAP/SENTINEL1 OBSERVATIONS, RESPECTIVELY.

HYDRAULIC MODEL

The hydraulic model is based on LISFLOOD-FP (Bates et al., 2010) and it uses the finite difference method to solve the inertial approximation of the shallow water equations. The implementation of the hydraulic model requires a Digital Elevation Model (DEM) and information on river bathymetry. The quality of these datasets is pivotal for accurate forecasts of flood wave routing and floodplain inundation.

Calibration of a model's parameters is essential to enable adequate representation of flood dynamics both at the local and reach scales. This objective is achieved by comparing model results and observations of historical flood events. Gauged water level or discharge data at discrete locations along the river and remote sensing-derived (RS-D) observations of inundation extent and level can be used for this purpose. Gauged data are continuous time series representing the lumped response of the catchment to a precipitation event. Remote sensing instruments provide spatially distributed observations of inundation extent and water level and enable model evaluation at large number of locations. Nevertheless, these data are acquired at the time of the

satellites overpass. Despite acquisition frequency is likely to increase, just a few (or one) observations might be available for a specific event, meaning that evaluation of floodplain temporal dynamics could be difficult and affected by the acquisition time.

To add to the existing knowledge, this project investigated optimal ways to use RS data to improve the implementation and the calibration of hydraulic flood forecasting models. The following paragraphs present the results for each test case.

Clarence catchment (NSW)

The hydraulic model computes flood wave routing in the river and, when the river flow capacity is exceeded, in the floodplain. Bathymetric data are critical for the assessment of river flow capacity and, hence, for the accurate prediction of floodplain inundation dynamics. However, it is impractical to measure river bathymetry along the total river length in large basins, especially considering that river geometry can change over time. Consequently, a data-parsimonious methodology for the definition of a river bathymetry representation which is effective for the implementation of medium to high resolution flood forecasting hydraulic models was derived using the Clarence catchment as study site. This study was developed using measured bathymetry data sampled during a field campaign in November 2015. According to the proposed methodology, simplified, yet effective cross section geometries can be defined based on a combination of limited field data (with a minimum of three sampling), global database, and remote sensing-derived observations of river width. The details of the methodology are explained in Grimaldi et al. (2018).

The hydraulic model was then applied to simulate the flood events in 2011 and 2013. . The input data were the measured discharge time series at Lilydale; the downstream boundary conditions were the measured tidal levels at Yamba. It was demonstrated that small uncertainties in the prediction of water level at Grafton (i.e. at one gauge station) could result in large errors in the prediction of the inundated area (Pauwels et al., 2019). These errors were not highlighted by the comparison between modelled and gauged water levels but could be detected by the synoptic view offered by RS-derived data. Spatially distributed RS-derived flood extent hence provided more robust strategies for the detection of model errors and constraint of model parameters than gauged dataset. However, gauged time series of water level data allow immediate evaluation of the predicted flood wave arrival time. Conversely, RS instruments provide information at a snapshot in time and so the existing performance metrics generally compare model results and observations at the acquisition time. Nevertheless, explicitly differentiating between model parameterizations which under predict or over predict the flood wave arrival time is valuable to assess models' predictive skill. To add to the existing state-of-the-art this project introduced a novel RS-based framework for the calibration of 2D hydraulic models.

More specifically, the calibration framework was designed to (1) make exclusive use of RS-derived observations and consequently enable model calibration in ungauged catchments; (2) allow discriminating between under prediction and over prediction of floodplain propagation speed; (3) require a limited number of model realizations. The latter requirement addressed the major pragmatic

challenge affecting the calibration of 2D-hydraulic models being the computational burden of each model realization. The large demand of time generally hampers the application of frameworks requiring a large number of model realizations, to by-pass this problem this project aimed at a rapid, yet effective calibration strategy.

A novel performance metric, the space-time score, was proposed to compare modelled and observed waterline (wet/dry interface) and discriminate between underestimation and overestimation of floodplain propagation speed. Binary performance metrics were used to compare modelled and observed inundation extents, model realizations were ranked according to increasing values of the CSI (Critical Success Index), FA (False Alarms), $(1 - HR)$ (Hit Rate), $|1 - Bias|$. The space-time-score and the binary performance metrics allowed quantifying the capability of different parameter sets to reproduce the observed data. A novel set of river roughness values is then computed to minimise the discrepancy between model results and observations. The iterative calibration methodology can be summarised as follows:

1) Initial set of model realizations with uniform river roughness values;
2) Computation of the performance metrics: 2a) space-time score and binary performance metrics;
3) Computation of novel set of river roughness values.

Steps 2 and 3 are repeated until there is no significant change in the computed river roughness values.

The 2011 and the 2013 flood events in the Clarence catchment (New South Wales) were used as test cases. Available remote sensing data included both Synthetic Aperture Radar and optical acquisitions. Gauged data were used as an independent validation dataset to verify the accuracy of the remote sensing derived calibration. Specifically, two SAR images were used to identify the spatially distributed parameter set. Figure 4 shows the results of the calibration when using two SAR (CosmoSkyMed images). These images were acquired over Grafton and immediately after the flood peak. Panel 4A allows the direct comparison between modelled and observed flood extent: the modelled wet/dry edges are in agreement with the RS-derived wet/dry boundary points. The modelled water depth showed in panel 4A highlights the added value of using hydraulic models for floodplain management. The panels 4B,C,D,E allow the validation of the RS-derived calibration: modelled water level time series predicted by the calibrated model (thick dashed black lines) are compared with gauged data (continuous black line); the results of the initial sample of model realizations are also shown (coloured lines) to allow a deeper understanding of the benefits of the RS-derived calibration.

The calibration was completed using two SAR (CosmoSkyMed) images acquired over Grafton and immediately after the flood peak. The investigation of the importance of RS acquisition footpring and timing was then achived through the analysis of a number of scenarios. These scenario made use of RS acquisition in different areas of the catchment and at different stages of the flood event and it allowed to demonstratethe importance of the footprint of RS acquisitions. RS acquisitions over Grafton during were essential to enable adequate flood inundation modelling in the Clarence catchment. Grafton is protected by a long levee system and the accurate modelling of the floodplain inundation volume in this area is crucial to avoid large errors in the prediction of flood wave routing in the downstream area. Both the 2011 and the 2013 floods

were valley filling events and model calibration was not possible when using acquisitions during the decreasing limb and over the downstream area.

The proposed framework was designed to minimise the discrepancies between model results and RS observations. Consequently, RS accuracy, timing and spatial coverage affected the performance of the calibration. The analyses developed within this project allowed the delivery of guidelines for the selection of RS observations, nevertheless, extensive further testing is essential to investigate the impacts of RS features on the effectiveness of the proposed methodology for a number of catchments with different morphologies and flooding dynamics.
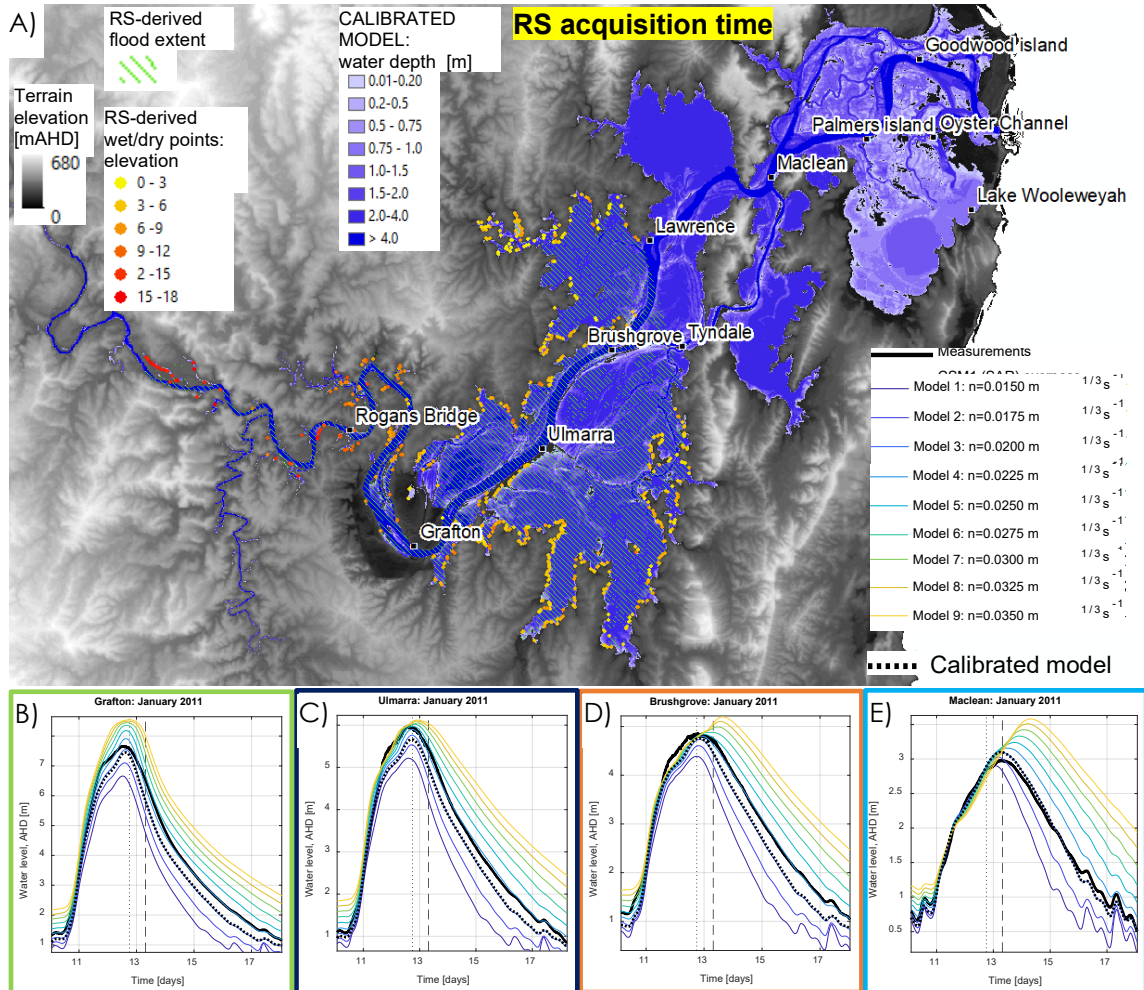
FIGURE 4 - (A) THE MODELLED WATER DEPTH COMPUTED USING THE CALIBRATED MODEL IS COMPARED WITH RS-DERIVED FLOOD EXTENT AND WET/DRY BOUNDARY POINTS; (B),(C),(D),(E) MODELLED AND GAUGED WATER LEVELS; MODELLED WATER LEVEL USING THE INITIAL PARAMETERS SETS (I.E. MODELS 1 TO 9) AND THE CALIBRATED PARAMETER SET (BLACK, DOTTED LINE). THE VERTICAL LINES INDICATE THE OVERPASS TIME OF THE RS ACQUISITION.

Condamine-Balonne catchment (NSW)

High resolution (10^{-1} to 10^{0} m), high accuracy (10^{-1} m) DEMs are derived from LiDAR data, however these datasets have limited spatial coverage and are rarely available. DEMs available at the continental scale were derived from satellite missions. Satellite-derived DEMs have medium resolution (10^{1} to 10^{2} m) and are affected by uncertainties and errors. This project completed an analysis of the accuracy of two satellite-derived DEMs for the representation of river flow capacity and floodplain morphology in the Condamine-Balonne catchment. These DEMs were the TanDEM-X-derived DEM and the SRTM-derived DEM-H. Bathymetric data and transects were sampled during a field campaign in May

2016. These field data, LiDAR data, and ground control points were used as benchmark. The analysis showed that riparian vegetation can cause large uncertainties and errors in both the DEM-H and TanDEM-X dataset; these errors often lead to the underestimation of the river flow capacity. The results were published in Wang et al. (2018). Moreover, a collaboration with CSIRO-Data61 (Clayton) led to the development of an automatic, fast algorithm for the interpolation of sparse bathymetric data (Hilton et al., 2019).

The set-up of the hydraulic model of the Condamine-Balonne catchment was the completed using the DEM-H. River bathymetry was assessed according to the studies completed within this project (Grimaldi et al., 2018; Hilton et al., 2019; Wang et al., 2018; unpublished report: Grimaldi et al., Bathymetric field campaign of the Balonne river in St. George QLD – data analysis and assessment of reservoir volume, prepared for SunWater Ltd, November 2016). The capability of the model set-up to adequately reproduce the flooding behaviour of the catchment was analysed using the 2011 flood event as case study. The input data were gauged discharge hydrographs at Cotswold (Condamine River), Gilweir (Dogwood Creek), Tabers (Bungil Creek), and Forestry station (Yuleba Creek), Cashmere (Maranoa River) (Figure 5). Normal flow conditions were imposed at the downstream boundary.
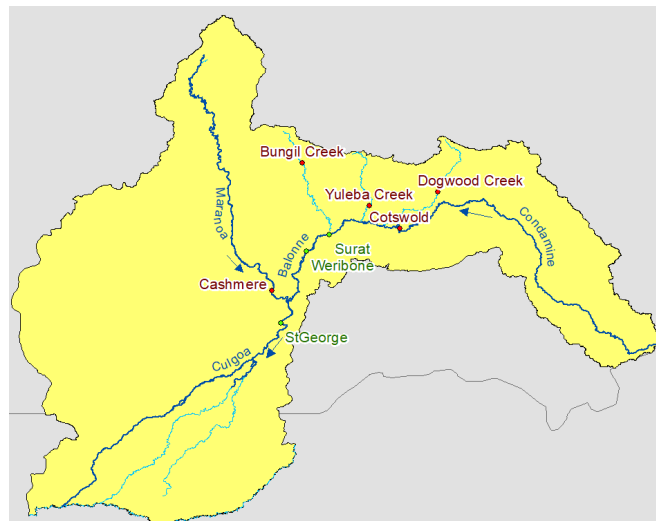
FIGURE 5 - CONDAMINE-BALONNE CATCHMENT: INPUT POINTS (RED); GAUGE STATIONS USED FOR MODEL EVALUATION (GREEN).

A sensitivity analysis of the impact of the main parameters on modelled inundation dynamics was completed for the purposes of evaluating the set-up of the hydraulic model. More specifically, four combinations of uniform values of river and floodplain roughness were used to complete the sensitivity analysis. Measured discharge time series at Surat, Weribone, and St.George (Figure 5) and inundation extent and level derived from nine satellite acquisitons were used as evaluation dataset. The list of the remote sensing acquisitions is provided in Table 2, SAR images are listed in bold. The SAR-derived flood extent layers were retrieved using the algorithm developed by this project (Grimaldi et al., 2020). Geoscience Australia provided the water extent layers derived from optical data. The comparison between modelled and observed flood extents focused on six Areas of Interest, AOI (Figure 6).

	Satellite	Acquisition date and time		Coverage	Comments
1	LANDSAT (optical)	30/12/2010	h 10	Upstream area	
2	**CosmoSkyMed (SAR)**	**4/01/2011**	**h 18**	**Surat**	

3	LANDSAT (optical)	6/01/2011	h 10	All the catchment	
4	**ALOS PALSAR (SAR)**	**7/01/2011**	**h 23**	**StGeorge**	
5	SPOT5 (optical)	8/01/2011	h 10	All the catchment	Clouds
6	**CosmoSkyMed (SAR)**	**8/01/2011**	**h 18**	**StGeorge**	
7	LANDSAT (optical)	14/01/2011	h 10	All the catchment	"Venetian blinds"
8	ASTER (optical)	14/01/2011	h 10	All the catchment	Clouds
9	LANDSAT (optical)	15/01/2011	h 10	Upstream area	

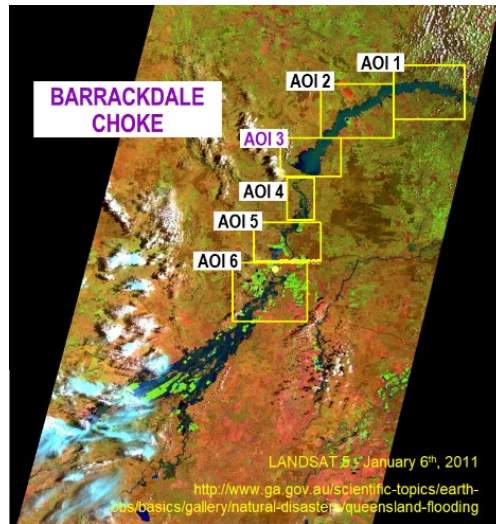TABLE 2: REMOTE SENSING DATA USED TO EVALUATE AND OPTIMISE THE SET-UP OF THE HYDRAULIC MODEL.

FIGURE 6 - DEFINITION OF THE AREAS OF INTEREST (AOI) FOR THE COMPARISON BETWEEN MODELLED AND OBSERVED FLOOD EXTENTS.

The Condamine River, the Balonne River up to the Barrackdale Choke, the Balonne River downstream of St.George, and the Culgoa River are anabranching rivers (i.e. multi-channel rivers composed of two or more interconnected channels that enclose floodplain areas). The Balonne River between the Barrackdale Choke and St.George is a unicursal river. It was found that adequate representation of river flow capacity allowed the accurate representation of flood extent and flood wave arrival time, nevertheless, the representation of river shape was of secondary importance. Two satellite-derived DEMs were tested for model implementation, more specifically, the DEM-H (Geoscience Australia, Gallant et al., 2011) and the Merit-Hydro (Yamazaki et al., 2019). It was found that the DEM-H had a more accurate representation of the anabranching river system thus enabling a more accurate representation of the flood wave arrival time.

The comparison between modelled and observed gauged data did not allow any conclusion on the performances of the model realizations. The comparison between modelled and observed inundation extents was achieve by computing binary performance metrics for the six AOIs. This comparison identified underestimation of the flooded area upstream of the Barrackdale Choke (AOI 3) and overestimation of the inundation extent in the downstream area (Table 3). These results were substantiated by comparing modelled and remote-sensing derived water level and led to hypothesise errors in the representation of terrain morphology and river bathymetry at the location of the Barrackdale Choke (AOI 3). These errors were identified and corrected using a RS-based workflow: a schematic of the main steps is shown in Figure 7.

	BIAS			
	MODEL 1	MODEL2	MODEL3	MODEL4
AOI 1	0.57	0.68	0.78	0.93
AOI 2	0.63	0.74	0.81	0.97
AOI 3	0.60	0.69	0.84	0.95
AOI 4	0.81	0.92	1.34	1.51
AOI 5	1.28	1.34	1.74	1.75
AOI 6	1.42	1.26	2.20	1.97

TABLE 3: COMPARISON BETWEEN MODELLED AND RS-DERIVED INUNDATION EXTENT ON JANUARY 6TH 2011(LANDSAT 5 DATA). BIAS VALUES COMPUTED FOR DIFFERENT MODEL REALIZATIONS AND FOR THE SIX AREAS OF INTEREST. BIAS<1 INDICATES UNDERESTIMATION OF THE OBSERVED FLOOD EXTENT; BIAS>1 INDICATES OVERESTIMATION OF THE OBSERVED FLOOD EXTENT.

The hydraulic model parameterization leading to highest agreement with RS data in the area upstream of the Barrackdale Choke was used to compute the modelled input volume to the AOI3. Figure 7A shows the modelled input discharge time series at the Barrackdale Choke and the measured discharge time series at St.George. The analysis of these hydrographs highlighted a large attenuation of the flood wave; this effect was caused by AOI3. As shown in Figure 7B, RS acquisitions from LANDSAT 5 and SPOT 5 allowed the assessment of the variation of water volume in the AOI3 between Jan 6th 2011 and Jan 8th 2011. The modelled storage volume variation in the AOI3 between the acquisition time of LANDSAT 5 and SPOT5 was then compared with the RS-derived value. Both the RS-derived and the modelled volume variations indicated an increase of storage in the AOI3. However, the RS-derived value was sensibly larger (approximately 8 times larger) than the modelled value thus indicating an overestimation of the
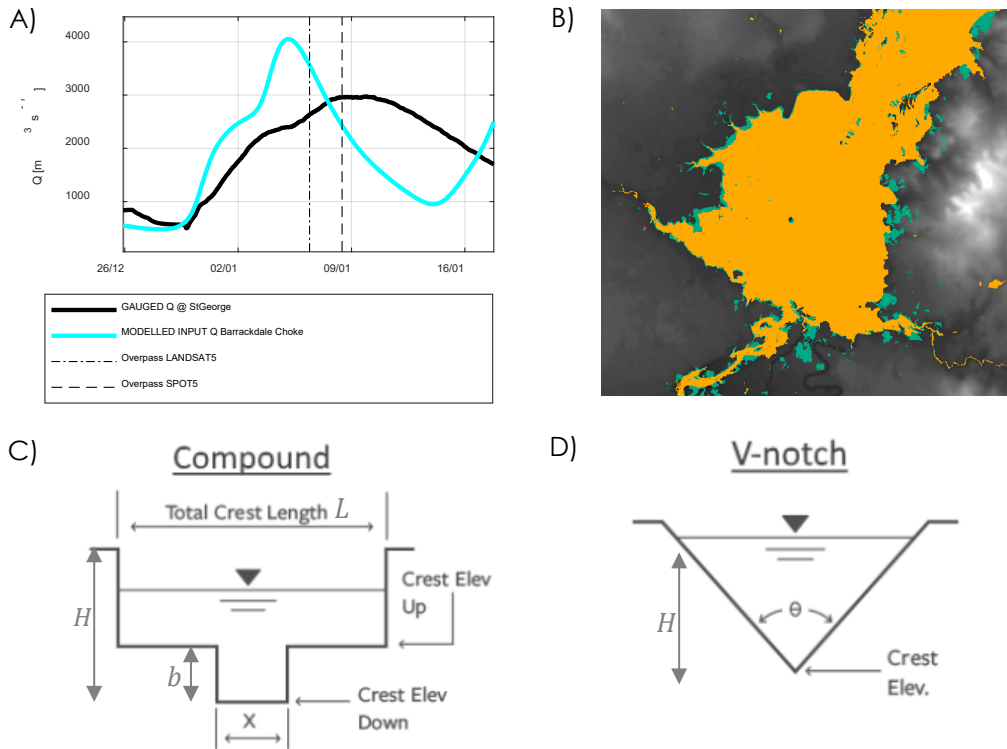
modelled discharge at the outlet of the Barrackdale Choke. To ameliorate this problem, the numerical code of the hydraulic model was then edited to incorporate the modelling of the flow behavior of the Barrackdale Choke. More specifically, the equations modelling weir discharge were introduced in the

numerical code. The schematics in Figure 7C show the two I geometries which were hyphotesised, that is, a compound weir and V-notch weir. For both the geometries, the coefficients were retrieved from Engineering Handbook, while the geometry was assessed using the DEM-H and RS-derived inundation widths. Gauged discharge data at St.George were used here as reference to assess the accuracy of the novel model set-up. Figure 8 allows the evaluation of the impact of the edited model set-up. This figure compares the measured discharge hydrographs at Weribone (upstream of the AOI3) and St.George, and modelled discharge hydrographs at the outlet of the Barrackdale Choke. It is shown that the flood dynamics predicted by the edited numerical model (green and blue lines) can allow more accurate predictions of the timing and value of the flood peak at St.George. It is here noted that the total gauged volume at St.George includes the volume from two upstream points: Weribone (considered here) and Cashmere (Maranoa River). Albeit underestimation of the measured flood peak at St.George in Figure 8 was expected, the predicted flood dynamics at the outlet of the Barrackdale Choke indicated a higher accuracy of the novel model set-up.
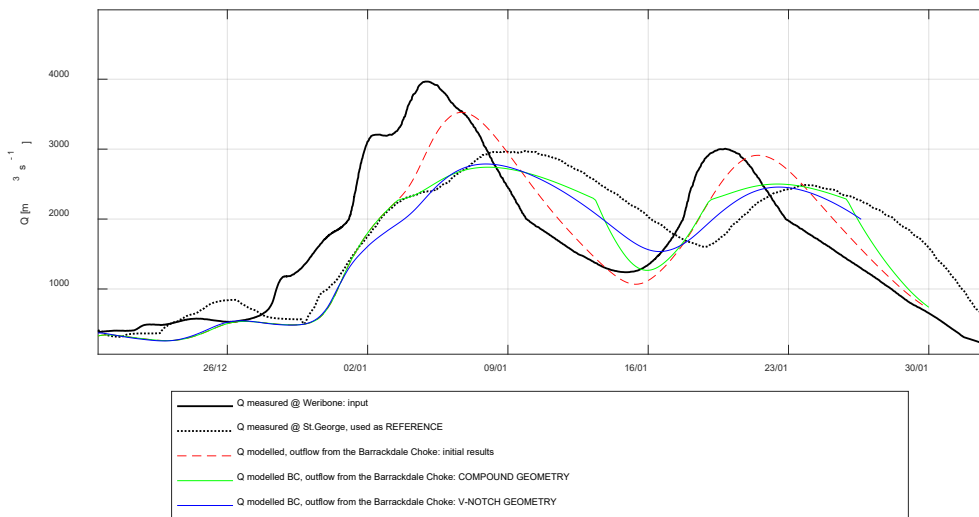

FIGURE 8 - MEASURED DISCHARGE HYDROGRAPHS AT WERIBONE (UPSTREAM OF AOI3) AND ST.GEORGE; MODELLED DISCHARGE HYDROGRAPHS AT THE OUTPUT OF THE BARRACKDALE CHOCKE. MODELLED DISCHARGE HYDROGRAPHS OBTAINED WHEN USING THE UNCORRECTED MODEL SET-UP (RED, DASHED LINE), THE MODEL SET-UPS INCLUDING THE WEIR EQUATIONS (GREEN AND BLUE LINES).

Fitzroy catchment (WA)

The hydraulic model of the Fitzroy catchment (WA) was set-up to develop a benchmark dataset for the validation of the SAR-derived flood extent layers. Moreover, this modelling exercise contributed to the investigation of the use of RS data to improve the implementation of the hydraulic model. This project hence developed knowledge   which will facilitate the implementation of the hydraulic model in many Australian catchments.

Figure 9A shows the modelled area, the input data were the measured discharge time series at Dimond Gorge, Margaret River at Mt. Krauss, Christmas Creek Homestead. Normal flow conditions were imposed at the downstream boundary. The modelling of the 2016-2017 flood event revealed errors in the representation of the terrain morphology at Geikie Gorge. More specifically, inaccuracies in the terrain data led to overestimation of the storage area upstream of Geikie Gorge and, consequently, underestimation of modelled flood extent and discharge data at Fitzroy Crossing. Figure 9B shows that the modelled discharge time series (blue lines) considerably underestimate the measured time series (black line). This problem was observed when using both the DEM-H and the Merit-DEM-Hydro thus highlighting the need for a methodology to improve model implementation in areas of complex morphology. Flood extent layers derived from

Landsat data (Water Observations from Space database) and gauged data at Fitzroy Crossing and Noonkanbah were used to derive a terrain dataset which is effective for the implementation of the hydraulic model. The results of the retrieved model implementation are shown in Figures 10. Figures 10A and 10B allow a visual evaluation of the agreement between the inundation extent derived from Sentinel-2 data and the modelled flood extent. It is here noted that the optical-derived layer in Figure 10A provides relevant information on flood extent. Nevertheless, further processing of the optical data would be required to adequately overlay the optical-derived layer on the model-derived layer. For instance, the optical-derived water layer shows a vertical line on the left side and many isolated pixels far from the river network (these features are highlighted by the black ovals). Moreover, optical sensors cannot generally detect water underneath trees canopy. Consequently, showing the optical-derived layers next to our own results allow a good overall understanding of the information value of the model-derived layers. Moreover, Figure 10C allows to complement the evaluation of the accuracy of the edited model set-up by comparing modelled (light blue line) and gauged (black line) discharge hydrograohs.
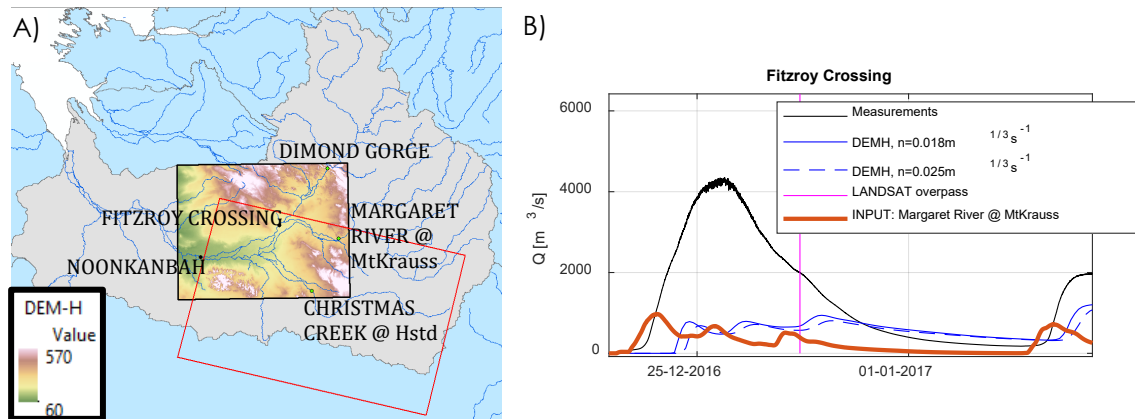
FIGURE 9 – (A) FITZROY CATCHMENT: MODELLED AREA, GAUGE STATIONS. RED RECTANGLE: EXAMPLE OF FOOTPRINT OF SENTINEL1 DATA. (B) MEASURED DISCHARGE HYDROGRAPHS AT FITZROY CROSSING AND MT.KRAUSS (MARGARET RIVER); MODELLED DISCHARGE HYDROGRAPHS AT FITZROY CROSSING FOR DIFFERENT PARAMETER VALUES AND THE UNCORRECTED MODEL SET-UP.
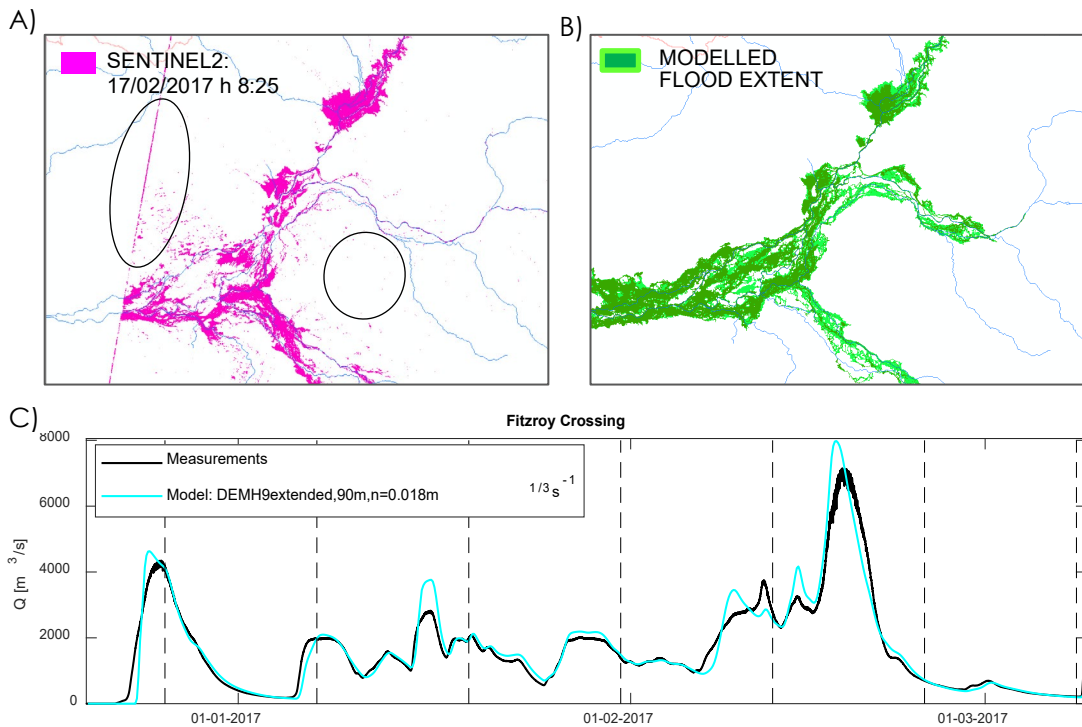
FIGURE 10 – (A) FLOOD EXTENT DERIVED FROM SENTINEL2 OPTICAL DATA (THIS LAYER WAS PROVIDED BY GEOSCIENCE AUSTRALIA); (B) MODELLED FLOOD EXTENT AT THE ACQUISITION TIME OF SENTINEL2 OPTICAL DATA, DARK GREEN AREAS: THE MODELLED WATER DEPTH IS HIGHER THAN 0.10 cm; LIGHT GREEN AREAS: THE MODELLED WATER DEPTH IS LOWER THAN 0.10 cm. (C) MODELLED AND MEASURED DISCHARGE HYDROGRAPHS AT FITZROY

CROSSING. THE RESULTS IN (B) AND (C) WERE OBTAINED USING THE CORRECTED MODEL SET-UP.

FINDINGS

This project adds to the current flood monitoring and modelling capabilities by providing methodologies for the optimal use of RS observations to monitor flood events, constrain the hydrologic model, implement and constrain the hydraulic model. The companion document "Guidelines on the optimal use of remote sensing data to improve the accuracy of hydrologic and hydraulic models" provide comprehensive and detailed recommendations on the selection and use of RS observations. The guidelines were generated from the analysis of three case studies, which are the Clarence (NSW), the Condamine-Balonne (QLD), and the Fitzroy (WA) catchment. Nevertheless, the methodologies and guidelines were developed for application to any Australian catchment. This document provides a summary of the findings of this project.The guidelines can be found at https://www.bnhcrc.com.au/publications/biblio/bnh-7198.

HYDROLOGIC MODEL

Leveraging from the experience developed within this project a set of recommendations on the choice of performance metrics, multi-objective calibration, selection of model and RS SM data sets for forecasting, and the assimilation of RS SM observations and streamflow observations are provided for hydrologic models.

Performance metrics

There is currently not a consensus on the optimal performance metric for hydrological flood forecasting. However the often-applied approach throughout Australia is to use an unweighted average of metrics which represent low, medium, and high flows, and bias is recommended.

Multi-objective calibration

Increased accuracy and capability to remotely sense SM may account for the increased frequency with which multi-objective calibration studies that use RS SM and streamflow data sets are being conducted. By improving the hydrological model's ability to simulate surface layer soil moisture dynamics, these approaches typically reduce the capability of models to simulate streamflow. This project unveiled a significant exception to this rule. At ungauged locations upstream of a gauge, RS SM observations can and should be used to improve streamflow simulation and forecasting capability.

Selection of hydrologic model and RS SM data set

No two hydrological models or RS SM data sets are alike. To enable hydrologic models to benefit most from the assimilation of RS SM observations it is prudent to evaluate the compatibility of the model, rainfall time series, and RS SM data set. It is suggested that the user do so by checking for white noise in the difference between simulated and observed time series.

Assimilation of RS SM and streamflow

A joint EnKS routine was developed to assimilate both RS SM and streamflow observations into hydrological models. Improved forecasting capability was observed for rainfall time series which had been optimised to yield superior

streamflow simulation skill. Improvements were not found when traditional areal rainfall estimates were used. As such it is recommended that considerable efforts, and further research, to improve the quality of rainfall forcing data are made. Data assimilation should not be applied to hydrologic models which do not have high quality forcing data.

SELECTION OF REMOTE SENSING OBSERVATIONS

The experience developed within this project enabled the delivery of a set of recommendations on the optimal acquisition time, spatial coverage, and accuracy of remote sensing images to be used for the evaluation of hydraulic models.

Acquisition time

- Remote sensing-derived observations of flood extent and level enable to effectively constrain the parameter space of the hydraulic model when the observed quantity changes rapidly over time (Grimaldi et al., 2016).
- Images acquired during the rising limb and up to the flood peak are generally more effective for the constraint of the parameter space of the hydraulic model.

Spatial coverage

- Use of images acquired over the upstream area of the catchment is recommended to improve inundation modelling accuracy in the downstream areas of the catchment.
- Generally speaking, the larger the footprint of the observed area, the higher the information content, the higher the potential to effectively constrain the parameter space of the hydraulic model.
- In the Clarence catchment, observations of Grafton are essential for model calibration.
- In the Condamine Balonne catchment, timely observations of the Barrackdale Choke are essential for accurate floodplain inundation modelling in the urban area of St.George.
- In the Fitzroy catchment, timely observations of the Geikie Gorge are essential for the adequate implementation of the hydraulic model.
- The analysis of the three catchments demonstrated the need for RS observations (1) in areas with levee systems; (2) in areas with morphological singularities (e.g. creeks, gorges).
- Areas with morphological singularities can be identified by off-line realizations of the hydraulic model (Grimaldi et al., 2019). This identification can then be supported and validated using historical database of observations of surface water. The recommended database is Water Observations from Space (Mueller et al., 2016).

Accuracy

- The accuracy of RS-derived inundation extent and level depends on the accuracy of the RS observations and on the accuracy of the algorithm for the retrieval of inundation extent and layer.
- Use of SAR data is recommended over optical acquisitions to enable surface water detection at night, under clouds, under vegetation.

- RS data spatial resolution is the size of the smallest object that can be resolved on the ground; the image pixel size quantifies the spatial coverage of a pixel in the real world. Generally speaking, the higher the resolution, the higher the accuracy. However, the higher the resolution, the lower the acquisition frequency, the smaller the spatial extent of the observed area. This project demonstrated that RS acquisitions having a spatial resolution of 20 to 40 m (i.e. medium resolution) are adequate for the purpose of evaluating the performances of the hydraulic model for the provision of floodplain inundation predictions at the catchment scale. Accurate tuning of the hydraulic model in urban areas was out of scope; such an objective is expected to require ~1m resolution images.
- RS-derived water level are retrieved by overlaying RS-derived inundation extent layers on a DEM. For this purpose, the use of high-resolution and high-accuracy LiDAR data is strictly recommended.
- This project proposed an algorithm for the use of SAR data to detect floods in vegetated areas (Grimaldi et al., 2020). It is expected that such an algorithm will contribute to improve the accuracy of the SAR-derived information of flood extent and level.

USE OF REMOTE SENSING OBSERVATIONS TO CONSTRAIN THE HYDRAULIC MODEL

The comparison between model results and RS-derived observation enables (i) the verification of model implementation; (ii) the calibration of model parameters.

Verification of model implementation

Inaccurate representation of river flow capacity and of floodplain morphological features unavoidably lead to inaccurate predictions of inundation dynamics. RS-derived observations can be used to detect and correct these inaccuracies:

- RS-derived water level can be used to identify and correct inaccurate representation of river bathymetry. The methodology for the diagnosis and correction is explained in Grimaldi et al. (2018).
- RS-derived inundation extent allows the detection of new flood paths that are not incorporated in the DEM (e.g. the SRTM mission was completed in 2001). Moreover, DEMs may be affected by the inaccurate representation of catchment morphological features such as gorges.

Model calibration

RS-derived flood extent
- Analysis of model behaviour at the large scale: the comparison between modelled and observed flood extent is recommended for any model implementation as it allows to gather an overall understanding of model performances and it is important to avoid overfitting problems.
- Analysis of the model behaviour for critical *areas* (e.g. levee systems, morphological singularities).
- Use of RS-derived flood extents is effective in large, low slope floodplains.
- Observed inundation extents derived from acquisitions during the decreasing limb of valley filling flood events have limited information content.

RS-derived flood extent and planar position of wet/dry points.
- Comparing the modelled and observed planar position of wet/dry points allows discriminating between under prediction and over prediction of floodplain propagation speed.
- This analysis is effective in large, low slope floodplains with the exclusion of valley filling events.

RS-derived flood extent and water level at the wet/dry points
- A LiDAR DEM is strictly required to effectively compare modelled and RS-derived water levels.
- This analysis is particularly useful in U-shaped areas and it can provide information for valley filling events. However, the use of water level at the wet/dry boundary is likely to return spurious results in nearly flat floodplains.

Key warnings:
- The capability of RS observations to provide reliable information of flooding dynamics is crucial to the success of the calibration process.
- Use of RS-derived flood extent and of the planar position of wet/dry boundary points is strongly recommended in low slope areas, in areas with levee systems, and in catchments with morphological singularities (e.g. gorges).
- Use of RS-derived water level is recommended in narrow, V or U-Shaped valleys. However, Lidar data are required for this analysis.
- Critically combining information from multiple acquisitions can help to avoid overfitting and equifinality problems and errors stemming from uncertainty and errors in RS acquisitions.
- Conjunct use of gauged data and RS data can support the calibration exercise. Nevertheless, it is imperative to remember that gauged data informative value can have very limited spatial value.

///////////////////////////////////

KEY MILESTONES

MONTH 12

The remote sensing data inversion algorithm is developed.

MONTH 18

A strategy to optimally use remotely sensed soil moisture data in an operational setting is developed. Due to the departure of Dr. Li this deliverable has been pushed back to Month 24.

MONTH 24

- Effective cross sections are established for the two test sites.

- A hydrologic forecasting system to dually assimilate soil moisture and streamflow measurements is developed. This deliverable has been delayed until Month 30.

MONTH 30

Effective digital elevation models are established for the two test sites.

MONTH 36

- The hydrologic forecasting system is evaluated in the BoM's testing catchments.

- The hydrologic-hydraulic flood forecasting system is working for the two test sites, optimised using remote sensing data.

UTILISATION OUTPUTS

REMOTE SENSING

The data inversion algorithm will be used by Geoscience Australia in the Water Observations from Space (WOfS) project.

FLOOD FORECASTING

- The dual soil moisture/discharge assimilation system will be used by the Bureau of Meteorology in their operational flood forecasting system.

- The framework for the optimal implementation of coupled hydrologic-hydraulic modelling constrained with RS data will be handed to the end-users.

- The implemented hydraulic model for the two test-sites will be handed to relevant end-users and stakeholders.

UTILISATION AND IMPACT

SUMMARY

This project adds to the current flood monitoring and modelling capabilities by providing methodologies for the optimal use of RS-SM to constrain the hydrologic model, the monitoring of floods using SAR data, the optimal use of RS observations to set-up and constrain the hydraulic model. The following paragraphs provide a detailed description of each project output.

Improving hydrological flood forecast skill using RS-SM data

Output Description

This sub-project developed algorithms to effectively assimilate RS-SM along with streamflow into hydrological models for flood forecasting purposes. These forecasts can be delivered to emergency services or coupled to a hydraulic model for an enhanced understanding of inundation extent and depth.

Extent of Use

- The dual observation calibration routine, rainfall gauge optimization routine, single and dual observation EnKS routines can be applied to all conceptual hydrological models and not just GRKAL.

- 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.

Utilisation Potential

- A robust dual EnKS assimilation routine which includes, optimization of rainfall gauge weighting 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.

- Currently, the assimilation of RS-SM improves forecast skill for catchments with larger times of concentration. As the acquisition of RS-SM data becomes increasingly more frequent so too does the ability for RS-SM to improve flood forecasting skill in flashier catchments.

Utilisation Impact

- The recent inclusion of GRKAL and future inclusions of dual observation calibration and assimilation routines along with a rainfall gauge optimization routine in SWIFT2 can improve the BoMs capability to forecast floods.

Utilisation and Impact Evidence

- The impact of publications resulting from this sub-project within the scientific community can be seen in Table 4

.

Title	Year	Scopus Citations	Authors
Application of remote sensing data to constrain operational rainfall-driven flood forecasting: A review	2016	30	Li,Y., Grimaldi, S.,Walker, J.P., Pauwels, V.R.N.
A comparison of the discrete cosine and wavelet transforms for hydrologic model input data reduction	2017	5	Wright, A., Walker, J.P., Robertson, D.E., Pauwels, V.R.N.
Estimating rainfall time series and model parameter distributions using model data reduction and inversion techniques	2017	6	Wright,A.J., Walker, J.P., Pauwels, V.R.N.
Impact of rain gauge quality control and interpolation on streamflow simulation: An application to the warwick catchment, Australia	2018	0	Liu,S., Li, Y., Pauwels, V.R.N., Walker, J.P.
Hydrologic model calibration using remotely sensed soil moisture and discharge measurements: The impact on predictions at gauged and ungauged locations	2018	24	Li,Y., Grimaldi, S., Pauwels, V.R.N., Walker, J.P.
Identification of hydrologic models, optimised parameters, and rainfall inputs consistent with in situ streamflow and rainfall and remotely sensed soil moisture	2018	5	Wright,A.J., Walker, J.P., Pauwels, V.R.N.

TABLE 4 – PUBLICATIONS AND THEIR IMPACT WITHIN THE SCIENTIFIC COMMUNITY AS MEASURED BY CITATIONS RECORDED BY SCOPUS

Algorithm for the analysis of SAR data of floods

Output Description

This sub-project is developing algorithms for the retrieval of inundation extents and water level from SAR images. The web service Water Observations from Space, developed and maintained by Geoscience Australia, provides information on flood extent based on optical remote sensing data. The algorithm for the detection of floods using SAR data developed in the frame of this research

has the objective to complement the current flood monitoring capabilities. Consequently, Monash University and Geoscience Australia have investigated optimal modalities to incorporate the algorithm for the analysis of SAR data into Water Observations from Space

Extent of Use

- The algorithm for the retrieval of inundation extents from SAR data will complement the current capabilities based on the use of optical sensors.

- SAR-derived flood extents enable flood monitoring in any catchment (gauged and ungauged), during day and night, regardless of the atmospheric conditions.

Utilisation Potential

- SAR observations enable 24 hours, all-weather, near-real-time monitoring of flood events, in both gauged and ungauged catchments.

- Spatially distributed information on flood extent and level can be derived from SAR observations to enable a better understanding of floodplain inundation dynamics.

- When compared to gauged data, SAR-derived flood extent and level enable more comprehensive ways to constrain the hydraulic model. This will to lead to more accurate prediction of floodplain inundation.

Utilisation Impact

- SAR-derived flood extent enables floodplain inundation monitoring at any time, in any catchment.

- SAR-derived flood extent and level disclose opportunities for improved hydraulic modelling of floods at the continental scale.

Utilisation and Impact Evidence

- A workshop on the use of RS data to improve flood forecast skill was held at Geoscience Australia (Canberra) in September 2016 (21st-22nd).

- The project team was invited to the workshop "*Earth observations for Water-Related Applications*" held in March 2018 (28th-29th) at the Australian National University (Canberra). The workshop had the purpose to assess the current state of affairs in Australia regarding the use of RS observations for water-related purposes. The participants of the workshop agreed on a list of recommendations for the optimal use of RS data within a broad community of researchers and end-users.

- A paper on the algorithm for the retrieval of flood extent maps in areas with emerging vegetation from single SAR acquisitions has been published by *Remote Sensing of Environment* (Grimaldi et al., 2020).

- Monash Univeristy and Geoscience Australia had regular meetings to discuss (1) the implementation of the algorithm for the analysis of SAR data and (2) the analysis the Sentinel-1 data. More specifically, two meetings

were hold at Geoscience Australia (Canberra) on May 14th, 2019 and December 3rd, 2019; zoom meetings were hold on February 10th, 2020 and March 16th, 2020.

Guidelines for the optimal use of RS-derived observations to improve flood extent, level, and velocity predictions

Output Description

This sub-project is developing a comprehensive experience on the optimal use of RS observations to improve the implementation and calibration of hydraulic models for flood forecasts.

Extent of Use

- This sub-project will deliver improved hydraulic modelling capabilities for two Australian catchments.

- Albeit this project is focusing on two specific study areas, the methodologies being developed make use of dataset available at the continental scale and have the potential to be used in a large number of Australian catchments.

- Guidelines for the optimal use of RS observations for the implementation and calibration of flood forecasting hydraulic models have been developed.

Utilisation Potential

- For the two selected study areas, the improved hydraulic modelling capabilities have the potential to enable more accurate predictions of floodplain inundation dynamics.

- The guidelines for the optimal use of RS observations for the implementation and calibration of flood forecasting hydraulic models has the potential to lead to the development of improved floodplain inundation prediction tools in many Australian catchments.

Utilisation Impact

- RS-constrained hydraulic models allow better understanding and modelling of floodplain inundation dynamics thus enabling the prediction of water depth and velocity in each point of the valley.

Utilisation and Impact Evidence

- The impact of publications resulting from this sub-project within the scientific community can be seen in Table 5.

Title	Year	Scopus Citations	Authors
Remote sensing-derived water extent and level to constrain hydraulic flood forecasting models: opportunities and challenges	2016	38	Grimaldi, S.,Li, Y., Pauwels, V.R.N., Walker, J.P.
Effective Representation of River Geometry in Hydraulic Flood Forecast Models	2018	8	Grimaldi, S., Li, Y., Walker, J.P., Pauwels, V.R.N.
Evaluation of TanDEM-X and DEM-H digital elevation models over the Condamine-Balonne catchment (Australia)	2018	0	Wang, A., Grimaldi,S., Shaadman,S.,Li, Y., Pauwels, V.R.N., Walker, J.P.
Challenges, opportunities and pitfalls for coupled hydrologic/hydraulic modelling at the large scale	2019	4	Grimaldi, S., Schumann, G,J-P., Shokri, A., Walker, J.P., Pauwels, V.R.N.
River reconstruction using a conformal mapping method	2019	1	Hilton, J.E., Grimaldi, S., Cohen, R.C.Z., Garg, N., Li, Y., Marvanek, S., Pauwels, V.R.N., Walker, J.P
Flood mapping under vegetation using single SAR acquisitions	2020	2	Grimaldi, S., Xu, J., Li, Y., Pauwels, V.R.N., Walker, J.P.

TABLE 5 – PUBLICATIONS AND THEIR IMPACT WITHIN THE SCIENTIFIC COMMUNITY AS MEASURED BY CITATIONS RECORDED BY SCOPUS.

CONCLUSIONS AND FUTURE OUTLOOK

The uncertainty in flood predictions is largely dependent on the observation quality of key variables, modelling skill and capability, and the quality of forecasted forcing data. This project takes advantage of recent increases in remote sensing observation skill by developing and detailing improved methods to use satellite remote sensing data to improve flood forecasting skill and capability. Advancements were made in:

- Hydrologic modelling,
- Flood mapping using Synthetic Aperture Radar acquisitions,
- Hydraulic model implemention,
- Hydraulic model calibration.

Key conclusions are as follows:

Use of remote sensing data to improve the accuracy of the hydrologic model
- Multi-objective calibration using RS SM can improve forecasting performance at ungauged locations.
- Choice in hydrological model, RS SM, and rainfall forcing data will significant influence performance.
- A new methodology to optimise gauge weights for areal rainfall estimation was developed.
- Improved rainfall estimates can significantly improve forecast skill.
- Limitations and opportunities for further development: data assimilation results are not generic; rainfall as an opportunity; rainfall as a challenge.

Flood mapping using Synthetic Aperture Radar (SAR) acquisitions:
- This project proposed an algorithm to automatically detect flooded vegetation using single SAR acquisitions and readily available ancillary data.
- Further testing is strictly required.
- Opportunity for further development: use of SAR data for the detection of floods in urban areas.

Use of remote sensing data to improve the implementation of the hydraulic model:
- Remote sensing-derived water level allow the diagnosis and correction of errors in the representation of river bathymetry (use of LiDAR DEM is imperative).
- Remote sensing-derived flood extent allow the diagnosis of errors in the modelled floodplain inundation volumes, especially in large catchments.
- Opportunity for further development: remote sensing observations can allow the detection of contingencies such as levee breaches. This capabaility can enable the near-real time correction of a model's implementation.

Use of remote sensing data to calibrate the hydraulic model:
- This project proposed a calibration framework that makes exclusively use of RS-derived observations and consequently enables model calibration in ungauged catchments.
- A novel performance metric was introduced to discriminate between underprediction and overprediction of floodplain propagation dynamics.

- Limitations and opportunities for further development: the accuracy, timing, and spatial coverage of the remote sensing observation largely impact the effectiveness of the calibration exercise; the testing of a large number of case studies is strongly recommended to optimise the calibration method for a range of different acquisition times and footprints.

Challenges and opportunities in coupled hydrologic-hydraulic models at the large scale:

- This project demonstrated that accurate prediction of flood peak values is crucial for accurate predictions of floodplain inundation extents and volumes.
- Floodplain inundation uncertainties and errors accumulated in a continuous modelling approach. Conversely, discrepancies could be reduced by using an event-based approach.
- Opportunity for further development: assimilation of inundation extents and water level in both low and high flow periods may provide a pragmatic strategy to improve the accuracy of flood predictions.

To leverage these research findings the next steps would feature (1) coding the RS-SM data assimilation algorithm into SWIFT2; (2) the operationalization of the algorithm for the analysis of SAR acquisitions.

//

PUBLICATIONS LIST

PEER REVIEWED JOURNAL ARTICLES

1. Grimaldi, S., Xu, J., Li, Y., Pauwels, V. R.N, & Walker, J. P. Flood mapping under vegetation using single SAR acquisitions. *Remote Sensing of Environment*, Volume 237, 2020, 111582, ISSN 0034-4257, https://doi.org/10.1016/j.rse.2019.111582
2. Hilton J.E., Grimaldi S., Cohen R.C.Z., Garg N., Li Y., Marvanek S., Pauwels V.R.N., Walker J.P. River Reconstruction Using a Conformal Mapping Method. *Enironmental Modelling & Software*, Volume 119, Pages 197-213, ISSN 1364-8152, https://doi.org/10.1016/j.envsoft.2019.06.006., 2019
3. Grimaldi, S., Schumann G.J-P., Shokri, A., Walker, J. P., and Pauwels V.R.N. Challenges, opportunities and pitfalls for coupled hydrologic/hydraulic modelling at the large scale. *Water Resources Research*, 55. https://doi.org/10.1029/2018WR024289 , 2019.
4. Grimaldi, S., Y. Li, J.P. Walker, and V.R.N. Pauwels, Effective Representation of River Geometry in Hydraulic Flood Forecast Models, Water Resources Research, 54, doi:10.1002/2017WR021765, 2018.
5. Wright, A.J., J.P. Walker, and V.R.N. Pauwels, Identification of hydrologic models, parameters and rainfall consistent with observed rainfall, streamflow, and remotely sensed soil moisture, *Journal of Hydrometeorology* 19.8, 1305-1320, 2018 .
6. Li, Y., S. Grimaldi, V.R.N. Pauwels, and J.P. Walker, Hydrologic model calibration using remotely sensed soil moisture and discharge measurements: the impact on predictions at gauged and ungauged locations, Journal of Hydrology, 557, 897-909, 2018.
7. Liu, S., Y. Li, V. R. N. Pauwels, and J. P. Walker, Impact of Rain Gauge Quality Control and Interpolation on Streamflow Simulation: An Application to the Warwick Catchment, Australia, Frontiers in Earth Science, 5(114), 2018.
8. Wright, A.J.,. Walker, J.P., and V.R.N. Pauwels, estimating temporal rainfall and model parameter distributions using model data reduction and inversion techniques, Water Resources Research, 53, doi:10.1002/2017WR020442, 2017.
9. Wright, A.J., J.P. Walker, D. Robertson, and V.R.N. Pauwels, A Comparison of the Discrete Cosine and Wavelet Transforms for Hydrologic Model Input Data Reduction, Hydrology and Earth System Sciences, 21(7), 3827-3838, 2017.
10. Grimaldi, S., Y. Li, V.R.N. Pauwels, and J.P. Walker, Remote sensing-derived water extent and level to constrain hydraulic flood forecasting models: opportunities and challenges, Surveys in Geophysics, 37(5), 977-1034, 2016.
11. Li, Y., S. Grimaldi, J.P. Walker, and V.R.N. Pauwels, Application of Remote Sensing Data to Constrain Operational Rainfall-Driven Flood Forecasting: A Review, Remote Sensing, 8(6), 456, doi:10.3390/rs8060456, 2016.

JOURNAL ARTICLES IN PREPARATION

1. Wright, A., Robertson, D.E., Walker, J., Pauwels, V.R.N., 2020. Insights from a new methodology to optimize rain gauge weighting for rainfall-runoff models. In preparation.
2. Grimaldi, S., Wright, A., Walker, J., Pauwels, V., 2020/21. On the use of remote sensing-derived waterlines to calibrate hydraulic flood forecasting models. In preparation.
3. Molari, G., Grimaldi, S., Paron, P., Walker, J., Pauwels, V., Domeneghetti, A., 2020/1. RiBEST – a tool for river bathymetry and hydraulic parameters estimation. In preparation.

CONFERENCE PAPERS

1. Wright A., Grimaldi S., Li Y., Walker J., Pauwels V., 2019. Improving flood forecast skill using remote sensing data. In B.N.H.C. Dr John Bates (Ed.), AFAC19 powered by INTERSCHUTZ, Research proceedings from the Bushfire and Natural Hazards CRC Research Forum (peer reviewed); Australian Journal of Emergency Management, Monograph No. 4, 2019. Melbourne
   Wang, A., Grimaldi, S., Shaadman, S., Li, Y., Pauwels, V.R.N., and Walker, J. P. Evaluation of TanDEM-X and DEM-H digital elevation models over the Condamine-Balonne catchment (Australia). In: *Hydrology and Water Resources Symposium (HWRS 2018): Water and Communities*. Melbourne: Engineers Australia, 2018: 989-1003. ISBN: 9781925627183, 2018
2. Nguyen, T.P.C., S. Grimaldi, and V. Pauwels, Use of remote sensing observations for improved understanding and modelling of flood waves routing, Oral Presentation at the AFAC Conference, Brisbane, August 30-September 1, 2016
3. Zhang, Y., Y. Li, J. Walker, V.R.N. Pauwels, and M. Shahrban, Towards operational hydrological model calibration using streamflow and soil moisture measurements, Oral Presentation at MODSIM 2015, 21th International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, Broadbeach, QLD -Australia, November 29- December 4, 2015.

EXTENDED ABSTRACT

1   Pauwels, Walker, Grimaldi, Wright, Li, Improving flood forecast skill using remote sensing data, Floodplain Management Australia National Conference, May 2019.

TECHNICAL REPORTS

1   Grimaldi S., Pauwels V., *Bathymetric field campaign of the Balonne river in St. George (QLD) – data analysis*, prepared for SunWater Ltd, November 2016

OTHER

1   Grimaldi S., Wright A., Walker J., Pauwels V., Verification of flood wave arrival time predictions using remote sensing-derived water levels; EGU General Assembly Conference Abstracts 2020.

2   Wright A., Robertson D.E., Walker J., Pauwels V., Optimizing rainfall gauge weightings to improving hydrological modelling skill.; AGU Abstracts 2019.

3   Grimaldi S., Wright A., Li Y., Walker J., Pauwels V., On the use of remote sensing observations for improved modelling of floodplain inundation dynamics; 23rd International Congress on Modelling and Simulation (MODSIM2019), Canberra (Australia), 1-6 December, 2019.

4   Grimaldi, S., Schumann, G. J. P., Shokri, A., Walker, J. P., Pauwels, V. Error propagation in coupled hydrologic-hydraulic modelling   of floods at the large scale; 23rd International Congress on Modelling and Simulation (MODSIM2019), Canberra (Australia), 1-6 December, 2019.

5   Grimaldi S., Yuan F., Mueller N., Xu J., Li Y., Pauwels V., Walker J. Surface water detection in areas with emerging vegetation using SAR data; 23rd International Congress on Modelling and Simulation (MODSIM2019), Canberra (Australia), 1-6 December, 2019.

6   Grimaldi S., Xu J., Li Y., Walker J., Pauwels V., Flood monitoring under vegetation using single SAR acquisitions; EGU General Assembly Conference Abstracts 2019.

7   Grimaldi S., Wright A., Li Y., Walker J., Pauwels V., Improving flood forecast skill using remote sensing data, European Joint Research Centre, April 2019 (invited presentation).

8   Grimaldi S., Li Y., Walker J., Pauwels V., On the use of remote sensing-derived river width and water level in hydraulic flood forecast models. EGU General Assembly Conference Abstracts 2018 (invited presentation)

9   Li Y., Grimaldi S., Pauwels V., Walker J., Assimilation of remotely sensed soil moisture for flood forecasting: a synthetic study; MODSIM 2017.

10 Grimaldi S., Li Y., Walker J., Pauwels V., Effective representation of river bathymetry in hydraulic flood forecasting models; MODSIM 2017

11 Hilton J., Grimaldi S., Cohen R., Li Y., Pauwels V., Walker J., River reconstruction using orthogonal distance maps; MODSIM 2017.

12 Li Y., Grimaldi S., Pauwels V., Walker J., Hydrologic and hydraulic flood forecasting constrained by remote sensing data; AGU Fall Meeting Abstracts, 2017.

13 Wright A.J., Vrugt J.A., Walker J.P., Pauwels V.R.N, (2016). Temporal rainfall estimation using input data reduction and model inversion; AGU Fall Meeting Abstracts, 2016.

14 Grimaldi S., Li Y., Walker J., Pauwels V., Implementation of remote sensing data for flood forecasting; AGU Fall Meeting Abstracts, 2016.

TEAM MEMBERS

Project Leader: A/Prof. Valentijn Pauwels

RESEARCH TEAM

Project Co-Leader: Prof. Jeffrey Walker

Research Fellows:

- Dr. Stefania Grimaldi

- Dr. Yuan Li (until April 21, 2018); Dr. Ashley Wright (since September 2018)

PhD. Student:

Ashley Wright obtained his PhD. on November 28, 2017

END-USERS

- Bureau of Meteorology

- Geoscience Australia

- New South Wales State Emergency Service

TEAM MEMBERS

REFERENCES

1   Bates, P.D., Horritt, M.S., Fewtrell, T.J., 2010. A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling. Journal of Hydrology. 387, 33-45

2   Gallant, J.C., Wilson, N., Dowling, T.I., Read, A., Inskeep, C., 2011. 1 second SRTM Derived Products User Guide In G. Australia (Ed.): Commonwealth of Australia (Geoscience Australia)

3   Grimaldi, S., Li, Y., Pauwels, V.R.N., Walker, J.P., 2016. Remote Sensing-Derived Water Extent and Level to Constrain Hydraulic Flood Forecasting Models: Opportunities and Challenges. Surveys in Geophysics. 37, 977-1034

4   Grimaldi, S., Li, Y., Walker, J.P., Pauwels, V.R.N., 2018. Effective Representation of River Geometry in Hydraulic Flood Forecast Models. Water Resources Research. 54, 1031-1057

5   Grimaldi, S., Schumann, G.J.-P., Shokri, A., Walker, J.P., Pauwels, V.R.N., 2019. Challenges, opportunities and pitfalls for global coupled hydrologic-hydraulic modeling of floods. Water Resources Research. 0

6   Grimaldi, S., Xu, J., Li, Y., Pauwels, V.R.N., Walker, J.P., 2020. Flood mapping under vegetation using single SAR acquisitions. Remote Sensing of Environment. 237, 111582

7   Hilton, J.E., Grimaldi, S., Cohen, R.C.Z., Garg, N., Li, Y., Marvanek, S., Pauwels, V.R.N., Walker, J.P., 2019. River reconstruction using a conformal mapping method. Environmental Modelling & Software. 119, 197-213

8   Li, Y., Grimaldi, S., Walker, J., Pauwels, V., 2016. Application of Remote Sensing Data to Constrain Operational Rainfall-Driven Flood Forecasting: A Review. Remote Sensing. 8, 456

9   Liu, S., Li, Y., Pauwels, V.R.N., Walker, J.P., 2018. Impact of Rain Gauge Quality Control and Interpolation on Streamflow Simulation: An Application to the Warwick Catchment, Australia. Frontiers in Earth Science. 5

10   Lymburner, L., Tan, P., Mueller, N., Thackway, R., Lewis, A., Thankappan, M., Randall, L., Islam, A., Senarath, U., 2011. Dynamic Land Cover Dataset. Canberra: Geoscience Australia

11   Mueller, N., Lewis, A., Roberts, D., Ring, S., Melrose, R., Sixsmith, J., Lymburner, L., McIntyre, A., Tan, P., Curnow, S., Ip, A., 2016. Water observations from space: Mapping surface water from 25 years of Landsat imagery across Australia. Remote Sensing of Environment. 174, 341-352

12   Pauwels, V., Walker, J., Grimaldi, S., Wright, A., Li, Y., 2019. Improving flood forecast using remote sensing data - annual report 2018-2019. In (p. 33). Melbourne: Bushfire and Natural Hazards CRC

13   Wang, A., Grimaldi, S., Shaadman, S., Li, Y., Pauwels, V., Walker, J.P., 2018. Evaluation of TanDEM-X and DEM-H digital elevation models over the Condamine-Balonne catchment (Australia). In, Hydrology and Water Resources Symposium (HWRS 2018): Water and Communities (pp. 989-1003). Melbourne: Engineers Australia

14   Yamazaki, D., Ikeshima, D., Sosa, J., Bates, P.D., Allen, G.H., Pavelsky, T.M., 2019. MERIT Hydro: A High-Resolution Global Hydrography Map Based on Latest Topography Dataset. Water Resources Research. 55, 5053-5073