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IMPROVING FLOOD FORECAST SKILL USING REMOTE SENSING DATA

Annual project report 2014-2015

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

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Cover: Flooding in Brisbane, January 2011.

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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. 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

Soori Sooriyakumaran, *Bureau of Meteorology*

The Bureau of Meteorology has a national responsibility for flood forecasting and warning. In this capacity, the Bureau collects, manages, and processes rainfall and river data using a variety of systems. The river level data are mostly provided by other agencies such as state water agencies. The flood warning service is provided as a collaborative effort between all three levels of government.

The Bureau currently uses event based, conceptual rainfall runoff hydrological models and empirical relationships to provide the forecasts. The forecasts are provided as heights for forecast locations, and emergency services interpret these forecasts into flood extents and then impacts.

The Bureau has previously used satellite data such as from the MODIS satellite during floods to ascertain flood movement, especially in remote areas of WA where on gound observations are limited.

This project promises to provide some improvements to existing methods by incorporating satellite data. This data will help improve the soil moisture estimates, which is important to determine rainfall losses before runoff starts. The data will also provide additional information to estimating the river level and flood extent.

There are likely to be challenges in the application of these data in terms of resolution, availability and latency. The project will address these and provide the best guidance in incorporating satellite data.

Adam Lewis, *Geoscience Australia*

As the national Geoscience agency Geoscience Australia (GA) provides knowledge and information to inform government and society in a range of areas including providing fundamental geographic information and ensuring community safety. Geoscience Australia provides products from remote sensing to emergency management agencies and responders, and to the Bureau of Meteorology, including mapping of flood areas from MODIS imagery and, most recently, the Water Observations from Space (WOfS) product. WOfS shows the surface water observed from the Landsat satellites from 1986 onwards. During major disasters GA also sources information from other space agencies under the International Charter, Space and Major Disasters, including flood map products.

There are a range of challenges and opportunities associated with the mapping of flood areas from remote sensing and GA would like to see the project address these in order to improve the services available to the public. These include the ability to project the flooded area from a partial satellite image (e.g., an image which is cloud affected), extraction of surface water from Himawari-8 data streams, and the linking of mapped surface area of water to water volume.

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 frequently 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 (ongoing). 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 will be 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. Similarly 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

END USER INVOLVEMENT

During 2014-2015, a number of end-user meetings were organized. More specifically, these meetings where held on

- July 21, 2014 (Bureau of Meteorology, Melbourne)
- September 24, 2014 (Monash University, Clayton)
- December 1, 2014 (Bureau of Meteorology, Melbourne)
- April 8, 2015 (Bureau of Meteorology, Melbourne)

During these meetings, the end-users were involved in the catchment and model selection process, the acquisition of the data base, and the initial application of the models. It was agreed to organize these meetings on a bi-mothly basis during the initial stages of the project. However, as results will start to be generated, more frequent meetings are envisaged.

The following visits of project researchers at the end users institutes have occurred:

- Ashley Wright, Bureau of Meteorology, Melbourne, June 2-27, 2014, to become familiar with the flood forecasting teams, tools, and data sets.
- Stefania Grimaldi visited Geoscience Australia (GA) twice:
    - The first visit, together with Yuan Li, was completed on October 27th, 2014 with the purpose of planning the best strategy for the collection of remote sensing data of flood extent/level that were acquired during significant, recent flood events in a number of selected Australian catchment (please, refer to the paragraph "Scientific progress" for details).

      Stefania and Yuan met Jeff Kingwell (Head of the Project Management Office, Information Services Branch, Geoscience Australia and former End User Representantive) and Norman Mueller (Earth Observation Scientist, National Earth and Marine Observation Group, Environmental Science Division - Geascience Australia). Jeff Kingwell suggested the set-up of a temporary work station for Stefania at GA so that she could explore the data base of GA and retrieve a list of the remote sensing data of interest for the project. Agreements were taken for the fulfillment of the paperwork required for the set-up of the work station.
    - The second visit was then completed on November 27th -28th, 2014. During this visit, Stefania could explore the data base of GA and then compile a list of the availble remote sensing data of flood extent/level for each significant, recent flood event that occurred in the previously selected Australian catchments. Stefania received great support from Norman Mueller and a number of team-members of the group led by Jeff Kingwell.

- Yuan Li visited the Bureau of Meteorology, Melbourne, four times:
  - June 10, 2014, for collection of shapefiles of sub-catchments and rain gauges.
  - August 15-17, 2014, to extract precipitation data for the Clarence River basin from the BoM system.
  - December 10, 2014, for a workshop on an ARC Linkage project with Melbourne University. The BoM suggested to further promote collaboration between Universities on research flood forecasting.
  - February 2-5, 2015, to extract precipitation data of the Condamine River basin from the BoM system.

RECRUITMENT

The researchers that were hired for the project are:

- Ashley Wright, PhD. student, commenced March 27, 2014, confirmed March 12, 2014.
- Yuan Li, Research Fellow, May 5, 2014.
- Stefania Grimaldi, Research Fellow, July 1, 2014.

CONFERENCE AND WORKSHOP ATTENDANCE

The following conferences, in which material on the project was presented, were attended during 2014-2015:

September 2-5, 2014, AFAC Conference, Wellington, NZ (Valentijn Pauwels, Ashley Wright)

December 3-4, 2014, BNH CRC Research Advisory Forum, Melbourne (Valentijn Pauwels, Stefania Grimaldi, Yuan Li)

SCIENTIFIC PROGRESS

Selection of the study sites

The selection of the catchments to be used as case test sites was based on the criteria listed above.

A first list was compiled based on the first three criteria; this list included the following catchments: Avon, Fitzroy and Ord (WA); Condamine-Culgoa-Balonne (QLD); Clarence, Murrumbidge (NSW); Wimmera, Loddon, Campaspe, Ovens, Murray-Riverina, and the Murray river upstream of the Lake Hume (VIC).

The observed significant impact of different soil moisture initial conditions on recent flood events and the interest shown by the local Council highlighted the Clarence catchment as possible first case study.

The forth and the fith criteria, i.e. the availability of data, was then decisive. Hydrological, hydraulic and remote sensing data of soil moisture are equally available for all catchments. A survey on the availability of remote sensing data of water extent/level was completed with the support of Geoscience Australia. A large number of SAR and high resolution optical images were available for the flood events that occurred in January 2011 and in February 2012 in the Condamine-Culgoa-Balonne and in January 2011 and February 2013 in the Clarence catchment. Limited remote sensing data of water extent/level were available for the remaining catchments. The Clarence and the Condamine-Culgoa-Balonne were then selected as case studies (December 1, 2014).

Hydraulic model: selection and preliminary application

The numerical modeling of flood waves routing requires the solution of the Shallow Water Equations (SWEs). The criteria listed above led to the selection of two numerical models among the large number listed in literature, these models were ANUGA (Nielsen et al., 2005; Geoscience Australia and Australia National University, 2010) and LISFLOOD-FP (Bates et al., 2000, 2010). Both ANUGA and LISFLOOD-FP were used for the assessment of the flood event that occurred in the Towaradgi catchment (NSW, Australia) in 1998. A comparison between observed and modelled water depth values proved that the accuracy of both models matched the purpose of our project. However, the higher computational efficiency along with the lower implementation effort of LISFLOOD-FP drove our final choice.

We then modified the original code of LISFLOOD-FP* in order to be able to implement a spatially variable mesh size: a refined mesh size is used for the modeling of the flood wave in the urban areas; a larger mesh size is used for the modeling of the flood wave in the floodplains.

Our code LISFLOOD-FP* was then used to model the flood event that occurrend in January (8-15) 2011 in the Clarence catchment. The partial availability of the data required for the implementation of the model limited the accuracy of our results. When compared to the values of water level measured by 4 gauging stations, the average RMSE of the model results was at about 1m.

The data collection will be completed by December 2015. In particular, a field campaign has been planned to complete the dataset of high resolution bathymetric data. Furthermore, high resolution DEMs and the geometric details of bridges and culverts will be collected and implemented. Finally, high resolution airbone imagery will be used to increase the accuracy of the assessment of the model parameters. These data will allow the calibration and the validation of our model LISFLOOD-FP* based on in-situ and remote sensing water extent and level measures.

Hydrological model: selection and preliminary application

Conceptual hydrologic models have been widely implemented for operational flood forecasting due to their better representativeness of catchment hydrologic processes compared to purely data-driven models, and their higher computational efficiency compared to fully process-based models. A recently developed flood forecasting system – Short-term Water Information Forecast Tools (SWIFT) (Pagano et al., 2011) by the Australian Bureau of Meteorology has included thirteen conceptual rainfall-runoff models. Among these models the GR4 model (modèle du Génie Rural à 4 paramètres) has been identified as an important forecasting candidate model, thanks to its satisfactory performance in Australian catchments (Li et al., 2014; Pagano et al., 2010). However, GR4 is not designed to use remote sensing data as it has one bulk soil water store only. To better use remote sensing information, another two GR models, GRHUM (Loumagne et al., 1996) and its newer version GRKAL (Francois et al., 2003), have been built into SWIFT. Both models have 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. Based on this, the GRKAL were then implemented for cabliration experiments using both streamflow and remote sensing soil moisture data. The results indicate that introducing soil moisture products can improve the soil moisture predictions, but the effect on streamflow prediction is not significant. Future work is to assimilate remote sensing soil moisture data for real-time state and/or parameter updating. The efficiency of soil moisture assimilation will be evaluated in synthetic and real-time scenarios.

PUBLICATIONS LIST

Conference Presentations

Grimaldi, S., Y. Li, A. Wright, J. Walker, V. Pauwels, Improving Flood Forecast Skill Using Remote Sensing Data, Poster Presented at the AFAC Conference, Wellington, NZ, September 2-5, 2014.

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, Extended Abstract Submitted to 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 Submitted to the AFAC Conference, Adelaide, SA -Australia, 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 Submitted to the AFAC Conference, Adelaide, SA -Australia, September 1-3, 2015.

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Li, Y., V. Pauwels, J. Walker, S. Grimaldi, and A. Wright. Evaluation of hydrological models for accepting in-situ and remote sensing observations, Extended Abstract Submitted to 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.

Pauwels, V., S. Grimaldi, Y. Li, A. Wright, J. Walker, Improving Flood Forecast Skill Using Remote Sensing Data, Presented at the BNH CRC Research Advisory Forum, Melbourne, December 3, 2014.

Wright, A., Y. Li, S. Grimaldi, V. Pauwels, J. Walker, A Holistic Approach to Rainfall Estimation for Operational Water Managment, to be Presented at the MODSIM 2015 conference, Gold Coast, November 29-December 4, 2015.

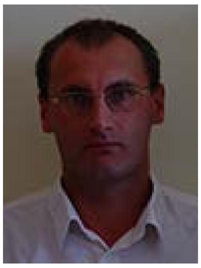
Wright, A., Y. Li, S. Grimaldi, V. Pauwels, J. Walker, Improving Flood Forecast Skill Using Remote Sensing Data, Poster Presented at the AFAC Conference, Wellington, NZ, September 2-5, 2014.

Wright, A., Y. Li, S. Grimaldi, V. Pauwels, J. Walker, A Holistic Approach to Rainfall Estimation for Operational Water Managment, to be Presented at the AFAC Conference, Adelaide, September 1-3, 2015.

CURRENT TEAM MEMBERS

Project Leaders

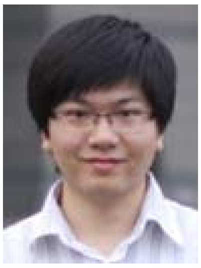
Valentijn Pauwels



Jeffrey Walker

Research Fellows

Yuan Li



Stefania Grimaldi

PhD. Student

Ashley Wright

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