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Quantitative precipitation forecasts and early flood warning: the Hunter Valley flood of June 2007

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Abstract: Traditionally, flood forecasting and warning systems are a customized user interface around hydrological and hydraulic models. While this model centric approach may represent a system perfectly able to provide forecasts using the model and data it was designed for, it offers disadvantages in the perspective of changing model and data requirements (Werner *et al.*, 2009). In the context of developments in Numerical Weather Prediction (NWP) and the collection and availability of on-line satellite, meteorological and hydrological data, a trend is observed in flood forecasting, signaling an increased need for flexibility with regard to data stream management and also the choice of forecasting model.

The Deltares' Flood Early Warning System (Delft-FEWS) is an example of a system that has been developed in response to this need. To evaluate the use of gauged and multiple spatially distributed, gridded rainfall data streams, a retrospective analysis is carried out through application of this system to an actual recent flood event, i.e. the Hunter Valley flood of June 2007, New South Wales (NSW), Australia. This involved simulating the operational modeling and forecasting of the event with (as much as possible) the actual model and data as used by the Bureau of Meteorology NSW Flood Warning Centre, along with other potentially useful data, such as spatially distributed, gridded fields of observed rainfall and Quantitative Precipitation Forecasts (QPF) from NWP model output.

The retrospective simulations show how the use of QPF from NWP model output data can assist in early flood detection. The hydrological model forced with QPF data is able to pick up river flows at flood level as early as 5 days before the onset of the Hunter Valley flood, while the forecasts forced with observed rainfall registers a flood signal not earlier than 4 days later. The early flood signal, however, is not persistent in the following forecast days in the lead up to the flood event. This is due to the relatively coarse spatial resolution of the QPF data in relation to the size of the river basin. It introduces an uncertainty in the location and magnitude of forecast peak rainfall, which is either inside or outside the river basin. A combination of flood forecasts forced with two separate QPF data streams results in a more persistent early warning signal and points to the potential benefit of the use of multiple QPF data.

While this study confirms the potential advantage of the quantitative use of QPF for early flood detection in this particular case, performances may differ from event to event and/or region to region (Gouweleeuw *et al.*, 2005). Hence, longer and continuous periods should be considered to include as many (historical) flood events as possible (including non-flood events) to gain insight in the ratio of false warnings.

Flood forecast simulations using a 'warm' start do not necessarily improve on 'cold' start forecasts unless initial conditions are correctly represented. This in turn requires an accurate input of observed variables and a correctly calibrated hydrological model to produce the initial conditions.

Keywords: *Spatially distributed rainfall, Quantitative Precipitation Forecasts, Early flood warning*

1. INTRODUCTION

The Australia Bureau of Meteorology (BoM) has provided national flood warning services for nearly a century (McKay, 2005). Since 1962 quantitative warning systems are in place, currently for over a hundred river basins in Australia. The Unified River Basin Simulator (URBS) (Caroll, 2007) is one of the hydrological models behind the quantitative warning systems and uses gauged rainfall, and gauged upstream flows if available, to forecast flow downstream. Typically operated in an event-based mode, initial rainfall loss is estimated at the start of a flood event. The model is semi-distributed, with a routing network connecting runoff generated from sub-catchments, the smallest spatial scale in the model setup. The use of spatially variable, gridded rainfall input is considered to have the potential to improve the accuracy of flood forecasts at the sub-catchment outlets as well as at the main catchment outlet.

When using measured or estimated rainfall that has fallen onto the catchment, forecast lead-time is largely determined by catchment and stream routing response time. In many cases, longer lead-times are needed for effective actions to be taken to prepare for potential flood events. This will require the use of rainfall forecasts in addition to gauged rainfall and upstream flows as input to the hydrological model. The effective use of quantitative precipitation for flood forecasting has been identified as the number one issue by the BoM's flood warning operational staff (Catchlove *et al.*, 2005). While Quantitative Precipitation Forecasts (QPF) from Numerical Weather Prediction (NWP) systems have been a qualitative input to flood warning operations for some years, it has only been recently that the accuracy and spatial resolution of these forecasts have approached the level where more quantitative input can be considered.

The point made above with regard to the use of QPF and gridded rainfall data illustrates a general trend observed in flood forecasting, signaling an increased need for flexibility with regard to data stream management and also the choice of hydrological/forecasting model. The Deltares' Flood Early Warning System (Delft-FEWS) is an example of a system that has been developed in response to this need. FEWS is build as a collection of configurable modules, which constitute an open shell system for managing forecasting processes, handling (spatial) time series data and operating external forecasting models. The FEWS wiki-page (http://fewswiki.wldelft.nl) provides a comprehensive description of the system.

With the BoM's new role in providing water resources information services for Australia, the flood forecasting and warning services will be expanded to also include the quantitative use of spatial rainfall observations and forecasts. To this end and within the context of the WIRADA[1] project, the URBS model has been linked to the FEWS platform, which is subsequently applied to a recent flood event, i.e. the Hunter Valley flood of June 2007 in NSW, Australia. This paper describes the retrospective simulation of the operational modeling and forecasting of the flood event in FEWS with the actual model and data as used by the BoM's NSW Flood Warning Centre, supplemented with gridded fields of observed rainfall and QPF data.

2. THE HUNTER VALLEY FLOOD OF JUNE 2007

Storms commenced on Friday 8 June 2007 and caused extensive flooding, damage of property and loss of life in the Hunter Region and on the Central Coast in NSW, Australia (Fig. 1). The Hunter Valley has a history of floods, the most notable being the February 1955 event, which devastated the City of Maitland and floodplains of the Hunter. The June 2007 flood was the largest Hunter river flood in 36 years.

An intense low pressure system developed off the Central Coast of NSW on the night of Thursday 7 June and over the next 36 hours the state's Hunter and Central Coast areas were battered by the system's strong winds and torrential rain. A number of fatalities occurred at the height of the storms on 8 June with two more storm related deaths occurring on 9 June bringing the total death toll to 10.

Rainfall exceeded 300 mm in the Hunter region and 200 mm in parts of the Central Coast and Sydney. The affected areas were declared a natural disaster zone by then New South Wales Premier Morris Iemma. Nearly 6000 State Emergency Service volunteers, including crews from across NSW, ACT and Victoria worked in the area and responded to over 10,000 calls for assistance. At one point, more than 105,000 homes were without power.

On the evening of Sunday 10 June, approximately 4000 residents in the Hunter Valley including residents of Maitland were forced to evacuate their homes in anticipation that the Hunter river would breach its levee.

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[1] Water Information Research and Development Alliance between CSIRO and the BoM

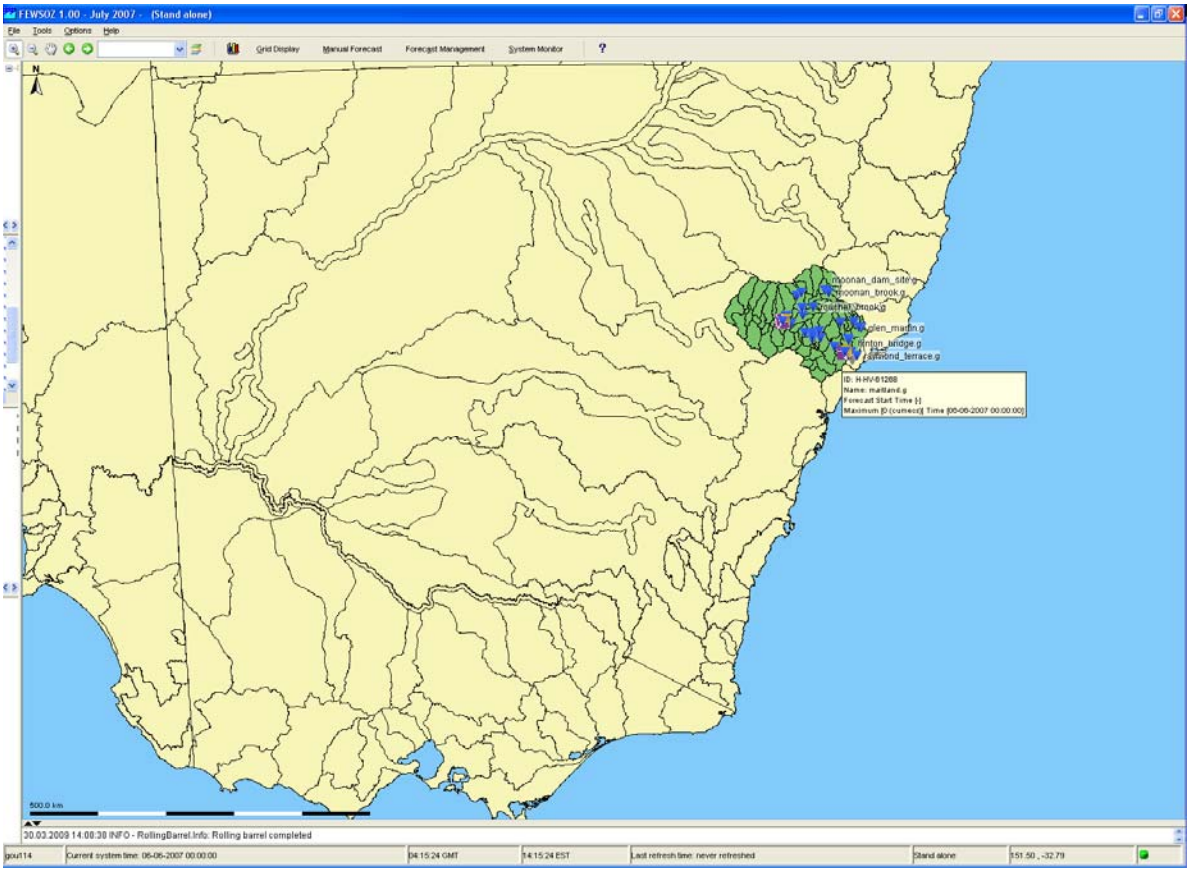

Figure 1. The FEWS explorer display of the Hunter Valley river basin, located on the NSW Central Coast, Australia with water level gauge locations provided by the BoM Water Division. The highlighted locations are Sandy Hollow and Maitland (tagged).

Evacuation centers were set up in Maitland However, by the morning of the 11 June the flood water had peaked without breaking the levee bank (Wikipedia, 2007).

3. DATA

3.1. Historical data

Point data of uncorrected gauged rainfall and water level for the period 4-16 June 2007 are provided by the BoM Water Division. As pointed out earlier, these are the actual data used by the NSW flood warning centre. Rainfall data of 21 gauges are made available as tipping bucket time series of accumulated rainfall. Water level data for 30 stations are made available together with rating data in order to enable the computation of the associated river flow.

In addition to the observed gauge data, gridded data of observed daily precipitation for the period 1 January-1 July 2007 are collected from the BoM SILO Climate Database. Data are provided for the Australian continent at 0.05 degree lat/lon resolution and are produced automatically from preliminary data, by the National Meteorological and Oceanographic Centre, with limited quality control on the data. Daily rainfall observations are made at 9am local time, and the daily rainfall for a particular day denotes the rainfall which falls during the 24 hours to 9am on that day. Further, the post real-time Tropical Rainfall Measuring Mission (TRMM) Multi-Satellite Precipitation Analysis (TMPA) product, 3B42. is collected from the NASA Goddard Space Flight Center Distributed Data Archive Center (GSFC DAAC) for the period 01/06/2007-01/07/2007 and subset for the Australian continent (Renzullo, 2008). The data are instantaneous precipitation rates at 0.25° x 0.25° degree grid resolution time-stamped at 3-hourly intervals.

3.2. Forecast data

Global Forecast System (GFS) data for the period 1-30 June are extracted from the US National Oceanic and Atmospheric Administration (NOAA) National Operational Model Archive and Distribution System (NOMADS), provided by the US National Climatic Data Center (NCDC) (nomads6.ncdc.noaa.gov). It is maintained as a backup server for the US National Weather Service (NWS) National Centers for Environmental Prediction (NCEP) real-time server. The forecast data fields have global coverage at a 1.0 degree resolution. The 180 hour forecast lead time is provided with a 3 hourly time step. In total, 157

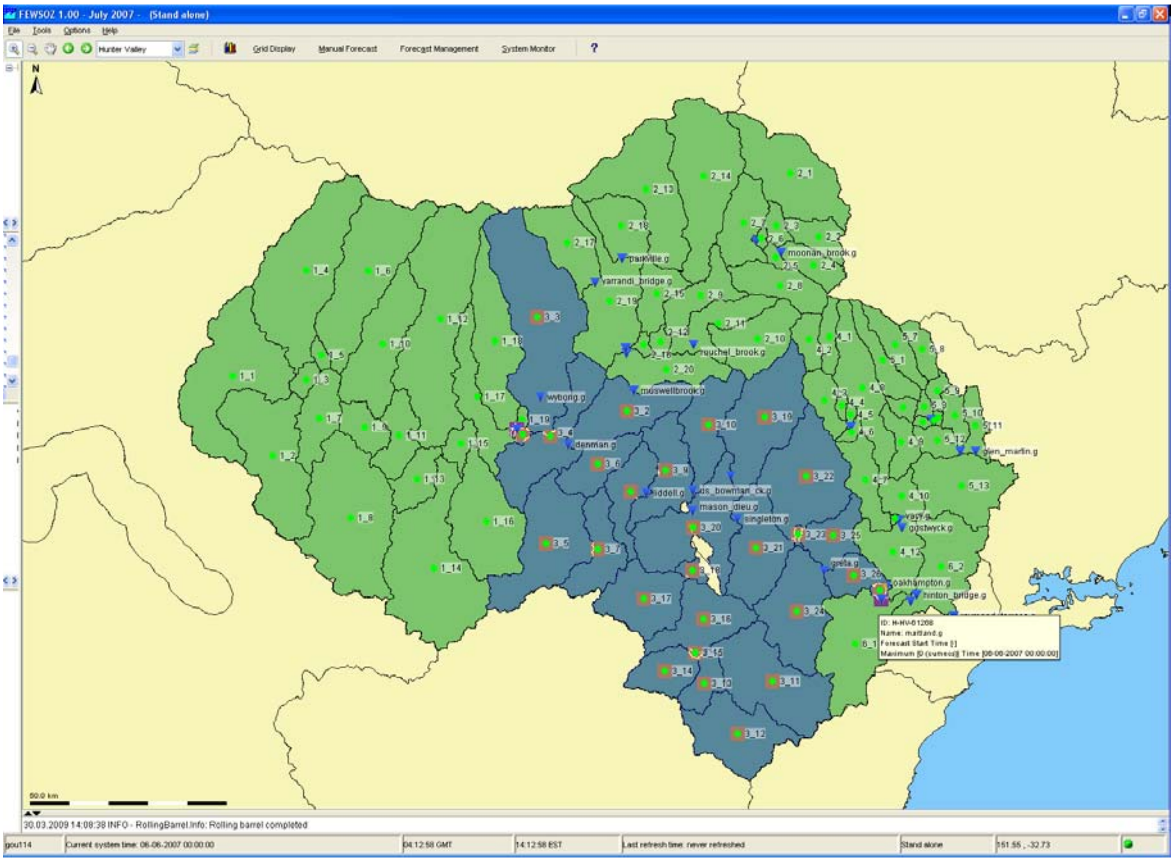

Figure 2. The FEWS explorer display of the Hunter Valley river basin, as defined in the URBS model. It distinguishes 6 catchments, which are subdivided into sub-catchments, represented by centroids. For example, the highlighted Middle Hunter catchment (3) is subdivided in 27 sub-catchments. The water level gauge locations are also shown. The gauges at the outlet of the Goulburn catchment (1), Sandy Hollow, and Middle Hunter catchment (3), Maitland (tagged), are highlighted.

variables are made available, of which only precipitation is used. Four forecast cycles are available at a 6 hour interval, of which only the midnight forecast at 00:00 is selected.

NWP data of the Limited Area Prediction Model (LAPS) of the BoM are provided for the period 1-16 June 2007. The LAPS data cover the Australian continent at a 0.375 degree resolution and are made available twice a day, at 00:00 and 12:00. The forecasts have a 72 hour lead time and an hourly time step. In total, 24 variables are provided, of which only precipitation is used.

4. MODELLING AND FLOOD FORECASTING

In flood forecasting two modes of operation may be distinguished, i.e. an event-based mode and a continuous mode. The latter is typically subdivided into a historical mode and a forecast mode. The historical mode utilizes hydrological and atmospheric forcing from observations over a period of time prior to start of the forecast. The internal model states at the end of the historical run are carried over as the initial conditions for the forecast, which is run over the length of the forecast lead time using quantitative predictions of rainfall. This is called a 'warm' start, as opposed to a 'cold' start, which does not use the carried over internal model states. In continuous flood forecasting, the 'warm' start generally produces a more accurate forecast, as it takes into account the water already in the system. An inaccurate historic simulation, however, will produce inaccurate initial conditions. By definition, event-based flood forecasting employs a 'cold' start. Rainfall lost to the river basin before surface run off occurs may be estimated as initial loss. This is the case in the URBS model, which is typically applied in event-based mode by the BoM in its flood forecasting operations. In this study, for forecast days when initial conditions deviate from 'cold' start conditions, the model is run in a proxy-continuous and event-based mode. The term proxy-continuous is used here, because no soil moisture accounting is provided for and the warm up period is relatively short, i.e. the length of period observed data is available to up to 2 weeks. The historical run of the URBS model is forced with gauged data of precipitation and water level and gridded SILO and TRMM precipitation data. In forecast mode, forcing is provided by the GFS data (180 hrs lead time) and the LAPS data (72 hrs lead time). A completely set-up and calibrated version of the URBS model for the Hunter Valley is provided by the BoM Water Divison (Fig. 2).

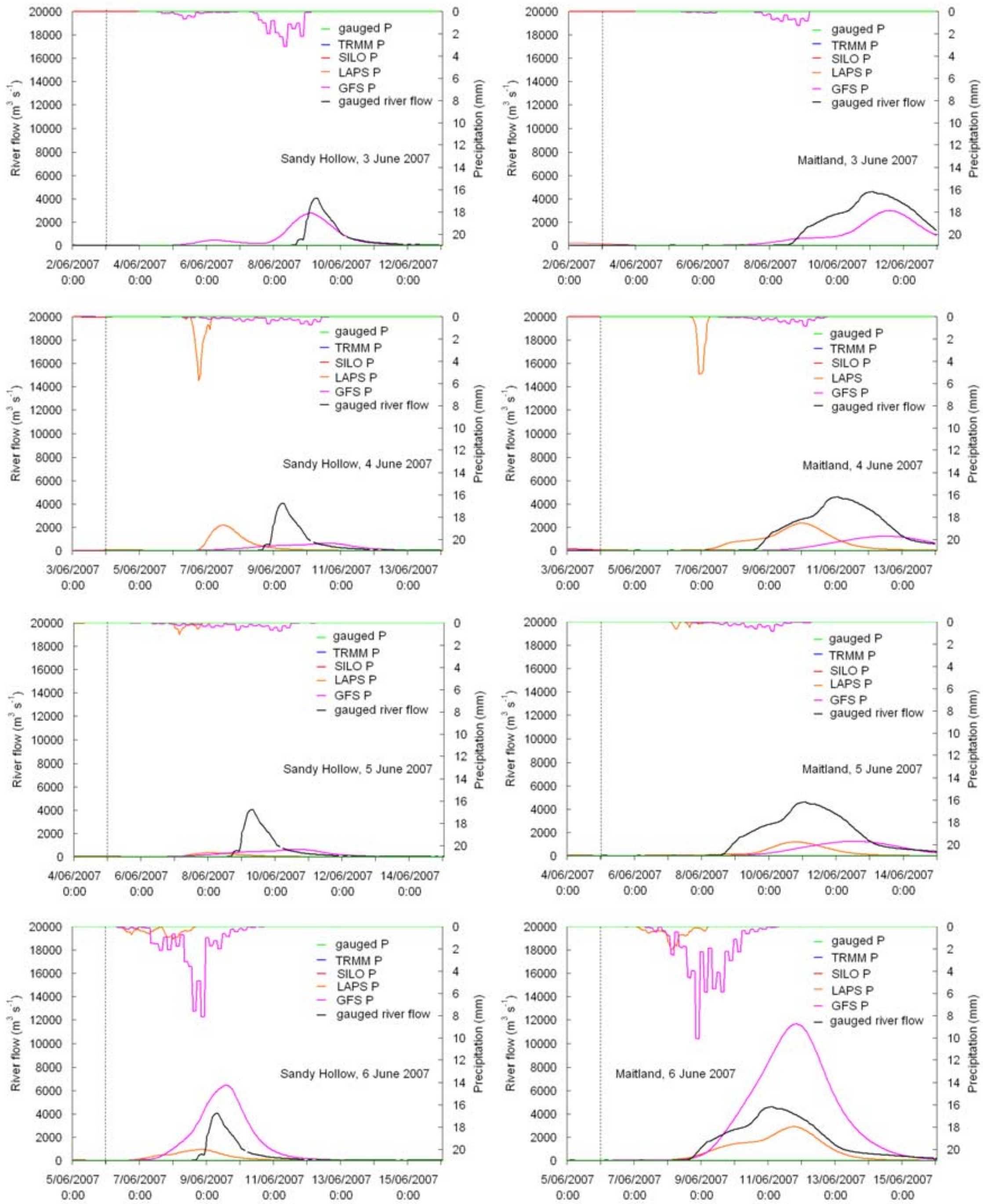

Figure 3. Observed and forecast precipitation and river flow at Sandy Hollow (left) and Maitland (right) in the Hunter Valley for 3-6 June 2007. The vertical dashed line indicates the forecast day. Key: P = Precipitation.

The adapter to link URBS to FEWS is provided courtesy of Don Carroll/Mekong River Commission.

Figure 3 shows a succession of forecast days from 3-6 June 2007 for two water level gauging stations in the Hunter Valley, Sandy Hollow and Maitland (Fig. 2). Sandy Hollow is located at the outlet of the Goulburn catchment and the most upstream station in western direction. Maitland is located at the outlet of the Middle Hunter catchment, far enough out from the coast to experience only minimal tidal influence. Figure 3 shows the flood forecasts forced with QPF data are able to register river flows at flood level as early as 3 June (GFS) and 4 June (LAPS), respectively. It also shows these early indications of elevated flow disappear and reappear from one forecast day to the next. This behaviour is reported in earlier studies (Mckay, 2005; Leahy *et al.*, 2007) and is explained by the relative coarse resolution of the LAPS (~37.5 km) and GFS (~100 km) data in relation to the size of the river basin (~4100 km^2). This causes an uncertainty in the location and magnitude of the forecast peak precipitation, which is either inside or outside the river basin. The flood forecast forced with GFS data overestimates the observed river flow on 6 June.

Figure 4 shows the forecasts for the same two locations for the next couple of days from 7-9 June 2007. The flood forecast forced with gauged precipitation data systematically underestimates the observed river flow. This is probably explained by the fact that the gauging stations for which data are made available are mainly located near or outside the river basin boundaries, resulting in an underestimation of the observed rainfall in the centre of the basin. The flood forecasts forced with observed gridded precipitation data agree better with the observed river flow. The flood forecasts forced with SILO data, however, peak too early for the Sandy Hollow station and overestimate the observed flow on 9 June for both stations. The forecasts forced with TRMM data plot between the two other forecasts forced with observed data. The early timing for the Sandy Hollow station, however, is identical, possibly indicating a model calibration issue. This is also observed on June 4 and June 6 (Fig. 3, left panel), although here it may be related to the early timing of precipitation in the QPF data too.

While flood forecasts for 3-6 June are run in event-based mode only, the forecasts for June 7-9 are run in both proxy-continuous and event-based mode. Figure 3 shows no or little water is present in the river (basin) at the time of forecast for 3-6 June. The initial conditions (IC) for these forecast days do not differ substantially from the 'cold' start (CS) conditions and, consequently, neither do the forecasts. This is illustrated in Figure 4 for the forecast of 7 June (top panels). The historical runs forced with gauged and TRMM precipitation data produce initial conditions, which are similar to 'cold' start conditions, i.e. no or

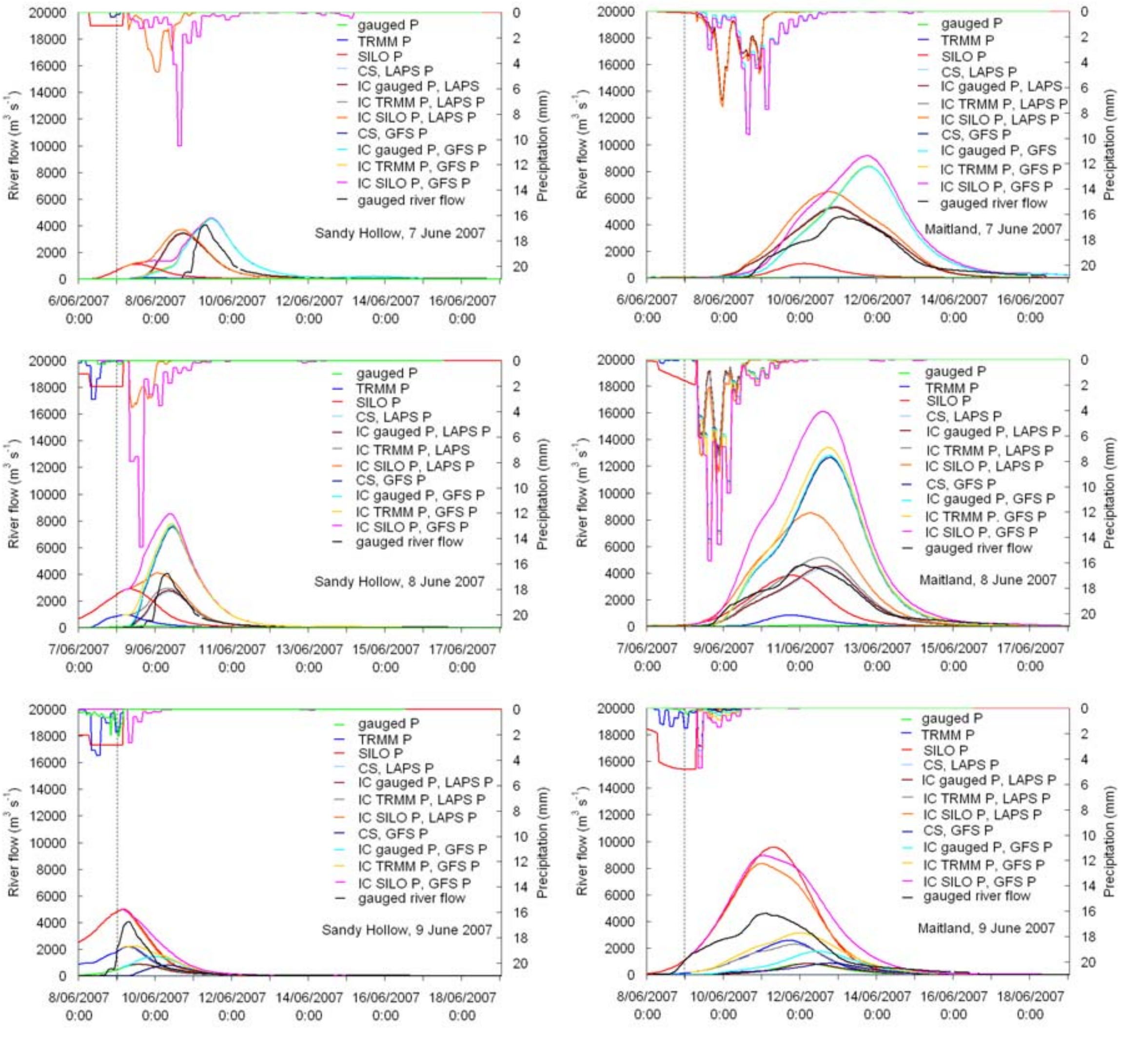

Figure 4. Observed and forecast precipitation and river flow at Sandy Hollow (left) and Maitland (right) in the Hunter Valley for 7-9 June 2007. The vertical dashed line indicates the forecast day. Key: CS = Cold Start, IC = Initial Conditions, P = Precipitation.

little water in the system. Hence, the forecasts forced with QPF data all more or less overlap, respectively, using either initial conditions or a 'cold' start. The forecasts using the initial conditions of the historical run forced with SILO data, however, do produce distinctly different flood forecast results. This is even more evident in the following forecast days, when the initial conditions forced by TRMM data (8 June) and gauged data (9 June) also start to differ from 'cold' start conditions. On June 8, however, initial conditions close or equal to 'cold' start conditions in combination with LAPS QPF data produce the more accurate flood forecasts. Initial conditions forced with SILO data seem to be on target for Maitland station on 9 June at forecast time, but turn out to cause a forecast overestimation of the observed flow. The overestimation of the initial conditions with SILO data at forecast time is also evident upstream at Sandy Hollow.

5. DISCUSSION AND CONCLUSIONS

River flows at warning level for the Hunter Valley flood are retrospectively reproduced in operational forecast simulations forced with QPF data as early as 3 June 2007. This is 4 days before a warning - a Flood Watch - was issued by the NSW Flood Warning Centre at 18:00 hrs, June 7 for the Hunter Valley (Justin Robinson, pers. comm.) and 5 days before the onset of the flood. The early flood signal in the individual forecasts forced with either LAPS or GFS data, however, is not persistent in the following forecast days in the lead up to the flood event. This is explained by the relatively coarse spatial resolution of the QPF data in relation to the river basin size, which introduces uncertainty in the location and magnitude of forecast peak rainfall, which is either inside or outside the river basin. A combination of the two flood forecasts forced with QPF data results in a more persistent early warning signal and points to the potential benefit of the use of multiple QPF data. This is in agreement with flood forecasting practice in NSW, where the qualitative use of a single-solution or deterministic forecast from multiple NWP models ('Poor Man's Ensemble' (PME)) is considered the most valuable guidance for issuing a Flood Watch (McKay, 2005). Alternatively, it could consist of an ensemble forecast of one NWP model or multiple models ('super-ensemble').

Flood forecast simulations using a 'warm' start do not necessarily improve on 'cold' start flood forecasts unless initial conditions are correctly represented. This in turn requires an accurate input of observed variables and a correctly calibrated hydrological model to produce the initial conditions.

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