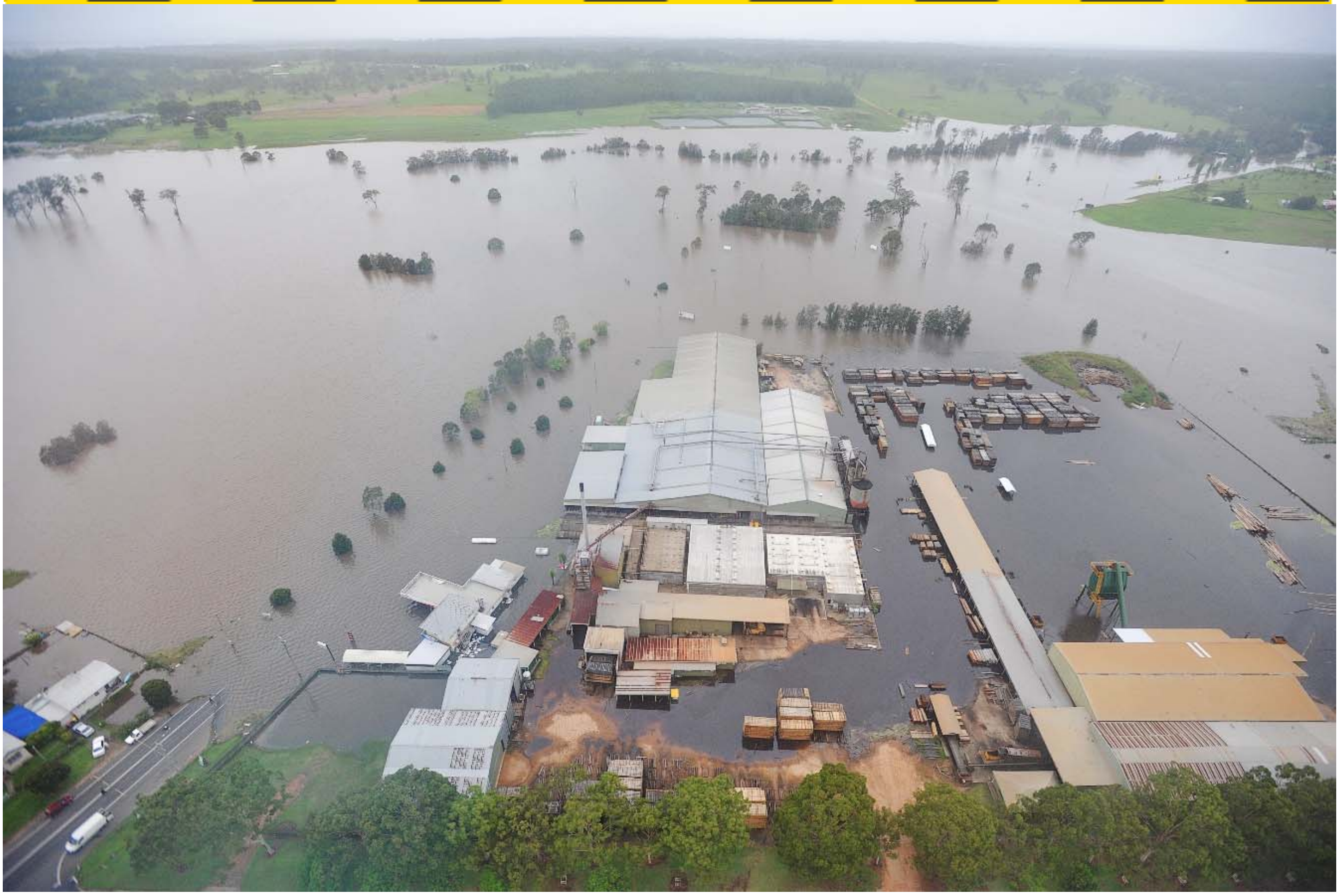
bushfire&natural HAZARDSCRC

bnhcrc.com.au

IMPROVING FLOOD FORECAST SKILL USING REMOTE SENSING DATA

Annual report 2018-2019

Valentijn Pauwels, Jeffrey Walker, Stefania Grimaldi, Ashley Wright, Yuan Li
Monash University & Bushfire and Natural Hazards CRC



Australian Government
Bureau of Meteorology

SES
NSW STATE EMERGENCY SERVICE

Australian Government
Geoscience Australia

Version	Release history	Date
1.0	Initial release of document	26/07/2019

Publisher:
Bushfire and Natural Hazards CRC

June 2019

Citation: Pauwels, V, Walker, J, Grimaldi, S, Li, Y 2019. Improving flood forecast skill using remote sensing data annual report 2018-2019. Bushfire and Natural Hazards CRC, Melbourne, VIC.

Cover: Clarence catchment, Timber Mill, South Grafton, January 2011.
Photo credit: New South Wales State Emergency Services.

TABLE OF CONTENTS

ACKNOWLEDGMENTS

We thank the following organizations for their continued support of the project:

- Bureau of Meteorology
- Geoscience Australia
- Commonwealth Scientific and Industrial Research Organisation
- New South Wales State Emergency Service
- Clarence Valley Council
- Balonne Shire Council
- Sunwater Ltd.

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 Queenslad, 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 totaling $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 heavily rely on flood forecasting systems. Further improvements to current flood forecasting systems are likely to reduce the personal and economic damage caused by floods.

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 converts this flow volume into river water levels/velocities and floodplain extents. 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 forcings (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, in this project we are constraining and updating 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. Further, we are constraining the hydraulic model using remotely sensed water levels and/or flood extents. Thus, every time a remote sensing image becomes available, we correct the model predictions. This process will lead to improved model forecasts of flow depth, extent and velocity for a number of days in the future.

END-USER PROJECT IMPACT STATEMENT

Author Name, *Norman Mueller, Geoscience Australia, Canberra, ! #4*

The project has progressed to the point where Geosci ence Australia is collaborating with the BNH-CRC team to begin integration into the Digital Earth Australia platform. The Height Above Nearest Drainage techniques employed in the research are showing application beyond just the SAR work, and have great potential, and the SAR and modelling work is looking very promising.

PRODUCT USER TESTIMONIALS

Author Name, *Norman Mueller, Geoscience Australia, Canberra, ACT*

The project is providing very beneficial contributions to the Short-term Water Forecasting and Prediction system of the Bureau of Meteorology, and the Water Observations from Space sy stem of Geosci ence Australia. Both tools are expected to significantly increase Australia's capacity to mitigate the impact of floods.

INTRODUCTION

Flood forecasting systems are useful tools that are used by operational water and emergency managers to minimize and hopefully mitigate the impact of floods. Rainfall data are essential to flood forecasts, which predict the level and extent 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 utilized 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 will be determined. After selecting the models, model-data fusion techniques will be 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 will be developed.

BACKGROUND

INTRODUCTION

The project will answer the following science questions:

1. How can satellite remote sensing data be best used to improve flood forecasting systems? Is it more important to update the state variables of the hydrologic model or the hydraulic model? 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 (finished), and the acquisition of required data to meet the project objectives (finished). 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, finished step was the selection of the hydrologic and hydraulic models to be used in the study. The models were selected from those typically used in Australia. 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 project phase is finished. 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. This step in the project is finished. Additionally, the uncertainty in the flood extent forecasts will be reduced by constraining the model forecasts with remotely sensed flood extent data and real-time gauge-based water levels.

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. The definition of adequate methodologies for the inversion of SAR imagery into maps of inundation extent and level is one of the objectives of this project.

METHOD OPTIMIZATION

The overall objective of the project is to aid operational flood forecasts through the use of remote sensing data. A remaining question in this context is the adequate spatial and temporal resolution of these data. In order to answer this question, a series of synthetic experiments will be performed. This will allow recommendations to be made on how to optimally use the methodology that has been developed as part of this project.

RESEARCH APPROACH

HYDROLOGIC MODELLING

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 will be available for operational purposes in the next 6 months

An ensemble Kalman filter (EnKF) along with a fixed-lag ensemble Kalman smoother (EnKS) were incorporated into SWIFT for experimentation. These assimilation routines along with the joint EnKS will be incorporated into SWIFT2 by the end of the project. The efficiency of the EnKF and the EnKS were investigated through a group of synthetic experiments on the assimilation of soil moisture and/or streamflow measurements. The experiments were conducted in the Condamine catchment upstream of Warwick.

The synthetic SM assimilation experiment indicated that, when compared to the EnKF, the EnKS addresses errors in antecedent state variables more thoroughly. The improvement in antecedent state variable analysis is further propagated to streamflow forecasts through the routing process. The superiority of the smoother is more significant for catchments with longer concentration times. It is expected that as the interval between RS-SM acquisitions decreases, data assimilation routines will have more significant impacts on catchments showing flash-flood behaviour with shorter lead times. The strength of the smoothing approach exhibited in this synthetic study demonstrates a potential to improve streamflow forecasting in real-world applications.

Consequently the EnKS was selected for the joint assimilation of soil moisture and streamflow. To assess the individual impacts of assimilating streamflow and SM in a joint assimilation scheme a synthetic study was conducted in which SM and streamflow were individually assimilated using the EnKS. Comparisons were then made between simulations and the joint assimilation of streamflow and SM using the EnKS. Streamflow assimilation exhibited a stronger effect than soil moisture assimilation on improving the accuracy of streamflow forecasting. However, the joint data assimilation scheme outperformed the single variable assimilation schemes (i.e., streamflow/soil moisture assimilation) demonstrating that including soil moisture information adds value to streamflow forecasts. This is particularly true for longer forecast lead times.

In an ideal scenario where error structures are known, the joint assimilation of SM and streamflow will consistently improve streamflow forecasting skill. However, model and observation error structures remain largely unknown. To assess the effectiveness of assimilating RS-SM into a conceptual hydrological model, SMOS RS-SM data were assimilated into GRKAL using the EnKF and EnKS . Assimilating SMOS SM data using the EnKS made the most significant improvement to peak flow simulation, which is shown in Figure 1. However, simulations that used the EnKF also demonstrated improved peak flow simulations compared to open loop simulations. However, the open-loop simulations do simulate streamflow better at multiple points on the discharge hydrograph. This suggests that assimilating RS- SM will not always improve streamflow simulations. This further demonstrates the need to understand observation and model error structures.

Furthermore, studies on the quality control QC of rainfall data, joint SM streamflow calibration of hydrologic models, and optimisation of rainfall gauge weighting were conducted. It was demonstrated that QC of rainfall data (Liu et al., 2018) vastly improves streamflow simulation skill. 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. Optimising the selection of rainfall gauges led to improvements in streamflow and soil moisture simulations. Once QC and optimisation of rainfall gauges has been conducted, it is essential that the hydrologic model be jointly calibrated to RS-SM and streamflow observations.

In a study designed to test the influence of jointly calibrating the hydrologic model to RS-SM and streamflow observations (Li et al., 2018), it was found that simulations of soil moisture improved whilst streamflow simulations degraded slightly. Interestingly, streamflow simulations at ungauged locations improved significantly. The degradation of streamflow simulations in calibration periods can be acceptable if it allows for more effective implementation of DA algorithm and leads to more robust streamflow forecasts. Testing this hypothesis is the objective of the next study. Further, improvements to this data assimilation framework are likely to be found by incorporating an adaptive smoothing algorithm which updates model and observation error structures.

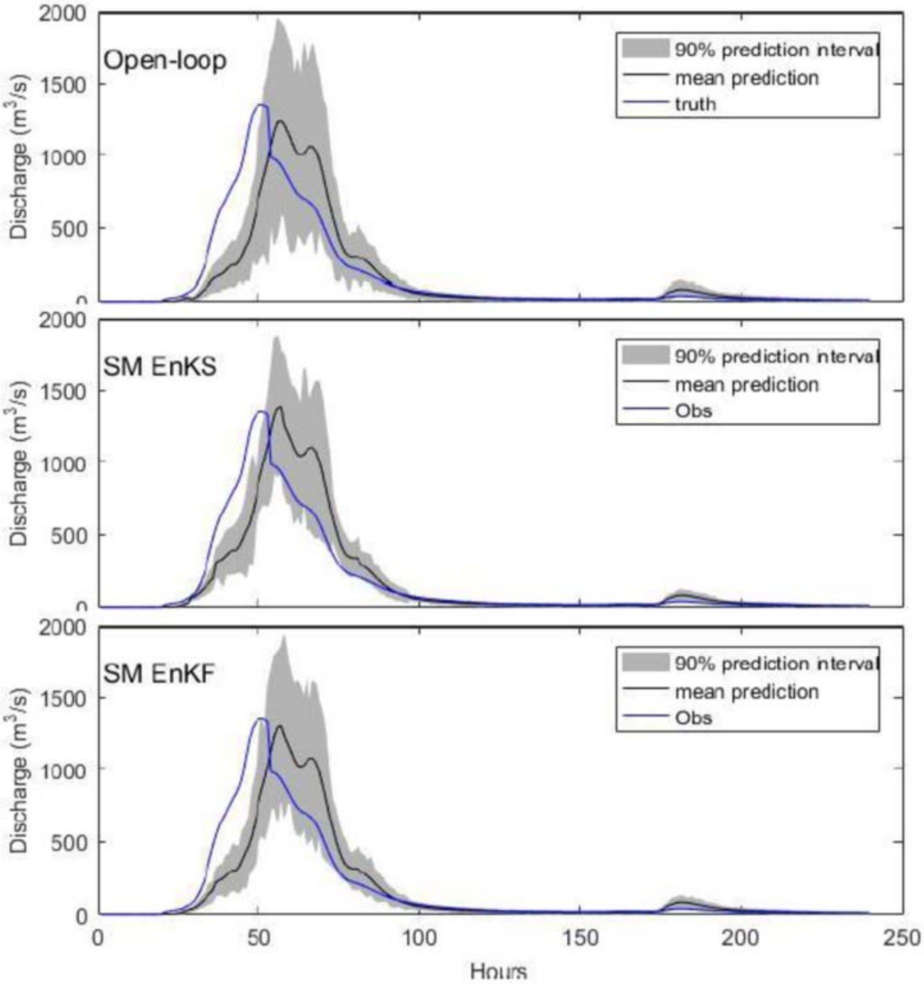


Figure 1 – a) Open loop simulations are displayed to provide a benchmark flood simulation b) Simulations where RS-SM data are assimilated into GRKAL using the EnKS c) Simulations where RS-SM is assimilated into GRKAL using the EnKF.

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 (e.g. the Condamine-Balonne) 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(s) are not readily available, especially for fine resolution images. To bypass this problem, this project is developing 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.

More specifically, 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. The algorithm has been tested on three fine resolution images (one ALOS-PALSAR and two COSMOSkyMed) acquired during the January 2011 flood in the Condamine-Balonne catchment. The SAR-derived flood extent layers have been validated using inundation maps derived from optical images which were provided by Geoscience Australia and the Queensland Department of Natural Resources and Mines. 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. Figure 2 shows the SAR data and the SAR-derived flood extent layers for the area of Surat (Condamine-Balonne catchment). Notwithstanding the difficulty to fully discriminate between dry vegetation backscatter heterogeneity and backscatter variation due to flooding using a single SAR image, the main benefit of the proposed algorithm is its ability to automatically detect flooded vegetation using one single SAR acquisition and commonly available ancillary data. A manuscript on this topic has been submitted for publication to *Remote Sensing of Environment* on May 17th (2019).

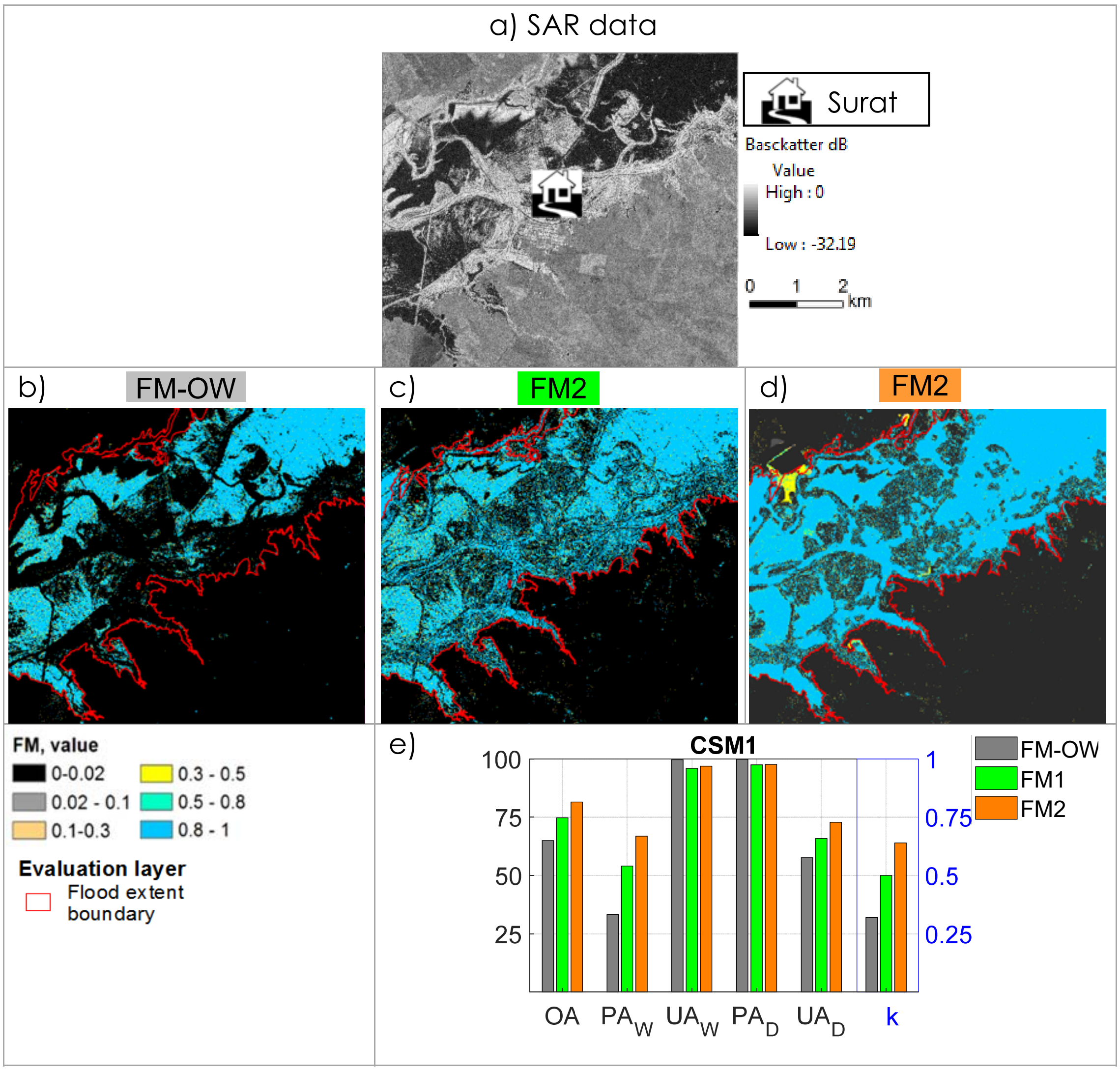


Figure 2 – a) SAR data: COSMOSkyMed acquisition on January 4th 2011, Surat area, Condamine-Balonne catchment (QLD). b,c,d) SAR-derived flood extent layers, FMapping (FM) values are the fuzzy membership values to the class "water". b) FM-OW: degree of membership to the open water areas; c) FM1: degree of membership to the op en water areas and th e flooded areas with emerging vegetation; d) FM2: degree of membership to the fl ood extent layer, after inclusion of information on morphology and context. e) Performance metrics within the footprint of the optical data: Overall Accuracy (OA), Producers' Accuracy for the class water and dry (PA_W,PA_D), Users' Accuracy for the classes water and dry (UA_W,UA_D), Cohen's kappa (k).

SAR-derived inundation maps are ov erlaid onto Digital Elevation Models (DEM) to provide spatially distributed water levels of the boundary between inundated and dry areas. Leveraging on the previous literature (e.g. Mason et al., 2012), this project has implemented an algorithm for the retrieval of RS-derived water level values at relevant location along the w et/dry boundary. This algorithm was tailored for Australian catchments having complex morphology and this objective was achieved by using the Australian Hydrological Geospatial Fabric (Geofabric) (Australian Bureau of Meteorology, 2015) as an auxiliary dataset. The algorithm has been applied for the retrieval of water level from two SAR images (COSMOSkyMed) acquired over the Clarence catchment during the flood event in January 2011. Figure 3 shows the SAR data and SAR-derived flood extent and water level.

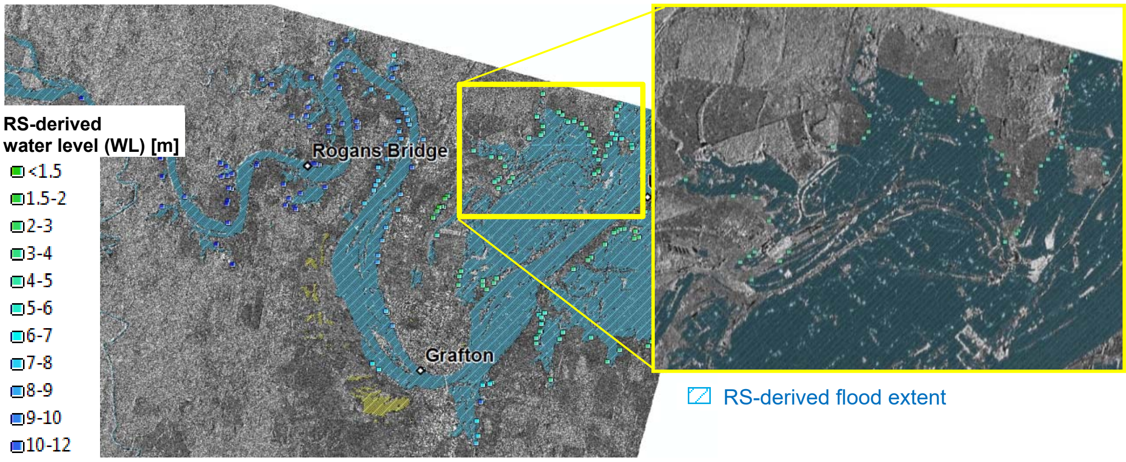


Figure 3 – COSMOSkyMed acquisition over the Clarence catchment in January 12th, 2011. The blue shaded area shows the SAR-derived flood extent. The points show the SAR-derived water level values at selected location of the wet/dry boundary.

HYDRAULIC MODELLING

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.

A high resolution (1 m), high accuracy LiDAR DEM is available only for the Clarence catchment. LiDAR DEM are available only for a limited number of townships in the Condamine-Balonne catchment. Two medium resolution (12 m and 30 m), medium accuracy DEMs, that is the TanDEM-X (Airbus Defence and Space) and the DEM-H (Geoscience Australia), provide full coverage of the Condamine-Balonne catchment. The DEM-H is the only dataset available at the continental scale. For this reason, methods for the delivery of corrected DEMs for hydraulic modelling are being investigated. Two field campaigns were organized to sample bathymetric data at strategic locations in the Clarence catchment (November 2015) and in the Condamine-Balonne catchment (May 2016).

This project completed an analysis of the accuracy of the TanDEM-X and the DEM-H for the representation of river flow capacity and floodplain morphology in the Condamine-Balonne catchment. Measured bathymetric data, LiDAR data and ground control points were used as benchmark. This analysis showed that riparian vegetation can cause large uncertainties and errors in both the DEM-H and TanDEM-X dataset; moreover, the DEM-H underestimates the flow capacity of the river (Figure 4). The results were published in Wang et al. (2018).

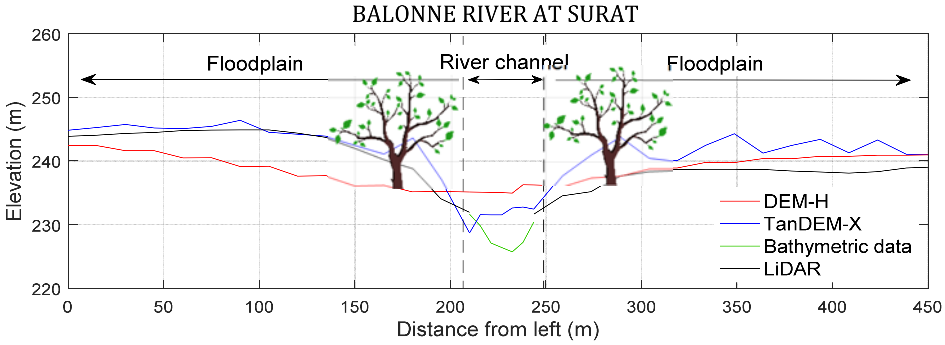


Figure 4 – Comparison between DEM-H, TanDEM-X, and the higher accuracy and resolution dataset composed by LiDAR data (in the floodplain) and measured bathymetric data.

Bathymetric data are critical for the assessment of river flow capacity and, hence, the application of hydraulic models. However, it is impracticalto measure river bathymetry along the total river length, especially in large basins. Consequently, a data-parsimonious methodology for the definition of an effective river bathymetry representation in medium to high resolution flood forecasting hydraulic models was derived using the Clarence catchment as study site. According to the proposed methodology, simplified, yet effective cross section geometries can be defined based on a combination of limited field data, global database, and remote sensing data. This methodology has been published in (Grimaldi et al., 2018).

The implementation of the hydraulic model for large catchments with long, complex river networks then requires to solve the practical hurdle to embed the estimated effective cross section geometries into the DEM. To solve this problem, an automatic, fast algorithm was developed in collaboration with CSIRO-Data61 (Clayton). This algorithm is based on conformal mapping and it has been tested on a 3 km long reach of the Balonne River near St. George (Figure 5). A paper on the proposed methodology has been accepted for publication to *Environmental Modelling and Software* on June 19th 2019. Figure 5 shows the bathymetric data collected in May 2016 and the results of the implementation of the conformal mapping algorithm.

The data-parsimonious methodology for the assessment of river geometry and the automatic algorithm for the inclusion of river geometry into DEMs is being applied for the implementation of the hydraulic model of the Condamine-Balonne catchment.

Figure 5 – Balonne River near St. George: a) measured bathymetric data; b) conformal map; c) reconstructed river bathymetry using conformal mapping.

The implementation of the hydraulic model of the Clarence catchment has been completed. The hydraulic model was applied to simulate the 2011 flood event. Two different datasets were used for model verification and calibration: (a) water level time series measured by 10 gauge stations and (b) spatially distributed water level derived from two SAR (COSMOSkyMed) images acquired close to the flood peak in Grafton.

It was found that spatially distributed RS-derived flood extent and level provided more robust strategies to for the detection of model errors and constraint of model parameters. More specifically, small uncertainties in the prediction of water level at one point (i.e. at one gauge station, Figure 6a) could result in errors in the prediction of the inundated area (false alarms, Figure 6a). These errors could be detected by the synoptic view offered by RS-derived data. However, gauged time series of water level data allow immediate evaluation of the predicted flood wave arrival time. Nevertheless, preliminary results of this analysis indicated that RS-derived wet/dry boundary points can be successfully used to verify predictions of flood wave arrival time (Figure 6b).

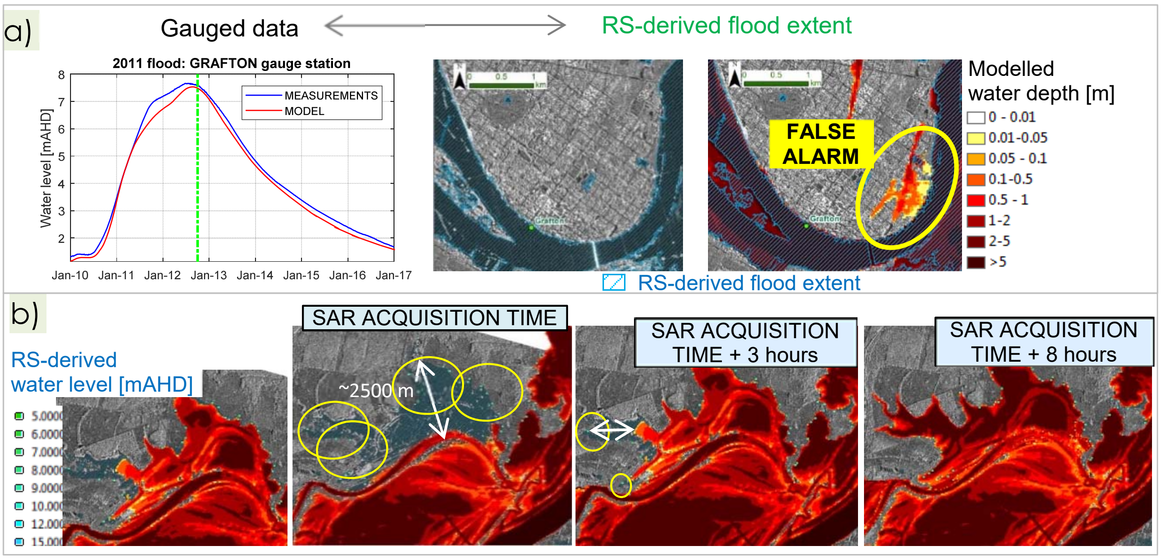


Figure 6 – a) Modelled and measured water level time series at Grafton. b) Modelled and RS-derived inundation extent in Grafton. Background: SAR data (Cosmo Sky Med). c) Comparison of the modelled flood extent and the RS-derived wet/dry boundary points at different time steps. The yellow circles highlight underprediction of the flooded area. This comparison shows that the model underpredicts the flood wave arrival time in the floodplain.

In summary, this analysis demonstrates a twofold use of RS data for hydraulic model evaluation:

1) RS-derived flood extent at sensitive locations;
2) RS-derived wet-dry selected boundary points.

Based on this investigation, a novel performance metric for the evaluation of the discrepancies between RS-derived and modelled wet /dry boundary points is being tested. Such a performance metric has the potential to enable rapid correction of models parameter set and reduce the number of required model realisations. It should be noted that a large computational time is a major hurdle for widespread operational applications of hydraulic models. Consequently, a methodology leading to a reduced number of model realisation has the potential to facilitate near-real time applications. These results will be explained in an original manuscript.

COUPLING OF HYDROLOGIC AND HYDRAULIC MODELS AT THE LARGE SCALE

Coupled hydrological-hydraulic models are at the core of flood forecasting and risk assessment models. Nevertheless, each model is subject to uncertainties from different sources (e.g. model structure, parameters, and inputs). Understanding how uncertainties propagate through the modeling cascade is essential to strategically inform investments in data collection, increase flood modeling accuracy, and comprehensively communicate modeling results to end users. A numerical experiment was used to quantify the propagation of errors when coupling hydrological and hydraulic models for multi-year flood event modeling in the Murray Darling Basin, from 2006 to 2012. Attention was paid towards the relevance of the Condamine-Balonne catchment. The impacts of discrepancies between simulated and measured flow hydrographs on the predicted inundation patterns were analyzed by moving from small upstream catchments to large lowland catchments.

The analysis illustrated the high sensitivity of floodplain inundation predictions to predicted streamflow peak values (Figure 7). When attempting to model a long time series of low and high flow periods, uncertainties in the inundation patterns increased over time and from upstream to downstream areas of the basin. These results demonstrated the need for accurate predictions of streamflow peak values and suggested that focusing on the modeling of each large flood event separately is a more effective strategy for reliable inundation predictions.

Moreover, in the Condamine-Balonne catchment, complex morphological features and low accuracy topographic data hamper accurate flood modeling at the catchment scale, with inundation prediction uncertainties during low flow periods strongly affecting modeling results across high flow periods. Consequently, it is suggested that better knowledge about critical morphologic terrain features, targeted Lidar data acquisitions, as well as data assimilation of inundation extents and water levels in both low and high flow periods may provide a pragmatic strategy to achieve acceptable skill in time-continuous flood inundation modeling. These results were pubished in Grimaldi et al. (2019).

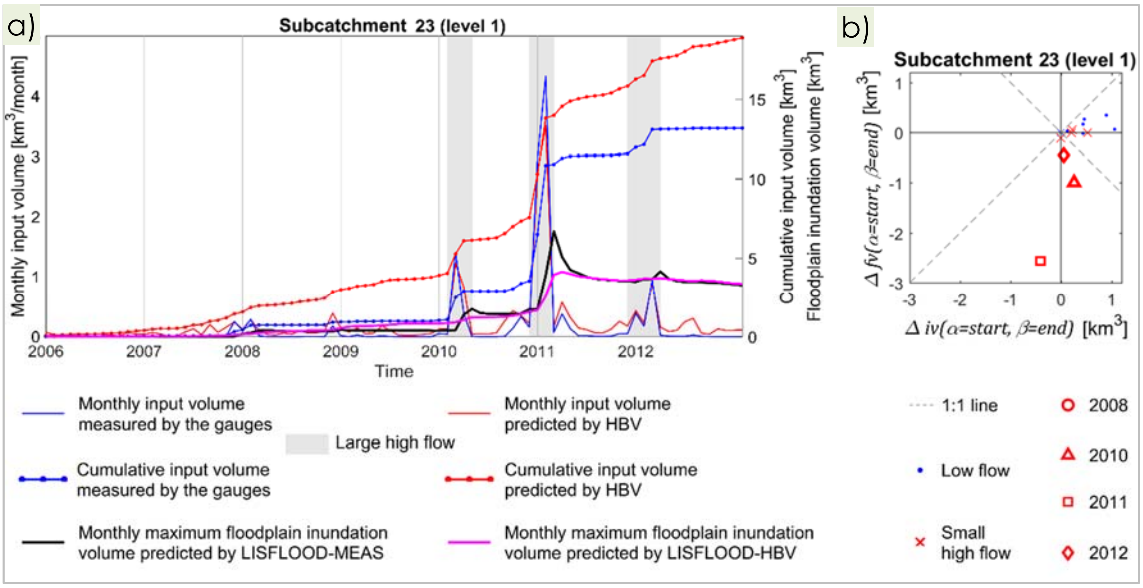


FIGURE 7 – Condamine-Balonne: sub catchment 23 of the Murray-Darling Bains. a) Time series of gauged and modelled input volumes (monthly and cumulative values), monthly maximum floodplain inundation volumes predicted by lisloodfp-meas and lisfloodfp-hbv. b) Event-based comparison of differences of input volumes ($\Delta\, iv(\alpha = start, \beta = end)$) and differences of monthly maximum floodplain inundation volumes ($\Delta\, fv(\alpha = start, \beta = end)$).

KEY MILESTONES

MONTH 12

The remote sensing data inversion algorithm is developed. This task has been completed and a publication is being prepared on this topic.

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 sy stem to dually assimilate soil moi sture and streamflow measurements is developed. T his 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 t esting catchments.
- The hydrologic-hydraulic flood forecasting system is working for the two test sites, optimized 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 mo isture/discharge assimilation system will be used by the Bureau of Meteorology in their operational flood forecasting system.
- The framework for the opti mal implementation of coupled h ydrologic-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 will add 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 is developing 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 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.
- 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 will improve the BoM capability to forecast floods.

Utilisation and Impact Evidence

- The impact of publi cations resulti ng from this sub-project within the scientific community can be seen in Table 1

Table 1 – Publications and their impact within the scientific community as measured by citations recorded by Scopus.

Title	Year	Scopus Citations	Authors
Application of remote sensing data to constrain operational rainfall-driven flood forecasting: A review	2016	21	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	3	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	10	Li,Y., Grimaldi, S., Pauwels, V.R.N., Walker, J.P.
Identification of hydrologic models, optimized parameters, and rainfall inputs consistent with in situ streamflow and rainfall and remotely sensed soil moisture	2018	1	Wright,A.J., Walker, J.P., Pauwels, V.R.N.

..
..
..

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.

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 (21^{st}-22^{nd}).
- The project team was invited to the workshop "*Earth observations for Water-Related Applications*" held in March 2018 (28^{th}-29^{th}) 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 meeting to discuss (1) the implementation of the algorithm for the analysis of SAR data and (2) the future work on the Sentinel-1 data has been held at Geoscience Australia (Canberra) in May 2019 (14^{th}).
- A paper on the algorithm for the retrieval of flood extent maps from single SAR acquisitions has been submitted to *Remote Sensing of Environment* on May 17^{th} (2019).

Roadmap 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, verification, 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 tw o specific study areas, the methodologies being developed make use of dataset av ailable at the continental scale and 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.

Utilisation Potential

- For the two selected study areas, the i mproved hydraulic modelling capabilities have the potential to enable more accurate predi ctions of floodplain inundation dynamics.
- The roadmap for the optimal use of RS observ ations for the implementation and constraint 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 u nderstanding and modelling of floodplain inundation dynamics.

Utilisation and Impact Evidence

- The impact of publicati ons resulting from this sub-pr oject within the scientific community can be seen in Table 2

Table 2 – Publications and their impact within the scientific community as measured by citations recorded by Scopus.

Title	Year	Scopus Citations	Authors

Remote sensing-derived water extent and level to constrain hydraulic flood forecasting models: opportunities and challenges	2016	24	Grimaldi, S.,Li, Y., Pauwels, V.R.N., Walker, J.P.
Effective Representation of River Geometry in Hydraulic Flood Forecast Models	2018	5	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	0	Grimaldi, S., Schumann, G,J-P., Shokri, A., Walker, J.P., Pauwels, V.R.N.

NEXT STEPS

The next steps will feature (1) coding the RS-SM data assimilation algorithm into SWIFT2; (2) the operationalization of the algorithm for the analysis of SAR acquisitions; (3) compiling a roadmap document on how to set up a coupled hydrologic-hydraulic flood forecasting system for any catchment in Australia. The following paragraphs provide more details on each next step.

RS-SM DA into SWIFT2

The dual RS-SM and streamflow EnKS algorithm will continue to be developed offline. Once fully tested the algorithm will streamlined and extensively documented such that someone can implement it into the SWIFT2 framework.

Operationalization of the algorithm for the analysis of SAR acquisitions of floods

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, the next steps of this sub-project will investigate the optimal modalities to incorporate the algorithm for the analysis of SAR data into Water Observations from Space

Moroever, to disclose the potential of current and upcoming SAR satellite missions, the next steps will test the possibility to include time-series and multi-polarization SAR data in the proposed algorithm. More specifically, the Sentinel-1 satellite mission, operated by the European Space Agency (ESA), provides fine resolution (~ 10 m) C-band dual-polarized data (VV, VH) with a frequency potentially as low as 10 days when combining acquisitions from Sentinel 1A and Sentinel 1B. Another SAR constellation of high interest will be NovaSAR-S (Surrey Satellite Technology Ltd and Astrium Ltd); the first satellite of the NovaSAR-S constellation (total 4 satellites) was launched in September 2018. The NovaSAR constellation has the capability to provide S-band imagery with medium resolution (6-30 m) in single polar mode and multi-polar mode (either at coarser resolution or with a narrower swath width) with revisit time between 3 and 14 days depending on the imaging mode. Sentinel 1 data are available free of charge; CSIRO has purchased 10 per cent share of time on NovaSAR-S acquisitions.

Roadmap for the implementation of coupled hydrologic-hydraulic flood forecasting system

This research is investigating strategies for the optimal set-up of coupled hydrologic-hydraulic flood forecasting models. A key point of this research is that the data used for models implementation, calibration, and constraint must be available at the continental scale. The next step of the work will feature the compilation of a roadmap for the implementation of hydrologic and hydraulic models which are constrained using RS data. These guidelines can be applied in any Australian catchment.

PUBLICATIONS LIST

PEER REVIEWED JOURNAL ARTICLES

1. 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
2. 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.
3. 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.
4. 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 .
5. 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.
6. 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.
7. 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.
8. 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.
9. 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.
10. 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 SUBMITTED FOR PEER-REVIEW

1. Grimaldi, S., Xu, J., Li, Y., Pauwels, V. R.N, & Walker, J. P. Flood mapping under vegetation using single SAR acquisitions. Submitted to *Remote Sensing of Environment* on May 17th 2019.

CONFERENCE PAPERS

1 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 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.
2 Grimaldi S., Li Y., Walker J., Pauwels V., Implementation of remote sensing data for flood forecasting; AGU Fall Meeting Abstracts, 2016.
3 Li Y., Grimaldi S., Pauwels V., Walker J., Assimilation of remotely sensed soil moisture for flood forecasting: a synthetic study; MODSIM 2017.
4 Grimaldi S., Li Y., Walker J., Pauwels V., Effective representation of riv er bathymetry in h ydraulic flood forecasting models; MODSIM 2017
5 Hilton J., Grimaldi S., Cohen R., Li Y., Pauwels V., Walker J., River reconstruction using orthogonal distance maps; MODSIM 2017.
6 Li Y., Grimaldi S., Pauwels V., Walker J., Hydrologic and hydraulic flood forecasting constrained by remote sensing data; AGU Fall Meeting Abstracts, 2017.
7 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)
2 Grimaldi S., Xu J., Li Y., Walker J., Pauwels V., Flood monitoring under vegetation using single SAR acquisitions; EGU General Assembly Conference Abstracts 2019.
3 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).

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

BIBLIOGRAPHY

Australian Bureau of Meteorology. (2015). *Australian Hydrological Geospatial Fabric (Geofabric) Product Guide*. Retrieved from http://www.bom.gov.au/water/geofabric/index.shtml

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*(1–2), 33-45. http://dx.doi.org/10.1016/j.jhydrol.2010.03.027

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*(5), 977-1034. 10.1007/s10712-016-9378-y

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*(2), 1031-1057. doi:10.1002/2017WR021765

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*(ja). 10.1029/2018wr024289

Lymburner, L., Tan, P., Mueller, N., Thackway, R., Lewis, A., Thankappan, M., . . . Senarath, U. (2011). *Dynamic Land Cover Dataset* (Vol. GA Record 2011/31). Canberra: Geoscience Australia.

Mason, D. C., Schumann, G. J. P., Neal, J. C., Garcia-Pintado, J., & Bates, P. D. (2012). Automatic near real-time selection of flood water levels from high resolution Synthetic Aperture Radar images for assimilation into hydraulic models: A case study. *Remote Sensing of Environment*, *124*, 705-716. http://dx.doi.org/10.1016/j.rse.2012.06.017

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).* Paper presented at the Hydrology and Water Resources Symposium (HWRS 2018): Water and Communities, Melbourne.