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IMPROVING FLOOD FORECAST SKILL USING REMOTE SENSING DATA

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ABSTRACT

IMPROVING FLOOD FORECAST SKILL USING REMOTE SENSING DATA

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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

Soori Sooriyakumaran, *Flood Policy Unit, Bureau of Meteorology, Melbourne, VIC*

The Bureau of Meteorology has a national responsibility for providing a flood forecasting and warning service. In this capacity, the Bureau collects, manages, and processes rainfall and river data using a variety of collection systems. The river level data from gauging stations 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 at forecast locations, and emergency services interpret these forecasts into flood extents and impacts.

The Bureau has recently begun using soil moisture estimates from a water balance model run at national scale. This model uses remotely sensed soil moisture data and helps in estimating possible initial losses at the start of a flood event. The use of flood extent models during flood warning operations will be a planned future activity to the Bureau.

This development of the hydrologic and hydraulic models by the project has the potential to further improve the modelling capability. The Water Observations from Space products contributed by Geoscience Australia can be used to understand flooding extents from past floods. There is potential for allied activities such as the better definition of the channel carried out by this project to contribute to indirect benefits such as improving rating curves, which are key to convert height to flow at a gauging station.

The project is addressing the challenges in the application of remotely sensed data in terms of resolution, availability and latency, and this effort is expected to provide good guidance to incorporating satellite data to improve soil moisture estimates and flood extent in the future.

David Hudson, *Geoscience Australia, Canberra, ACT*

Geoscience Australia is excited about the potential of this project to improve operational data to emergency managers. Using remote sensing measurements connected to ground observations is an exciting research area which has the potential to improve operational decision making by creating more accurate, simpler and more actionable flood advice.

The most exciting part of this project for GA is the development of an operational Sentinel 1 water classifier which can be added into our Water Observations from Space product or WoFS. The WoFS product can then be ingested into the operational flood modelling tools built by this project within the Bureau of Meteorology.

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.

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 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 OPTIMIZATION

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.

METHODS

HYDROLOGIC MODELLING

Two conceptual hydrologic models, GRHUM (Loumagne et al., 1996 [3]) and its updated version GRKAL (Francois et al., 2003 [4]), were built into the BoM's streamflow forecasting framework – Short-term Water Information Forecast Tools (SWIFT). The GRKAL was finally selected for of the assimilation of remote sensing soil moisture (RS-SM) data, due to its advantage in propagating surface SM information into root-zone. Figure 1 provides a schematic of the model.

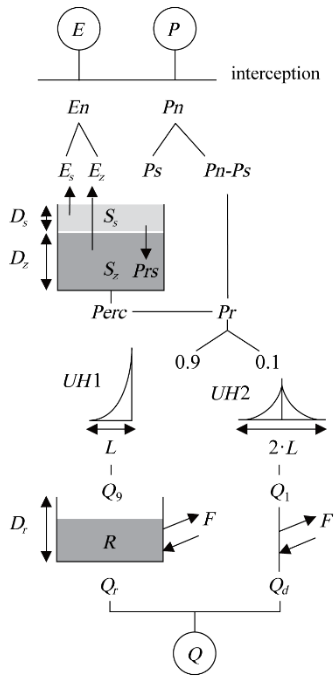

FIGURE 1 THE STRUCTURE OF THE GRKAL MODEL (FRANCOIS ET AL., 2003).

Data collected for this project include gauged precipitation, gauged streamflow, potential evapotranspiration (PET), SMOS RS-SM, and RS fractional vegetation cover (fc) for January 2010–June 2014. The precipitation data were obtained from the Australian Bureau of Meteorology. The streamflow data were obtained from the New South Wales Office of Water and Queensland Department Natural Resources and Mining. The PET was extracted from the Australian Water Availability Project (AWAP) monthly PET product (Raupach et al., 2009; Raupach et al., 2012). The 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). The MODIS vegetation cover data were obtained from National Computational Infrastructure (NCI).

A joint calibration scheme using streamflow measurements and RS-SM values was developed and compared with a streamflow only calibration scheme. An experiment was conducted to investigate the efficiency of the calibration schemes in three modelling setups: 1) a lumped model; 2) a semi-distributed model with only the outlet gauge available for calibration; and 3) a semi-distributed model with multiple gauges available for calibration. Based on the calibrated model, a fixed-lag ensemble Kalman smoother (EnKS) (Dunne and Entekhabi, 2006; Li et al., 2013) was introduced to assimilated RS-SM data. A synthetic experiment was conducted to demonstrate the benefit of using the EnKS compared with using the ensemble Kalman filter (EnKF). The proposed method will be further implemented for real data assimilation for real-time forecasting.

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 of 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 DEM is available only for the Clarence catchment. A medium resolution (30 m), medium accuracy DEM is available for the Condamine-Balonne catchment. A research proposal for the application of the 12 m TanDEM-X DEM for flood forecast in the Condamine-Balonne catchment was approved by the TanDEM-X Science Service System thus securing the availability of a higher resolution, more recent DEM. DEMs' co-registration errors, vegetation artefacts, and poor representation of the river network cause large uncertainties and errors in the numerical modelling of floods. 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). A data-parsimonious methodology for the definition of an effective river bathymetry representation in medium to high resolution flood forecasting hydraulic models was derived. Simplified, yet effective cross section geometries can be defined based on a combination of limited field data, global database, and remote sensing data.

The hydraulic model is being calibrated using a multi-objective calibration protocol based on a combination of field data, remote sensing-derived observations of flood extent and water levels. The effectiveness of a calibration protocol based on remote sensing-derived observations only will also be investigated. For these purposes an accurate inversion of remote sensing data into maps of flooded and non-flooded areas is essential. Methodologies to complement and improve the existing inversion algorithms are being investigated.

RESULTS

HYDROLOGIC MODELLING

The joint calibration experiment was conducted for two large catchments, the Clarence upstream of Lilydale and the Condamine upstream of Chinchilla using a semi-distributed hydrologic model. A slight degradation in streamflow simulation was generally found at the calibration locations during the calibration period when RS-SM was used for calibration, which is expected. However, improvements were also obtained in the independent validation period for some sub-catchments. Although the improvement did not pass the overall significance test, it unveiled a potential to improve future forecasts through the identification of more robust parameter sets by including RS-SM information in the calibration. A more consistent improvement, brought by using RS-SM data, was identified at gauges where streamflow data were not used for calibration (assumed "ungauged" locations). The improvement in Nash-Sutcliffe model efficiency coefficient was found to be statistically significant at the 0.01 significance level. Figure 2 illustrates the hind-casting results of two flood events at Paddys Flat. It shows that the joint calibration (with RS-SM information) leads to better match between model predictions and observations compared with streamflow only calibration (without RS-SM information) at an "ungauged" site. Furthermore, it was also found that the improvement was stronger at upstream and tributary sub-catchments than the downstream locations.

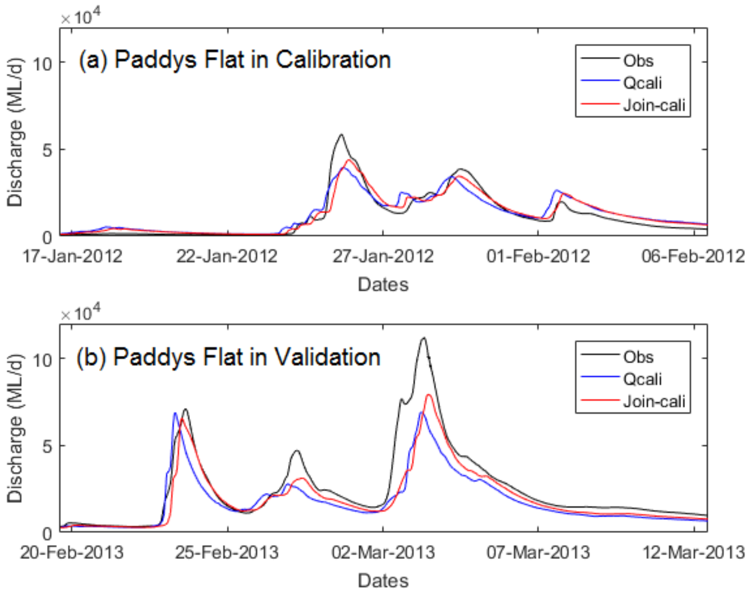

FIGURE 2 STREAMFLOW PREDICTION AT "UNGAUGED" LOCATIONS OF PADDYS FLAT SHOWING ONE FLOOD EVENT IN THE CALIBRATION PERIOD AND ANOTHER IN THE VALIDATION PERIOD.

The synthetic RS-SM assimilation experiment was conducted for a lumped GRKAL model in the Condamine upstream of Warwick. The results indicate that the smoothing method (EnKS) addressed errors in antecedent state variables more thoroughly compared with the direct filtering approach (EnKF). The improvement in the antecedent state variable analysis was then propagated to the streamflow forecasts through the routing process so as to improve flood forecasting. The benefit of using the EnKS compared with the EnKF had its highest significance right after the assimilation and decreased with the increase of forecasting lead time, as illustrated in Figure 3. The strength of the smoothing approach exhibited in the synthetic study indicates a potential to improve flood forecasting in real world applications.

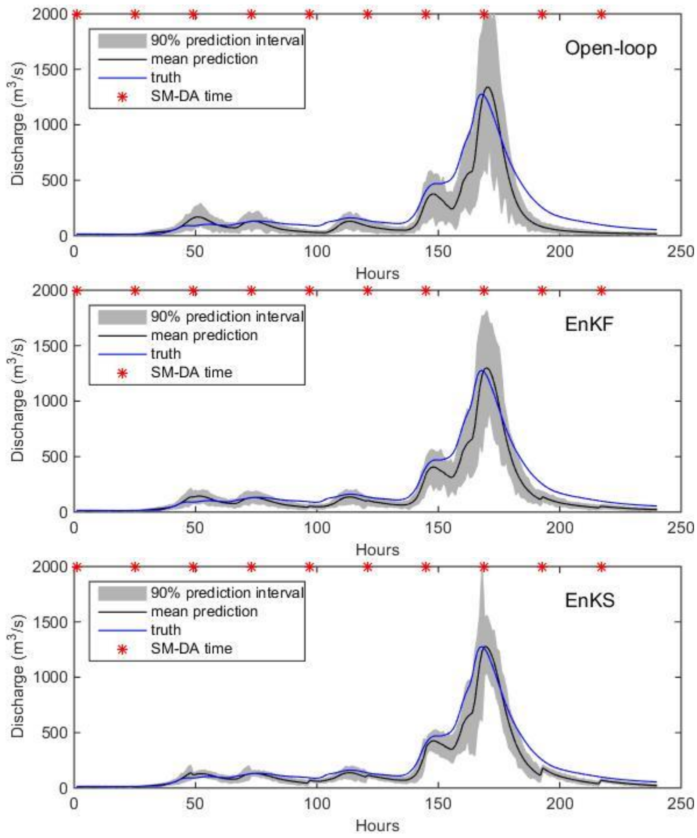

FIGURE 3 ENSEMBLE STREAMFLOW PREDICTION BEFORE AND AFTER DATA ASSIMILATION FOR AN EVENT IN 2011.

Hydraulic modelling

Accurate modelling of river flow dynamics is essential to simulate floodplain inundation. Bathymetric data are thus critical to the application of hydraulic models. However, it is impossible to measure river bathymetry along the total river length, especially in large basins. While river width can generally be retrieved from space, river depth and channel shape cannot be systematically observed remotely. Where channel geometry is unknown, channel shape, depth, and friction can be estimated through calibration, but different parameter sets can often map model predictions to the observed data generating an equifinality problem. Conversely, even an approximated knowledge of river bathymetry can provide a more robust model setup.

Bathymetric data were available for ~80% of the total modelled length of the Clarence River. This peculiarly data rich case study provided the opportunity to investigate (1) the level of geometrical complexity required for the representation of river bathymetry in hydraulic flood forecasting models; and (2) the definition of a data parsimonious methodology for the representation of river bathymetry in many data scarce catchments in Australia and worldwide.

A number of simplified geometrical models of river bathymetry were derived from cross sections sampled along the Clarence River. These simplified geometrical models had to be data-parsimonious. That is, each geometrical model was built from the combination of a limited number of measured cross sections selected from the complete field database, a global database and remote sensing data of river width.

The effectiveness of the proposed simplified geometrical models for flood prediction was tested using a numerical experiment. A high resolution model realization based on all available bathymetric field data was considered as truth. Subsequently, each simplified geometrical model of river shape was embedded into LISFLOOD-FP and the results compared against "true" water level hydrographs and maps of flood extent and levels. Based on this analysis, a data-parsimonious methodology for the definition of an effective river bathymetry representation in medium to high resolution raster-based flood forecasting hydraulic models was derived. A rectangular, width-varying shape was identified as the most effective simplified geometrical model, with width values derived from remote-sensing data; depth values assessed using a combination of global database and limited field data. Alternatively, an exponential cross section shape could be used; shape, depth and width were estimated using a combination of a global database and limited field data. Fig. 4a shows a schematic of the simplified shapes; fig. 4b shows the agreement between floodplain water levels predicted using the high resolution, data rich true model and the parsimonious model based on a simplified representation of the river.

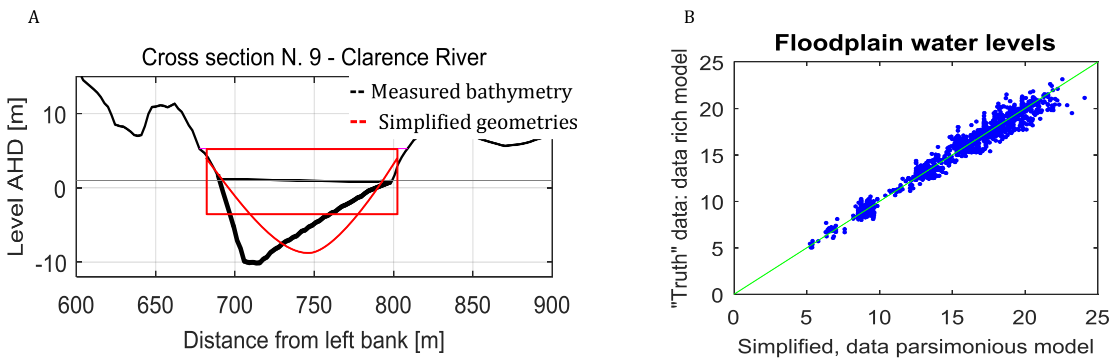

FIGURE 4A - CLARENCE RIVER, EXAMPLE OF CROSS SECTION. BLACK: FIELD DATA; MAGENTA: BANKFULL LEVEL; RED: RECTANGULAR SIMPLIFIED GEOMETRY AND EXPONENTIAL SIMPLIFIED GEOMETRY. FIGURE 4B - COMPARISON OF THE RESULTS OF DATA RICH MODEL WITH THE RESULTS OF THE SIMPLIFIED MODEL

The outcomes of to this numerical experiment allowed the implementation of the hydraulic model for the Clarence catchment, from Lilydale (the output point of the hydrologic model) to Yamba (the river mouth). The calibration of the model is based on multi-objective protocol using a combination of field data, and remote sensing-derived observations of flood extent and water levels.

The inversion of RS images into maps of flooded areas is in progress. In particular, this project aims at improving the detection of floods in densely vegetated areas using active microwave imagery from synthetic aperture radar (SAR). Thanks to its all-weather, 24 hours acquisition capabilities, SAR is deemed to be the only reliable source of information for monitoring floods on rivers less than 1 km in width. SARs are active systems that emit microwave pulses at an oblique angle towards the target. The amount of microwave energy scattered off an object or feature is primary 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, multiple reflections due to emerging vegetation cause an increased backscatter that can lead to an underestimation of the flood extent. This is a frequent condition in many Australian drylands (e.g. the Condamine-

Balonne catchment) where dense vegetation in the riparian zone hampers the detection of the flood margin. The backscatter response of dry and flooded vegetation has been investigated using nine SAR images (three Cosmo Sky Med images and eight Alos Palsar images) acquired over the Condamine-Balonne catchment during the flood event in January 2011. The statistical analysis of backscatter response from different land cover classes in dry and wet conditions has led to the definition of a method for the detection of floods in densely vegetated areas. The accuracy of this method is being assessed using airborne optical imagery.

In the panel below, Fig 5a shows SAR data acquired by Cosmo Sky Med satellite upstream of the township of Surat on January 2001, 4th at 6 pm; Fig. 5c shows an optical airborne image acquired over the same area on January 2011, 4th at 2 pm (QLD-DNRM). Fig. 5b shows the distribution of backscatter values for the land cover "trees –sparse" in dry and wet conditions. Fig. 5d shows the proposed classification of the Cosmo Sky Med SAR image. Light blue areas were classified as flooded using a thresholding algorithm widely used in literature. Dark blue areas and pink areas were respectively classified as flooded and non-flooded using the algorithm developed by this project. Based on these preliminary results, the method developed by this project has the potential to improve the detection of floods in densely vegetated areas.

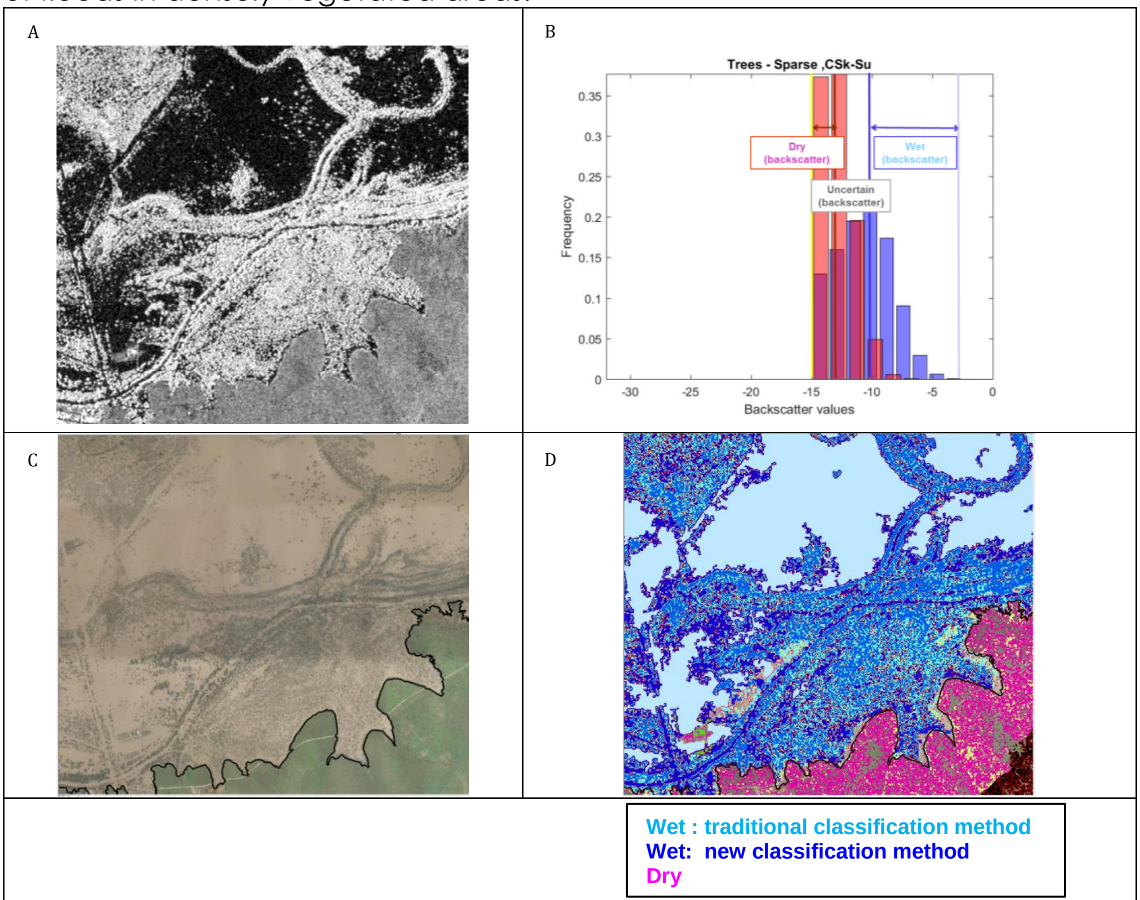

FIG. 5A – COSMO SKY MED IMAGE ACQUIRED ON JAN. 4TH, 2011 UPSTREAM OF SURAT; 5B- STATISTICAL ANALYSIS OF THE DISTRIBUTION OF THE BACKSCATTER RESPONSE OF THE LAND COVER "TREES SPARSE" IN DRY AND WET CONDITIONS; 5C – AIRBORNE OPTICAL IMAGE ACQUIRED ON JAN. 4TH 2011 UPSTREAM OF SURAT; 5D – RESULST OF THE CLASSIFICATION METHOD APPLIED TO THE COSMO SKY MED IMAGE.

DISCUSSION

The objective of this project is to improve flood forecasting systems through the use of remote sensing data. For the two models upon which flood forecasting systems are based, a different approach has been developed. For the hydrologic part, soil moisture has been proven to make the results of the parameter estimation more robust. Model results for ungauged areas have improved strongly. The use of remotely sensed soil moisture data for online state updating also improved the forecasted hydrographs. The use of a fixed-lag smoother has been shown to lead to the best results.

For the hydraulic model, an algorithm to invert the satellite data into flood extents is being developed. The preliminary results show that this algorithm has the potential to provide more accurate flood detection in densely vegetated areas. The remote sensing data, combined with in-situ data, are being used to implement a multi-objective calibration scheme. A data-parsimonious methodology for the definition of an effective river bathymetry representation in flood forecasting hydraulic models was derived. A preliminary assessment of river bathymetry is derived from the combination of remote sensing data, global database, and a very limited number of field data. Remote-sensing observations are pivotal to calibrate the parameters of the preliminary assessment.

CONCLUSION

The project has already achieved a number of important steps towards the use of remote sensing data in flood forecasting systems. A scheme for both the calibration and on-line updating of hydrologic models using remotely sensed soil moisture has been developed. A classification algorithm to invert satellite data into flood extents is being developed. The impact of river geometry on flood wave inundation modelling has been analyzed. The calibration of the hydraulic model using these remote sensing data, combined with in-situ data, is ongoing. Further steps in the project will work on a further integration of the remote sensing data with the models.

ACKNOWLEDGEMENTS

We want to thank our end users, Geoscience Australia, the Bureau of Meteorology, and the New South Wales State Emergency Service for the continuous support. We also want to thank the Clarence Valley Council, the Balonne Shire and Sunwater Ltd. for their support of the project.

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