Condamine-Balonne project final report

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Cover Photograph

Title: *Buckinbah Weir No 2*

Description: An image of Buckinbah Weir, 15km SE from St. George. Used with the permission of the author.

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Glossary

AMSR
Advanced Microwave Scanning Radiometer.

AWRIS
Australian Water Resources Information System, currently being constructed by the Bureau of Meteorology.

BoM
The Bureau of Meteorology.

COTS
Commercial off-the-shelf software. Commercial software available from 3rd parties.

DEM
Digital Elevation Model – a digital representation of ground surface topography or terrain.

DERM
Queensland Department of Environment and Resource Management.

FEWS
The Flood Early Warning System is a workflow system used to run simulation models. It also provides a database to store input and output data for model runs.
http://www.wldelft.nl/soft/fews/int/index.html

ICT
Information and Communications Technology.

IDL
Interactive Data Language. A programming environment that provides useful tools for data processing and geospatial data.
http://www.ittvis.com/ProductServices/IDL.aspx

IQQM
Integrated Quantity and Quality Model, Simons et al. (1996).

LIDAR
Light Detection And Ranging is an remote sensing technology that measures properties of scattered light to find range and/or other information of a distant targets.

LIMO
The Lateral Inflow Model created for the forecasting’s data assimilation, see section 7.4.4 on page 51.

MODIS
Moderate Resolution Imaging Spectroradiometer satellite.
http://modis.gsfc.nasa.gov/

MRT

4
MODIS Swath Reprojection Tool.

**REST**
Representational State Transfer is a web service protocol that allows a client application to obtain data from a web server.

**SRTM**
Shuttle Radar Topography Mission.
http://www2.jpl.nasa.gov/srtm/

**UML**
Unified Modeling Language, a software modeling scheme used for the design and documentation of software.
1 Executive Summary

The Condamine-Balonne catchment, in Southern Queensland, forms a significant source of water for the Murray-Darling system and a large portion of the catchment is devoted to growing cotton and other crops. A map of the catchment can be found on page 9.

For the successful management of any river catchment, water budgeting is a key consideration which requires the regular observations of the flow in the system at representative locations. In order to assist with the optimisation of water budgeting in the Condamine-Balonne system, the National Water Commission initiated the Condamine-Balonne project\(^1\) to develop an ICT platform that:

1. Generates flood extent maps for the Condamine-Balonne flood plain;
2. Estimates the volume of water on the flood plain using a digital elevation model (DEM) and the flood extent map; and
3. Generates regular short-term flow forecasts of the major rivers within the catchment.

1.1 Flood extents

Traditionally, the closure of the water balance of a flood event is a lengthy exercise of which results may take up to a year to become available as data from gauging stations, storage water meters and water accounts of individual farmers is collated and processed. This has created the demand for faster, near-real time information on the amount and location of flood waters. The project implemented an ICT platform that uses satellite imagery to produce flood extent and volume in near real-time.

Two different sources of satellite data, multi-spectral surface reflectance (MODIS) and passive microwave (AMSR-E), were combined to produce an “Open Water Likelihood” (OWL) index to identify surface water in the catchment’s lower-Balonne flood plain, south-west of St. George. This process was integrated into an ICT platform that generates daily flood extents. During the March 2010 floods the process proved to be robust to cope with the biggest flood event in 120 years. Figure 1.1 on the next page shows the flood extent for March 9\(^{th}\), 2010 as displayed by the platform’s web application.

1.2 Flood volumes

The Condamine-Balonne project developed a procedure that combines the water surface map from the flood extent (area) and a digital elevation model (DEM) of the flood plain (depth) to estimate the volume of water in the flood plain. The DEM was obtained from a separate CSIRO project which is processing the data from the Space Shuttle Radar Topography Mission (SRTM) to produce a DEM for the whole of Australia. The DEM project allocated resources to generate a quality DEM of the Condamine-Balonne catchment’s flood plain.

Although the estimates inherit the errors and uncertainties from both the satellite data and the DEM, the volume estimates are close to those estimated by traditional methods. The computed water volume of the flood extent shown in figure 1.1 on the next page is 1,280 Gigalitres.

A validation exercise was conducted for the floods in 2004 and 2010 Gouweleeuw et al. (2009).

\(^1\)Officially called the “Decision support system for real time management of water use in the Condamine-Balonne”
The report concludes that the satellite-based estimates give an accurate indication of both the timing and the magnitude of the flood peak compared to the net volume of water calculated from the recorded flow at the QLD and NSW gauge stations. In the flood recession, however, the satellite-derived water volume declines rapidly, while the net flow volume remains level – implying that there is a sizable amount of water residing in the flood plain that cannot be seen by the satellite system. The difference may be explained by a combination of:

- Unaccounted losses such as ungauged outflows and evaporation; and
- “Hidden” water in the flood plain such as soil infiltration and diversion of flood water into many large open reservoirs for irrigation purposes

It was observed that the water volume product is not sensitive enough to capture the change in storage water levels, thus is not able to include the storage depths in its calculations of water volume. Additional information on the water depth, for example via telemetered buoys or satellite altimetry, may circumvent this limitation.

1.3 Flow forecasts

The automation of flow forecasts has become a key issue because it will allow water budgeting to be performed on a daily basis. Currently, the Queensland Department of Environment and Resource Management (DERM) employs a number of river models to assist with the planning of water allocations. These models are usually run on an ad-hoc basis to estimate the water conditions under specific scenarios. The project was tasked to determine if these models can be run continuously to produce short-term forecasts using the latest weather and flow conditions as input.

In order to manage the execution of the river models the project selected the Flood Early Warning System (FEWS), developed by the Deltasres Institute. This software employs a workflow system to control the execution of the river models and manage the models’ input and output data. Data feeds from the Bureau of Meteorology and DERM were organised and stored in the

Figure 1.1: Flood waters around St. George, March 9 2010. The white area at the top-left is cloud, while the various shades of blue indicate the likelihood of surface water. Background image from Google Maps.
FEWS database for each model run and the output of the runs were also stored in the FEWS database.

FEWS workflows were created to control the execution of the forecasting models and it was found that there is no practical obstacle to convert scenario-based models to real-time operational tools. However, the results of the forecasts were poor. If the system were to be used in an operational environment, effort must be made to review the model’s calibration parameters and update them to reflect current climate conditions.

Overall, the project found:

- The flow forecasts are more reliable on the up-stream and down-stream areas of the catchment than the central area;
- The recalibration of the rainfall-runoff parameters was beneficial, especially for the lowest performing models; and
- A data assimilation procedure, using historical data to correct the forecasts, did not deliver a systematic performance improvement. It appeared particularly useful when combined with the recalibrated parameters.

1.4 Future work

The application of near-real time flood extent and volume estimation and flow forecasting has significant potential in the field of water resources monitoring, which is useful for both irrigation and water allocation purposes as for environmental objectives such as wetland regeneration.

The project has demonstrated the feasibility of an operational system that has been tailored to a specific region. Future work could generalise this capability to allow the monitoring of other areas and catchments. Other possible improvements include:

- The use of other satellite assets, for example satellite radar and altimetry.
- The evaluation of the use of a high resolution LIDAR DEM.
- Recalibration of the river models used here, or the inclusion of alternative hydrological/river models.
2 Introduction

The Condamine-Balonne catchment is an area in Southern Queensland of approximately 136,000 square kilometers. The catchment forms a significant source of water for the Murray-Darling system. A map of the catchment area is given in figure 2.1.

Figure 2.1: The Condamine-Balonne catchment. The flood plain stretches from St. George, QLD, down to Goodooga, NSW.

2.1 Project aims

The aim of the Condamine-Balonne project is to develop a decision support system for the improved management of water use and flows in the Condamine-Balonne catchment. The system will:

- Identify the extent of a flood using satellite imagery. A map of the flood extent will be generated using imagery from the MODIS satellites. In the event of cloud cover over the flood plain, passive-microwave data from AMSR-E will be combined with the MODIS data. See Section 5 on page 20
- Estimate the volume of water in the flood plain using satellite data and a digital elevation
model of the region. See Section 5.1.5 on page 24.

- Automate the production of flow forecasts for daily water budgeting activities using the existing forecasting models used by DERM. The scenario-based models from DERM, Sacramento and IQQM, will be run daily using the latest environmental data from the BoM and DERM to generate daily forecasts for the rivers within the catchment. To improve the quality of the forecasts, “data assimilation” techniques will be employed to correct the forecasts based on historical data. See Section 7 on page 38.

- Construct the ICT platform to manage the entire process of collection the data, processing it and displays the results. A central component will be the Flood Early Warning System, and it will be used to manage the execution of the river models. See sections 6 on page 35 and 8 on page 66.

### 2.2 Project publications


3 Project evaluation

3.1 Introduction

The project has developed a computing platform that provides the following outputs:

- A procedure to generate a flood extent map for the Condamine-Balonne flood plain from satellite data;
- Daily estimates of the water volume in the flood plain; and
- Daily forecasts of river flows in the catchment, 3-days in advance.

Figure 3.1 gives an overview of the software system.

Each day the software that generates these outputs is run automatically:

1. Download satellite data.

   Satellite data is downloaded from Geoscience Australia and NASA. The system uses two satellite packages: MODIS for normal day-to-day operations and AMSR-E to provide data for the surface conditions during cloudy days. After the data is downloaded, the “reflectance” data for specific frequencies is extracted.

2. Generate the flood extent and volume.

   The satellite reflectance data and the DEM of the catchment is combined to generate the flood extent map of the flood plain and the volume of water residing in the plain. The extent maps are created in several file formats, such as the images which are used by the web application. The volume estimate is imported into the FEWS database.

3. Download environmental data.

   The latest rainfall data for the catchment is fetched from the BoM, and the river gauge data is obtained from DERM. This data is imported into the FEWS database.

4. Run river models.
The river models are run in the sequence:

(a) Sacramento models are used to estimate the inflow, such as rainfall, into the sub-catchments.

(b) IQQM uses the output of the Sacramento models to generate the river flows, as well as the losses & extractions.

(c) LIMO is run to perform the “data assimilation” – historical data is used to correct the estimates generated by the IQQM models.

The output from all of the models are imported into the FEWS database and are also used by the web application.

5. Update the web application.

All forecasts and estimates generated by the system are imported into the reporting database and the flood extent images are transferred to the web server.

The COTS software and the bespoke software developed by the project are installed on two CSIRO servers:

1. Processing server.

This server performs all of the data processing steps such as fetching the data from remote sites, processing the satellite data and running the river models. The processing is scheduled to run at 12:15PM to provide sufficient time for the BoM’s rainfall data to be made available.

All of the software required to process the data is installed on this server, including FEWS, IDL and Java. The server is located on the CSIRO network and cannot be accessed from outside the CSIRO network.

2. Web server.

This is the platform’s external face. The web application and the reporting database are held on this machine. The web pages can be accessed from external hosts and is password-protected.

3.2 Evaluation

The Condamine Balonne Project Plan (Parashar and Finn (2008)) identifies the following objectives, and “in-scope” functionality, for the project:

1. Provide all regional Water users access to a reporting tool which will help them to comply with Water extraction policy set by government...  
Provide a system by CSIRO that can be made operational by Queensland Natural Resources and Water. There will be as outputs:

- Model-data fusion software system.  
- Web based public front end  
- Documentation on the system.

The data fusion functionality is provided by FEWS and the models it controls especially the LIMO processing that uses historical gauge data to improve the accuracy of the flow forecasts.

2The time-frame for rainfall data is 9AM – 9AM. The data can take an hour or two to become publicly available.
The web application exists and provides a simple display of the system’s products. The development of the web application was not the focus of the project and further work is required to develop a more sophisticated web front end.

Documentation on the system includes this report, an installation guide and documentation generated from the system’s source code (including UML diagrams of the class hierarchy).

2. Allow Water Managers to have an accurate estimate of the catchment water status and forecasts...
The outputs of the system will provide a forecast and water status in terms of inundation extent maps. Each product as defined in the project schedules will have an estimated accuracy associated with it. For example an the flow forecast at a particular gauge will have an accuracy associated with the short term forecast.

Flood inundation maps are produced daily along with the volume estimates. The web application provides the end-user the ability to examine the extents maps. At the time of writing the maps are available from August 2009 to the present day.

The flood extents are described in Section 5 on page 20.

The flow forecasting portion of the project also provides an overview of the catchment’s water status via the observed river flow data provided by Queensland DERM.

The flow forecasting is described in Section 7 on page 38.

3. Will provide improved management of the available water resources for all water users including irrigators and the environment...

Products at present that have approval of the Steering Committee will be developed, i.e. inundation extent mapping and ICT Platform development.

The system developed by the project delivers the following products:

- Observed river flow data.
- 3-day forecasts of river flow.
- A flood extent map.
- An estimation of the volume of water in the flood extent.

All of the above data is available from either the web front-end, or directly from FEWS.

4. The development of a AWRIS compliant decision support tool consisting of the following modular components...

The development of AWRIS compliant tools is only in scope if AWRIS takes an early leadership of the development of relevant to this project.

The project is not using any AWRIS products, nor will it provide any services suitable for ingestion into AWRIS at this stage, however this could be implemented when suitable interfaces are available.

A possible enhancement is to determine whether the flow forecasting can take advantage of the AWRIS water storages services that has just been released to the general public as a “beta” release (June 2010).

5. Reporting Systems (focusing on the provision of web-based reporting to suit different end-user needs)...
The end web based reporting systems will provide basic visualisation of model runs and also access to model run outputs. The system will also provide access to data used as input for a given model run.

The web application provides the end-user with a simple interface to view the output from the model runs and the flood extent processing.

Further work is needed to examine the interface to determine what improvements can be made to the display and presentation of the outputs.

6. Forecasting Systems (implementing automated forecasting tool for the Condamine-Balonne linked to AWRIS data sources)...

Delivery of:
- Model for forecast
- Input and output interfaces to data for driving the model
- Framework for integrating model and data.

The project successfully integrated the river models from Queensland into the Flood Early Warning System (FEWS). The models were supplied by Queensland and were configured to run in the catchment using the data obtained from the BoM, DERM and SunWater. The final forecasting system involved invoking the following modules:
- 18 instances of the Sacramento rainfall-runoff model;
- 3 instances of the Integrated Quantity and Quality Model (IQQM) river flow model; and
- 1 instance of a IQQM model heavily modified for the town of St. George and surrounds.

The flow forecasting is described in Section 7 on page 38; and FEWS is described in Section 6 on page 35.

7. Data Integration (focusing on the interoperability of existing data sets pertinent to water resource management systems in the Condamine-Balonne)...

The interoperability will be focused in the context of models that are developed being able to accept data from the required data sources. There may be converters to facilitate the interactions between models and data services. The aim to use de-jure or de-facto standards to expose data services and convert the data to formats that can be accepted by the models.

The FEWS platform supports a large number of data formats in its “import” processing. However, the data formats obtained from the providers all had to be converted into a format suitable for FEWS. The conversions are described in Section 7.3 on page 42.

3.3 Conclusions

The project has been successful in the technology areas, namely:
- Implementing a continuous flow forecasting system for the Condamine-Balonne catchment using the existing “scenario” based models such as IQQM currently being used by DERM.
- Using satellite imagery to identify the flood extent and calculating the volume of water within the flood plain.
The system in its current form provides a robust foundation to deliver flood extent, flood volume and flow forecast information. However, there is significant opportunities to further develop this capability beyond the Condamine-Balonne to other flood-prone regions throughout Australia.

The next sections of the report provide details on individual components of the system:

- The flood extent processing based on a digital elevation model of the flood plain and satellite imagery.
- Continuous river flow forecasting using FEWS and the current DERM river models.
- Finally, the ICT platform is described.
4 Digital Elevation Model

4.1 DEM processing

A suitable digital elevation model (DEM) was required to estimate the volume of water on the floodplain from maps of inundated area. The Shuttle Radar Topographic Mission (SRTM) digital elevation model (DEM) was selected as the best available data for the Lower Balonne area. With low relief and a myriad of subtle drainage features, the Lower Balonne is a difficult landscape to represent in a DEM. The radar-based SRTM data was not ideal, having substantial levels of noise in this area as well as height offsets due to trees, but contained significantly more information than other available DEMs that were interpolated from scattered spot heights.

The SRTM DEM was processed in several steps to improve its utility for this project. Systematic striping was removed and voids (areas without data) were filled. Areas where the elevations were affected by trees were identified with the aid of vegetation mapping derived from Landsat imagery. The height offset induced by the trees was estimated around the edge of each patch and the estimated offset was subtracted from the DEM elevations to produce a bare earth elevation model. This processing has been applied to the entire continent but the Condamine-Balonne area was prioritised in the early processing of the SRTM DEM to produce an elevation model usable for this project.

A field trip to the Condamine-Balonne catchment was conducted in December 2008 as part of the project, focusing primarily on the Lower Balonne between St George and Dirranbandi but also including a traverse of the catchment from St George to Toowoomba via Surat, Condamine and Chinchilla. The aim of the field trip from the DEM point of view was to get a better understanding of the vegetation patterns, flow pathways and the landforms of the area. The trip contributed significantly to our understanding of the patterns in the SRTM data and its ability to represent the landscapes in the project area. The main finding was confirmation that the SRTM DEM could represent the subtle features of interest, but that the unusually high noise levels in the Lower Balonne significantly reduced the accuracy in that area.

Figures 4.2 and 4.3 on page 18 show an area in the upper reaches of Lake Kajarabie (the impoundment behind Beardmore Dam) as portrayed in the DEM before and after the removal of tree offsets and in a photograph taken during the field trip in 2008 (Figure 4.1 on the next page).

The water level in the dam was higher when the photograph was taken than at the time the SRTM data was acquired, so the flat water body areas in the DEM with uniform blue colours are less extensive than in the picture. The removal of tree offsets has resulted in more consistent land surface heights as would be expected in this low relief floodplain landscape. Much of the finer scale variation still evident after removing the effects of trees is due to noise in the DEM rather than actual topographic structure.

In spite of the improvements made to the DEM and the noise-tolerance of the water volume calculation method (see Section 5.1.5 on page 24), the DEM is a source of substantial uncertainty in the volume predictions. Much of the area in the Lower Balonne floodplain is covered by open woodland with variable tree density and height, which was not well represented by the vegetation maps needed to support the removal of height offsets due to trees. The channels themselves are mostly too small to resolve in the SRTM DEM, which can only see features larger than about 50 m across, even if they are not obscured by trees. The ground elevations are therefore quite uncertain in much of the floodplain area (in addition to the random noise) so there may be substantial errors in the estimation of water surface height and volume.
The key advantage of the SRTM DEM is its continental coverage so the methods used in this project could be applied to any similar area of Australia without further investment in DEM data. With a horizontal resolution of about 30 m and vertical precision of ±5 metres, it is clearly the best DEM for most areas of inland Australia. However, much better results could be obtained with higher quality elevation data provided by airborne laser scanning (LIDAR) or airborne radar (IFSAR). LIDAR is the preferred technology for this application due to its ability to acquire ground elevations through tree cover; the airborne radar, like the SRTM radar, is unable to penetrate trees and cannot provide detailed topographic information in wooded areas.
Figure 4.2: Digital surface model (including vegetation offsets).

Figure 4.3: Digital elevation model after removal of vegetation offset.

The arrow shows the direction of photograph from Figure 4.1 on the preceding page, and the box shows extent of the photograph on the ground.
4.2 Conclusions and future developments

The DEM used by the project was an early version of the product that provides a suitable baseline for building the platform. The DEM project is continuing to improve the data’s quality by reducing the nose (uncertainty) from the data. Future plans also include creating a “hydrologically enforced” DEM that contains mapped stream lines, see Figure 4.4.

![Figure 4.4: An early version of an hydrologically enforced DEM of the Lower Balonne river (before and after images).](image)

The use of the DEM in the flood volume estimation process is discussed in Section 5.1.5 on page 24.
5 Flood Extents

This section describes the identification of flood extents using satellite imagery and the estimation of the volume of water in the extents. The algorithm developed by the project analyses the data from two separate satellite systems: MODIS for reflectance data from non-cloudy days; and AMSR-E for microwave radar for cloudy days. The project developed code to process the reflectance data from the MODIS satellites and estimate the location of surface water. A percentage, representing the proportion of surface water area, is allocated to each image pixel in the target area. The next step is to overlay the water “surface” onto a digital elevation model (DEM) to identify the lowest areas – MODIS data coverage is approximately 500m and the DEM is 30m. This step provides an estimate of how much water is in each MODIS pixel. These amounts are then summed to provide the volume of water in the target area. The DEM was derived from the Shuttle Radar Topography Mission and provides 1 second (approximately 30m) elevation data for the whole of Australia.

The flood extent and flood volume is calculated using IDL and ENVI programming language. The methods described here are the final version used in the code which calculates flood extent and volume from MODIS, AMSR and the two combined.

![Figure 5.1: MODIS image from 17 March 2010 and flood extent.](image)

5.1 Calculating flood extent and volume using MODIS

5.1.1 MODIS data files

A daily TERRA and an AQUA MODIS image is provided for calculating flood extent and volume for each day. Following pre-processing (Section 5.4.2 on page 31), the filenames are:

- X_1km_Reflectance_Data_State_QA.dat
- X_1km_Reflectance_Data_State_QA.hdr
- X_500m_Surface_Reflectance_Band_x.dat
- X_500m_Surface_Reflectance_Band_x.hdr

Where “X” is either an “O” for Terra (i.e. MOD) or “Y” for Aqua (i.e. MYD), and “x” is the band number (bands 1, 2, 3 and 6 are used here). The filename with “_QA” is the quality band
Table 5.1: Average monthly reflectance (x10000) for each band used to calculate flood extent.

<table>
<thead>
<tr>
<th>Month</th>
<th>Band1</th>
<th>Band2</th>
<th>Band3</th>
<th>Band6</th>
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<td>2012.64</td>
<td>383.69</td>
<td>2644.56</td>
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<td>1868.02</td>
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<td>476.57</td>
<td>1618.89</td>
<td>247.04</td>
<td>1884.30</td>
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used for producing a cloud/cloud shadow mask. Files ending in .dat are the flat binary files, and the .hdr files are their accompanying header files.

5.1.2 Combining AQUA and TERRA for daily water extent

A normalization process is first applied to both the Aqua and Terra images to help account for the variations across the swath track due to the position of the sun, since the area of interest (i.e. Lower Balonne Floodplain) doesn’t always occur in the same part of the image each time it is acquired. To help normalize this, two Regions of Interest (ROIs) were selected such that they were at a similar across-track position to the flood plain for Terra (ROI 1) and Aqua (ROI 2). The two ROIs were over forested areas since it tends to remain reasonably stable through time. However, since there are still seasonal variations, the reflectance for these ROIs needed to be calculated for each month. This was done using the MOD43B BRDF 16-day composite surface reflectance data which uses the best data of the 16-days to help reduce cloud effects as well as correct for variations due to the sun angle. The average monthly value was calculated for the two ROIs using the MOD43B data, ranging from 2000 to 2008. These values are shown in table 5.1.

The image is normalized using the following formula:

\[
Norm_x = \frac{Refl_x \times ROI_{MAM}_x}{Av_{Refl_{ROI}}_x}
\]

(5.1)

Where \(Norm_x\) is the new surface reflectance for band \(x\) following the normalization correction; \(Refl_x\) is the surface reflectance of band \(x\) before correction; \(ROI_{MAM}_x\) is the monthly average surface reflectance for the ROI for band \(x\) from Table 5.1; and \(Av_{Refl_{ROI}}_x\) is the average surface reflectance for the ROI in band \(x\) before correction.

The normalization is applied to both the Terra and Aqua images only if its associated ROI, and surrounding pixels, is completely free of cloud and cloud shadow, otherwise no normalization is applied to that image. If the normalization process is successfully applied to both the Terra
and Aqua images for that day, then both images are used to calculate water extent. If the normalization process is only applied to one image, then only that image is used to calculate water extent. If the normalization process cannot be applied to either image (i.e. both ROIS are covered by cloud/cloud cover or are null pixels), then both of the non-normalized images are used to calculate water extent. An output text file provides information on which images were normalized. If the water extent is calculated on non-normalized images then the output results should be treated with some caution.

Following the normalization process, the Optical Water Likelihood (OWL), Guerschman et al. (2008), is calculated for each image used. A description is provided in the following section.

### 5.1.3 Open Water Likelihood

The Open Water Index was developed for quantifying temporal and spatial patterns of open water surfaces in Australia.

The open water index is based on the combination of the Enhanced Vegetation Index (EVI), Huete et al. (2002), and the Global Vegetation Moisture Index (GVMI), see Ceccato et al. (2002b) and Ceccato et al. (2002a):

\[
EV I = G \times \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + C_1 \times \rho_{red} - C_2 \times \rho_{blue} + L}
\]

\[
GV MI = \frac{(\rho_{nir} + 0.1) - (\rho_{swir2} + 0.02)}{(\rho_{nir} + 0.1) + (\rho_{swir2} + 0.02)}
\]

where \(\rho_{red}, \rho_{nir}, \rho_{blue} \& \rho_{swir2}\) are the reflectances in red, nearinfrared, blue and shortwave infrared 2 respectively and correspond to MODIS bands 1, 2, 3 and 6. In the EVI formula \(G, C_1, C_2 \& L\) are parameters that account for aerosol scattering and absorption and their values are 2.5, 6, 7.5 and 1 respectively, see Huete et al. (2002).

The EVI and GVMI were shown to be useful for distinguishing between vegetated and open water areas. Figure 5.2 on the next page shows the distribution of different land cover types in the space defined by the two indices.

An Open Water Index (OWI) was calculated as:

\[
OWI = 0 \text{ when } EVI \geq 0.2 \text{ and } \quad (5.4)
\]

\[
OWI = GV MI - EVI \text{ when } EVI < 0.2
\]

Then an “Open Water Likelihood” index was calculated as:

\[
OWL = \frac{1}{1 + \exp(-50 \times (OWI - 0.1))}
\]

The expression above gives a sigmoideal function which is exemplified in Figure 5.3 on the next page.
Figure 5.2: Scatter plot of the Global Vegetation Moisture Index (GVMI) and the Enhanced Vegetation Index (EVI) in Australia. Point color indicates vegetation type (inset map) as: blue=water, green=forests, red=grasslands and croplands, yellow=shrub lands and brow=woodlands. The dotted line indicates the criteria for separating the open water from the vegetation domain.

Figure 5.3: Relationship between the open water likelihood and the open water index through the sigmoideal function.
The OWL can be interpreted as the likelihood that a given pixel contains water or, additionally, as the proportion of the pixel occupied by open water. It is important to note that the two indices presented here have not been validated with field measurements.

5.1.4 Using the Open Water Likelihood

The OWL is calculated for both the Aqua and Terra images (when both normalized, or both not normalized), or for just one image if only one is normalized. It provides a value from 0 to 100 indicating an estimation of the percentage of water in a pixel, a value of -1 indicates cloud cover or cloud shadow, and -2 represents no-data (null values). If both images are used, then they are averaged to give one OWL image for calculating water extent. If one of the images has null values (i.e. no data), or cloud cover/cloud shadow, then the OWL from the other image is used if it has real data. An example is shown in Figure 5.4.

![Figure 5.4](image)

**Figure 5.4:** Example of combining the Terra and Aqua images. The images, from left to right, are legend, Terra OWL, Aqua OWL and Combined OWL.

The final OWL image is the water extent image used for flood volume calculations. Figure 5.5 shows a final flood extent image. The light blue represents low proportion of water within a pixel, and the darker blue represent higher proportions. The white areas are cloud. Where there is cloud, there is no information available on surface water.

![Figure 5.5](image)

**Figure 5.5:** An example of the final flood extent image as calculated from MODIS. The project focused on the flood-plain to the south-west of the town of Dirranbandi, Queensland.

5.1.5 Calculating water volume using the MODIS OWL and a DEM

The MODIS water extent image is then combined with the SRTM DEM, described in Section 4 on page 16, to calculate an estimate of the water volume within the floodplain. This is a very
challenging task as the floodplain is extremely flat. Any noise in the MODIS or the DEM will change the volume estimates considerably. A number of measures have been applied to both datasets to help reduce this where possible: the normalization of the MODIS images; and smoothing of the DEM using an Enhanced Lee Filter (Lopes et al. (1990)).

Firstly a water height surface needs to be calculated for all pixels with water in it. Any pixel with less than 10% water is not used as it may also be indicating moist soil. An illustration of an OWL flood extent image is shown in Figure 5.6, below. The blue pixels indicate MODIS pixels with > 90% water in it, this is considered to be a fully flooded pixel. The green represents mixed pixels (10-90% water - called a border mixed pixel) next to a fully flooded pixel. Orange represents mixed pixels that are not next to a fully flooded pixel (called an isolated mixed pixel).

![Figure 5.6: Example of MODIS OWL flood extent image of a water body. Blue indicates where there is > 90% water, green is mixed pixels (ie 10 – 90% water) adjacent to a blue pixel, and orange is a mixed pixel not adjacent to a blue pixel. The dark output shows the edge of a water body.](image)

To generate a water height surface the DEM needs to be georegistered with the MODIS image. There are about 16x16 DEM pixels within each MODIS pixel. The DEM is used to calculate a water height for each flooded MODIS pixel. Figure 5.7 on the next page shows a simplified example. The left square shows a MODIS pixel which has 9 DEM pixels within it. If the MODIS water proportion is 30%, then the lowest 30% of the DEM pixels are considered under water, hence a water height of 115 is selected.

To help address any noise fluctuations still in the DEM, the threshold is set so that DEM heights at the high and low extremes within a MODIS pixel are not used. Hence any MODIS pixel which has < 30% water in it, is set to 30% for calculating water height, and any MODIS pixel which has as > 70% water in it, is set to 70%. Following this adjustment, the water height needs to be calculated for the border mixed pixels (green in Figure 5.6) and fully flooded pixels (blue) along the edge of a water body, as well as the isolated mixed pixels (orange). The dark outline in Figure 5.6 shows the outline of a water body (the isolated mixed pixels in orange are patches of water). The water height of the corner points of this water body is used to generate a water height surface. To do this TRIANGULATION, in IDL, is first performed using the corner points. These triangles are then used to generate a surface by interpolating the water height
across all water body pixels from the corner points, using TRIGRID in IDL. An example of the interpolation can be seen in the right hand box of Figure 5.7. The four corner point water heights are calculated using the DEM and proportion of water within the MODIS pixel. These four corner points are then interpolated to give water height for the rest of the water body.

![Figure 5.7: An example of calculating the water height within a MODIS pixel. The left square represents a MODIS pixel with 3x3 DEM pixels within it.](image)

The DEM is then subtracted from the water heights of all water pixels (both mixed pixels and fully flooded pixels) giving water depth. Any negative water depths within the mixed pixels (both border mixed pixels and isolated mixed pixels) are set to zero since some of the surface within a mixed MODIS pixel is expected to be above the water height. It must be noted that there are some negative water depths within a water body (i.e. the blue pixels in Figure 5.7). This is partly due to remnant fluctuations in the DEM, and any mismatch between the DEM and MODIS images, since the floodplain is extremely flat. The water depth for all DEM pixels in flooded areas are then summed together and multiplied by the pixel area to give total water volume for the floodplain. The total water volume is calculated for each day in the Lower Balonne Floodplain, and the proportion of clouds pixels and null pixels is also provided for assessing the quality of the results.

## 5.2 Calculating flood extent and volume using AMSR

### 5.2.1 AMSR data files

Following pre-processing (Section 5.4.2 on page 31) the AMSR files are named according to the example below:

```
AMSR_E_L2A_BrightnessTemperatures_V10_200906191453_D_18HgeoS
```

Where V10 is the version of the data, as processed from NASA; 200906191453 is the year, month, day, hour and minutes of the acquisition; D represents descending mode (A for ascending), and 18HgeoS indicates it is for the 18GHz Horizontal band which has been georeferenced and subset.

### 5.2.2 Calculating Flood Extent

The AMSR data used here represents Brightness Temperature, which is low for water. Since the data comes from varying times of the day, one in the afternoon and the other after midnight,
a Polarization Ratio was used on the 37 GHz band Brightness Temperatures (Kerr and Njoku, 1993). The Polarization Ratio (PR) is:

\[ PR = \frac{37H - 37V}{37H + 37V} \]  

(5.7)

The 37 GHz PR image was still influenced by the proportion of vegetation cover, creating particular confusion between surface water and bare soil (Figure 5.8 – Left). To help reduce this effect, a desert correction was applied (Figure 5.8 – Right) based on the threshold by Grody (1991) which uses the 18 GHz vertical minus horizontal value, but here we used the near-linear relationship between the 37 GHz PR and the 18 GHz V-H to correct for the variation in the 37 GHz PR band (where the corrected 37GHz PR = 37GHz PR − 0.00144 × (18GHz V H)). The relationship was near-linear because the 37 GHz PR was more sensitive to water pixels than the 18 GHz data, particularly for the finer water features which were more difficult to detect in the 18 GHz data due to its larger spatial footprint of 28 × 16 km.

Figure 5.8: The 37 GHz Polarization Ratio over eastern Australia.  
Left: The red and yellow represents a high PR, indicating water or bare areas, the green and blue represents low PR.  
Right: The 37 GHz PR image following desert correction.

While the AMSR data has a longer wavelength than the MODIS, making it less susceptible to cloud cover, it is still affected by precipitation. Hence a rainfall mask of 85 GHz vertical minus 22 GHz vertical (Ferraro et al., 1998) was also applied to the imagery to help remove these effects from the data.
While the desert-corrected 37GHz PR image is related to surface water, the actual proportion of surface water still needed to be determined. To do this, a cloud-free MODIS image acquired at the same time as an AMSR image, for a large flood event, was used. It included a large flood in southwest Queensland, which meant there were AMSR-E pixels having up to 100% water in them. The OWL image was calculated for the MODIS image, and then it was resampled to the same pixel size as the AMSR image to provide proportion of water within an AMSR pixel. The pixel values from both images were then plotted against each other (Figure 5.9), to allow a linear relationship to be developed between AMSR corrected PR and MODIS OWL (proportion of water resampled to AMSR pixel size). As Figure 5.9 shows there is a relationship between the two, however there is also a large scatter of points ($RMSE = 0.0056 PR$). This is partly due to any minor spatial mismatch between the MODIS and AMSR pixels, and also due to moist soil in the AMSR being confused with surface water.

**Figure 5.9:** AMSR desert-corrected PR plotted against MODIS proportion of water (resampled to AMSR pixel size).

The figures below, show the MODIS (Figure 5.10 on the next page) and AMSR (Figure 5.11 on the next page) proportion of water within each pixel. As Figure 5.11 on the next page shows, there are more low water proportion pixels (blue/green) in the AMSR image compared to the MODIS. This is possibly indicating areas of moist soil, as well as residual noise in the data.

The flood extent images from each AMSR overpass for the same day are then combined using the same method as the MODIS. That is, the rain pixels and null pixels are replaced by the other image where possible. Where there is real data for the same area on the ground, the AMSR water proportion is averaged.
**Figure 5.10:** OWL MODIS image of large flood event, re-sampled to same pixel size as the AMSR image.

**Figure 5.11:** AMSR image showing proportion of water within each pixel. With the same colour scale as the previous figure, for the same flood event as above.
Once a flood extent image is calculated, the flood depth image is created and the flood volume is calculated for the lower-Balonne floodplain. The same method as described in the MODIS section (5.1.5 on page 24) is employed.

5.3 Using AMSR and MODIS data

The MODIS data allows for more detailed flood extent, water depth and hence flood volume estimates to be made due to its finer spatial resolution, however it is subjected to more atmospheric effects than the AMSR, in particular due to cloud. Hence a combined MODIS/AMSR product is also produced.

All the MODIS data is used and the AMSR is only used to replace the MODIS data where there are clouds or null pixels (Figures 5.12 and 5.13) There still may be some pixels that have clouds/rain, or nulls, in both the MODIS and AMSR flood extent images, and will remain as null values.

**Figure 5.12:** An example of a MODIS flood extent image for the lower-Balonne floodplain. The black areas indicate areas of no-data.

**Figure 5.13:** The same example but with the AMSR flood extent pixels filling in the null values from the previous figure.

Following calculation of the flood extent image, the flood volume image is calculated using the
same method as MODIS section (5.1.5 on page 24). The IDL program MODIS_AMSR_Water_Vol_Op.pro performs the above steps to produce a combined flood extent image and a flood volume image from AMSR for each day.

5.4 Image Acquisition

5.4.1 Downloading MODIS Images

Geoscience Australia makes available a range of data products they receive from remotely sensing instruments carried on board satellites that orbit the globe. The MODIS instruments on board the NASA Earth Observation System (EOS) satellites TERRA and AQUA collect optical and thermal imagery and directly broadcast the data back to the ground as they overpass Australia. Two reception stations, Alice Springs and Hobart, collect the data which is processed into standard NASA image products and provided free for download via a website and file transfer service (FTP). The repository of imagery, “the data pool,” is automatically updated as data products are received and processed. This near-real time data service is a 12 day rolling archive. Data older than 12 days are archived and may be manually retrieved upon request. The process of obtaining the data from the data pool is a matter of automatically checking for new data at daily or regular sub-daily intervals.

Downloading data is managed by the FTP adaptor described in section 8.4 on page 68. The data of interest for flood mapping is known as the “MOD09GA” product which is a file containing a set of images from seven electro-magnetic (EM) wave bands ranging through the EM spectrum from Blue to Short Wave Infra-red (SWIR). The specification of the data is provided in Vermote et al. (2008).

The data files are held in a directory tree structure which itself describes the source of the data and the derived products. The data pool directory tree for the MOD09GA Full Swath product is for example, /nnnnnnnnnn/MDO9/POST, where nnnnnnnnnn is the 10-digit satellite orbit number. There are other product sub-directories under each orbit directory that are to be ignored.

5.4.2 MODIS Pre-processing

The MODIS imagery downloaded from Geoscience Australia is a single large “swath” in a Hierarchical Data Format (HDF) data file. The swath file contains 17 separate image bands each of which are 2330 km wide and cover the entire length of the north-south satellite track across Australia. Geoscience Australia processes the whole data set to a stage defined as a NASA Level 2 image product. This image set is considered to represent the optical reflectance as measured at the Earth’s surface, without atmospheric effects. A further description of the product may be found at the USGS MODIS web site (the URL is available on page 4).

Upon arrival the swath data files are pre-processed to extract and subset the data required for flood mapping. The pre-processing uses a freely available software tool called the MODIS Reprojection Tool – Swath (MRT-Swath). This software is available through the Land Processes Distributed Active Archive Centre web site. MRT-Swath accept inputs parameters through a simple text parameter file.

The MRT-Swath tools are managed via a Perl script that performs the following tasks:

1. Read in the list of input file names to be processed.
2. Read the Latitude and Longitude from swath HDF header records.
3. Select the files that covered the area of southern QLD and Northern NSW.

4. Write out a MRT-Swath parameter file.

5. Execute MRT-Swath to perform the following tasks:
   (a) Extract optical bands 1-7 and the Reflectance data state band.
   (b) Subset the data to the Condamine-Balonne area (24.00°S : 145.00°E, 35.00°S : 153.00°E)
   (c) Reproject each image band to Geographic coordinates.
   (d) Write each band to a single binary file (BIL format)
   (e) Write out a standard BIL header file describing each image file.

5.4.3 Downloading and pre-processing of AMSR images

The AMSR-E data is freely available from NASA. The data used here is level 2a brightness temperatures in swath format. There can be up to three images a day that fall within the time specifications, however there will only be one, possibly two images which cover the Condamine-Balonne site (this cannot be determined before downloading and reading the data). An example of a downloaded file is:

AMSR_E_L2A_BrightnessTemperatures_V10_200906191453_D.hdf

Where V10 is the version of the data, as processed from NASA. Only the files containing V10 will work for the current program; 200906191453 is the year, month, day, hour and minutes of the acquisition; D represents descending mode (A for ascending). It is the hours which are important for determining which hdf files are likely to cover eastern Australia, see Table 8.1 on page 69.

Once the AMSR files have been downloaded (these are .HDF files) they are georeferenced, resampled to 10 x 10 km pixel size and subset for the Condamine-Balonne region using an IDL program (AMSR_data.pro). The .HDF file contains all the AMSR bands and georeferencing information for that particular overpass, hence the IDL program extracts all the bands that will be used for calculating flood extent and volume with AMSR. These bands are: 18 GHz Horizontal (18H) and Vertical (18V) polarization; 23 GHz Vertical polarization (23V), 37 GHz Horizontal (37H) and Vertical (37V) polarization and 89 GHz Vertical (89V) polarization.
5.5 Conclusions and future developments

The flood extent procedures developed by the project successfully combined two different sources of satellite data to generate a reasonably accurate flood extent map within a few days of a flood event occurring. The experience during the March 2010 floods demonstrated that the process is robust enough to cope with the biggest flood event in 120 years.³

Although the volume estimates inherit the errors and uncertainties from both the satellite data and the DEM, the values are close to those estimated by traditional methods.

A validation exercise was conducted for the floods in 2004 and 2010 Gouweleeuw et al. (2009). The report concludes that the satellite-based estimates give an accurate indication of both the timing and the magnitude of the flood peak compared to the net volume of water calculated from the recorded flow at the QLD and NSW gauge stations. In the flood recession, however, the satellite-derived water volume declines rapidly, while the net flow volume remains level – implying that there is a sizable amount of water residing in the flood plain that cannot be seen by the satellite system. The difference may be explained by a combination of:

- Unaccounted losses such as ungauged outflows and evaporation; and
- “Hidden” water in the flood plain such as soil infiltration and diversion of flood water into many large open reservoirs for irrigation purposes

It was observed that the water volume product is not sensitive enough to capture the change in storage water levels, thus it is not able to include the storage depths in its calculations of water volume.

The remainder of this section identifies areas where further work may provide beneficial in improving the accuracy of the procedures and their performance.

Continuing improvement to blended satellite data sources

Other satellite data sources will provide data redundancy and increase system reliability and accuracy. There are other passive microwave platforms, including freely available (TRMM, SeaWIFS) and soon to be available (SMOS, SMAP, Sentinel).

A further extension to the current status of flood volume estimation, using satellite imagery and a DEM, is to include satellite altimetry to determine the water height in open water storages/ring tanks. The current flood volume estimation algorithm is insensitive to changes in water volume in the particular case of unchanged inundated area, e.g. in open water storages. The assessment of water height in storage tanks using satellite altimetry may circumvent this current limitation.

Apart from open water extent, microwave imagery (both passive and active) is able to provide surface moisture estimates. Because antecedent conditions are both critical and mostly unknown at the onset of flood events, the inclusion of surface moisture in a satellite-derived product service is worth considering.

Incorporating higher resolution DEM data.

Inaccuracy in the derived flood extent and volume product is mainly the result of a combination of two factors:

1. Uncertain flood boundaries due to blurred signal response on the land-water contact zone and image geo-location errors; and

³http://www.abc.net.au/news/stories/2010/03/05/2837162.htm
2. Coarse resolution DEMs.

The current method for flood volume estimation employs the Shuttle Radar Topography Mission (SRTM) DEM. This is the only DEM with global coverage, enabling Australia wide transferability, despite typical vertical noise of approximately $\pm 5m$. Application of regionally available LIDAR-derived DEMs (using laser altimetry) at higher vertical and horizontal and higher accuracy would improve flood volume accuracy. There is an opportunity to investigate (1) the computational implications of using something as data rich as a LIDAR; and (2) to what extent using the LIDAR improves the estimates.

System scalability.

During the March 2010 Queensland floods there was a large increase in the flood extent processing time: from minutes to hours.

A new system architecture has to be developed to handle these large datasets. The system will have to manage the data in its original format as well as sub-sets that have been produced for specific regional processing. Depending on the architecture of the new system, this will provide an opportunity to process imagery on a specialised computing platform such as a Compute cluster or a GPU cluster.
6 FEWS

6.1 Introduction

Deltares is a Dutch research institute, which provides advisory services on water, soil and subsurface issues. One of their products is the Flood Early Warning System (FEWS), which is in use throughout the world both as an operational and a research tool. For example, the Environment Agency for England & Wales is using FEWS since 2003 to provide river and coastal flood forecasting for England and Wales. The US National Weather Service began using FEWS in their Community Hydrologic Prediction System in 2008. The Australian Bureau of Meteorology is currently running an evaluation of FEWS to determine if it is a suitable candidate to replace some of their existing flood forecasting systems.

FEWS consists of a graphical user interface, a database of hydrological data and a workflow engine that is used to execute models and perform other data-processing activities.

The graphical user interface, see Figures 6.1 and 6.2 on the next page, allows the operator to display a map of the area of interest and display the locations such as river flow gauge stations. A click on these locations displays a graph, in case dynamic data for these locations are stored in the database. Dynamic data covers mainly time series data in various formats (scalar – 0D, vector – 1D, grid – 2D, and polygon data – 2D). Dynamic data also includes the management of model states produced by the system.

The database is used to store all data that FEWS will process. FEWS can import a large number of data formats; either timeseries or gridded data.

A central element in the FEWS configuration is the model wrapper or general adapter (Figure 6.3 on the following page). It contains a number of activities defined in a single XML file, which is used to execute a (native) model run. While all activities are executed in sequential order, it is possible to configure the engine to halt should an error occur.

The FEWS configuration for the Condamine-Balonne catchment is relatively straightforward: All native models are external executables, each of which are invoked in a general adapter XML file:

1. The data for the model run is exported from the FEWS database, normally as an XML
document. The FEWS developers have defined a standard for these documents, called Public Interface (PI).

2. The XML document is converted into a format suitable for ingestion by the model, which in many cases is comma-separated data.

3. Execute the model in a temporary working directory.

4. Convert the model’s output, again usually comma-separated data, into a PI XML document.

5. Import the XML into FEWS.

![Figure 6.2: The FEWS “grid” display – in this case, rainfall data.](image)

6.2 Locations

In the FEWS configuration approach, location is key. It may represent any point of interest, such as a gauging station or a reservoir. All data stored in FEWS is associated with a location. Table 7.1 on page 40 shows some of the locations for the CB configuration.

The configuration of FEWS for the CB catchment may be regarded as the identification of...
locations and their properties, such as latitude and longitude, through XML files. Locations may also be grouped into sets, which may prove useful when data generated by several models have to be combined as input into another model further down the systems workflow.

6.3 Data

Setting up and running a river model system generally requires a large amount of data, which may include:

- Rainfall;
- Evapotranspiration (evaporation plus plant transpiration);
- Dam levels;
- River levels; and
- River flow.

While operational data is key to produce up-to-date forecasts, hydrological models typically need a warm-up period to simulate the appropriate initial conditions using historical data – sometimes over a 100 years. The data used by the forecasting models is described in Section 7.3 on page 42.

6.4 Workflows

A FEWS workflow contains a number of activities that are run sequentially. Activities are normally packaged as a module. While this modular set-up provides a range of functionality for data transformation, interpolation, validation etc., it also offers flexibility to include models and data, as they become available. Figure 6.4 shows a typical sequence of modules in a FEWS workflow.

![Figure 6.4: Typical FEWS workflow (courtesy of Deltas)](image_url)
7 Continuous Flow Forecasting

7.1 Introduction

This section describes the system that produces the flow forecasts on the Condamine-Balonne basin. The section is split into five subsections:

- Subsection 7.2 on the next page details the products delivered by the system. These products consist of forecasts of the flow at 18 points within the Condamine-Balonne basin.
- Subsection 7.3 on page 42 lists the data used to test the system with historical flood events and provide real-time input to the forecasts.
- Subsection 7.4 on page 42 presents the rainfall-runoff and river system models used to generate the forecasts. The method to nudge the models in real-time is also described.
- Subsection 7.5 on page 56 indicates how uncertainty bounds are attached to the forecasts.
- Subsection 7.6 on page 60 gives some elements to assess the performance of the system and suggests further development.

The building of the flow forecasting system was based on four assumptions:

**Nature of the system**: according to the project plan (Parashar and Finn, 2008, Attachment 6, page 1), “The purpose of (the continuous flow forecasting activity) is to develop a proof of concept that achieves some of the long-term goals of this project”. As a result, the system presented in this section remains a research tool and not a system made to support operational decisions due to missing functionality – summarised in the following points. Details are given in subsection 7.6 on page 60.

**No real-time availability of rainfall forecasts**: real-time rainfall forecasts could not be obtained during the course of the project. Because rainfall constitutes one of the inputs to rainfall-runoff models, an alternative solution had to be identified regarding the rainfall forecasts. It was decided to use a “zero rainfall forecast” which sets the rainfall forecasts to zero.

**No estimation of rainfall uncertainty**: there was no attempt to estimate and propagate the uncertainty attached to rainfall inputs through the rainfall-runoff and river system models. Rainfall input is thus considered as a deterministic variable.

**Use of existing models**: one of the core objectives of the project was to develop a real-time system out of existing scenario-based models (Parashar and Finn, 2008, page 8). As a result, there was limited attempt to develop or refine the existing models described in subsection 7.4 on page 42 even if they were recognized as sub-optimal for the task of real-time flow forecasting. An exception is described in paragraph 7.4.2 on page 44 regarding the recalibration of the rainfall-runoff models.

The next section describes the products delivered by the forecasting system. A quick overview of this workflow is given here, in order for the reader to understand the building blocks of the system:

1. The first task performed by the system is the downloading of recent observations of rainfall and streamflow across the basin.
2. The rainfall data are extended in the future with a “zero rainfall forecast”.

38
Figure 7.1: Simplified schematic diagram of the flow forecasting system. A detailed diagram is presented in Figure 7.9 on page 54.

3. The rainfall data (observations and forecasts) are processed by the rainfall-runoff models to calculate the inflows from lateral sub-catchments.

4. The inflows are given to the river system models that route them and manipulate the different infrastructures (storages and water extractions) in agreement to the basin management plan.

5. Finally, the streamflow calculated by the river system models are extracted at certain locations named forecasting points to produce the flow forecasts. Uncertainty bounds are attached to these forecasts in order to quantify their reliability.

A schematic diagram of this process is presented on Figure 7.1. This is a simplified presentation of the workflow. A more detailed version is presented in Figure 7.9 on page 54.

The components of the system refer to three types of spatial entities:

- The 18 forecasting points: these points correspond to the locations where forecasts are generated (see subsection 7.2),

- The 21 rainfall-runoff sub-catchments: these sub-catchments correspond to area where a rainfall-runoff models was calibrated (see subsection 7.4.1 on page 44),

- The 16 parallel model reaches: these areas correspond to the reaches where a parallel model was set-up to implement the data assimilation algorithm (see subsection 7.4.4 on page 51 and Figure 7.9 on page 54). This model is not mentioned in the simplified scheme presented previously.

### 7.2 Products

The product generated by the flood forecasting system is a set of forecasts of the expected stream flow starting from the forecasting instant and ending at the forecasting lead-time. The forecasts are produced on a series of forecasting points.
The products delivered by the system can be characterized by the following items:

- 18 forecasting points (see table 7.1),
- Maximum lead time of 3 days: the system was designed to provide forecasts for the period \([t_0, t_0 + 3 \text{ days}]\) were \(t_0\) is the forecasting instant.
- 6 hourly time step: the forecasts consist of time series with a time increment of 6 hours between each value.
- Uncertainty bounds: each forecast value is accompanied by an interval around the value. This interval is an estimation of the cumulative probability 0.1 and 0.9.

### 7.2.1 Forecasting points

The Condamine Balonne Project Plan defines the number of points where the flow forecasts should be produced (21 points according to the description of the milestones 23, page 13). The project plan does not mention the location of these points.

The flow forecasting points have been chosen to match with the reaches defined in the Murray Darling Basin Sustainable Yields project (Chiew et al., 2008). These reaches correspond to the 18 gauging stations indicated in Table 7.1 and located on Figure 7.2 on the next page which constitute the forecasting points in the system.

### 7.2.2 Time step

The time resolution was not defined in the Project Plan. The choice of this resolution is a compromise between

- The availability of real time data (see subsection 7.3 on page 42),

<table>
<thead>
<tr>
<th>GS Code (DERM)</th>
<th>Name</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 422394A</td>
<td>Condamine River @ Elbow valley</td>
<td>325</td>
</tr>
<tr>
<td>2 422310C</td>
<td>Condamine River @ Warwick</td>
<td>1375</td>
</tr>
<tr>
<td>3 422355A</td>
<td>Condamine River @ Talgai Tail water</td>
<td>3105</td>
</tr>
<tr>
<td>4 422319B</td>
<td>Dalrymple Creek @ Allora</td>
<td>246</td>
</tr>
<tr>
<td>5 422334A</td>
<td>Kings Creek @ Aides Bridge</td>
<td>516</td>
</tr>
<tr>
<td>6 422352A</td>
<td>Hodgson Creek @ Balgownie</td>
<td>560</td>
</tr>
<tr>
<td>7 422338A</td>
<td>Canal Creek @ Leyburn</td>
<td>395</td>
</tr>
<tr>
<td>8 422316A</td>
<td>Condamine River @ Cecil Weir</td>
<td>7795</td>
</tr>
<tr>
<td>9 422350A</td>
<td>Oakey Creek @ Fairview</td>
<td>1970</td>
</tr>
<tr>
<td>10 422333A</td>
<td>Condamine River @ Loudouns Bridge</td>
<td>12380</td>
</tr>
<tr>
<td>11 422308C</td>
<td>Condamine River @ Chinchilla</td>
<td>19190</td>
</tr>
<tr>
<td>12 422325A</td>
<td>Condamine River @ Cotswold</td>
<td>28930</td>
</tr>
<tr>
<td>13 42213A</td>
<td>Balonne River @ Weribone</td>
<td>51540</td>
</tr>
<tr>
<td>14 422401D</td>
<td>Maranoa River @ Mitchell</td>
<td>11920</td>
</tr>
<tr>
<td>15 422404A</td>
<td>Maranoa River @ Cashmere</td>
<td>19490</td>
</tr>
<tr>
<td>16 422201E</td>
<td>Balonne River @ St. George</td>
<td>75370</td>
</tr>
<tr>
<td>17 422204A</td>
<td>Culgoa River @ Whyenbah</td>
<td>79330</td>
</tr>
<tr>
<td>18 422205A</td>
<td>Balonne-minor River @ Hastings</td>
<td>79330</td>
</tr>
</tbody>
</table>

Table 7.1: List of the streamflow gauging stations (GS) comprising the 18 forecasting points
Figure 7.2: Location of the 18 gauging stations being used as forecasting points
• The complexity of the input data processing and the model calculation,
• The precision required for the forecasts.

The time resolution chosen for the forecasting system is a 6-hourly time step.

7.3 Data

This section describes the two types of data used during the project. Historical data were used to evaluate the performance of the system on historical floods. Further details on the evaluation procedure are given in subsection 7.6 on page 60. Real-time data are provided to the system in its current configuration.

7.3.1 Historical data

Three types of data were collected:

• Streamflow data: variable time step data was obtained from DERM on the 18 forecasting points for the period 1970-2006. Each time series was processed to calculate 6 hourly time series.

• Rainfall and potential evapotranspiration data: gridded daily data was extracted from the SILO archive for the period 1970-2006. 6 hourly data were calculated by disaggregating each daily data equally over four time step of 6 hours.

7.3.2 Real-time data

Three types of data are currently collected (situation on July 12, 2010, see section 8 on page 66 for more details on the downloading procedure):

• Streamflow data: instantaneous flow data are downloaded from a FTP site run by DERM. The irregular time series are converted to a 6 hourly time step within the FEWS system (see section 6 on page 35).

• Rainfall data: gridded daily data is extracted from the publicly accessible SILO website. 6 hourly data are calculated each daily data equally over four time step of 6 hours within the FEWS system.

• Potential evapotranspiration data: historical gridded PE data were averaged for each Julian calendar day over the period 1970-2006. The resulting data is a set of 365 grids of PE data that are assigned to the appropriate day during the simulation period. The different steps leading to this data set are illustrated by Figure 7.3 on the next page. As a result, the PE data do not need to be downloaded in real-time from external sources. They are stored locally and extracted on demand.

7.4 Models

This section describes the three components of the modelling system used to generate the products:

• The rainfall-runoff models are described in subsection 7.4.1 on page 44. They transform the rainfall and PE time series into lateral inflow in the river system,

• The river system models mentioned in subsection 7.4.3 on page 49 route the lateral inflows through the river system, the storing infrastructures and subtracting extractions from the routed flows.
Figure 7.3: Processing of the historical potential evapotranspiration (PE) data to obtain an operational data set. The plots show the PE time series on the catchment of the Condamine river at Elbow Valley (422394A).
The data assimilation procedure detailed in subsection 7.4.4 on page 51 corrects the models predictions to match them with the recent observations of streamflow on each forecasting point.

7.4.1 Rainfall-runoff models

The Sacramento model is used as a rainfall-runoff model. It was developed in the US in the early seventies (Burnash et al., 1973) and forms one of the core components of the flood forecasting system of the US National Weather Service. This model is of conceptual type: it simulates the runoff observed at the outlet of a catchment based on rainfall and potential evapotranspiration inputs. It has the following characteristics:

- The soil moisture dynamic is modelled with 6 stores representing the different components of moisture storage,
- It requires the calibration of 13 to 18 parameters (depending on the model version). The parameter values are dependent on the time step length. Daily parameters may not be applicable to sub-daily simulations (Nalbantis, 1995; Finnerty et al., 1997).

The Sacramento rainfall-runoff model was calibrated at the daily time step by DERM on 15 sub-catchments of the Condamine-Balonne catchment. These sub-catchments are either headwater catchments defined by an outlet gauging station or intermediary areas delimited by an upstream and downstream gauging station. For clarity, short codes were assigned to each sub-catchment. These codes are listed in Table 7.2 on the next page along with the gauging stations delimiting the corresponding area. The parameters are given in Appendix A on page 78 and the location of the 15 sub-catchments is shown on Figure 7.4 on page 47.

An analysis of the sub-catchments boundaries revealed that the 15 previous models were not covering all the Condamine-Balonne basin area. 6 models were added to account for the missing area. These models are listed in Table 7.3 on page 46. The parameters assigned to these models were copied from existing neighbouring models as stated in Table 7.3 on page 46.

As a result, 21 Sacramento models were used within the flow forecasting system. These 21 models should not be confused with the 18 forecasting points mentioned in subsection 7.2 on page 39.

7.4.2 Recalibration of rainfall-runoff models

Initial testing revealed that the parameters provided by DERM resulted in large errors within the Sacramento simulations. This can be explained by several factors:

- DERM calibrated the Sacramento model at the daily time step whereas the flow forecasting system operates at the 6 hourly time step. As indicated earlier, parameters are not transferable from one time step to another.
- The calibration was performed on the period 1970-1995 (see Table 7.2 on the next page). The Condamine experienced significantly drier conditions during the recent years that may not be captured by this calibration. An illustration of this point is given on Figure 7.5 on page 47 with the evolution of yearly rainfalls on the Elbow Valley catchment (422394A). The figure shows a clearly decreasing trend over the recent years.
- The data utilized by DERM are point rainfall and pan-evaporation data whereas the forecasting system uses SILO gridded products.
- DERM does not utilize the simulations produced by the Sacramento models as an input...
<table>
<thead>
<tr>
<th>Code</th>
<th>Model Name(DERM)</th>
<th>Calib. Start</th>
<th>Calib. End</th>
<th>Area (km²)</th>
<th>Up. Station</th>
<th>Down. Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>elbwV</td>
<td></td>
<td></td>
<td>325</td>
<td></td>
<td>422394A</td>
</tr>
<tr>
<td>2</td>
<td>elbwV2Wck</td>
<td></td>
<td></td>
<td>1035</td>
<td></td>
<td>422310C</td>
</tr>
<tr>
<td>3</td>
<td>leslie</td>
<td>1970</td>
<td>1993</td>
<td>603</td>
<td></td>
<td>422395A</td>
</tr>
<tr>
<td>4</td>
<td>wck2Talg</td>
<td>1978</td>
<td>1989</td>
<td>1127</td>
<td></td>
<td>422310C</td>
</tr>
<tr>
<td>5</td>
<td>kingsCk</td>
<td></td>
<td></td>
<td>516</td>
<td></td>
<td>422334A</td>
</tr>
<tr>
<td>6</td>
<td>canalCk</td>
<td></td>
<td></td>
<td>939</td>
<td></td>
<td>422338A</td>
</tr>
<tr>
<td>7</td>
<td>yarr2Cecil</td>
<td>1990</td>
<td>1995</td>
<td>1438</td>
<td></td>
<td>422316A</td>
</tr>
<tr>
<td>8</td>
<td>northB</td>
<td>1981</td>
<td>1995</td>
<td>880</td>
<td></td>
<td>422347B</td>
</tr>
<tr>
<td>9</td>
<td>oakeyCk</td>
<td>1981</td>
<td>1995</td>
<td>1970</td>
<td></td>
<td>422350A</td>
</tr>
<tr>
<td>10</td>
<td>lound2Chin</td>
<td>1970</td>
<td>1995</td>
<td>6810</td>
<td></td>
<td>422333A</td>
</tr>
<tr>
<td>11</td>
<td>chin2Cotsw</td>
<td></td>
<td></td>
<td>19740</td>
<td></td>
<td>422308C</td>
</tr>
<tr>
<td>12</td>
<td>cotsw2Weri</td>
<td></td>
<td></td>
<td>22610</td>
<td></td>
<td>422325A</td>
</tr>
<tr>
<td>13</td>
<td>fVale</td>
<td>1978</td>
<td>1992</td>
<td>9030</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>fVale2Mitch</td>
<td>1978</td>
<td>1992</td>
<td>2890</td>
<td></td>
<td>422401D</td>
</tr>
<tr>
<td>15</td>
<td>Mitch2OCash</td>
<td>1970</td>
<td>1995</td>
<td>7570</td>
<td></td>
<td>422401D</td>
</tr>
</tbody>
</table>

**Table 7.2:** List of the Sacramento models provided by QLD-DERM. The gauging stations defining the upstream and downstream boundaries of the subcatchment are indicated in the last 2 columns when known.
<table>
<thead>
<tr>
<th>Code Name</th>
<th>Area (km²)</th>
<th>Up. Station</th>
<th>Down. Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 dalCk</td>
<td>273</td>
<td>Dalrymple Creek</td>
<td>kingsCk</td>
</tr>
<tr>
<td>2 hogCk</td>
<td>630</td>
<td>Hogson Creek</td>
<td>kingsCk</td>
</tr>
<tr>
<td>3 ashCk</td>
<td>1025</td>
<td>Ashall Creek</td>
<td>oakeyCk</td>
</tr>
<tr>
<td>4 coobCk</td>
<td>160</td>
<td>Coobie Creek</td>
<td>oakeyCk</td>
</tr>
<tr>
<td>5 weri2Bar</td>
<td>6206</td>
<td>Weribone to Barackdale</td>
<td>cotsw2Weri</td>
</tr>
<tr>
<td>6 bar2Stge</td>
<td>132</td>
<td>Barackdale to St George</td>
<td>cotsw2Weri</td>
</tr>
</tbody>
</table>

Table 7.3: List of the Sacramento models added to complete the models provided by QLD-DERM. The gauging stations defining the upstream and downstream boundaries of the subcatchment are indicated in the last 2 columns when known.
**Figure 7.4:** Sub-catchments corresponding to the Sacramento rainfall-runoff models

**Figure 7.5:** Trend in the yearly rainfall on the Elbow Valley catchment (422394A)
Figure 7.6: Comparison between the inflows used by the river system models and the simulations generated by the Sacramento model on the sub-catchment located between Costwold and Weribone gauging stations (cotsw2Weri) during the May 1990 flood. The first Sacramento simulation corresponds to the parameters provided by DERM and the second to recalibrated parameters. Rainfall is plotted on an inverse Y-axis.

for the river system models. According to Ryan (2002):

for most of the model, the local catchment inflow between two gauges along the river had to be derived from the flow recorded at those stream gauges. This process . . . uses IQQM sub-models that also gave estimates of the routing and loss parameters.

Although this approach can be used for scenario modelling; it is not applicable in a forecasting mode where the measurements on neighbouring gauges are not available over the forecasting period.

To illustrate this point, the inflow data used by the river system models are plotted along with two simulations generated with the Sacramento rainfall-runoff model on Figure 7.6. The difference between the two types of data can be large. In this example (sub-catchment cotsw2Weri, see Table 7.2 on page 45), the Sacramento model with parameters from DERM simulates three large flood peaks (end of March and beginning of June 1990) whereas the IQQM input only have one.

To improve the simulation produced by the Sacramento rainfall-runoff model, a recalibration was performed with the following characteristics:

- The calibration algorithm is the Shuffled Complex Evolution (SCE) developed by Duan et al. (1993).
- The models were calibrated to reproduce the inflows used within the IQQM simulations. The inflow data were extracted from the IQQM configuration files and used as a calibra-
tion target for the Sacramento models. The calibration period is 1990-2006.

- The rainfall and PE input data were extracted from the SILO archive.
- The calibration was performed at the 6 hourly time step (6 hourly data were calculated by disaggregating each daily data equally over four time step of 6 hours).

The recalibrated parameters are given in appendix B on page 81. Figure 7.7 on the following page compares the parameter value before and after recalibration for the 15 models listed in Table 7.2 on page 45. This figure reveals significant differences between the original and recalibrated parameters: most points on Figure 7.7 are located away from the 1:1 lines. A comparison of the performance between the two sets of parameters in a forecasting context is provided in section 7.6 on page 60. Figure 7.6 on the preceding page shows two simulations produced with the two parameter sets on the sub-catchment located between Costwold and Weribone gauging stations (cotsw2Weri). The recalibrated model shows a much smoother response with lower peaks and longer recessions. The flood peak is better reproduced by the initial model but the recalibrated model has a better timing.

7.4.3 River systems models

Four river system models were developed in the Condamine-Balonne basin by DERM Chiew et al. (2008):

- Upper Condamine (named UCON): the model was developed with IQQM (v6.73.4).
- Middle Condamine (named MCON): the model was developed with IQQM (v6.73.4).
- St. George reservoir (named STGE): the model was purposely developed by the Qld government.
- Lower Balonne (named LBON): the model was developed with IQQM (v6.36.1).

The area covered by each model is shown on Figure 7.8 on page 51.

Ryan (2002) provides a detailed description of the IQQM software:

- the model represents the system as a series of links and nodes with the links describing the routing of river flows and the nodes representing system processes such as the operation of storages, demands and losses. IQQM was developed as a tool for planning and evaluating water resource management policies at the river basin scale. . . . The model operates on a continuous basis and can be used to simulate river system behaviour for periods ranging up to hundreds of years. The major processes that are simulated include:
  - Flow routing in rivers, effluent systems and irrigation channels,
  - Reservoir operation,
  - Resource assessment,
  - Irrigation,
  - Urban water supply and other consumptive uses,
  - Wetland and environmental flow requirements.

The St George model is described by Harding (2002):

The St George Regulated System was simulated using the daily St George Model
Figure 7.7: Comparison between the initial and recalibrated parameters for the 15 sub-catchments listed in Table 7.2 on page 45 and the 17 parameters listed in Appendix A on page 78. The X axis corresponds to the initial parameters and the Y axis to recalibrated parameters.
Figure 7.8: Area covered by the river system models with the forecasting points

(SGOS) developed by the Department of Natural Resources ... At the commencement of the study, a decision was made not to use the Integrated Quantity-Quality Model developed by the Department of Land and Water Conservation in New South Wales, as it did not simulate (some) aspects of the St George system.

7.4.4 Data assimilation

Simulations produced by a combined application of the Sacramento and river system models contain large errors. These errors could considerably reduce the value of a forecasting model if they are not corrected. This is the objective of a data assimilation procedure.

Considering the complexity of the Condamine-Balonne forecasting system, it was not possible to apply classical data assimilation techniques. This task was undertaken in two steps. First, a simplified model called “Parallel model” was developed. Second, the data assimilation was applied on this model to update it at every forecasting instant. The next two sections describe this approach.

Parallel Modelling (LIMO)

The real-time correction of flood forecasting models is usually applied to rainfall-runoff models alone. The Condamine-Balonne system is much more complex with the combination of rainfall-runoff and river system models. This coupling significantly increases the runtime of the whole system which is in the order of minutes on a machine with average performance. Classical correction techniques require multiple runs that would lead to unacceptable calculation time. An alternative solution was developed in order to maintain the original modelling system and, at the same time, apply correction techniques with acceptable run times. The concept was called parallel modelling and abbreviated as LIMO (Lateral Inflow MOdel) in the forecasting
system. It generates the forecasts according to the following workflow illustrated by Figure 7.9 on page 54:

1. The original modelling system based on the coupling between the Sacramento and IQQM/St George models is first run without any correction. This constitutes the baseline simulation. From this simulation, two variables are exported: the extracted water from each extraction nodes (Irrigation or water supply) and the stored water from storage nodes (reservoirs and weirs).

2. A set of river reaches is defined. Each reach is delimited by an upstream and downstream forecasting point. Table 7.4 on the next page gives the list of the 16 reaches that were retained. The reaches were defined starting from the headwater catchments up to the Beardmore dam. No reach was retained further downstream because of the complexity introduced by the St. George model. Note that the reaches roughly correspond to the Sacramento subcatchment (see Table 7.2 on page 45 and 7.3 on page 46). Each node of the river system models are assigned to a particular reach. The extracted and stored water is calculated on each reach by summing the contributions from the corresponding nodes.

3. The parallel model is run on each reach with 5 inputs: Rainfall and potential evapotranspiration, upstream flows (from the upstream forecasting point), extracted and stored water from the baseline simulation. The parallel model calculates the lateral inflow with the Sacramento model, adds it to the routed upstream flow and subtracts the extracted and stored water. The final result is the flow at the downstream forecasting point. The parameters used for the Sacramento model within the parallel model are the ones provided by DERM or the recalibrated ones (see section 7.4.2 on page 44). The two options are discussed in section 7.6.1 on page 60. The routing model is a lag model defined by the following equation:

\[
Q_{i}^{rout} = \alpha Q_{i-d}^{up} + (1 - \alpha) Q_{i-d-1}^{up}
\]

\[
d = \lfloor \delta \rfloor
\]

\[
\alpha = 1 - \delta + \lfloor \delta \rfloor
\]

with \(Q_{i}^{rout}\) and \(Q_{i}^{up}\) are the routed and upstream flow on time step \(i\) respectively, \(\delta \in \mathbb{R}\) the lag parameter and \(\lfloor \rfloor\) the floor function. The lag parameter \(\delta\) was calculated by setting a fixed travelling speed of 1 m/s over the reach which is a classical value for flood propagation (Lerat et al., 2009). The reach length was obtained from the difference between the Adopted Middle Thread Distance (AMTD, the distance from the river’s outlet) of the upstream and downstream stations. The corresponding figures are given in Table 7.4 on the next page.

**Updating procedure**

In a flood forecasting context, the updating aims to modify the model set-up in order to better match with recent observed data and improve the model predictions in the near future. Refsgaard (1997) provides an overview of the methods that can be used to do so. On the Condamine-Balonne, two types of updating were retained:

- **Updating of input variables:** according to Refsgaard (1997), “updating of input variables, typically precipitation and air temperature, is the classical method justified by the fact that input uncertainties may often be the dominant error source in operational forecast-
<table>
<thead>
<tr>
<th>Code</th>
<th>Parallel Model Name</th>
<th>Up. Station</th>
<th>Down. Station</th>
<th>Distance (km)</th>
<th>Lag Parameter (h)</th>
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<tbody>
<tr>
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<td></td>
<td>422394A</td>
<td></td>
<td>0</td>
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<td>2</td>
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<td>Elbow Valley to Warwick</td>
<td>422341A</td>
<td>422310C</td>
<td>36</td>
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<td>Warwick to Talgai</td>
<td>422310C</td>
<td>422355A</td>
<td>72</td>
</tr>
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<td>Kings Creek</td>
<td></td>
<td>422341A</td>
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<td>Canal and Thanes Creeks</td>
<td></td>
<td>422338A</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>yan2Cecil</td>
<td>Yarramalong to Cecil</td>
<td></td>
<td>422316A</td>
<td>138</td>
</tr>
<tr>
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<td></td>
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</tr>
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<td>8</td>
<td>cecil2Lound</td>
<td>Cecil to Loundoun</td>
<td>422316A</td>
<td>422333A</td>
<td>57</td>
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<td>lound2Chin</td>
<td>Loundon to Chinchilla</td>
<td>422333A</td>
<td>422308C</td>
<td>137</td>
</tr>
<tr>
<td>10</td>
<td>chin2Cotsw</td>
<td>Chinchilla to Cotswold</td>
<td>422308C</td>
<td>422325A</td>
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<td>422325A</td>
<td>422213A</td>
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<td></td>
<td>422319B</td>
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<td>hogCk</td>
<td>Hogson Creek</td>
<td></td>
<td>422352A</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 7.4:** List of the Parallel models used to implement the data assimilation procedure. The gauging stations defining the upstream and downstream boundaries of the subcatchment are indicated in the last 2 columns when known.
This type of updating appeared particularly relevant in the case of the Condamine-Balonne basin considering the limited number of meteorological stations in its middle part. Only input rainfall was updated.

- Updating of state variables: State variables are the internal time varying variables used by a model. Updating these variables can correct the internal dynamic of a model. This type of updating is complementary with the previous one because it mitigates the errors coming from the model structure itself. In the present system, the state variable LZFPC\(^4\) from the Sacramento model was updated at the beginning of the assimilation window. This state variable represents a deep storage which was not considered by Seo et al. (2003) in his data assimilation procedure. Trial and errors revealed that the updating on this variable was more efficient than on the ones proposed by Seo et al. (2003). This interesting result would require further investigations that will not be detailed here.

Two main strategies are available to implement the updating procedure. The first one is the Kalman filter (Kalman, 1960). Initially limited to linear models, it was further extended by Evensen (1994) to cope with non-linearities. The corner stone of the Kalman filter is a re-formulation of the model according to a state-space representation. The state-space representation introduced by Kalman (1960) consists of two matrix equations that relate the observations, the model states at one time step and the states at the following time step. This procedure can be complex for highly non-linear models like the Sacramento rainfall-runoff model.

Seo et al. (2003) recommend another method called variational data assimilation. The method was applied by Seo et al. (2003) to develop an updating procedure for the Sacramento rainfall-runoff models within the flood forecasting system of the US National Weather Service. This approach does not require a reformulation of the model which is a great advantage when developing an updating procedure for complex models such as Sacramento or IQQM. It was retained for the Condamine-Balonne system.

\(^4\)Lower zone free primary contents
Assume that a forecast has to be issued at time step \( i_0 \) over the period \([i_0 + 1, i_0 + L]\) on one forecasting point. The updating method developed by Seo et al. (2003) relies on four steps illustrated by Figure 7.10 on the following page:

1. An assimilation window is defined over \([i_0 - D + 1, i_0]\) where \( D \) is the duration of the window. The value of \( D \) was set to 40 time steps (10 days at the 6 hourly time step) for all updating routines within the Condamine-Balonne system.

2. During the assimilation window, the following least-square minimization problem is solved:

\[
(\lambda^*_p, \lambda^*_s) = \underset{\lambda_p \geq 0, \lambda_s \geq 0}{\text{arg min}} \left( \frac{1}{\sigma^2_Q} \sum_{i = i_0 - D + 1}^{i_0} (\hat{Q}_i - Q_i)^2 + \frac{1}{\sigma^2_P} \sum_{i = i_0 - D + 1}^{i_0} (\hat{P}_i(\lambda_p, P_i) - P_i)^2 \right)
\]

\[
+ \frac{1}{\sigma^2_S} (\hat{S}_{i_0-D+1}(\lambda_s, S_{i_0-D+1}) - S_{i_0-D+1})^2 \right) \quad (7.4)
\]

where \( \lambda^*_p \) and \( \lambda^*_s \) are the optimal correction factors, \( Q_i \) and \( P_i \) are the observed flow and the observed rainfall before correction respectively, \( S_{i_0-D+1} \) is the state variable at the beginning of the assimilation window before any correction. \( \sigma_Q, \sigma_P \) and \( \sigma_S \) are the standard deviations of the streamflow, rainfall and state variable respectively. \( \hat{P}_i(\lambda_p, P_i) \) and \( \hat{S}_{i_0-D+1}(\lambda_s, S_{i_0-D+1}) \) are the corrected rainfall and the state variable respectively which are functions of the correction factor and the original variable. \( \hat{Q}_i \) is a model prediction given by

\[
\hat{Q}_i = f \left( \theta, \{\hat{P}_k(\lambda_p, P_k)\}_{k \in [i_0-D+1, i]} \right) \quad \text{with} \quad i \geq i_0 - D + 1 \quad (7.5)
\]

Where \( \theta \) is the vector of model parameters. To simplify the notation, only the updated state variable \( \hat{S}_{i_0-D+1} \) is mentioned in Equation 7.5 whereas the Sacramento model has 6 internal states (see section 7.4.1 on page 44).

If we further assume that the corrections are multiplicative, the corrected variables are given by the following equations:

\[
\hat{P}_i(\lambda_p, P_i) = \lambda_p P_i \quad (7.6)
\]

\[
\hat{S}_i(\lambda_s, S_i) = \lambda_s S_i \quad (7.7)
\]

The minimization problem expressed by Equation 7.4 can be simplified into

\[
(\lambda^*_p, \lambda^*_s) = \underset{(\lambda_p, \lambda_s) \in \mathbb{R}^2}{\text{arg min}} \left( \frac{1}{\sigma^2_Q} \sum_{i = i_0 - D + 1}^{i_0} (\hat{Q}_i - Q_i)^2 + \frac{(\lambda_s - 1)^2}{\sigma^2_P} \sum_{i = i_0 - D + 1}^{i_0} P_i^2 \right)
\]

\[
+ \frac{(\lambda_s - 1)^2}{\sigma^2_S} S_{i_0-D+1}^2 \right) \quad (7.8)
\]

To further simplify the minimization problem, the standard deviations \( \sigma_P \) and \( \sigma_S \) were considered infinite which eliminates the last two terms of Equation 7.8.

The minimization problem was solved by systematically testing all possible correction factors within the interval \([0.5, 3.5]\) with 0.1 increments.

3. When the correction factors \( (\lambda^*_p, \lambda^*_s) \) are identified, they are applied on the forecasting period \([i_0 + 1, i_0 + L]\) using Equation 7.5.
7.5 Uncertainty

The previous section describes the method to generate the deterministic flow forecasts on the 18 forecasting points listed in Table 7.1 on page 40. This section indicates how uncertainty bounds corresponding to the 0.1 and 0.9 percentiles are attached to these forecasts.

Let $\hat{Q}_{i_0+1}, \ldots, \hat{Q}_{i_0+L}$ be a set of $L$ flow forecasts generated on time step $i_0$ for one forecasting point. In the present system, these forecasts are produced by implementing Equation 7.5. To generate the uncertainty bounds, a Bayesian approach was retained where the objective is to estimate the following probability densities

$$f_{i_0,k}(q, \hat{Q}_{i_0+k}, Q_{i_0}) = Pr \left[ Q_{i_0+k} = q \bigg| \hat{Q}_{i_0+k}, Q_{i_0} \right] \text{ for } i_0 \in \mathbb{N}, k \in [1, L] \tag{7.9}$$

where $q \geq 0$ is a dummy variable and $Q_{i_0}$ is last observed flow on the forecasting point. This objective can be interpreted as the estimation of the chances of observing a flow $Q_{i_0+k}$ at time step $i_0 + k$ given a forecast $\hat{Q}_{i_0+k}$ and the last observation $Q_{i_0}$. The concept is illustrated by Figure 7.11 on the next page.

Note that rainfall inputs are not mentioned in Equation 7.9. This can be explained by one of our starting assumptions (see section 7.1 on page 38): there was no attempt to estimate and propagate the uncertainty attached to rainfall inputs. As a result, the rainfall disappears from any probabilistic equation such as 7.9 because it is considered as a deterministic variable.

The function $f_{i_0,k}$ is indexed by $i_0$ and $k$ because it could be non-stationary (dependence on $i_0$, the forecasting instant) and variable across different forecasting lead-times (dependence on $k$). A simplifying assumption applied here is to remove the dependence on $i_0$ and retain stationary densities:

$$f_{i_0,k}(q, \hat{Q}_{i_0+k}, Q_{i_0}) = f_k(q, \hat{Q}_{i_0+k}, Q_{i_0}) \tag{7.10}$$
Figure 7.11: Generation of uncertainty bounds on flow forecasts

Once the density $f_k$ has been estimated, the uncertainty bounds for a forecast with lead time $k$ are obtained by inverting the cumulative distribution of $f_k$ for the two quantiles 0.1 and 0.9. This cumulative distribution is noted $F_k$ and has the following expression

$$F_k(q, \hat{\mathcal{Q}}_{i_0+k}, Q_{i_0}) = \int_0^q f_k(u, \hat{\mathcal{Q}}_{i_0+k}, Q_{i_0}) du$$  \hspace{1cm} (7.11)

The uncertainty bounds obtained by inverting $F_k$ are noted

$$U_{10}(i_0 + k) = \left\{ q \geq 0 : F_k(q, \hat{\mathcal{Q}}_{i_0+k}, Q_{i_0}) = 0.1 \right\}$$  \hspace{1cm} (7.12)

$$U_{90}(i_0 + k) = \left\{ q \geq 0 : F_k(q, \hat{\mathcal{Q}}_{i_0+k}, Q_{i_0}) = 0.9 \right\}$$  \hspace{1cm} (7.13)

where $U_{10}(i_0 + k)$ and $U_{90}(i_0 + k)$ are the uncertainty bounds having a cumulative probability of 0.1 and 0.9 respectively.

The method applied to estimate the density $f_k$ in Equation 7.9 on the preceding page is the Bayesian Forecasting System (BFS) developed by Krzysztofowicz (1999). With this approach, $f_k$ is determined by applying the Bayes theorem:

$$f_k(q, \hat{\mathcal{Q}}_{i_0+k}, Q_{i_0}) = \frac{Pr[Q_{i_0+k} = q | \hat{\mathcal{Q}}_{i_0+k}, Q_{i_0}]}{\int_{0}^{\infty} Pr[Q_{i_0+k} = q | \hat{\mathcal{Q}}_{i_0+k}, Q_{i_0}] dq} \cdot Pr[Q_{i_0+k} = q | Q_{i_0}]$$  \hspace{1cm} (7.14)

The term $I$ is called the posterior density, the numerator of term $II$ is the likelihood function and the term $III$ is the prior density.

Four steps illustrated by Figure 7.12 on the following page are required to obtain the density $f_k$:
1. The three variables $Q_{i_0+k}$, $\hat{Q}_{i_0+k}$, $Q_{i_0}$ are transformed using the Normal Quantile transform (NQT) described in appendix C on page 84. An example of a variable transformation is given on Figure 7.13 on the next page with the observed flow from the gauging station of Elbow Valley (422394A). Let us note $X$ the transformed variables:

$$X_{i_0+k} = \text{NQT}(Q_{i_0+k}, \lambda_Q) \text{ transformed of the future flow} \quad (7.15)$$

$$\hat{X}_{i_0+k} = \text{NQT}(\hat{Q}_{i_0+k}, \lambda_{\hat{Q}}) \text{ transformed of the flow forecast} \quad (7.16)$$

$$X_{i_0} = \text{NQT}(Q_{i_0}, \lambda_Q) \text{ transformed of the last observed flow} \quad (7.17)$$

with $\lambda_Q$ and $\lambda_{\hat{Q}}$ two parameters defining the NQT (see appendix C on page 84).

2. Two assumptions are introduced (Krzysztofowicz and Kelly, 2000) to estimate the three terms of Equation 7.14 for the transformed variables ($X_{i_0+k}$, $\hat{X}_{i_0+k}$, $X_{i_0}$) :

   • The estimation of the prior density is based on the assumption that $X_{i_0+k}$ is a process described by the following linear equation

     $$X_{i_0+k} = c_k X_{i_0} + \Xi \quad (7.18)$$

     where $c_k$ is a parameter and $\Xi$ is a variable stochastically independent of $X_{i_0}$ and normally distributed with mean 0 and variance $1 - c_k^2$. Consequently, the prior density of $X_{i_0+k}$ (term $III$ in Equation 7.14) is normal with mean and variance given by

     $$E\left(X_{i_0+k} \mid X_{i_0}\right) = c_k X_{i_0} \quad (7.19)$$

     $$Var\left(X_{i_0+k} \mid X_{i_0}\right) = 1 - c_k^2 \quad (7.20)$$

   • The estimation of the likelihood function rests on the assumption that $\hat{X}_{i_0+k}$ is a process governed by the following linear equation

     $$\hat{X}_{i_0+k} = a_k X_{i_0+k} + d_k X_{i_0} + b_k + \Theta \quad (7.21)$$

     where $a_k$, $d_k$ and $b_k$ are parameters and $\Theta$ is a variable stochastically independent of $(X_{i_0}, X_{i_0+k})$ and normally distributed with mean 0 and variance $\sigma_k$. Consequently,
the likelihood function (numerator of term II in Equation 7.14) is normal with mean and variance given by

$$E \left( \tilde{X}_{i_0+k} | X_{i_0}, X_{i_0+k} \right) = a_k X_{i_0+k} + d_k X_{i_0} + b_k$$

$$Var \left( \tilde{X}_{i_0+k} | X_{i_0}, X_{i_0+k} \right) = \sigma_k^2$$

The two previous assumptions introduce $L$ sets of 5 parameters $(c_k, a_k, d_k, b_k, \sigma_k)_{k=1,...,L}$ to be determined for each of the $L$ lead-times from historical data. The total number of parameters to be estimated in the BFS is thus $5L + 2$ including the two parameters $\lambda_Q$ and $\lambda_{\tilde{Q}}$ (see Equations 7.15 on the preceding page to 7.17 on the preceding page).

3. With the two assumptions mentioned in the previous point, the prior, likelihood and posterior densities can be estimated for the transformed variables $(\tilde{X}_{i_0+k}, X_{i_0}, X_{i_0+k})$. The details are given by (Krzyżtofowicz and Kelly, 2000).

4. Finally, the posterior density $f_k$ (term I in Equation 7.14) can be calculated for the untransformed variable $Q_{i_0+k}$. Krzyżtofowicz and Kelly (2000) give the expression of the cumulative distribution $F_k$ of the density $f_k$ which is required to calculate the uncertainty.
bounds (see Equations 7.12 and 7.13):

\[
F_k(q, \hat{Q}_{i_0+k}, Q_{i_0}) = N\left( \frac{NQT(q, \lambda_Q) - A_k NQT(\hat{Q}_{i_0+k}, \lambda_{\hat{Q}}) - D_k NQT(Q_{i_0}, \lambda_Q) - B_k}{T_k} \right)
\]

(7.24)

\[
A_k = \frac{a_k(1 - c_k^2)}{a_k^2(1 - c_k^2) + \sigma_k^2}
\]

(7.25)

\[
D_k = \frac{c_k \sigma_k - a_k d_k (1 - c_k^2)}{a_k^2(1 - c_k^2) + \sigma_k^2}
\]

(7.26)

\[
B_k = \frac{-a_k b_k (1 - c_k^2)}{a_k^2(1 - c_k^2) + \sigma_k^2}
\]

(7.27)

\[
T_k = \sqrt{\frac{a_k^2(1 - c_k^2)}{a_k^2(1 - c_k^2) + \sigma_k^2}}
\]

(7.28)

where \( N \) is the cumulative density of a centred normal variable:

\[
N(x) = \int_{-\infty}^{x} e^{u^2/2} du
\]

(7.29)

When the parameters \((c_k, a_k, d_k, b_k, \sigma_k)\) and \((\lambda_Q, \lambda_{\hat{Q}})\) are known, Equation 7.24 gives a straightforward method to calculate the uncertainty bounds. Compared to most uncertainty methods:

- It does not require multiple model runs like the Monte-Carlo methods,
- It is completely independent from the model code,
- It allows the introduction of a prior knowledge based on the Bayesian framework.

The parameters were obtained by solving the linear regressions expressed by Equations 7.18 and 7.21 on historical flow data and forecasts during the floods listed in Table 7.5. For this exercise, the forecasts were generated with recalibrated Sacramento parameters and the data assimilation procedure. The tables containing the parameters are provided in Appendix D on page 85.

### 7.6 Evaluation, future developments

This section describes the evaluation procedure that was conducted to verify the quality of the forecasts generated with the system described in the sections 7.4 on page 42 to 7.5 on page 56. After this evaluation, a conclusion is given to the presentation of the flow forecasting system in the form of recommendations for future developments in subsection 7.7.

#### 7.6.1 Evaluation of the forecasts

The deterministic forecasts are generated on the 18 forecasting points listed in Table 7.1 on page 40. These forecasts are 3 days ahead forecasts produced with the parallel models described in subsection 7.4.4 on page 51.

To evaluate the quality of forecasts, the persistence index (Kitadinis and Bras, 1980) was calculated for all the forecasts generated during the 5 historical floods listed in Table 7.5. The
Table 7.5: Historical floods used for the flow forecasts evaluation. The maximum discharge is indicated for each flood and each forecasting point (ML/d)

<table>
<thead>
<tr>
<th></th>
<th>Flood.1</th>
<th>Flood.2</th>
<th>Flood.3</th>
<th>Flood.4</th>
<th>Flood.5</th>
</tr>
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<tbody>
<tr>
<td>1 Start</td>
<td>11/01/2004</td>
<td>9/01/1996</td>
<td>20/05/1990</td>
<td>27/08/1998</td>
<td>1/05/1983</td>
</tr>
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<td>3 Forc. Pt. 01 (422394A)</td>
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<td>0.9</td>
<td>2.7</td>
<td>0.3</td>
<td>6.3</td>
</tr>
<tr>
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<td>4.3</td>
<td>5.9</td>
<td>1</td>
<td>33.4</td>
</tr>
<tr>
<td>5 Forc. Pt. 03 (422355A)</td>
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<td>8.1</td>
<td>11</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
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<td>1</td>
<td>2.4</td>
<td>0.4</td>
<td>6.7</td>
</tr>
<tr>
<td>7 Forc. Pt. 05 (422334A)</td>
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<td>4.6</td>
<td>6.2</td>
<td>0.2</td>
<td>13.5</td>
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<td>11.2</td>
<td>11.2</td>
<td>11.2</td>
</tr>
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<td>1.4</td>
<td>0.9</td>
<td>17.2</td>
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<td>4.3</td>
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<td>14.6</td>
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<td>73.6</td>
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<td>2.2</td>
<td>0.2</td>
<td>19.8</td>
</tr>
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<td>17 Forc. Pt. 15 (422404A)</td>
<td>29.9</td>
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<td>2.7</td>
<td>0.5</td>
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<td>73.8</td>
<td>8.1</td>
<td>65.2</td>
<td>72</td>
</tr>
</tbody>
</table>

The persistence index is a relative measure of goodness of fit:

\[ P_k = 1 - \frac{\sum_i (\hat{Q}_{i+k} - Q_{i+k})^2}{\sum_i (Q_i - Q_{i+k})^2} \]  

(7.30)

where \( k \) is the lead-time (varying from 0 to 3 days in our system), \( Q_i \) and \( Q_{i+k} \) are the observed flow at time step \( i \) and \( i + k \) respectively and \( \hat{Q}_{i+k} \) is the forecast for the flow at time step \( i + k \). This index varies between \(-\infty\) and 1 for a perfect forecast \((\sum_i (\hat{Q}_{i+k} - Q_{i+k})^2 = 0)\). A positive value of \( P_k \) indicates that the forecast has a smaller error than the persistence model which is a minimal requirement for a forecasting system.

The tables showing the values of the persistence index for all the forecasting points and all the lead time are given in Appendix E on page 92. The persistence are given for 15 forecasting points only. The 3 forecasting points located downstream of St. George reservoir were not included in the verification scheme.

Figures 7.14 on page 63 and 7.15 on page 64 present the persistence criteria for 24 hours and 72 hours lead time forecasts. On the two figures, the persistence of the initial configuration (initial Sacramento parameters without data assimilation, i.e. with \( (\lambda_P, \lambda_S) = (1, 1) \) in Equation 7.5) is compared with two alternative configurations (data assimilation with initial and recalibrated parameters).

These figures reveal that

- For 24 hours forecasts (see Figure 7.14 on page 63), about half of the points present
a negative persistence index, whatever configuration is selected (lower left quadrant on Figure 7.14.a). The negative criteria are mostly obtained on the central part of the basin (points 2, 4, 5 and 8). This could be explain by the important interactions between ground-water and surface water in this area. Rainfall-runoff model cannot reliably reproduce these interactions which may limit the accuracy of the forecasts.

- For 24 hours forecasts, the use of recalibrated parameters (gray circles on Figure 7.14 on the next page) improved the forecasts on the worst performing points with significant increase of the index on points 2, 5 and 8.

- For 24 hours forecasts, the data assimilation (DA) presented in subsection 7.4.4 on page 51 improved the forecasts with most points located over the 1 : 1 line. DA is more efficient on recalibrated parameters. When it is applied on the initial parameters provided by DERM, DA can be counterproductive with points falling below the 1 : 1 line (e.g. points 9, 10, 14 and 15 on Figure 7.14 on the next page.a).

- For 72 hours forecasts (see Figure 7.15 on page 64), most persistence indexes are positive which constitute a better result than the one obtain for 24 hours forecasts. This improvement can be explained by the degradation of the persistence model used as a benchmark in the persistence index (see Equation 7.30 on the preceding page): compared to the persistence model, 72 hours forecasts have a better value than 24 hours forecasts. Further work would be required to compare the forecasts with other simple model like a routing model.

- For 72 hours forecasts, DA did not improve the performance. This can be explained by the limited effect of DA over a long forecasting period. The updating introduced by the DA targets short memory variables which influence the forecasts on the first time steps only.
Figure 7.14: Persistence indexes for the 18 forecasting points with a 24 hours lead time, the numbers refer to Table 7.1 on page 40. The X axis shows the persistence of forecasts using the initial Sacramento (SACSMA) parameters provided by DERM and no data assimilation (DA, see section 7.4.4 on page 51). Two persistence indexes are plotted on the Y axis: the gray dots show the index corresponding to forecasts using the DA and the initial SACSMA parameters, the black circles show the index of forecasts using DA and recalibrated parameters. The second figure is a zoom of the first one in the region $[0, 1] \times [0, 1]$. 
Figure 7.15: Persistence indexes for the 18 forecasting points with a 72 hours lead time, the numbers refer to Table 7.1 on page 40. The X axis shows the persistence of forecasts using the initial Sacramento (SACSMA) parameters provided by DERM and no data assimilation (DA, see section 7.4.4 on page 51). Two persistences are plotted on the Y axis: the gray dots show the index corresponding to forecasts using the DA and the initial SACSMA parameters, the black circles show the index of forecasts using DA and recalibrated parameters. The second figure is a zoom of the first one in the region $[0, 1] \times [0, 1]$. 

64
7.7 Conclusions and future developments

The findings from the previous sections reveal that:

- The flow forecasts are more reliable on the up-stream and down-stream part of the catchment than on the central part;
- The recalibration of the rainfall-runoff parameters was beneficial, especially for the lowest performing models; and
- The data assimilation procedure is not delivering a systematic performance improvement. It appeared particularly useful in combination with the recalibrated parameters.

In conclusion, there is no practical obstacle to convert scenario-based models to real-time operational tools. This point is demonstrated by the successful implementation of the forecasting system on the Condamine-Balonne basin. Recalibration or adjustment of the models is a priority task to be undertaken before any data assimilation is applied. Data assimilation can only refine an already acceptable model simulation.

The current flow forecasting system suffers from the lack of rainfall forecasts. The current assumption is to use a zero rainfall forecast (see section 7.1 on page 38) which limits the forecasting capacity to flow routing on the downstream reaches. As a result, the use of rainfall forecasts could bring important improvements.

To conclude this section, three core recommendations can be identified for future development of the system:

Use of rainfall-forecasts from Numerical Weather Prediction models (NWP)

This constitutes the first recommendation because it would add some knowledge about the future meteorological conditions which are lacking in the present system.

Recalibrate/reconfigure the rainfall-runoff and river system models

Scenario based models are not developed to produce real-time flow forecasts. The current system demonstrates that it is feasible to transfer them into a flow forecasting context but this won’t guarantee an optimal result. Important improvement could be obtained by recalibrating and reconfiguring the models.

Pursue the testing of data assimilation procedures

The implementation of the data assimilation has not been extensively tested. Updating was limited to one state variable of the rainfall-runoff model and rainfall inputs. Improvement could be expected with the updating of other components of the system.
8 Operational System

8.1 Overview

The operational system consists of a number of software elements:

- Commercial software such as FEWS and IDL;
- Free 3rd-party software such as MRT and Java libraries; and
- Bespoke software developed by the project.

A diagram of the data flow and the system’s components is at Appendix G on page 99. A full list of the software used by the system is in Appendix F on page 97.

The design of the system centers around the modularity of FEWS, i.e. how it divides workflows into modules and adaptors. As described earlier, a module is a configuration item that provides specific functionality such as data import or interpolation (Figure 6.4 on page 37). Adaptors are wrappers around external models or Java classes enabling FEWS to execute these models. A workflow may comprise any number of modules and adaptors.

A Java-based adaptor implements a specific Java interface class defined by the FEWS software. The adaptor interface is simple enough for it to be used by other software, allowing an adaptor to be invoked by non-FEWS software. Class diagrams of some of these classes is available in Figure G.2 on page 100.

One of the FEWS design patterns is that fetching external data should be performed by processes external to FEWS. A FEWS workflow expects the data to reside in a specific folder which is imported into the FEWS database as the first activity of the workflow.

With this in mind, it was decided the Apache Ant software provides sufficient functionality to manage the data processing steps, that is: download the data, perform any port-processing and prepare the data for FEWS import. In order to execute the FEWS adaptors from Ant, a simple Ant “task” class was written to pass the arguments from Ant to a specific FEWS adaptor.

This decision turned out to be fortuitous as FEWS provides a Java class to execute a FEWS workflow and it was trivial to call this class from an Ant build script. See Figure 8.1 on the next page for an extract from the Ant build script.

8.2 Module folder organisation

All modules have a similar folder hierarchy. There is a standard set of sub-folders for each module to store files and data used by the module. The standard sub-folders are:

**bin**

Programs and scripts used my the module.

**cache**

Working data – data is kept here to avoid re-running processing scripts.

**config**

Configuration files.

**download**

“Raw” download files.

---

5[^ant]

[^ant]: http://ant.apache.org

66
<adaptor classname="csiro.ict.fews.adaptors.FloodExtentAdaptor">
  <arg value="${flood.home}"/>
  <arg value="${flood.home}/work"/>
  <arg value="14"/> <!-- days processing -->
</adaptor>

<java classname="nl.wldelft.fews.system.workflowtestrun.WorkflowTestRun"
  fork="true"
  dir="bin"
  maxmemory="768m"
  classpathref="fews-libs">
  <arg value="FEWSOZ"/>
  <arg value="../FEWSOZ/Batch/RunAll.xml"/>
</java>

**Figure 8.1:** Ant definitions for the flood extent adaptor and invoking FEWS.

log

Log files.

work

Working directory for temporary files and processing data.

**Figure 8.2:** Example folder structure for the flood extent module.

### 8.3 Scheduling

All of the tasks needed by the system are defined as Ant targets and scheduled to run daily in the following order:
1. Fetch data from external sources
   (a) MODIS satellite
   (b) AMSR satellite
   (c) BoM rainfall
   (d) DERM river levels & FEWS import

2. Flood extent processing
   (a) Extract reflectance data from MODIS
   (b) Extract reflectance data from AMSR
   (c) Run flood extent code to generate maps and volume
   (d) Convert flood maps to images for web application

3. FEWS data preparation
   (a) Rainfall grids
   (b) Evaporation
   (c) Flood extent time series
   (d) Create import archive

4. FEWS workflow
   (a) Import data
   (b) Run SACSMA
   (c) Run IQQM
   (d) Run LIMO
   (e) Run BFS
   (f) Create export archive
   (g) Archive FEWS database

5. Update reporting database

The following section provides an overview of the actions performed by each of these processing steps.

8.4 Fetch remote data

![Sequence diagram for fetching external data](image)

Data from the remote sites is fetched using FTP. A Java FTP client was built upon a 3rd-party FTP library and the client’s behaviour is controlled by a configuration file that contains:

1. Server information: the host name of the FTP server.
2. Login information: A user name and password for the site.
3. File locations: The “root” directory of the data and whether to process files located in sub-folders.
4. The name of a Java class that works as a file “selector.” The selector determines whether a file is to be downloaded based on a number of properties:

- File name: most satellite data files use a timestamp as part of file’s name and as satellites fly a fix orbit, the time they fly above the flood plain is known (within a few hours). The timestamps that are used to identify MODIS and AMSR candidate files are listed in Table 8.1.

In addition to the timestamp, a database table can be used to record when a file has been downloaded. This prevents the same file form being downloaded more than once.

- Parent directory: some FTP sites contain a large number of files in a complex directory hierarchy. The selector also decides which portions of the hierarchy to traverse if the feature is enabled.

5. Other configuration options include:

- Automatically uncompress files.
- Pause for certain time limits to prevent overwhelming the server with requests.

### 8.5 Flood extent processes

Flood processing is described in Section 5 on page 20, a sequence diagram is shown in Figure 8.4 on the next page.

The raw data downloaded from Geoscience Australia and NASA is processed to separate the reflectance data bands into separate files: the original data is held in the download folder and the reflectance data files are written to the cache sub-folders – a separate folder for each day’s data.

The MODIS data from Geoscience Australia is processed by the MRT tools as described in Section 5.4.2 on page 31. The AMSR data, from NASA, is processed by a bespoke IDL program described in Section 5.4.3 on page 32.

The flood extent code is then run over each day’s reflectance data and the flood map and the volume estimates\(^6\) (section 5.1.5 on page 24) are written back into the day’s folder. The last step in the processing is to convert the flood maps into images (PNG format) using a palette for percentages ranges, see Table 8.5 on the next page.

Note that the last 14 days are always processed. This provides the opportunity to re-calculate the flood extent if new satellite data becomes available (this is especially true for AMSR as it is

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\(^6\)Possibly three estimates: MODIS, AMSR and Combined, depending on the availability of the data for that day.
Figure 8.4: Sequence diagram for flood extent processing

<table>
<thead>
<tr>
<th>Water percentages</th>
<th>Colour</th>
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<tbody>
<tr>
<td>1–20</td>
<td>rgb(204, 204, 255)</td>
</tr>
<tr>
<td>20–40</td>
<td>rgb(153, 153, 255)</td>
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<tr>
<td>40–60</td>
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<tr>
<td>60–80</td>
<td>rgb(51, 51, 255)</td>
</tr>
<tr>
<td>80–100</td>
<td>rgb(0, 0, 255)</td>
</tr>
</tbody>
</table>

Figure 8.5: Pseudo-colour palette for flood images

Figure 8.6: Pseudo-colour palette for flood waters.
normally 7-10 days behind).

### 8.6 FEWS pre-processing

Before running the river models the FEWS database has to be populated with the latest data collected that day. This step processes some of the external data and copies the results into FEWS import folder. Data that doesn’t need to be converted is just copied into the FEWS import folder.

The steps are:

1. Rainfall data from the BoM’s SILO repository is converted from grid format to Arcview ASCII grids (asc). See Section 7.3 on page 42 for a full description of this data.
2. For each day of rainfall data, a corresponding evaporation file is created from averaged data files. This data is also described in Section 7.3 on page 42.
3. Copy the preferred flood volume estimate into the import directory. The estimates are generated based in the available data at the time of processing which is usually MODIS. When the AMSR data becomes available it is combined with the MODIS data. The preferred estimate is the combined result, but the MODIS-only result will be used if there is no AMSR data.

At the end of this step the import folder has been populated with the latest data and a snapshot of the directory is created and archived\(^7\).

### 8.7 FEWS model execution

The typical FEWS model run, Figure 8.7, involves:

1. Exporting data. The timeseries data is normally exported from FEWS as XML called “public interface” (PI). It can also be exported as binary or comma-separated data.
2. (optional) Pre-processing to convert the exported data into the model’s native input format.

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\(^7\)All archives created by the system are ZIP files.
3. Run the model.

4. (optional) Perform post-process on the data by converting it from the model’s native output into PI.

5. Import the data into the FEWS database.

The FEWS workflow implemented by the system is described in Section 7 on page 38. As mentioned above the Java adaptors run by Ant manage the data processing steps external to FEWS. The ensure that:

1. All input data is located in the correct import folders, ready for the first activity of the the FEWS workflow (import).
2. The results of the model runs (exports) are inserted into the reporting database and archived.
3. The FEWS database is also archived.

8.8 Reporting database

During the execution of the FEWS workflow the output of the models is exported into a specific set of folders. The last step of the daily processing is to insert the timeseries data from the exported PI files into the reporting database. A FEWS timeseries is identified by a forecasting location and a “parameter” such as river flow or precipitation.

The XML data files are parsed and each data point is inserted into the database:

**If the timeseries is observed data** then the data is appended to the existing timeseries.

**If the timeseries is a forecast** then a new timeseries is created and all of the data is associated with the new timeseries. This means that a forecasting history is maintained for each location.

See Appendix G, Figure G.3 on page 101, for the database schema.

8.9 Web application

The results of the data processing, both flood extents and flow forecasts, needs to be displayed to people. The data generated by the system is in two forms:

8.9.1 Timeseries

The timeseries data is a sequence of pairs: \((time, value)\). The data comes from many sources such as the river gauge data from DERM or the river flow forecasts from the river models.

The data officially resides in the FEWS database, but access from external applications is not possible at present (FEWS are developing an interface to programatically extract data from their database). The system’s workflow includes an activity to export the data from FEWS as XML and import that data into a Postgres relational database. A set of web services provide access to the data via the Tomcat web server.

The web application’s client is built upon the JQuery Javascript library and accesses the timeseries data via a REST call to the Tomcat server. The FLOT plotting library (a plugin to JQuery) is used to plot the data in the client’s web browser.
8.9.2 Image data

The images for the flood extent are located in a folder under the web server’s root directory. One of the last steps in the flood extent processing is to update the Postgres database with the URL to the image as well as its dimensions, that is, the image’s latitude, longitude, width and depth. The dimensions are used by the client code to create an overlay for Google Maps.

Display of the image is controlled by Javascript code using JQuery.

1. Apache Tomcat web server\(^8\);
2. Spring Java web framework\(^9\); and
3. Jersey web library.\(^{10}\).

---

\(^8\)[http://tomcat.apache.org](http://tomcat.apache.org)
\(^9\)[http://www.springsource.org](http://www.springsource.org)
\(^{10}\)[https://jersey.dev.java.net](https://jersey.dev.java.net)
8.10 Conclusions and future developments

The operational system is a typical ICT platform that performs standard data-processing activities: obtain data, process it and display the results. The uniqueness of the system is the types of data being processed (satellite imagery and timeseries) and the processing of the data (flood extents and river models).

The system has proven itself to be robust, processing the satellite data for over 9 months and coping with the data volumes obtained during the 2010 floods.

The remainder of this section identifies areas where further work may improve the operational system.

**Improve the user interface.**

There is scope to improve the web application by involving a wider community. This will provide an opportunity to identify an expanded set of user requirements and priorities.

**Management of missing data**

Collecting real-time data is not perfect and data will be missing. As a default the system currently assumes zero values for missing data which is probably not the best solution. Alternate solutions, such as interpolation, should be examined to determine a better method of handling missing data.

**Faster downloads**

The current FTP downloads are slow as the FTP servers contain a larger number of folders. These folders are examined one at a time to determine if they contain data that is relevant to the project. The FTP client should be enhanced to skip top-level folders it has already examined during previous sessions. For example the MODIS “orbit numbers” may provide a hint as to whether the client should examine that folder’s contents.

**Web services**

At present the services provided by the web application and are specifically designed to support the client developed for the project. The application could be enhanced to supply data in multiple formats to allow new clients to be developed. Options include:

- The flood extent map could be supplied as a shape-file instead of an image.
- The water volumes could be supplied as shape files or gridded data (to allow cross-sections to be made).
- Timeseries can be returned in the new water data transfer format (WDTF).
- Images of flood progressions over time.
References


Appendices
Appendix A  Sacramento model parameters provided by the Queensland government

The parameters corresponding to the 15 models provided by DERM are listed in Tables A.1 and A.2. The tables indicate the value of the 17 parameters used in the IQQM software along with the ordinates of the unit hydrograph. The parameters are the following:

1. UZTWM: Upper Zone Tension Water Storage Maximum (mm)
2. UZFWM: Upper Zone Free Water Storage Maximum (mm)
3. UZK: Upper Zone Lateral Drainage Rate
4. PCTIM: Permanently impervious fraction of basin
5. ADIMP: Maximum value of impervious area when tension storages are filled (fraction)
6. RIVA: Fraction of basin covered by streams, lakes and riparian vegetation
7. ZPERC: Proportional increase in percolation from saturated to dry conditions
8. REXP: Exponent in percolation relationship
9. LZTWM: Lower Zone Tension Water Storage Maximum (mm)
10. LZFSM: Lower Zone Free Water Supplemental Storage Maximum (mm)
11. LZFPM: Lower Zone Free Water Primary Storage Maximum (mm)
12. LZSK: Lower Zone Supplemental Drainage Rate
13. LZPK: Lower Zone Primary Drainage Rate
14. PFREE: Proportion of percolated water that directly enters free water storages
15. SIDE: Ratio of non channel subsurface outflow to channel baseflow
16. RSERV: Fraction of lower zone free water incapable of resupplying lower zone tension water
17. SSOUT: Discharge required by channel underflow

The parameters are given in the two tables A.1 on the next page and A.2 on page 80.
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<th>wck2Talg</th>
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Table A.1: Sacramento parameters provided by QLD-DERM (1/2). The signification of the codes are given in Table 7.2.
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Table A.2: Sacramento parameters provided by QLD-DERM (2/2). The signification of the codes are given in Table 7.2.
Appendix B  Sacramento model parameters after recalibration

The re-calibrated parameters are given in the two tables B.1 on the next page and B.2 on page 83.
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Table B.2: Recalibrated Sacramento parameters (2/2)
Appendix C  The Normal-Quantile transform (NQT)

The Normal-Quantile transform was introduced by Kelly and Krzyszttofowicz (1994) and transforms a variable of a known probability distribution into a normal Gaussian variable.

Let \( V \) be a random variable with a cumulative probability distribution \( F(v) = Pr[V \leq v] \) and a probability density \( f(v) = dF/dv \). The NQT associates to a value \( v \), the value \( x \) of a normal centred variable which has the same cumulative probability:

\[
x = N^{-1}(F(v)) = \text{NQT}_F(v)
\]

where \( N^{-1} \) is the inverse of the cumulative distribution of a normal centred variable:

\[
N : u \rightarrow \frac{1}{2\pi} \int_{-\infty}^{u} e^{-\frac{t^2}{2}} \, dt
\]

When the distribution \( F \) is unknown, a parametric distribution can be fitted to the data. This last approach was retained in the Condamine-Balonne system where an exponential distribution was used:

\[
F(v) = 1 - e^{\lambda v}
\]

where \( \lambda (\cdot) \), the parameter, can be inferred simply by the inverse of the mean of a set of measurements \( (v_i)_{i=1,...,n} \). Krzyszttofowicz and Kelly (2000) suggest the use of a more complex log-Weibull distribution with 3 parameters.

The NQT transform using an exponential distribution is noted \( \text{NQT}(v, \lambda) \) with \( \lambda \) given by the estimation of \( 1/\bar{v} \).
### Table D.1: Parameters of the BFS for the Balonne River @ Weribone (Forecasting point 13, 422213A), recalibrated parameters

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<th>$\sigma_k$</th>
<th>$\lambda_Q$</th>
<th>$\hat{\lambda}_Q$</th>
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### Table D.2: Parameters of the BFS for the Condamine River @ Chinchilla (Forecasting point 11, 422308C), recalibrated parameters

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<th>$\lambda_Q$</th>
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### Appendix D Parameters of the Bayesian Forecasting System

The Tables D.1 to D.14 on page 91 give the BFS parameters $(c_k, a_k, d_k, b_k, \sigma_k)$ for $k = 1, \ldots, 12$ (lead time of 6 to 72 hours) and $(\lambda_Q, \hat{\lambda}_Q)$.

The parameters were obtained by calibrating the BFS on 14 forecasting points using the deterministic forecasts generated with re-calibrated parameters and the data assimilation procedure.
Table D.3: Parameters of the BFS for the Condamine River @ Warwick (Forecasting point 02, 422310C), recalibrated parameters

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<th>$\lambda_Q$</th>
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Table D.4: Parameters of the BFS for the Condamine River @ Cecil Weir (Forecasting point 08, 422316A), recalibrated parameters

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<td>165.77</td>
<td>139.43</td>
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### Table D.5: Parameters of the BFS for the Dalrymple Creek @ Allora (Forcasting point 04, 422319B), recalibrated parameters

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<th>d&lt;sub&gt;k&lt;/sub&gt;</th>
<th>b&lt;sub&gt;k&lt;/sub&gt;</th>
<th>σ&lt;sub&gt;k&lt;/sub&gt;</th>
<th>λ&lt;sub&gt;Q&lt;/sub&gt;</th>
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<td>0.03</td>
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### Table D.6: Parameters of the BFS for the Condamine River @ Cotswold (Forcasting point 12, 422325A), recalibrated parameters

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<th>d&lt;sub&gt;k&lt;/sub&gt;</th>
<th>b&lt;sub&gt;k&lt;/sub&gt;</th>
<th>σ&lt;sub&gt;k&lt;/sub&gt;</th>
<th>λ&lt;sub&gt;Q&lt;/sub&gt;</th>
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### Table D.7: Parameters of the BFS for the Kings Creek @ Aides Bridge (Forcasting point 05, 422334A), recalibrated parameters

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### Table D.8: Parameters of the BFS for the Canal Creek @ Leyburn (Forcasting point 07, 422338A), recalibrated parameters

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**Table D.9:** Parameters of the BFS for the Oakey Creek @ Fairview (Forcasting point 09, 422350A), recalibrated parameters

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**Table D.10:** Parameters of the BFS for the Hodgson Creek @ Balgownie (Forcasting point 06, 422352A), recalibrated parameters
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**Table D.11:** Parameters of the BFS for the Condamine River @ Talgai Tail water (Forecasting point 03, 422355A), recalibrated parameters

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**Table D.12:** Parameters of the BFS for the Condamine River @ Elbow valley (Forecasting point 01, 422394A), recalibrated parameters
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**Table D.13:** Parameters of the BFS for the Maranoa River @ Mitchell (Forecasting point 14, 422401D), recalibrated parameters

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**Table D.14:** Parameters of the BFS for the Maranoa River @ Cashmere (Forecasting point 15, 422404A), recalibrated parameters
Appendix E  Persistence indexes of the forecasts on historical floods

The persistence index is given for the forecasts on the 5 historical floods listed in Table 7.5 on page 61 and the 4 following configurations:

- Table E.1 on the next page shows the persistence for the forecasts without data assimilation (see section 7.4.4 on page 51) and the Sacramento parameters provided by DERM (see section 7.4.1 on page 44),

- Table E.2 on page 94 shows the persistence for the forecasts using data assimilation and the Sacramento parameters provided by DERM,

- Table E.3 on page 95 shows the persistence for the forecasts without data assimilation and the recalibrated Sacramento parameters (see section 7.4.2 on page 44),

- Table E.4 on page 96 shows the persistence for the forecasts with data assimilation and the recalibrated Sacramento parameters.

The persistence indexes are calculated for 15 forecasting points only. The 3 forecasting points located downstream of Saint George reservoir were not included in the verification scheme.
Table E.1: Persistence index for the forecasts without data assimilation and the initial Sacramento parameters calculated on the historical flood for the 18 forecasting points

<table>
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<tr>
<th></th>
<th>6h</th>
<th>12h</th>
<th>18h</th>
<th>24h</th>
<th>30h</th>
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<th>42h</th>
<th>48h</th>
<th>54h</th>
<th>60h</th>
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<th>72h</th>
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<tr>
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<td>0.43</td>
<td>0.47</td>
<td>0.36</td>
<td>0.69</td>
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<td>0.44</td>
<td>0.88</td>
<td>0.96</td>
<td>0.95</td>
<td>0.88</td>
</tr>
<tr>
<td>FP02 (422310C)</td>
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<td>-0.05</td>
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<td>0.96</td>
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<tr>
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<tr>
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</table>
Table E.2: Persistence index for the forecasts using data assimilation and the initial Sacramento parameters calculated on the historical flood for the 18 forecasting points.

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<th>Persistence Index</th>
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</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
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Table E.3: Persistence index for the forecasts without data assimilation and the recalibrated Sacramento parameters calculated on the historical flood for the 18 forecasting points
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Table E.4: Persistence index for the forecasts using data assimilation and the recalibrated Sacramento parameters calculated on the historical flood for 18 forecasting points.
Appendix F  Java libraries

The following 3rd-party Java libraries are used by the system.

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Appendix G  System diagrams

Below are diagrams of various system views:

1. A diagram of the data flow through all system components: Figure G.1.
2. A UML class diagram of some of the main Java classes, Figure G.2 on the following page.
3. The reporting database schema, Figure G.3 on page 101.

Figure G.1: Data flow through the system
Figure G.2: Class diagrams for sample Java classes
Figure G.3: The reporting database schema
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