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IMPROVING FLOOD FORECAST SKILL USING REMOTE SENSING

Annual project report 2015-2016

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Cover: The Clarence River has flooded areas around Grafton NSW, four times between 2009-2015.
Credit: NSW State Emergency Service, Clarence Nambucca region.

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EXECUTIVE SUMMARY

Floods are among the most damaging natural disasters in Australia. Over the last 40 years, the average annual cost of floods was approximately $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 recent floods in 2016 resulted in three casualties with three more people missing. The Insurance Council of Australia stated on June 7 that about 14,500 claims totaling $56 million have already been lodged from across the country. In order to limit the personal and economic damage caused by floods, operational water and emergency managers heavily 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 converts this flow volume into river water levels/velocities and floodplain extents. Over recent times, the accuracy and reliability of these flood forecasting systems has significantly improved. However, it remains difficult to provide accurate flood warnings. This is because of errors and/or uncertainties in the model structure, the model parameters, and/or the meteorological forcings (mainly the rainfall). The hypothesis of this project is that remote sensing data can be used to improve modelled flood forecasts.

More specifically, in this project we are constraining the hydrologic model using remotely sensed soil moisture values, as this variable determines 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, which should lead to improved model forecasts of flow depth, extent and velocity for a number of days in the future.

END USER STATEMENT

John Bally, *Bureau of Meteorology*

The project has demonstrated methodologies to incorporate remotely sensed (RS) data into hydrologic and hydraulic models. The motivation for the project is to achieve an improvement in the accuracy, and hence the utility of flood forecasts by constraining the model predictions with RS data.

Results to date have shown only limited improvements in forecast skill, and have demonstrated the sensitivity of the results to the accuracy of the detailed bathymetry of the basins and river reaches being modelled. Considerable effort has been expended on field campaigns to better characterise bathymetry and hence improve model results. The sensitivity to bathymetry accuracy illustrates the technically challenging nature of the project.

The methodologies being investigated by the project show promise, but there is still a considerable gap between the results obtained so far and significant operational impact for catchments outside the study area. It is recognised that the very high quality bathymetry developed by the project is not available for most catchments, and work is underway to develop a method to estimate river bathymetry, as a model parameter, through merging RS flood extent/level data with a hydraulic model to improve results in sites with very limited bathymetry data.

The project has also demonstrated improvements in operationally used soil moisture models gained by incorporating RS data, especially (and unsurprisingly) at locations with less in-situ data. Opportunities exist to work with other teams working in the soil moisture field, who are also looking at assimilating RS data.

A relatively small set of end users have been regularly engaged with the project and have provided input along the way.

INTRODUCTION

Floods are among the most damaging of natural disasters in Australia, costing an average $377 million per year. One tool that is being used by operational water and emergency managers to mitigate the impact of floods is flood forecasting systems, which use rainfall data and forecasts to predict the extent and level of floods. Even though these systems have improved during the last decades, further research is needed to make the forecasts more accurate.

The hypothesis of this project is that remote sensing can be a very helpful tool for operational flood forecasting. For this purpose, remote sensing data are being used in two different ways. First, estimated soil moisture profiles from hydrologic models are improved through the merging of these model predictions with remotely sensed surface soil moisture values. 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 remotely sensed observations of flood inundations or water levels. This is expected to improve the predictive capability of the hydraulic model. Overall, using remote sensing data in flood forecasting is expected to 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 assimilate remote sensing data into operational hydrologic and hydraulic models will be determined. After selecting the models, the data assimilation techniques will be implemented and tested using a data base that will be developed as part of this project. A list of recommendations on how to best use remote sensing data for operational water management will be developed.

PROJECT BACKGROUND

INTRODUCTION

The project is expected to answer the following science questions:

1. How can terrestrial remote sensing data be best used to improve flood forecasting systems? In other words, is it more important to update the state variables of the hydrologic model or the hydraulic model? How frequent do we need acquisitions; do we need remote sensing data during the flood, or can remote sensing data from 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 highly accurate digital elevation models at fine spatial resolution.

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.

The selected hydrologic model is currently being calibrated using observed discharge records and remotely sensed soil moisture data. Furthermore, the hydraulic model is being calibrated using a combination of anecdotal flood height information, aerial photographs and radar-based remotely sensed flood extents. Existing imagery of soil moisture and inundation are used for this purpose.

UNCERTAINTY ESTIMATION

A very important issue is the estimation of the uncertainty of the flood forecasts, which is the third part of the project. Precipitation forecasts will be 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 will be applied to each member of the precipitation 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 precipitation, the spread in the ensemble will be a measure of the uncertainty in the modelled water levels and flood extends.

MODEL-DATA FUSION

The uncertainty in the hydrologic model results will be 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 will be made. The weight of the model results and the observations will be dependent on their level of uncertainty. Additionally, the uncertainty in the flood extent forecasts will be reduced through the merging of the model forecasts with remotely sensed flood extent data and real-time gauge-based water levels.

METHOD OPTIMISATION

A fourth and final part of the project is the optimal application of the coupled models in a data assimilation framework. 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.

WHAT THE PROJECT HAS BEEN UP TO

WORKSHOPS

During 2015-2016, the following end user meetings were organised:

- July 16, 2015 (Bureau of Meteorology, Melbourne)
- November 2, 2015 (Bureau of Meteorology, Melbourne)
- March 18, 2016 (Bureau of Meteorology, Melbourne)

During these meetings, the end users were kept informed on the progress of the modelling activities. Feedback was given, and recommendations on the best use of the data sets were made. All the involved parties agreed to have the next end user meeting in July 2016.

FIELD CAMPAIGNS

Two major field campaigns were organised during the last year:

1. The Clarence river, NSW (November 8-15, 2015). During this campaign, the river bathymetry of the Clarence was measured from Mountain View to Copmanhurst (the navigation head), covering a distance of 21 km. These data are very important as model input.
2. The Condamine river, QLD (May 1-13, 2016). During this campaign, river bathymetry data were measured at various locations in this river basin. In particular, 13 km of the Balonne River in St. George, 1 km of the Maranoa River close to Cashmere, 4 km in Surat, and 3 km in the Condamine were measured. These data are again very important as model input.

PROJECT PRESENTATIONS

A/Prof. Pauwels, Dr. Li, and Dr. Grimaldi presented an overview of the project aims and results at the Clarence Valley Council (Grafton, NSW, November 9, 2015) and at the Balonne Shire Council (St. George, QLD, May 3, 2016). Representatives of the Council, the NSW SES, the Ambulance Service, the QLD Fire and Emergency Service, and Sunwater Limited (QLD) attended the presentations.

A/Prof. Pauwels presented project results in a number of invited presentations:

- Pauwels, V., Inverse Modeling to Support Flood and Drought Management in Australia, Presented at the Catholic University Leuven, Belgium, May 27, 2016.
- Li, Y., S. Grimaldi, A. Wright, J. Walker and V. Pauwels, Improving flood forecast skill using remote sensing data, Presented at the 9th Collaboration for Australian Weather and Climate Research (CAWCR) Annual Workshop, Melbourne, October 19-22, 2015.

- Pauwels, V., Assimilation of Remote Sensing Data into Process-Based Models: Non-linear Observation systems, Biases, and Other Issues..., Presented at the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Adelaide, September 15, 2015.

Dr. Grimaldi presented project results at the BNHCRC Research Advisory Forum and at the 21st International Congress on Modelling and Simulation:

- Pauwels, V., J. Walker, Y. Li, S. Grimaldi, A. Wright, Improving flood forecast skill using remote sensing data, Presented at Bushfire & Natural Hazards CRC Research Advisory Forum, Brisbane (QLD), November 17-18, 2015.
- Grimaldi S., Y. Li, A. Wright, V. Pauwels, J. Walker, Use of remote sensing data to improve hydraulic model for real time flood wave routing prediction, Presented at 21st International Congress on Modelling and Simulation (MODSIM 2015), Gold Coast (QLD), November 29-December 4, 2015.

Dr. Li presented project results at the AFAC Conference and at the 21st International Congress on Modelling and Simulation:

- Li, Y., V. Pauwels, J. Walker, S. Grimaldi, and A. Wright. Evaluation of hydrological models for accepting in-situ and remote sensing observations, Presented at Presented at 21st International Congress on Modelling and Simulation (MODSIM 2015), Gold Coast (QLD), November 29-December 4, 2015.
- Li, Y., S. Grimaldi, V. Pauwels, J. Walker, A. Wright. Combining hydrologic and hydraulic models for real time flood forecasting, Presented at the AFAC Conference, Adelaide, September 1-3, 2015.
- Li, Y., S. Grimaldi, A. Wright, V. Pauwels, J. Walker. Improving Flood Forecast Skill Using Remote Sensing Data - the hydrological model component, Poster presented at the AFAC Conference, Adelaide, September 1-3, 2015.
- Grimaldi, S., Y. Li, A. Wright, V. Pauwels, J. Walker, Improving Flood Forecast Skill Using Remote Sensing Data - the hydraulic model component, Poster presented at the AFAC Conference, Adelaide, September 1-3, 2015.

Mr. Wright presented project results at the 21st International Congress on Modelling and Simulation:

- Wright, A., Y. Li, S. Grimaldi, V. Pauwels, J. Walker, A Holistic Approach to Rainfall Estimation for Operational Water Management, Presented at the 21st International Congress on Modelling and Simulation (MODSIM 2015), Gold Coast (QLD), November 29-December 4, 2015.
- Wright, A., Y. Li, S. Grimaldi, V. Pauwels, J. Walker, A Holistic Approach to Rainfall Estimation for Operational Water Management, Presented at the AFAC Conference, Adelaide, September 1-3, 2015.

Ms. Zhang presented project results at the 21st International Congress on Modelling and Simulation:

- Zhang, Y., Y. Li, J. Walker, V. Pauwels, and M. Shahrban, Towards operational hydrological model calibration using streamflow and soil moisture measurements, Presented at the 21st International Congress on Modelling and Simulation (MODSIM 2015), Gold Coast (QLD), November 29-December 4, 2015.

MEDIA MENTIONS

The field campaign in the Clarence river was discussed in the following media:

- Maps to help flood forecast, The Daily Examiner, February 6, 2016 (http://www.dailyexaminer.com.au/news/maps-to-help-flood-forecast/2922474/)
- ABC North Coast radio, February 4, 2016.
- *Fire Australia*, Remote Sensing data is filling the gaps, *Fire Australia*, Autumn 2016, pages 26-27.

  (http://www.bnhcrc.com.au/news/2016/remote-sensing-flood-data-filling-gaps/)

SCIENTIFIC PROGRESS

Hydraulic modelling

The Monash version of LISFLOOD-FP was used to model the flood events that occurred in in 2011 and 2013 in the Clarence catchment and in 2011and 2012 Condamine-Balonne catchment. Techniques for the assessment of the roughness values and the modelling of specific features (e.g. bridges and levees) were investigated. The results of the hydraulic model were compared to field data measured by a large number of gauging stations (10 in the Clarence catchment, 7 in the Condamine-Balonne catchment) and RS observation of flood extent (at this stage this comparison against RS data was limited to a visual observation).

In the Clarence catchment, the root mean square error of the modelled water levels, when averaged over the ten gauging stations, was 0.30 m. A comparison with RS observations of flood extent pointed out that, despite providing rather satisfactory results at the local level, the model failed the prediction of the flood extent in the relevant urban area of Grafton. These results underlined the limits of a punctual model-measurements comparison and highlighted that more coherent and explicative modalities of comparison are possible thanks to the intrinsically two dimensional features of RS observations. The visual analysis of RS data supported the diagnosis of errors. The main source of inaccuracy was the lack of bathymetric data over a 47 km long river reach. This gap was reduced during a field campaign in November 2015 resulting in the measurement of the bathymetry of a 21.2 km long river reach. A methodology to assess the river bathymetry of the remaining 26.8km was then elaborated based on the analysis of field data, remote sensing data, and literature studies (Victorian rivers). The reliability and effectiveness of the proposed methodology is currently under investigation and it is based on the comparison of the model's results with RS-derived observations of flood extent.

A multi-objective calibration protocol based on a combination of field data, RS-derived observations of flood extent and water levels has been outlined as the appropriate strategy and will be implemented in the next months. The effectiveness of a calibration protocol based on RS-data only will also be investigated.

In the Condamine-Balonne catchment, the low accuracy and the scarcity of the implementation data (DEM, bathymetric data) impede the delivery of accurate flood forecast (this challenge has been recognised in the literature of flood modelling in Australia, e.g. Thew et al., 2010 [1]; Tinnion, 2013 [2]). Precise elevation measurements are limited to less than 10 cross sections (QLD-DNRM) and point out errors of up to 3 m in the DEM. The existing bathymetric dataset is limited to 20 waterholes measured by the QLD-DNRM in 2015, nevertheless this dataset is not currently embedded in the DEM. The hydraulic model built using the existing dataset yielded flood peak discharge errors between 3% and 18%. Levee breaches and the above highlighted issues impeded the accurate prediction of the flooded area. A field campaign was completed in May 2016 with the purpose of measuring the river bathymetry of strategic river reaches. A total of 21 km of river extent and 5 transects were sampled. A protocol for the improvement of the implementation of the hydraulic model is under investigation. Similarly to the approach developed for the Clarence catchment, this protocol is based on the combination of field data (at a limited number of strategic locations), remote sensing data and literature studies. The comparison of the model results with RS derived observations of flood extent and levels will allow the validation of the protocol and the calibration of the numerical model. When validated, the RS-based protocol for the improvement of the implementation of hydraulic models will have the potential to be applied to many data-scarce catchments worldwide at low cost.

The interpretation of the RS images is in progress. The RS-derived observations of flooded area and water levels will be used for the calibration and validation of the hydraulic model. A total of 38 RS images have been collected, 24 images have been analysed, the interpretation of 4 images is in progress. The interpretation of 10 images was provided by GA. Monash University signed a contract with RPS-Australia for the analysis of 7 images. Monash University established collaboration with E-Geos for the purpose of improving the capability of the COSMO-SkyMed satellite constellation for flood monitoring and mapping in Australia. This collaboration resulted in the delivery of the interpretation of 8 images. Monash University analysed 2 images and is currently working at the interpretation of 4 images.

Hydrologic modelling

Two conceptual hydrologic models, GRHUM (Loumagne et al., 1996 [3]) and its updated version GRKAL (Francois et al., 2003 [4]), have been built into BoM's streamflow forecasting framework – Short-term Water Information Forecast Tools (SWIFT). Both two models are based on widely implemented GR4 model (modèle du Génie Rural à 4 paramètres) but with two soil moisture layers. The difference is that the surface layer is independent from a zoot-zone layer in GRKAL while the surface layer is included within a bulk layer in GRHUM. Both GRHUM and GRKAL have been tested in the Clarence River basin. They were first calibrated using streamflow measurements at Lilydale, and the GRKAL exhibits a slightly better prediction than the GRHUM in both the calibration and validation periods. Consequently, the GRKAL model was finally selected for application of remote sensing soil moisture (RS-SM) data.

Hourly rainfall, hourly discharge, and monthly potential evapotranspiration (PET) have been collected for two study basins, the Clarence River basin upstream of Lilydale and the Condamine-Balonne River basin upstream of St. George. Sub-catchment polygons have been generated using the Australian Hydrological Geospatial Fabric (Geofabric) with the consideration of discharge gauge locations. Rainfall and PET data have been interpolated to sub-catchment centroids as model inputs.

A joint calibration experiment using both streamflow and RS-SM data have been conducted in the Clarence. Four scenarios with different number of sub-catchments and calibration gauges were tested. The results indicate that 1) RS-SM has potential to improve streamflow estimation during forecasting periods at gauged locations; 2) RS-SM has a stronger impact on streamflow forecasts at ungauged locations; 3) the impact of RS-SM decreases when the density of calibration sites increases; and 4) the more information included (e.g., RS-SM and gauges) in calibration, there is a higher chance to obtain a more accurate and robust model. Currently, the same calibration strategies are implemented in the Condamine-Balonne basin, and a comparative study in the two basins will be conducted and submitted as a journal article.

The ensemble Kalman filter has been coded into SWIFT for soil moisture assimilation. An initial test in a sub-catchment in Clarence indicated that soil moisture assimilation has the potential to benefit streamflow forecasting; however, the benefit is affected by the model calibration strategy. Future work includes 1) addressing the bias issue in flood-orientated RS-SM assimilation; 2) identification of optimal strategy for information propagation from surface to root-zone; 3) comparison of different RS-SM products on flood forecasting; and 4) joint-assimilation of RS-SM and discharge for flood forecasting. The final aim is to develop an integrated strategy to optimal integrate RS-SM and in-situ discharge measurements into an operational flood forecasting system.

PUBLICATIONS LIST

Journal papers

- Grimaldi, S., Y. Li, V. R. N. Pauwels, J. P. Walker, Remote sensing-derived water extent and level to constrain hydraulic flood forecasting models: opportunities and challenges, conditionally accepted for publication in *Surveys in Geophysics (GEOP)*.
- Li, Y., S. Grimaldi, J. P. Walker, and V. R. N. Pauwels (2016), Application of Remote Sensing Data to Constrain Operational Rainfall-Driven Flood Forecasting: A Review, *Remote Sensing*, *8*(6), 456, doi: 10.3390/rs8060456.
- Wright, A., J. Vrugt, J.P. Walker, and V.R.N. Pauwels, Doing Hydrology Backwards: Retrieving Rainfall Distributions Using the Discrete Wavelet Transform, submitted for publication to Water Resources Research (June 6, 2016).

Conference papers and presentations

- Grimaldi, S., Y. Li, A. Wright, V. Pauwels, J. Walker, Use of remote sensing data to implement, calibrate, validate and constrain a hydraulic model for real time prediction of flood wave routing, 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.
- Grimaldi, S., Y. Li, A. Wright, V. Pauwels, J. Walker, Improving Flood Forecast Skill Using Remote Sensing Data - the hydraulic model component, Poster presented at the AFAC Conference, Adelaide, September 1-3, 2015.
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- Li, Y., S. Grimaldi, V. Pauwels, J. Walker, A. Wright. Combining hydrologic and hydraulic models for real time flood forecasting, Oral Presentation at the AFAC Conference, Adelaide, September 1-3, 2015.
- Li, Y., V. Pauwels, J. Walker, S. Grimaldi, and A. Wright. Evaluation of hydrological models for accepting in-situ and remote sensing observations, 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.
- 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.

- Pauwels, V., S. Grimaldi, Y. Li, A. Wright, J. Walker, Improving Flood Forecast Skill Using Remote Sensing Data, Oral Presentation at the BNH CRC Research Advisory Forum, Brisbane, November 18, 2015.
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- Wright, A., Y. Li, S. Grimaldi, V. Pauwels, J. Walker, A Holistic Approach to Rainfall Estimation for Operational Water Management, Oral Presentation at the MODSIM 2015, 21th International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, Gold Coast, November 29-December 4, 2015.
- Wright, A., Y. Li, S. Grimaldi, V. Pauwels, J. Walker, A Holistic Approach to Rainfall Estimation for Operational Water Management, Oral Presentation at the AFAC Conference, Adelaide, September 1-3, 2015.
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CURRENT TEAM MEMBERS

Project Leaders

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Jeffrey Walker

Research Fellows

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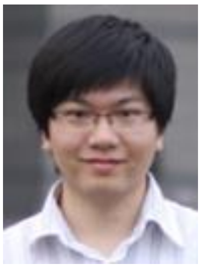

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