Hydrological Advice to Commission of Inquiry Regarding 2010/11 Queensland Floods

TOOWOOMBA AND LOCKYER VALLEY FLASH FLOOD EVENTS OF 10 AND 11 JANUARY 2011

- Report to Queensland Floods Commission of Inquiry
- Revision 1
- 12 April 2011

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1 Executive Summary

1.1 Description of Flash Flooding in Toowoomba and the Lockyer Valley

Rainfall totals between 20 and 30 mm were recorded over the three day period between 7 and 9 January 2011 in the Lower Brisbane River catchment (including the Lockyer Creek catchment) and in the Upper Condamine River catchment (including Gowrie and Oakey Creek catchments). The rainfall totals over the period prior to 10 January 2011 would have “primed” the Gowrie Creek, Oakey Creek and Lockyer Creek catchments, saturating or almost saturating the soil column in these catchments prior to the flood events.

Radar rainfall imagery from the Mount Stapylton weather watch radar shows that between 9:00 am and 9:30 am two intense thunderstorms crossed the coast – one of these storms crossing near Redcliffe and the other near Maroochydore. The storm that crossed the coast near Redcliffe moved in a westerly direction and the storm that crossed near Maroochydore moved in a south-westerly direction for the next two hours. The storms converged to form a single intense storm at about 11:00 am, with the combined storm cell extending from Wivenhoe Dam to Moore. At this time the combined storm cell was moving in a south-westerly direction at about 30 km/h.

The area of high intensity rainfall was located over the Upper Brisbane River valley on the 11:48 am radar scan and was moving in a south-westerly direction toward the Toowoomba Range. Rainfall intensities increased as the storm cell approached the Toowoomba Range due to orographic enhancement of the rainfall, with high humidity air forced upward by the rising terrain and driving more rainfall out of the humid air mass.

Actual point rainfall intensities recorded by raingauges in Toowoomba peaked at 144 mm/h for a period of 10 minutes, 128 mm/h for a period of 30 minutes and 94 mm/h for a period of 60 minutes at the Prince Henry Drive rainfall recording station in Toowoomba, which translates to annual exceedance probabilities of 1 in 18 for 10 minutes, 1 in 200 for 30 minutes and 1 in 370 for 60 minutes. Although no automatic reporting raingauges, which returned data, were in the correct position to record them, rainfall intensities of similar and perhaps even lower annual exceedance probability would reasonably have been expected to occur across parts of the catchments of the tributaries of Lockyer Creek above Grantham.

These high rainfall intensities were observed on both sides of the Great Dividing Range. Runoff was therefore generated on both sides of the Range, with some of the runoff flowing into the upper tributaries of Lockyer Creek, which eventually joined the Brisbane River downstream of Wivenhoe Dam, and some of the runoff flowing via the catchments of Gowrie and Oakey Creeks into the Upper Condamine River system.

Weather radar data shows that the intense rainfall system was moving from the north east to the south west, first across the upper catchment of Oakey Creek and then into the Gowrie Creek catchment. The radar data shows that intense rainfall was widespread across the catchment of Oakey Creek, including the catchment of Cooby Dam, for a two hour period between 11:45 am and 1:45 pm on 10 January 2011.

The thunderstorm cell continued its movement toward Toowoomba and the catchment of Gowrie Creek. Very heavy rainfall, with intensity exceeding 20 mm/h commenced across the catchment between 12:45 and 1:00 pm and continued at a rate of 20 mm/h or greater for a period of approximately 90 minutes. These very high rainfalls resulted caused a flash flood in Toowoomab, which was recorded by the streamflow gauge on Gowrie Creek at Cranley as a rapid rise in the recorded water levels between 1:00pm and 2:00 pm on 10 January 2011, up to a water level of 3.67 m gauge height.

Due to the steep terrain present in the upper tributaries of Lockyer Creek and the saturated condition of the catchment, it is most likely that runoff and rapid increases in overland flow and flows in watercourses would have commenced in these tributaries within minutes after the commencement of intense rainfall. Rapid observations of water level rise started at the stream level gauge at Murphys Creek at Spring Bluff at 1:20 pm on 10 January 2011 and peaked at 4.96 metres gauge height just 20 minutes later, at about 1:40 pm.

Water levels started to rise abruptly at the streamflow gauge on Lockyer Creek at Helidon at 2:30 pm on Monday 10 January 2011 The estimated peak flow at Helidon was between 3,500 and 4,000 m^3/s. Flood flows from Monkey Waterholes Creek appear to have coincided with flows travelling along Lockyer Creek at Helidon. Insurance Council of Australia Hydrology Panel (2011b) estimate that flows peaked at the confluence between Lockyer and Monkey Waterholes Creek at a flow rate between 4,000 and 4,500 m^3/s.

1.2 Capacity of Existing Flood Warning Systems

Providing clear, timely and accurate forecasts of flash flooding for specific locations is difficult because the intense thunderstorms that typically cause flash floods develop and move very quickly and there are many thousands of locations across Australia fed by small catchments, with times of concentration less than 6 hours, that could be afflicted by flash flooding if the right meteorological conditions were to occur.

The Bureau of Meteorology states that it has arrangements in place whereby specific guidance about flash flooding is provided by local agencies. As a result of the current arrangements, the Bureau of Meteorology has organised itself internally in each region with a Flood Warning Centre that provides warnings of non-flash floods and a severe weather meteorology section that provides generalised warnings of situations that may cause flash flooding, but not specific flash flood forecasts. These two forecasting teams operate independently to issue warnings and although they are co-located in the Brisbane regional office there is no documented process for communication between the Flood Warning Centre and severe weather meteorologists during an event.

The Bureau of Meteorology's Flood Warning Centres have developed their data collection, modelling and warning preparation systems to forecast and warn of non-flash floods.

Technological developments over recent years appear to have made it possible to provide a more specific flash flood warning service for much of the populated areas of Australia that are exposed to a significant threat of flash flooding. A flash flood warning system providing useful lead times would require:

- A greater degree of automation, with model runs initiated automatically at a regular frequency without any forecaster intervention;
- Consideration of the possible implementation of a different hydrological model, such as a spatially distributed model, more amenable to automated production of accurate forecasts for small catchments without forecaster intervention;
- Spatially and temporally distributed quantitative rainfall estimates, which are most likely to be obtained from a combination of weather radar and reporting raingauges;
- Insertion of quantitative rainfall forecasts with limited or no manual intervention; and
- Automated production of pro-forma forecasts and warnings for specific locations, with appropriate systems put in place for the forecaster to review and approve the automated warning prior to its issue.

A significant investment would be required to develop, implement, operate and maintain an effective and specific flash flood warning system for Australia of this type. As demonstrated by the events of 10 January 2011, the potential to save lives and property from improved flash flood warning capability may justify that investment. The Bureau of Meteorology are more likely to be able to develop this capacity on a national basis than local government authorities and transferring future responsibility for flash flood warning to the Bureau of Meteorology should be considered.

1.3 Performance of Warnings Issued for the 10 January 2011 Flash Flood Events

The Bureau of Meteorology released a large number of warnings relevant to the Lockyer Valley and Toowoomba in January 2011. These warnings fall into three categories:

- severe weather warnings of heavy rainfall leading to localised flash flooding;
- flood warnings for Lockyer Creek, which often also discuss flood conditions in the rest of the Brisbane River basin; and
- flood warnings for the Condamine Balonne River system.

Severe weather warnings issued during the entire period between 5 and 12 January 2011 and typical severe weather warnings issued provide virtually identical advice, which did not reasonably characterise the specific level of threat posed by flash flooding to specific communities, when it may be possible to provide more urgent and specific advice in some situations.

On the basis of the evidence available to severe weather meteorologists by sometime between 12 noon and 12:15 pm on Monday 10 January, they should have been alerting the Flood Warning Centre and local authorities with responsibilities under current arrangements for flash flooding of the meteorological situation which should have alerted those groups to the prospect of rapid rises in water level.

An automated procedure flagged the water level returns from the Helidon streamflow gauge on the rapid rising limb of the hydrograph between 2:30 and 2:53 pm on 10 January 2011 as erroneous, and masked the evidence of the actual streamflow rise occurring from personnel in the Bureau of Meteorology Flood Warning Centre for about 90 minutes. If this had occurred, the Bureau of Meteorology using its current systems and procedures should have been in a position to issue a flash flood warning for Grantham at 2:45 pm, on the basis of the rapid rises in flow observed at the Helidon gauge, in addition to the other evidence of rainfall totals from weather radar and raingauges to that time. Although this could have provided little lead time prior to the commencement of rapid streamflow rises in Grantham it could have provided 2 hours of lead time to the estimated peak level at Grantham. It would also have increased the available lead time to the on-set of flooding in Gatton.

Had the Toowoomba Regional Council been provided with advice by the Bureau of Meteorology severe weather forecasters at 12:15 pm, this would have provided at least 30 minutes of lead time before the on-set of heavy rainfall in the Gowrie Creek catchment and associated rapid rises in streamflow in East and West Creeks and approximately 1 hour and 45 minutes of lead time before flows are expected to have peaked in the Toowoomba Central Business District. The Bureau of Meteorology contacted the State Disaster Coordination Centre (SDCC) at 1:00 pm on 10 January to inform them of the high rainfall intensities expected for Toowoomba. Although this message was issued about 45 minutes later than the earliest such time that a message of this type could have been issued for Toowoomba, it was at least issued at around the time that increases in stream levels would have started to have been observed in East and West Creeks. No advice of the heavy rainfall was provided by the Bureau of Meteorology directly to Toowoomba Regional Council or Lockyer Valley Regional Council.

1.4 Flood Risk Mitigation Options Other than Warning Systems

There are likely to be a large number of options, other than warning, available for the mitigation of flooding risk in Toowoomba and the Lockyer Valley Regional Council areas. More comprehensive assessment of flood risk mitigation options could be considered in conjunction with more detailed hydrological and hydraulic modelling.

The Cooby Dam low level scour outlet pipe is not designed to be operated during a flood event and would have made no difference to flows passing into Oakey Creek downstream of the dam even if it had been operated. Maintenance of the outlet conduit is not a material issue with regard to operation of the dam during the January 2011 flood event.

The railway embankment between Ipswich and Helidon has been in operation for more than 140 years and pre-dates virtually every other structure on the floodplain at Grantham. It would be unusual to expect an owner of existing infrastructure, in this case QR National, to provide additional culverts or bridges underneath the railway to allow for movement of flood waters underneath the railway line at Grantham, unless they were undertaking works to increase the height of the railway embankment from its existing level. An “as-built” survey of the railway line since the repair works should be undertaken and a comparison performed to embankment levels determined from the latest reliable available survey undertaken prior to the January 2011 flood event.

The January 2011 flash flood event was sufficiently large that much of the vegetation removed from in-channel and riparian zones would have been stripped during the early stages of the flood event, well before the occurrence of the peak flow. In general, it is unlikely that for most parts of the Lockyer Valley catchment that removal of trees and shrubs from waterways and riparian zones would have had any appreciable impact on flooding during the January 2011 event. There may be specific locations where removal of in-stream or riparian vegetation prior to the flood event may have had an impact but detailed hydrological modelling of those particular locations would be required to confirm this.

Designers of culverts and bridges crossing waterways should consider that in large flood events there will be significant volumes of vegetation and other debris transported by the event.

The January 2011 flood event was a major creek flooding event and it is most likely that the water that flooded Forest Hill came from breakouts of flows from Sandy and Laidley Creeks. Aerial photography from 18 January 2011 shows that flood water spread out over a width of more than 2 km across the floodplain at Forest Hill. Reduction in the height of vegetation and cleaning of table drains in Forest Hill would have made negligible difference to the overall hydraulic roughness of the entire floodplain and therefore had negligible influence on flood depths in Forest Hill during the January 2011 flood. Maintenance of table drainage infrastructure in Forest Hill may have a larger influence on more frequent local runoff events in Forest Hill.

2 Introduction

2.1 Introduction to the Events Considered

Flooding occurred across a large area of southern and central Queensland in December 2010 and January 2011. Intense thunderstorm activity, following a period of several days of high rainfall caused a devastating flash flood in Lockyer Creek and its upper tributaries on Monday 10 and Tuesday 11 January 2011. Thunderstorms also contributed to a flash flood in the Gowrie Creek catchment, which inundated parts of City of Toowoomba on the afternoon of 10 January and led to flooding in the catchment of Oakey Creek.

During the Lockyer Creek flood event on Monday 10 January twenty lives were lost in townships of Spring Bluff (2), Murphys Creek (2), Postmans Ridge (2), Helidon (1) and Grantham (13). Two lives were lost in Toowoomba during the flash flood event.

2.2 Scope of this Report

The Queensland Floods Commission of Inquiry ("the Commission") has commissioned Dr. Phillip William Jordan of Sinclair Knight Merz Pty Limited ("SKM") to prepare this report on the flash flood events in the Lockyer Valley and Toowoomba on 10 and 11 January 2011.

The sole purpose of this report and the associated services performed by SKM, in accordance with the scope of services set out in the contract between Sinclair Knight Merz and the Commission is as follows:

- This report discusses some aspects of the meteorology and hydrology occurring in the lead up to, and during, the flood events (Section 4). The information contained in this report is compatible with the relevant reports released by the Insurance Council of Australia Hydrology Panel. Those reports, with regard to the Brisbane River Basin overview (Insurance Council of Australia Hydrology Panel, 2011a), the Lockyer Valley Regional Council Local Government Area (Insurance Council of Austalia Hydrology Panel, 2011b) and Toowoomba (Insurance Council of Australia Hydrology Panel, 2011c), provide more extensive descriptions of the flood events.
- A brief discussion is included of the available systems for observation and forecasting of flood and flash floods in Australia generally and more specifically in the Lockyer Valley and Toowoomba (Section 3).
- The report analyses the clarity, accuracy and timeliness of public warnings and advice provided by warning agencies to the State Disaster Coordination Centre, to the extent that information was available to SKM (Section 5).
- Based on the performance of the warnings issued for this event, a commentary is provided on how flash flood warning services might be improved in Australia (Section 6).

- Communities affected by flooding in January 2011 have specifically raised a number of flood risk mitigation options since the event. This section addresses some of the issues brought to SKM's attention by the Commission. However, it is not a comprehensive assessment of flood risk mitigation options for Toowoomba and the Lockyer Valley Regional Council areas.

2.3 Reliance Statement

In preparing this report, the author has relied upon, and presumed accurate, any information (or confirmation of the absence thereof) provided by the Commission and/or from other sources. Except as otherwise stated in the report, the author has not attempted to verify the accuracy or completeness of any such information. If the information is subsequently determined to be false, inaccurate or incomplete then it is possible that our observations and conclusions as expressed in this report may change.

The author derived the data in this report from information sourced from the Commission and/or available in the public domain at the time or times outlined in this report. The passage of time, manifestation of latent conditions or impacts of future events may require further examination of risks and subsequent data analysis, and re-evaluation of the data, findings, observations and conclusions expressed in this report. The author has prepared this report in accordance with the usual care and thoroughness of the consulting profession, for the sole purpose described above and by reference to applicable standards, guidelines, procedures and practices at the date of issue of this report. For the reasons outlined above, however, no other warranty or guarantee, whether expressed or implied, is made as to the data, observations and findings expressed in this report, to the extent permitted by law.

This report should be read in full and no excerpts are to be taken as representative of the findings. No responsibility is accepted by Sinclair Knight Merz for use of any part of this report in any other context.

This report has been prepared on behalf of, and for the exclusive use of the Commission, and is subject to, and issued in accordance with, the provisions of the agreement between Sinclair Knight Merz and the Commission. Sinclair Knight Merz accepts no liability or responsibility whatsoever for, or in respect of, any use of, or reliance upon, this report by any third party.

2.4 Information Relied Upon

Restrictions on the timeframe available to prepare this report, less than three weeks, placed limitations on the author's ability to review, in detail, all material that might have been available and/or desirable to report on the flash flood events. The limitation on the timeframe also meant that no hydrological or hydraulic modelling was performed by the author as part of this engagement to inform preparation of the report.

The report relied upon a number of documents that are in the public domain, as cited in the report and as listed in the References section (Section 9).

The author was also provided with access to several submissions to the Commission and other documents obtained by the Commission. Documents of this type used by the author in preparing this report are as follows:

Australian Government Bureau of Meteorology. (2011). *Provision of Preliminary Meteorological and Hydrological Information: Background Briefing for the Queensland Floods Commission of Inquiry*. Submission to Commission of Inquiry.

Australian Government Bureau of Meteorology. (2011). *Report to Queensland Floods Commission of Inquiry: Provided in Response to a Request for Information from the Queensland Floods Commission of Inquiry received by the Bureau of Meteorology on 4 March 2011*.

BMT WBM (2007). *Gowrie Creek System Flood Risk Management Study*, Volumes 1 and 2.

Cornelius, A. (2011). *Submission to Queensland Floods Commission of Inquiry*. Weatherwatch.

Davidson, J. T. (2011). *Witness Statement of John Thomas Davidson to Queensland Floods Commission of Inquiry*.

Flanagan, K. (2011). *Statement to Queensland Floods Commission of Inquiry*. Toowoomba: Toowoomba Regional Council.

Queensland Reconstruction Authority (2011) Aerial photography of Lockyer Valley, flown 18 January 2011. Aerial photographs were provided for Helidon, Grantham, and Murphys Creek. Larger scale aerial photograph maps were also provided for Lockyer Valley East and Lockyer Valley West.

Queensland Reconstruction Authority (2011) Aerial photography of Lockyer Valley, flown April 2009. Aerial photographs were provided for Helidon, Grantham, and Murphys Creek. Larger scale aerial photograph maps were also provided for Lockyer Valley East and Lockyer Valley West.

Toowoomba Regional Council. (2010). *Emergency Action Plan: Cooby Dam. Water Services Branch*. Toowoomba: Toowoomba Regional Council.

Toowoomba Regional Council. (2010). *Emergency Action Plan: Cressbrook Dam and Perseverance Dam*. Water Services Branch. Toowoomba: Toowoomba Regional Council.

Toowoomba Regional Council. (2011). *Emergency Event Report: Cressbrook, Perseverance and Cooby Dams, Flood Event, December 13, 2010 - February 11, 2011*. Toowoomba: Toowoomba Regional Council.

A field inspection was undertaken by Dr. Phillip Jordan, accompanied by Detective Mark Ainsworth of Queensland Police Service on 5 April 2011 of some of the flood affected areas in Toowoomba and the Lockyer Valley. Whilst there was still a considerable amount of visual evidence of the flooding that took place in January and the conditions that existed prior to the event, restoration activities and other changes have occurred between the flood event and the field inspection on 5 April 2011.

2.5 Credentials of Report Author

The author of this report is Dr. Phillip William Jordan. Dr. Jordan is a Senior Hydrologist and has been employed by Sinclair Knight Merz since January 2003. Dr. Jordan holds a Bachelor of Engineering (Civil) with First Class Honours from the University of Queensland (awarded 1993) and a Doctor of Philosophy from Monash University (awarded 2001). Dr. Jordan's Ph.D. thesis was on the "Effect on Flood Modelling of Rainfall Variability and Radar Rainfall Measurement Error." He is a Member of Engineers Australia, a Certified Practicing Engineer (C.P.Eng.) and is Registered by the Board of Professional Engineers in Queensland (R.P.E.Q.) Dr. Jordan worked as a civil engineer for the Queensland Water Resources Commission / Queensland Department of Primary Industries / Queensland Department of Natural Resources between 1994 and 1997. He worked for SMEC Victoria as a consulting hydrologist between 2000 and 2001. From July 2001 to December 2002 he was employed by the Bureau of Meteorology to perform research on the application of dual polarisation weather radar to quantitative rainfall measurement and flood forecasting. In his more than eight years working with Sinclair Knight Merz, Dr. Jordan has worked on a number of consulting projects involving hydrological and hydraulic analysis and modelling. Dr. Jordan has co-authored six papers that have been published in international and Australian peer reviewed journals and he has been author or co-author for twenty-four papers that have been presented at national and international conferences. Dr. Jordan has also acted as peer reviewer for papers submitted to several international journals and conferences.

3 Systems Available to Observe and Forecast Flash Floods in Toowoomba and the Lockyer Valley

3.1 Continuously reporting rainfall gauges

The Bureau of Meteorology operates and/or receives data from a large number of rainfall stations across Queensland, primarily but not exclusively for the purposes of providing a flood warning service. Many of these stations report in real-time via a radio telemetry system to the Bureau of Meteorology's Flood Warning Centre in Brisbane. Some stations report via a telephone telemetry system and data from these stations is available in near to real time. Finally, the Bureau of Meteorology operates a number of automatic weather stations that typically report rainfall accumulations approximately every 3 hours.

Appendix B reproduces the flood warning network maps for the Brisbane River basin, showing the raingauge and streamflow sites that are available to the Bureau of Meteorology for the purposes of flood warning. It shows that there are twelve radio telemetered rainfall stations across the Lockyer Valley catchment but that most of these sites are located in the Southern and Eastern parts of the catchment. There are no automated reporting rainfall stations in the catchments of the northern tributaries of upper Lockyer Creek that were well positioned to record the highest rainfall intensities observed during the 10 January 2011 flash flood event. The best positioned gauges to capture the most intense rainfalls were the two gauges in Toowoomba (designated as Toowoomba AWS and Toowoomba AL).

Appendix C shows that there was one telemetered raingauges that produced data available to the Bureau of Meteorology in real time in the catchment of Oakey Creek upstream of Oakey and two gauges in the catchment of Gowrie Creek upstream of Toowoomba.

Toowoomba Regional Council operates its own real-time reporting rain gauge network. The Bureau of Meteorology do not currently have access to the telemetry from this network to obtain the data in real-time.

Lockyer Valley Regional Council operates just two telemetered raingauges: on Sandy Creek at Sandy Creek Road and in Upper Sandy Creek. The council operates one telemetered streamflow gauge, located with the raingauge on Sandy Creek at Sandy Creek Road. Data from these sites are telemetered in real-time to the Bureau of Meteorology.

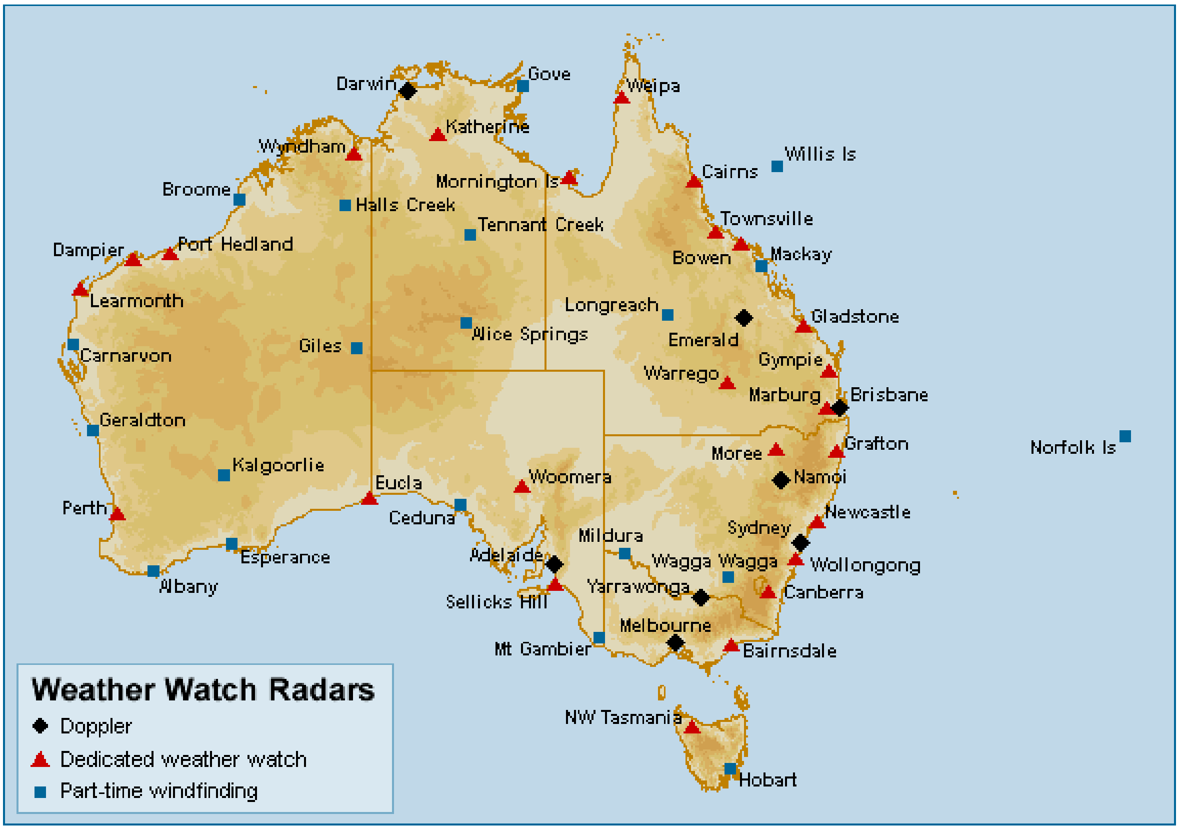
3.2 Daily rainfall gauges

The Bureau of Meteorology operates and receives data from a large number of rainfall stations that report data once per day on the basis of the total rainfall recorded between 9:00 am on one day and

9:00 am on the next. Data from these sites may not be available for several hours, or even days, after 9:00 am on the day that the data is recorded. Data from these stations provides some benefit in determining the spatial pattern of rainfall for the purposes of non-flash flood warning in larger basins where it can take several days for rainfall generated runoff to make its way through the river network. Data from the daily rainfall network are of limited use for operational flash flood forecasting, due to the delays in receiving the data and that flash floods are generated from rainfall events occurring over durations much shorter than one day. They can be useful to provide additional rainfall in post-event analysis of rainfall and flood events.

3.3 Conventional (single polarisation) Doppler weather radar

The Bureau of Meteorology currently operates a network of 53 weather watch radars across Australia, with locations shown in Figure 1. Fourteen of those radar are located in Queensland. The weather watch radar at Marburg and Mount Stapylton (shown in Figure 1 as Brisbane) provided coverage of rainfall occurring across South East Queensland during the January 2011 event. Both radars provided continuous coverage for the entire rainfall event.



- **Figure 1 Location of weather watch radars in Australia (Australian Government Bureau of Meteorology, 2011a)**

Unlike a raingauge that directly measures the volume of water falling into its catcher, meteorological radar cannot provide a direct measurement of rainfall intensities. Weather radars emit a beam of electromagnetic radiation (a radio wave). When this beam intercepts an object, a fraction of the radiation is scattered by the object in other directions. A small fraction of this radiation may be scattered back to the radar receiver. Radar therefore makes a direct measurement of the power of the electromagnetic radiation that is backscattered in comparison to the power that was originally emitted from the radar. If more objects are intercepted by the radar beam in a given area and each of those objects is larger in size then more power will be backscattered. Physical equations can be used to convert the power measurements into a quantity known as reflectivity, which is the sum of the diameters raised to the sixth power of all of the raindrops in 1 m^3 of air. Reflectivity returned by rain typically varies across a large range (from less than 10 mm^6/m^3 to more than 1,000,000 mm^6/m^3) and it is therefore normally expressed in a unit known as dBZ, where:

$$dBZ = 10 \log_{10} Z \quad \text{where } Z = \text{reflectivity in } mm^6/m^3 \qquad \text{Equation 1}$$

There is not a unique conversion between reflectivity and rainfall intensity. The relationship between reflectivity and rainfall intensity depends upon the sizes of the individual raindrops that are intercepted by the radar beam. The dependence upon the raindrop size distribution in conversion between reflectivity and rainfall rate is one cause of radar providing an inexact estimate of rainfall intensities. Australian Government Bureau of Meteorology (2011f, p. Appendix M), Joss & Waldvogel (1990) and Collier (1996) discuss other uncertainties associated with the estimation of rainfall intensities using conventional weather radar.

The rainfall intensities estimated from the radar intensity data are often calculated using the reflectivity to rainfall intensity conversion equation of Marshall and Palmer (1948):

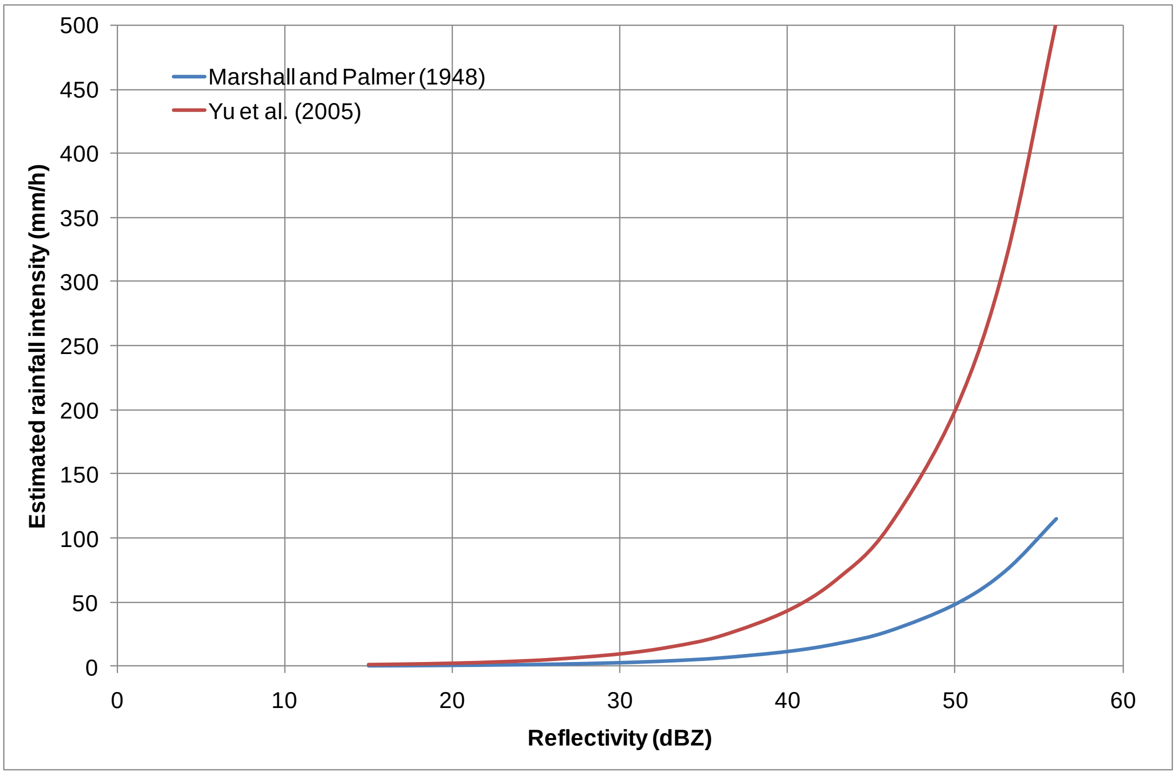
$$Z = 200\, R^{1.6} \qquad \text{Equation 2}$$

where Z is the reflectivity in mm^6/m^3 and R is the rainfall intensity in mm/h. This equation assumes a particular form (exponential) of the raindrop size distribution, which is most appropriate for use with widespread stratiform rainfall events. In convective rainfall events the drop size distribution typically changes to such that for a given value of reflectivity, larger rainfall intensities are observed than would be estimated using Marshall and Palmer (1948). Because the 10 January event was an intense convective thunderstorm, preliminary estimates of rainfall rates from radar data alone applying Marshall and Palmer (1948) are likely to be lower than the actual rainfall rates that were observed.

Yu et al. (2005) performed a calibration of rainfall estimates from the Marburg weather watch radar to ground based rainfall measurement totals for an event observed on 7-9 February 1999 that produced widespread rainfall totals of more than 200 mm across the Brisbane River basin for the three day period. Their adopted equation, which minimised the bias between the radar rainfall estimates and the rainfall totals from across a network of 100 raingauges was given by the equation:

$$Z = 35.3\ R^{1.5} \qquad \text{Equation 3}$$

Figure 2 shows that the rainfall rates estimated using the equation of Yu et al. (2005) lie between a multiple of three and four times the rainfall rates that would be estimated using Marshall and Palmer (1948). Because both events contained thunderstorm cells located in South East Queensland, the conversion of reflectivity to rainfall intensity for the January 2011 event is likely to be more closely represented by the equation of Yu et al. (2005) than by Marshall and Palmer (1948). Rainfall intensity estimates from weather radar imagery for this report have been inferred using the equation of Yu et al. (2005). This also demonstrates the importance of calibrating weather radar to rain accumulations from gauges for the purposes of quantitative rainfall estimation.



- **Figure 2 Comparison between the equations of Marshall and Palmer (1948) and Yu et al. (2005) for estimation of rainfall intensities from radar reflectivity.**

In SKM's experience, quantitative rainfall estimates with reasonable accuracy can normally be determined for a radius of between 100 and 150 km around the radar if there is a network of real time reporting rain gauges located under the radar envelope to calibrate the reflectivity to rainfall intensity conversion. Australian Government Bureau of Meteorology (2011f, p. Appendix M) states that for widespread rainfall events, reasonably reliable quantitative rainfall estimates can be achieved with a radar calibrated using a network of about 25 reporting raingauges, although the efficacy of calibration with gauges drops when the event is less widespread and there are fewer rainfall gauges to observe the event. Australian Government Bureau of Meteorology (2011f, p. 50) quotes the typical useful range of weather radar as being up to 200 km but the ability of the radar to provide accurate quantitative rainfall estimates in the outer 50 to 100 km of this range is typically lower. The range of the radar for quantitative rainfall estimation may be reduced in situations where:

- the lower elevation scans are blocked by the terrain surrounding the radar; or
- in storms with areas of hail; or
- in some meteorological conditions, particularly when air temperatures are lower, when the radar beam can intercept melting snow instead of liquid rain; or
- in the case of radar operating at 5 cm wavelength, when high rainfall intensities or hail are located between the radar and another storm located further away, resulting in attenuation of the radar signal; or
- in the case of radar designated as "part time wind finding" (see Figure 1), rainfall estimates are not available for periods of approximately 1.5 hours, four times a day, when the radar is used to track weather balloons; or
- if the radar is not operational due to planned or unplanned maintenance.

The existing weather watch radar network therefore provides reasonable coverage for the purposes of quantitative rainfall estimation and flood forecasting across most of the heavily populated areas of Australia.

There has been considerable research over many years in adaptive application of different reflectivity to rainfall rate conversion equations and adjustment of radar derived rainfall intensity and accumulation estimates using telemetered raingauges (Ahnert, Krajewski, & Johnson, 1986)(Smith & Krajewski, 1991) (Seo, 1998)(Anagnostou & Krajewski, 1999) (Sinclair & Pegram, 2005) (Yu, Seed, Pu, & Malone, 2005) (Mazzetti & Todini, 2009). The author had insufficient radar and raingauge data to apply such techniques but the Bureau of Meteorology should have had the data at hand to perform correction of radar derived rainfall intensities and accumulations using telemetered raingauges in real-time during the 10 January event, if systems were in place to do this.

The Mount Stapylton weather radar is equipped with Doppler capability, which measures the average speed of movement of precipitation detected by the radar either toward or away from the radar receiver. It does this by measuring the shift in phase of the electromagnetic radiation between the radar emitted and received by the radar. The Marburg radar is older than Mount Stapylton and is not fitted with Doppler capability (Australian Government Bureau of Meteorology, 2011a).

Doppler capability or otherwise does not have any effect on the reflectivity values recorded by the radar, which are then used to infer rainfall intensities from single polarisation weather watch radar.

3.4 Dual polarisation weather radar

Dual polarisation weather radar offer the capability to produce more reliable estimates of rainfall intensities than single polarisation weather radar, without the need for adjustment of the reflectivity to rainfall intensity conversion equation. The Bureau of Meteorology notes its role as a partner in development of research on dual polarisation radar (Australian Government Bureau of Meteorology, 2011f, p. 54) and the author of this report was involved in that research when employed by the Bureau of Meteorology in 2000 and 2001. Application of dual polarisation radar is still in the research domain and it has not yet been deployed operationally for use by weather or flood forecasters in Australia.

3.5 Streamflow Gauges

The Bureau of Meteorology operates and/or receives real-time data from a large number of streamflow stations across Queensland, primarily but not exclusively for the purposes of providing a flood warning service. The locations of telemetered streamflow gauging stations providing real-time data are shown in Appendix A for the Brisbane River basin and Appendix C for the Upper Condamine River Basin.

Insurance Council of Australia Hydrology Panel (2011b) analysed streamflow data from several other streamflow sites that are operated by Queensland Department of Environment and Resource Management to provide a post-event analysis of the magnitude and timing of the January 2011 flood event. Data from these sites is recorded on data-loggers stored at the flow gauging sites and is not available to the Bureau of Meteorology or the station owner (Queensland Department of Environment and Resource Management in this case) for a period between several days and months after an event.

4 Description of 10 and 11 January 2011 Flash Flood Event

4.1 Meteorology and Catchment Conditions Leading Up to the Flood Events

Australia experienced one of the strongest La Nina events on record during the 2010/11 season. Record high sea surface temperatures were recorded off the Queensland coast. Previous strong La Nina events, such as those of 1974 and 1995, were associated with widespread and severe flooding in Eastern Australia (Australian Government Bureau of Meteorology, 2011e). Southeast Queensland experienced above average (above the 90th percentile) or highest on record monthly rainfall totals for December 2010. Rainfall totals between 20 and 30 mm were recorded over the three day period between 7 and 9 January 2011 in the Lower Brisbane River catchment (including the Lockyer Creek catchment) and in the Upper Condamine River catchment (including Gowrie and Oakey Creek catchments) (Australian Government Bureau of Meteorology, 2011e).

Not all rainfall that falls on a catchment is converted into runoff during the subsequent flood event: some is intercepted by vegetation in the catchment; some infiltrates into the soil column and is retained in the soil; some infiltrates into groundwater and some fills and is retained in minor depressions or hollows in the landscape. Hydrologists refer to the difference between the rainfall on the catchment and the runoff generated during the flood event as “losses”. Typically the largest loss occurs at the start of the rainfall and is therefore know as the “initial loss”, representing the process of “wetting up” the catchment sufficiently for the first appreciable runoff to be generated.

The rainfall totals over the period prior to 10 January 2011 would have “primed” the Gowrie Creek, Oakey Creek and Lockyer Creek catchments, saturating or almost saturating the soil column in these catchments. Under these conditions, initial losses of any rainfall occurring during an event would be minimal and a large proportion of any rainfall occurring on the catchment would be quickly converted into runoff.

4.2 Description of Meteorology and Hydrology of 10 January 2011 Flash Flood Events

During the period between 9 and 12 January 2011 inclusive an active monsoon trough extended across northern Queensland and over the Coral Sea, linking a series of low pressure systems. A high pressure system over the southern Tasman Sea directed moist easterly winds into the Southeast corner of Queensland (Australian Government Bureau of Meteorology, 2011e). The south-westward movement of an upper level low pressure system across the Southern Queensland coast on 9 January directed moist tropical air into southeast Queensland. This caused intense rainfall to move into the Sunshine Coast, the catchment of the Brisbane River (including Lockyer Creek) and the Upper Condamine River basin (including Gowrie Creek) (Australian Government Bureau of Meteorology, 2011e).

Prior to the development of individual storm cells it is very difficult to forecast exactly when or where these cells would form and move. Once thunderstorm cells form, remote sensing via satellite based sensors and ground based weather radar allow the movement and development of these thunderstorm cells and associated intense rainfall to be tracked and forecast.

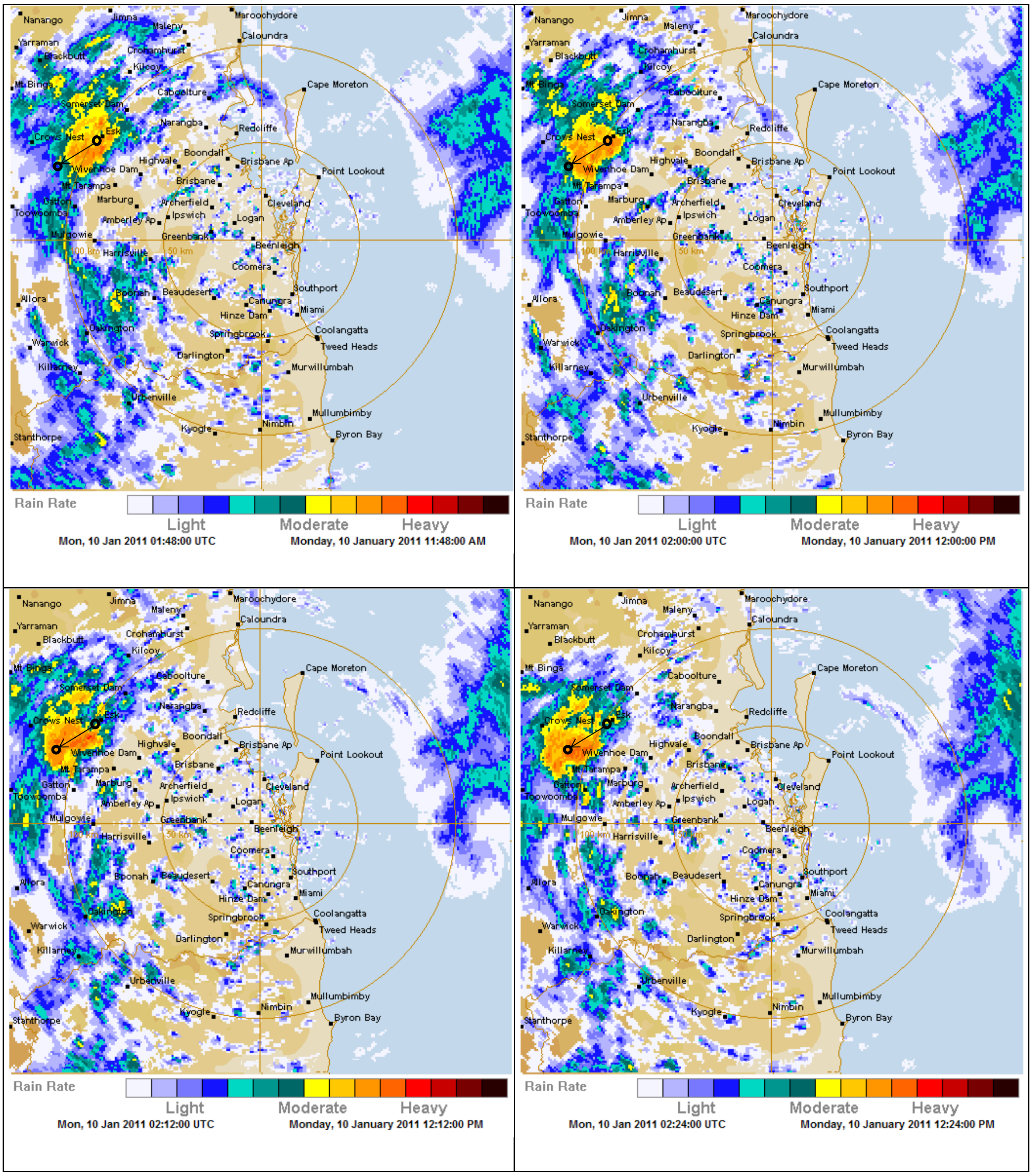
Appendix A shows maps obtained every 6 minutes from the Mount Stapylton weather watch radar for the period between 11:30 am and 2:52 pm on 10 January 2011.

Radar rainfall imagery from the Mount Stapylton weather watch radar shows that a group of intense thunderstorms started to cross the coast north of Brisbane from 1:00 am on 10 January 2011. The showers and thunderstorms were moving in a south-westerly to westerly direction. Between 9:00 am and 9:30 am two intense thunderstorms (with radar maximum reflectivities greater than 40 dBZ[1]) crossed the coast – one of these storms crossing near Redcliffe and the other near Maroochydore. The storm that crossed the coast near Redcliffe moved in a westerly direction and the storm that crossed near Maroochydore moved in a south-westerly direction for the next two hours. The storms converged to form a single intense storm at about 11:00 am, with the combined storm cell extending from Wivenhoe Dam to Moore. At this time the combined storm cell was moving in a south-westerly direction at about 30 km/h. The radar reflectivities within the storm continued to intensify and by the time of the radar scan at 11:48 am (see Appendix A and Figure 3), the most intense part of the storm was recording reflectivity values of more than 45 dBZ, which translates to a rainfall intensity of about 100 mm/hour using Equation 3 (derived from Yu et al., 2005). The intense part of the storm covered an area that was approximately 40 km in diameter.

Figure 3 shows that the area of high intensity rainfall was located over the Upper Brisbane River valley on the 11:48 am radar scan and was moving in a south-westerly direction toward the Toowoomba Range. Ground elevations along the projected path of the high intensity rainfall increase from around 160 m AHD at Esk to about 620 m AHD at the top of the Toowoomba Range. Rainfall intensities increased as the storm cell approached the Toowoomba Range due to orographic enhancement of the rainfall, with high humidity air forced upward by the rising terrain and driving more rainfall out of the humid air mass.

[1] Radar rainfall imagery of provided publicly by the Bureau of Meteorology does not provide a detailed legend that attaches colours to reflectivity values, instead designating reflectivities from "Light" through to "Heavy". A request has been made to the Bureau of Meteorology for the reflectivity colour scale used on imagery provided. In the absence of this information, reflectivity levels have been estimated for this report by the author on the basis of his knowledge about typical colour range scales that the Bureau of Meteorology have previously applied to publicly available radar imagery.

SINCLAIR KNIGHT MERZ
SKM



- **Figure 3 Radar images from the Mount Stapylton Weather Watch Radar at 12 minute intervals between 11:48 am and 12:24 pm on 10 January 2011. The track of the approximate centre of the highest intensity core of the thunderstorm during this period is shown on each image by black circles and the arrow.**

Rainfall intensities in the storm continued to increase over the period between 11:48 am and 12:36 pm on 10 January 2011, as indicated by the increase in radar reflectivity values recorded by Mount Stapylton radar over this period (see Figure 3 and Appendix A). The radar rainfall imagery shows consistent areas of rainfall rates in the yellow, orange and red colour ranges (inferred radar reflectivity between 36 and 55 dBZ) within the storm for all of the radar scans between 11:48 am and 2:18 pm on Monday 10 January 2011, which would indicate rainfall rates of at least 20 mm/h over this entire period if rainfall rates were estimated from Equation 3 (derived from Yu et al., 2005). Radar data shows that intense rainfall would have been widely distributed across most of the catchments of Lockyer Creek upstream of Helidon by 12:42 pm.

Actual point rainfall intensities recorded by raingauges in Toowoomba peaked at 144 mm/h for a period of 10 minutes, 128 mm/h for a period of 30 minutes and 94 mm/h for a period of 60 minutes at the Prince Henry Drive rainfall recording station in Toowoomba (Insurance Council of Australia Hydrology Panel, 2011c).

The highest peak rainfall intensities available from gauges in the Lockyer Creek catchment during this period were 111.2, 83 and 73.6 mm/h for periods of 10, 30 and 60 minutes respectively recorded in the rainfall gauge at Lyons Bridge (Insurance Council of Australia Hydrology Panel, 2011a). As discussed in Section 3.1 and shown in Appendix A, there are no continuously recording rainfall gauges in the parts of the Lockyer Creek catchment to record the highest rainfall intensities and the radar imagery indicates that rainfall intensities were much higher in this area than where the rainfall gauges are located to the south and east. Peak rainfall intensities observed at the Prince Henry Drive rainfall station had annual exceedance probability (AEP) of 1 in 18 for 10 minutes, 1 in 200 for 30 minutes and 1 in 370 for 60 minutes. Rainfall intensities, for durations of between 1 and 2 hours, recorded at several rain gauges across Toowoomba were identified to have AEP of between 1 in 100 and 1 in 300 (BMT WBM, 2011).

Queensland Rail recorded 93 mm in a period of 1 hour at Holmes, near Spring Bluff, which would correspond to an AEP of 1 in 250. “It is possible that rainfall severities at other locations within the upper catchment of the Lockyer Creek were higher than those recorded at the official rainfall recording stations.” (Insurance Council of Austalia Hydrology Panel, 2011b).

These high rainfall intensities were observed on both sides of the Great Dividing Range. Runoff was therefore generated on both sides of the Range, with some of the runoff flowing into the upper tributaries of Lockyer Creek, which eventually joined the Brisbane River downstream of Wivenhoe Dam, and some of the runoff flowing via the catchments of Gowrie and Oakey Creeks into the Upper Condamine River system.

4.3 Definition of a Flash Flood

Flash floods have been defined as "sudden and unexpected flooding caused by local heavy rainfall or rainfall in another area of the catchment. Often defined as flooding that occurs within six hours of the onset of the flood-generating rainfalls" (NSW Department of Infrastructure Planning and Natural Resources (DIPNR), 2005). Hapuarachchi et al. (2011) adopt a similar definition, "Flash floods are characterized by their rapid onset (within six hours of rainfall), which leaves very limited opportunity for effective response," and ICA Hydrology Panel (2011a) note that, "in the USA, flash floods are defined as floods that peak within 6 hours of commencement of the period of intense rainfall."

The Bureau of Meteorology does not provide a distinct criteria in determining a flash flood from other types of flood, instead publishing criteria that, "Flash floods occur when soil absorption, runoff or drainage cannot adequately disperse intense rainfall. The most frequent cause of flash flooding is from slow-moving thunderstorms. These systems can deposit extraordinary amounts of water over a small area in a very short time" (Australian Government Bureau of Meteorology, 2011b). However, the consensus from the published literature is that a flash flood peaks within six hours of the commencement of intense rainfall.

Insurance Council of Australia Hydrology Panel (2011a, 2011b) has concluded that flooding on 10 January 2011 through the Lockyer Valley townships of Murphys Creek, Postmans Ridge, Helidon and Grantham is consistent with its accepted definition of flash flooding since, "flooding was sudden and abrupt, and occurred within 6 hours of the flood-producing rainfalls." ICA Hydrology Panel (2011c) also concluded that the flood in Toowoomba on 10 January 2011 was a flash flood.

4.4 Hydrological Description of Flooding in the Gowrie and Oakey Creek Catchments

4.4.1 Characteristics of the Gowrie and Oakey Creek Catchments

Oakey Creek is a tributary of the Condamine River. The eastern boundary of the catchment is formed by the Great Dividing Range and it flows in a north westerly direction before it meets the Condamine River just upstream of Louden Bridge. Gowrie Creek is a tributary of Oakey Creek, which joins Oakey Creek just downstream of the town of Oakey. The catchment of Oakey Creek upstream of Oakey is mainly cleared land, used for agricultural activities.

East and West Creeks drain much of the city and suburban area of Toowoomba and they join near the centre of Toowoomba's central business district to form Gowrie Creek. There is another tributary of Gowrie Creek known as Black Gully that joins Gowrie Creek downstream of the city centre. Insurance Council of Australia Hydrology Panel (2011c) provides a description and maps that characterise the hydrology of the Gowrie Creek catchment in the Toowoomba city area. The catchments of East Creek, West Creek and Black Gully are mainly urban and suburban areas, with surface runoff from the developed parts of the catchment is now conveyed to Gowrie Creek and its tributaries via a piped drainage system. The waterways of East and West Creeks have been heavily modified with concrete and grass lined channels, detention basins, water features, drop structures and several road crossings that modify the hydraulic behaviour of the creek system.

The catchment of Gowrie Creek between the urban area of Toowoomba and where it joins Oakey Creek just downstream of Oakey is also mainly cleared land, used for agricultural activities.

4.4.2 Hydrological Influence of Cooby Dam

Oakey Creek has a tributary known as Cooby Creek and there is a dam on Cooby Creek known as Cooby Dam. Cooby Dam is owned and operated by Toowoomba Regional Council to provide drinking water for Toowoomba. Cooby Dam has a spillway elevation of 478.54 m AHD[2], which also defines the full supply level for the dam. When runoff occurs in the catchment area of Cooby Dam and the dam is full it is conveyed via the spillway into Cooby Creek downstream of the dam. The dam is a concrete faced rock fill dam with a fixed crest level at 482.9 m AHD and a 1.1 metre high concrete wave wall on the top of the fixed cress that brings the crest of the wave wall to 484.0 m AHD. During an extreme flood event, the integrity of the dam is likely to be compromised if the water level in the dam overtops the wave wall (exceeds 484.0 m AHD) or if the wave wall were to fail, which is possible for water levels between 482.9 m AHD and 484.0 m AHD. The author has made no attempt to assess the structural integrity of the wave wall or any other part of Cooby Dam for this report.

Although Cooby Dam is not specifically designed or operated to provide a flood mitigation benefit to downstream communities, during flood events it will act to mitigate floods. During floods, dams will store water in their reservoir behind the dam wall, both below and above the level of the spillway crest. Even though outflows will occur over the spillway of the dam during a flood, physics dictates that the peak rate of outflow from the dam must be less than the peak rate of inflow to the dam. It is therefore the case that had the dam not been there, the peak flow rate in the stream at that location must be greater than the peak outflow rate over the spillway of the dam with the dam in place.

The magnitude of the difference between the peak inflow rate (or equivalently the rate of flow in the stream had the dam not been there) and the peak outflow rate will vary for every different flood event. It depends upon the magnitude of the rainfalls occurring over the catchment, the temporal and spatial pattern of rainfalls occurring during the event, the antecedent wetness of the catchment prior to the event and the volume of water stored in the dam below the spillway prior to the event.

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[2] Elevations in this report are normally referred to using units of m AHD, which means metres above the Australian Height Datum. The Australian Height Datum is a survey datum that is close to the accepted mean sea level.

As stated above, Cooby Dam's primary function is to provide urban water supply for residents in Toowoomba Regional Council. It would provide some flood mitigation benefit to communities along Oakey Creek downstream of the dam, although this is not its primary function.

4.4.3 Hydrological Description of the January 2011 Event

Weather radar data shows that the intense rainfall system was moving from the north east to the south west, first across the upper catchment of Oakey Creek and then into the Gowrie Creek catchment. Intense rainfall would have started in the catchments of Cooby and Oakey Creeks at about 11:45 am on 10 January. Because of the saturated condition of the catchment it is likely that runoff and overland flow would have commenced within minutes after the commencement of the intense rainfall.

The radar data shows that intense rainfall was widespread across the catchment of Oakey Creek, including the catchment of Cooby Dam, for a two hour period between 11:45 am and 1:45 pm. Runoff generated from the catchment upstream of Cooby Dam, an area of 159 km², flowed into the reservoir of the Dam. Cooby Dam was already spilling by 11:45 am due to rainfall and runoff that had occurred over the hours and days prior to the event. The water level in Cooby Dam rose rapidly from about 1 pm on 10 January 2011 and peaked at a level of approximately 479.8 m AHD (about 1.3 metres above the spillway level) at about 4:30 pm on 10 January 2011. The flow rate over the spillway for this peak would have been approximately 200 m³/s. Water levels in Cooby Dam receded from this second peak over the following period of several hours. It is certain that there would have been flooding generated in the remaining catchment area of Oakey Creek, upstream of Oakey. The total catchment area of Oakey Creek upstream of Oakey is 560 km². The catchment of Cooby Dam therefore represents 28% of the total catchment area of Oakey Creek upstream of Oakey.

The thunderstorm cell continued its movement toward Toowoomba and the catchment of Gowrie Creek. Estimates of rainfall intensity from the radar only were that prior to 12:45 am, rainfall intensities over the Gowrie Creek catchment were less than 5 mm/h. The radar scan from Mount Stapylton at 12:48 am shows reflectivity in the yellow colour range on the Bureau of Meteorology radar scan imagery (reflectivity greater than 40 dBZ), which translates into an estimated rainfall rate of at least 40 mm/h using Equation 3 (derived from Yu et al., 2005). The radar rainfall imagery in Appendix A shows consistent areas of rainfall rates in the yellow, orange and red colour ranges (radar reflectivity between 36 and 55 dBZ) over the Gowrie Creek catchment for all of the radar scans between 12:48 pm and 2:18 pm on Monday 10 January, which would indicate rainfall rates of at least 20 mm/h over this entire period if rainfall rates were estimated from Equation 3 (derived from Yu et al., 2005).

Toowoomba Regional Council operates a network of eleven recording raingauges, which are located in and near the catchment of Gowrie Creek (Insurance Council of Australia Hydrology

Panel, 2011c, p. 23). On 10 January 2011, two of these rainfall stations malfunctioned and the remaining nine gauges recorded rainfall during the event. The numbers and locations of these stations are reported in Insurance Council of Australia Hydrology Panel (2011c, pp. 18, 23). In addition, the Bureau of Meteorology operates two recording rainfall gauges in and near the catchment of Gowrie Creek (Insurance Council of Australia Hydrology Panel, 2011c, pp. 18, 23). The rainfall gauges operated by Toowoomba Regional Council reported accumulated rainfall in 15 minute increments. The data from the Bureau of Meteorology rainfall gauge was provided as the time when the rainfall tipping bucket tips to record an additional 1 mm of rainfall.

Hyetographs from the nine Toowoomba Regional Council stations that were in operation during the event show that there had been intermittent rainfall at a rate of less than 1 mm per 15 minute recording period (i.e. less than 4 mm/h average intensity) between 9 am and 12 noon on 10 January 2011. The rainfall intensity increased slightly, generally between 0.5 and 1.5 mm per 15 minute recording period (4 to 12 mm/h) between 12:00 and 12:45 pm on 10 January 2011. Very heavy rainfall, with intensity exceeding 20 mm/h commenced across the catchment between 12:45 and 1:00 pm and continued at a rate of 20 mm/h or greater for a period of approximately 90 minutes. Recorded rainfall intensities dropped to less than 20 mm/h from 2:30 pm (Insurance Council of Australia Hydrology Panel, 2011c). The timing of intense rainfall over the Gowrie Creek catchment area is entirely consistent between the radar images and the raingauges.

Insurance Council of Australia Hydrology Panel (2011c) analysed data from the streamflow gauge at Cranley that identified a rapid rise in the recorded water levels between 1:00pm and 2:00 pm on 10 January 2011, up to a water level of 3.67 m gauge height. They identified that, "the erratic trace at the Cranley gauge between 1400 hours and 1600 hours indicates that the gauge malfunctioned during that period.... Water levels in East and West Creeks through the Toowoomba City Centre area *would have peaked earlier* than the Cranley stream gauge and therefore within a shorter period after the most intense rain burst."

At the time when the flow gauge malfunctioned (gauge height 3.67 metres), the corresponding estimated flow rate at the Cranley streamflow gauge was in excess of 300 m^3/s (BMT WBM, 2011). A flood frequency analysis of peak flows at the Cranley gauge, using the estimated flow at the time when the gauge recorder malfunctioned, reveals that the 10 January 2011 event had an AEP greater than 1 in 100 and that the AEP of the event may have been as low as 1 in 400 (BMT WBM, 2011). Inundation extents for the 10 January 2011 flood event were wider across the flood plains of West and East Creeks than design flood extents computed from the most recent flood study conducted in Toowoomba. Based upon recorded flood heights, flow rates along West and East Creeks were close to double the design flow estimated for the 1 in 100 AEP event (BMT WBM, 2011).

Water continued to flow from Cranley down Gowrie Creek until it's confluence with Oakey Creek. It is possible that flood levels around the confluence of Gowrie and Oakey Creeks could have caused flooding in Oakey, although more detailed hydrological and hydraulic modelling would be required to confirm this.

Further heavy rainfall over the catchment of Cooby Dam during the early hours of 11 January 2011 caused further inflows to the dam, which resulted in water levels in the dam rising to a third peak. Water levels in the dam rose at a relatively constant rate from about 2 am on 11 January 2011 until the third and highest of the three peaks was observed at 480.09 m AHD at 7:43 am on 11 January. These flows would have continued down Cooby and then Oakey Creeks until they flowed past the town of Oakey. It is considered likely that over this same timeframe there was also runoff generated from the remaining 72% of the catchment area of Oakey Creek upstream of Oakey that is not impounded by Cooby Dam.

4.5 Hydrological Description of Flooding in the Lockyer Valley

4.5.1 Characteristics of the Lockyer Creek Catchment

Insurance Council of Australia Hydrology Panel (2011b, pp. 21-24) provides a description and maps that characterise the hydrology of the Lockyer Creek catchment. The most notable features of the catchment pertinent to the January 2011 flood event are that the upper areas of the Lockyer Creek catchment are steep and mainly forested and the lower areas of the catchment have extensive floodplains that are used mainly for agriculture with a number of small communities spread across them.

4.5.2 Hydrological Description of the January 2011 Event

Weather radar data shows that the intense rainfall would have started in the northern part of the Fifteen Mile Creek catchment at about 12 noon on 10 January 2011. Because of the saturated condition of the catchment, as explained in Section 4.1, and the steep terrain present in the upper tributaries of Lockyer Creek, it is most likely that runoff and rapid increases in overland flow and flows in watercourses would have commenced in these tributaries within minutes after the commencement of intense rainfall.

Rapid observations of water level rise started at the stream level gauge at Murphys Creek at Spring Bluff at 1:20 pm on 10 January 2011 and peaked at 4.96 metres gauge height just 20 minutes later, at about 1:40 pm. The estimated peak flow at the Murphys Creek at Spring Bluff gauge was 360 m^3/s (Insurance Council of Austalia Hydrology Panel, 2011b). Data at this streamflow gauge is recorded by the Queensland Department of Environment and Resource Management but the gauge is not telemetered. Consequently, neither the Queensland Department of Environment and Resource Management nor the Bureau of Meteorology would have had access to water level data from this gauge during the flood event.

"Flooding in Murphys Creek township was caused by waterway flows in Murphys Creek itself," and "Flooding in Postmans Ridge was caused by waterway flows in Rocky Creek, a major tributary of Lockyer Creek and to a lesser extent by Six Mile Creek, a relatively small eastward flowing tributary of Rocky Creek." (Insurance Council of Australia Hydrology Panel, 2011a). Since all of these tributaries are upstream of the gauge on Lockyer Creek at Helidon, flood peaks would have occurred at Murphys Creek and Postmans Ridge at some time prior to the estimated peak at Helidon at 3:30 pm on Monday 10 January 2011.

It is difficult to provide an accurate timing for the commencement of water level rises in the upper tributaries of Lockyer Creek. Intense rainfall would have commenced at about 12:00 noon in the northern most part of the catchment and was widely spread through the catchments of Fifteen Mile, Six Mile, Alice, Rocky and Murphys Creeks by 12:42 pm. Because of the saturated condition of the catchment and the steep terrain present in the catchments of Fifteen Mile, Six Mile, Alice, Rocky and Murphys Creeks, it is most likely that runoff and rapid increases in overland flow and flows in watercourses would have commenced in these tributaries within minutes after the commencement of intense rainfall.

Amateur video (redviking1963, 2011), claimed to have been taken at or about 1:59 pm on 10 January 2011, near the railway bridge that crosses Lockyer Creek just downstream of the junction between Murphys and Alice Creeks, mid-way between Murphys Creek and Helidon, shows that flows were already out of bank. The video shows that the flood peaked at this location at or about 2:21 pm. On this basis, rapid rises in water levels appear to have commenced in Spring Bluff, Murphys Creek and Postmans Ridge before 2:00 pm, although it is difficult to estimate the exact time, and relies upon the accuracy of the time recorded by the amateur videographer.

Australian Government Bureau of Meteorology (2011f, p. 48) notes note that the direction of movement of the storm across the catchment from north east to south west, "may have allowed peak runoff from the five sub-catchments (Alice, Fifteen Mile, Murphys, Six Mile and Rocky Creeks) to align more closely in downstream areas." The estimated velocity of the flood wave between Spring Bluff and Helidon was 16 km/h" (Insurance Council of Austalia Hydrology Panel, 2011b, p. 53).

Water levels started to rise abruptly at the streamflow gauge on Lockyer Creek at Helidon at 2:30 pm on Monday 10 January 2011 (Insurance Council of Australia Hydrology Panel, 2011a). The streamflow gauge at Helidon failed at 2:53 pm and "anecdotal evidence suggests that the flood at Helidon township peaked around 1530 hours" (Insurance Council of Australia Hydrology Panel, 2011a). The estimated peak flow at Helidon was between 3,500 and 4,000 m^3/s.

Flood flows from Monkey Waterholes Creek appear to have coincided with flows travelling along Lockyer Creek at Helidon. Insurance Council of Australia Hydrology Panel (2011b) estimate that flows peaked at the confluence between Lockyer and Monkey Waterholes Creek at a flow rate between 4,000 and 4,500 m³/s. The onset of flooding was estimated to have occurred around 2:30 pm.

The next flow gauge on Lockyer Creek downstream of Helidon is located at Gatton. On the basis of the estimated time of peaks at Helidon and Gatton, Insurance Council of Australia Hydrology Panel (2011a) made a reasonable estimate that the time of the peak in the Lockyer Creek at Grantham was around 5:00 pm. This estimated timing of the peak is supported by the timing of a recorded peak in the water level at the streamflow gauge on Sandy Creek at Sandy Creek Road, which would be consistent with flood water backing up Sandy Creek from its confluence with Lockyer Creek. Since the gauge on Sandy Creek at Sandy Creek Road is only 3 km upstream of the Lockyer Creek confluence, the difference in the timing of the peak at the streamflow gauge and for Lockyer Creek at Grantham would be expected to be only a few minutes. The Sandy Creek at Sandy Creek road streamflow gauge shows the commencement of a rapid rise in water levels from 2:43 pm on 10 January 2011, although it is possible that the initial water level rises recorded on Sandy Creek at Sandy Creek Road were caused by runoff generated from the Sandy Creek catchment instead of water backing up Sandy Creek from Lockyer Creek. Rapid water level rises leading to out of bank flows from Lockyer Creek at Grantham could have commenced as early as 2:45 pm on 10 January. Insurance Council of Australia Hydrology Panel (2011b, p. 53) is reasonably consistent with this timing, estimating that the on-set of flooding was between 3:00 pm and 3:30 pm. They also estimated the peak flow at Grantham to be between 3,500 and 4,000 m³/s.

A peak was also recorded at about 5:00 pm on 10 January 2011 on Flagstone Creek at the stream flow gauge at Brown-Zirbels Road (Insurance Council of Australia Hydrology Panel, 2011a), which is located 5 km upstream of the confluence with Lockyer Creek. The confluence of Flagstone and Lockyer Creeks is a further 6 km upstream of Grantham.

At 5:00 pm on Monday 10 January 2011, the level recorded at the streamflow gauge at Gatton was approximately 7.4 metres gauge height. Flood levels had been gradually receding at Gatton since the first recorded peak at around 10.4 metres gauge height at around 4:00 am. Flood levels rose rapidly at Gatton from 5:00 pm on 10 January 2011 until the streamflow gauge at Gatton recorded a level of 13.87 metres gauge height at 6:40 pm on Monday 10 January when the streamflow gauge failed. Insurance Council of Australia Hydrology Panel (2011a) and Australian Government Bureau of Meteorology (2011f) both estimate that the peak occurred in Lockyer Creek at Gatton at about 8:00 pm.

The releases from Wivenhoe Dam elevated flood waters in the Brisbane River downstream of Wivenhoe, causing flows to back up from the confluence with the Brisbane River along the lower parts of Lockyer Creek. seqWater increased releases from Wivenhoe Dam from 2087 m³/s to 2695 m³/s between 3 pm and 10:00 am on 10 January 2011, held releases approximately constant at no more than 2832 m³/s until 8:00 am on 11 January 2011 and then commenced increases in releases until dam releases peaked at 7458 m³/s at 7 pm on 11 January 2011 (seqWater, 2011). Flows in the Brisbane River are likely to have impeded the passage of flood waters flowing down Lockyer Creek from around 4:00 am on 11 January 2011. Peaks in flooding for Lockyer Creek downstream of Glenore Grove were contributed to by the combined effects of releases from Wivenhoe, flows from the catchment of Lockyer Creek and its tributaries and flows from other tributaries of the Brisbane River downstream of Wivenhoe.

4.5.3 Hydraulics of Flooding in Grantham

It is impossible to determine the exact pathway of flood waters without a calibrated hydraulic model of Grantham. A calibrated hydraulic model of Grantham has not yet been created. A calibrated hydraulic model should be established for Grantham to inform prudent flood plain management for the town and surrounding properties. Setting up and calibrating a hydraulic model of Grantham to previously observed flood events has not been possible in the limited time available to prepare this report.

This commentary on the possible pathway of floodwaters and hydraulic response in Grantham is made on the basis of a field inspection undertaken on 5 April 2011 and aerial photography of Grantham area flown on 18 January 2011. Trails of sediment left by the receding flood waters in the aerial photography were used to postulate the hydraulic characteristics of the flood. A detailed calibrated hydraulic model of the area is required to confirm all of the statements made in this section of the report. References are also made to a similar description in Insurance Council of Australia Hydrology Panel (2011b, pp. 58-59).

Flood flows would have flowed down Lockyer Creek in a roughly westerly direction. Debris lines and sediment marks on aerial photography demonstrate that at the peak, the flood was travelling outside of the normal watercourse, along the floodplain, before it reached Wagners Quarry. Wagners Quarry is located approximately 3.5 km upstream (west) of the centre of Grantham. The normal watercourse of Lockyer Creek is incised in a channel that makes a “hair pin” shaped bend around Wagners Quarry. At the peak of the flood event, debris marks demonstrate that flows were flowing out of bank along the floodplain upstream of Wagners Quarry.

As flood waters rose they would have broken out of the banks of the creek to the south of the processing plant at Wagners Quarry. Flood waters also broke out to the north of the quarry and at their peak would have surrounded the quarry. The quarry has a number of buildings and stockpiles. These may have influenced flood levels in the local area and possibly resulted in marginally more water being forced out through the breakout to the north of the quarry than the water that broke out to the southern side of the quarry. A detailed hydraulic model would be required to confirm this. Given the large volumes of water and depths of flow that broke out from the creek, any differences in flood levels or velocities in the January 2010 event resulting from the existence of the quarry itself were likely to be relatively minimal and were likely to be constrained to the immediate vicinity of the quarry.

Upstream of the quarry, the Ipswich-Toowoomba railway line is located on higher ground on the northern side of the flood plain and this natural higher ground would have contained the northern boundary of the flood water. The railway did not influence flood levels upstream of Wagners Quarry because it is located on higher ground not inundated during the flood event.

Moving eastward from Wagners Quarry, the railway is located along an embankment. The railway continues along an embankment within the floodplain until it reaches the bridge crossing of Sandy Creek near its confluence with Lockyer Creek. The railway embankment would have impeded the passage of flood waters to the north. As flood waters rose, the railway embankment would have partially contained flood water to the southern side of the railway embankment. Once the level of the flow on the southern side of the embankment reached the peak of the railway embankment, flow would have commenced over the railway embankment. An 1100 m long section of the railway embankment was repaired following the flood event, indicating that flow occurred over this portion of the embankment during the event (Insurance Council of Austalia Hydrology Panel, 2011b, p. 58). A detailed model calibrated to flood levels is required to confirm that weir flow did occur over the railway embankment. Flood water would have backed up through the railway bridge across Sandy Creek on to the floodplain on the northern side of the railway embankment.

At the time of the peak of the flood in Grantham, virtually all of the flows were coming from Lockyer and Muddy Waterholes Creeks. Insurance Council of Australia Hydrology Panel (Insurance Council of Austalia Hydrology Panel, 2011b, p. 59) estimates that there were only modest flows contributed from Ma Ma and Tenthill Creeks on the afternoon of Monday 10 January that would not have materially influence peak flows in Grantham.

Flood levels on the floodplain to the southern side of the railway line from around Wagners Quarry and downstream through Grantham would have been higher than if the railway line did not exist. Without a detailed hydraulic model of the floodplain it is not possible to quantify the difference that the railway line would have made to flood levels along this part of the floodplain. Further comments are made about the railway embankment and flooding in Grantham in Section 7.2.

Flow velocities in Grantham on the southern side of the railway line were estimated to be between 2 and 3 m/s and the depth of flow was between 2 and 2.5 metres across the floodplain (Insurance Council of Austalia Hydrology Panel, 2011b, p. 59).

5 Assessment of Flash Flood Warnings and Advice Provided to Emergency Authorities Prior to and During the Event

5.1 Current Institutional Arrangements and Regulations with Regard to Warnings for Flash Flooding and Thunderstorms

There is a lack of clarity regarding responsibility for the production of forecasts and warnings for flash floods in Australia. Bureau of Meteorology states in its *Annual Report* (Australian Government Bureau of Meteorology, 2010) that the objective of its Flood Warning and Forecasting Service is:

> "To provide high-quality flood forecasting and warning (including short-term flow forecasting) services for Australia, based on the best available science and a sound understanding of user needs, and in close cooperation with State and Territory partners."
>
> "The Bureau also provides forecasts of severe thunderstorms, which are particularly intense convective storms producing destructive winds, damaging hails, tornados and/or heavy rain leading to flash flooding, in the form of severe thunderstorm warnings. Thunderstorms are usually highly localised (a few kilometres across) and short-lived (several minutes to a few hours), and forecasters depend critically on the use radar to identify their existence, severity and movement."

Provision of flood warnings is also included in the Bureau of Meteorology's *Service Charter* (Australian Government Bureau of Meteorology, 2006), although that document does not distinguish between flash and non-flash floods.

The Key Performance Indicator noted in Australian Government Bureau of Meteorology *Annual Report* (2010) with regard to the Flood Warning and Forecasting Service is that, "For all critical (non-flash) flood events, the Bureau issues understandable, accurate and timely warnings to emergency services and affected sectors of the Australian community."

Australian Government Bureau of Meteorology (2011b) acknowledges that, "In some areas, the Bureau is working with local councils to install systems to provide improved warnings for flash flood situations," but they stop short of transferring the responsibility for flash flood forecasting and warning to local government or other agencies. Australian Government Bureau of Meteorology (2011e) states in their submission to the Queensland Floods Commission of Inquiry that, "The Bureau does not routinely issue location specific flash flood warnings because it does not have the knowledge of local conditions at individual locations." The Bureau of Meteorology states that they have arrangements in place with local governments for those authorities to provide response in flash flood situations within their own local jurisdictions (Australian Government Bureau of

Meteorology, 2011f). The author has not sighted any further documentation that would clarify the nature of these arrangements.

The Bureau of Meteorology has developed its data collection, flood forecasting and flood warning systems on the basis that it provides specific non-flash flood warning advice but it does not provide specific warning of flash flooding. The Bureau of Meteorology .therefore has not developed systems place that could reasonably enable it to routinely produce clear, accurate, timely and location-specific flash flood forecasts. Some elements of a flash flood warning system, including networks of real time reporting rainfall and streamflow gauges, weather radar and numerical weather prediction modelling are currently available to the Bureau of Meteorology.

As discussed in Section 4.3, whilst there is a generally accepted definition in the hydrological community that a flash flood occurs within six hours of the onset of the flood-generating rainfalls, the Bureau of Meteorology does not appear to provide a clear public statement, on its website or elsewhere, of what it considers the difference between a flash or a non-flash flood. It may therefore be difficult for the public to determine which areas and flood situations they could expect to receive flood warnings from the Bureau of Meteorology and where they should be looking to other agencies for this information. The Bureau of Meteorology could rectify this situation by providing a clearer statement on its public website of what it considers the difference between a flash and a non-flash flood.

5.2 Bureau of Meteorology Internal Arrangements for Warnings

The Bureau of Meteorology separates responsibility for warnings between:

(a) severe weather meteorologists, who are responsible for issuing severe weather warnings; and

(b) hydrologists in the Flood Warning Centre that issue non-flash flood warnings.

The severe weather meteorologists and the Flood Warning Centre for the Queensland region are co-located in the Bureau of Meteorology's regional office in Brisbane City.

Since the Bureau of Meteorology does not currently have formal responsibility for issuing warnings for flash flooding, it does not currently have dedicated staff responsible for nor dedicated systems for forecasting flash floods. Severe weather meteorologists do issue severe weather warnings that may provide mention of the potential for flash flooding to occur and/or worsen. The Flood Warning Centre does not have data collection, modelling or forecasting systems set up to issue warnings of flash floods, as systems have been established primarily to warn of non-flash flood situations.

5.3 Dam Management

Circumstances can arise that lead to catastrophic failure of dams, leading to a rapid release of water from the dam into downstream waterways. An extreme flood occurring in the catchment of a dam is one circumstance that could conceivably cause a dam to fail, although the probability of such an event is extremely low. Owners of large dams manage this risk by maintaining dams at an appropriately low level. Dam management is dictated by the Queensland Dam Safety Management Guidelines (Queensland Government Department of Natural Resources and Mines, 2002).

Toowoomba Regional Council owns and operates three dams: Cressbrook, Perseverance and Cooby Dams. Water from these dams is treated and used for urban water supply in Toowoomba. All three dams have ungated spillways that allow for the unrestricted outflows of flood waters from the dam in a controlled manner during flood events. None of the three dams are operated specifically for flood mitigation purposes. This is in contrast to some other dams, such as Wivenhoe Dam, that are specifically designed to provide a flood mitigation function in addition to a role as a water supply dam. Outflows from Cressbrook, Perseverance or Cooby Dams cannot be modified during a flood event, which is in contrast to dams such as Wivenhoe with gates for this purpose.

As part of management arrangements, Toowoomba Regional Council is required to have Emergency Action Plans in place for each of these dams and it is required to implement these Plans once it becomes clear that an event is unfolding that could threaten the safety of the dam (Queensland Government Department of Natural Resources and Mines, 2002). The Emergency Action Plans in place for Cooby (Toowoomba Regional Council, 2010a), Perseverance and Cressbrook Dams (Toowoomba Regional Council, 2010b), were updated only a few months prior to the 10 January 2011 event.

5.4 Purposes of Flash Flood Warning

The primary objective of flash flood warning is to provide timely warnings for potentially affected areas to enable action to mitigate the risk of injuries and loss of life by evacuation to a safe area. The secondary objective would be to provide opportunity to remove property that is quickly and easily moved and that has particularly high value, including pets, livestock, vehicles, valuables, important records and items of high sentimental value such as photographs.

To achieve the above objectives, it is not necessary for estimates to have a high level of accuracy in terms of the depth and extent of flooding at a particular area, notwithstanding that this would be difficult to achieve, in the timeframes required for this information to be of assistance. It will often be sufficient to provide guidance about the nature of the impending flash flood threat for a particular waterway or even for a particular town, suburb or local government area.

In non-flash flood forecasting, the rate of rise of waters is typically much slower than for flash floods and therefore the objectives of flood warning and forecasting are slightly different. In addition to the preservation of life, prevention of injuries and protection of easily moved, high value items it becomes possible to provide warnings that allow people to move a much larger proportion of their property, which may include furniture, electrical appliances, carpets, rugs, tools and white goods to higher ground or higher elevations in their structures. In non-flash floods, warning times may be sufficient that it also becomes possible for emergency services to proactively disable power supplies to reduce the risk of electrocution. Accurate prediction of the depth and extent of flooding, at least at key forecasting locations, becomes useful in planning the response.

5.5 Criteria for Assessment of the Performance of Flash Flood Warnings

The Bureau of Meteorology's key performance indicator for non-flash flood warnings (Australian Government Bureau of Meteorology, 2010) is that they are "understandable, accurate and timely". It is therefore considered reasonable to use similar criteria for the assessment of the performance of flash flood warnings, albeit acknowledging the particular difficulties in flash flood warning that make a different standard applicable to non-flash flood warning situations.

To explore appropriate criteria for the assessment of flash flood warnings, the following more detailed criteria might be applied:

- **Understandable**: unambiguous wording as to the locations exposed to the potential threat of flash flooding, providing an appropriate call to action from those hearing the warning. An understandable warning would distinguish the assessed level of threat presented in the current situation from other apparently similar warnings that may have been produced earlier in the event or for previous flash flood events.
- **Accurate**: identifying as accurately and specifically as possible the location of likely flooding, the inundation level or depth of flooding and the time that flood levels are likely to commence rising and / or peak. It should be recognised however, that the nature of flash flooding makes accurate forecasting of levels and timing more difficult for flash than non-flash floods.
- **Timely**: sufficiently early to allow authorities to disseminate warnings to people in threatened areas, for those people to understand the warnings that have been issued and for them to evacuate to safety. Ideally a flash flood warning would be issued at a time that allows the maximum time available from the time that the threat is first identified for people to evacuate themselves and easily moved high value property to safety.

For a warning to be effective it must satisfy all three criteria of being understandable, accurate and timely simultaneously. A failure in any one of the three performance measures severely undermines the effectiveness of the warning. For example a warning that is understandable and accurate but released too late for the warning to be disseminated and allow people in the threatened area to take effective action is of no practical value.

Flood Warning: An Australian Guide (Emergency Management Australia, 1995, p. 9) stresses that flood warning systems should be, "sufficiently robust to cope with the range of magnitudes of events which can occur ... and it is important that systems are able to cope with floods approaching extreme proportions. Flood warning systems must, therefore, be designed to predict and cater for rare, severe events as well as less serious and more common ones."

5.6 Potential for Forecasting the 10 January Flash Flood in Toowoomba and the Lockyer Valley

A professional meteorologist, Mr. Anthony Cornelius, employed by a private meteorological company, Weatherwatch, was monitoring the meteorological events that were occurring in South East Queensland on 10 January 2011. According to his submission to the Commission, Cornelius completed a Science Degree majoring in climatology from the University of Southern Queensland in 2004. He had been working for Weatherwatch since 2001 and had "spent many years researching and forecasting thunderstorm activity across Australia" (Cornelius, 2011). He states that his responsibility within Weatherwatch is to provide, "high risk clients of Weatherwatch with detailed severe weather and thunderstorm information" (Cornelius, 2011).

Cornelius (2011) claims that there was a consensus forecast for between 100 and 200 mm in 24 hours on Monday 10 January of rainfall across Southeast Queensland from several numerical weather prediction models, which are produced by weather forecasting services in different countries and which the Bureau of Meteorology forecasters would have had access to. On the morning of 10 January air temperatures at the surface over South East Queensland were 26°C and dew points were 24°C, which indicates that humidity in the lower atmosphere was high. The forecast Convective Available Potential Energy in the atmosphere for 1:00 pm 10 January 2011, based upon forecast conditions at 10:00 am (3 hours earlier) across the Brisbane and Lockyer Valley areas was 2456 J/kg. Cornelius observes that Convective Available Potential Energy in the atmosphere is indicative of high instability and this "combined with a cool and very moist upper atmosphere is a sign of very heavy rainfall potential" (Cornelius, 2011).

Prior to the development of individual storm cells it is difficult to forecast exactly when or where these cells would form and move. Once thunderstorm cells form, remote sensing via satellite based sensors and ground based weather radar allow the movement and development of these thunderstorm cells and associated intense rainfall to be tracked and forecast.

The Doppler radar imagery from Mount Stapylton radar at 11:49 am also indicated wind speeds of at least 80 km/h in an area to the Southeast of the storm (measured by the radar beam with its centre between 1 and 2 km above the ground). There was rainfall at estimated intensities of less than 2 mm/h and no rainfall in some parts of this area at the time, which Cornelius (2011) claims, "suggests a very large updraft, one capable of producing high amounts of precipitation." The author does not have the meteorological expertise to independently test Cornelius's claim.

The area of high intensity rainfall was located over the Upper Brisbane River valley on the 11:48 am radar scan and was moving in a south-westerly direction toward the Toowoomba Range. Ground elevations increase from around 160 m AHD at Esk to about 620 m AHD at the top of the Toowoomba Range. The increase in ground elevation could reasonably be expected to cause orographic enhancement of the storm as it approached the Toowoomba Range. The combined effects of strong low level inflows to the storm from the southeast, indicating strong updrafts, and the reasonable expectation of orographic enhancement of the storm as it approached the Toowoomba Range should have indicated by the time that the 11:48/11:49 am radar scan[3] was available that rainfall intensities would increase from those observed on this radar scan.

It typically takes a few minutes for a weather radar to complete its entire scan pattern, for the data to be processed, automated quality control to be implemented and for the radar data to be transmitted to the Bureau of Meteorology forecasters. It would be reasonable to assume that the forecasters would have had access to the radar imagery within 10 minutes after the data was collected by the radar, which means that the weather forecasters would have had the 11:48 am radar scan (and the preceding radar data) by 11:58 am.

Bureau of Meteorology weather forecasters could reasonably have been aware by 11:58 am that there was a thunderstorm cell with rainfall intensities of at least 25 mm/hour across an area approximately 40 km across moving at 30 km/h in a south-westerly direction. Maximum radar reflectivity values observed within the storm at this point were 50 dBZ, which translates to rainfall intensities of at least 150 mm/h (using Equation 3, derived from Yu et al., 2005). There was also evidence available that the rainfall intensities observed to that point would increase as the storm approached Toowoomba and the Lockyer Valley. If the storm were to continue moving with the same horizontal velocity and maintained the same intensities displayed in the radar scan at 11:48 am, then rainfall accumulations of more than 50 mm over a period of one hour would be expected to occur in Toowoomba and the catchment of Upper Lockyer Creek and its tributaries

[3] Weather radar are operated by the Bureau of Meteorology to rotate through a full 360° rotation at the lowest vertical angle, which is at 0.5° above the horizontal in the case of the Mount Stapylton radar. The radar then shifts up to a higher vertical angle and scans for another full 360° rotation. The radar completes this pattern for a number (typically between five and fifteen) different vertical elevation angles before returning to the lowest scan elevation angle and repeating the process. This means that the first scan of the set from the lowest elevation angle is completed and the data transmitted to forecasters before the second scan and so on. Rainfall intensities are returned from the lowest (0.5° vertical angle) and Doppler wind velocities are returned from the second (0.9° vertical angle) scan, so rainfall intensities may be available about 1 minute before Doppler wind velocities.

within the next two hours. A rainfall depth of 50 mm in one hour translates to an AEP for the rainfall of approximately 1 in 10. As explained in Section 4.1, the soils in the catchments of Gowrie Creek and Lockyer Creek were saturated and initial losses were minimal. The AEP of the flood runoff resulting from rainfall intensities with an AEP of 0.1 would be expected to be lower than 0.1. On the basis of the radar imagery available by noon on 10 January 2011, Severe weather forecasters could reasonably be expected to be informing the Flood Warning Centre of heavy rainfall, with an AEP of less than 1 in 10, that was likely to occur within the next few hours in Gowrie Creek, Upper Lockyer Creek and their tributaries.

A professional meteorologist working for a private meteorological service not related to the Bureau of Meteorology made a specific prediction of heavy rainfall leading to flash flooding for Gatton and Grantham at 12:16 pm on 10 January 2011. Mr Anthony Cornelius posted an entry on an on-line forum at 12:16 pm that stated (Cornelius, 2011):

> "Concerning (sic) for the Gatton-Grantham area right now with that very large storm/rain area moving towards it with no doubt, torrential rainfall! Sandy Creek (in Grantham) has caught quite a few people by surprise and I hope they're prepared for it, but sadly I think most won't know until the water starts lapping up at their homes due to our insufficient warning system.
>
> "Event is definitely not over – the dry slot is there, but the moist air in front of it is the danger zone which is what's passing through / moving towards Southeast Queensland right now! Not to mention the instability – and the radar is certainly showing a clear picture of the instability right now."

The meteorological information noted above would have been monitored by the Severe Weather forecasters and the hydrologists in the Flood Warning Centre may not have been aware of the developing meteorological situation. Ideally at this point, severe weather forecasters could have alerted the Flood Warning Centre of the developing meteorological situation and as a result may have been in a better position to consider issuing warnings. The Flood Warning Centre's rainfall and streamflow gauge network would not have been detecting the event by this time and, without specific advice from the severe weather forecasters, it is unlikely that they would have been in a position to issue a specific flash flood warning.

The Bureau of Meteorology did not contact Toowoomba Regional Council or Lockyer Valley Regional Council to specifically communicate the message about the prospect of heavy rainfall and flash flooding (Australian Government Bureau of Meteorology, 2011f). Specific information about heavy rainfall leading to the prospect of flash flooding in the two local government areas could have been provided and may have assisted the two local authorities to monitor and provide advice to their local communities about imminent flash flooding.

The Bureau of Meteorology contacted the State Disaster Coordination Centre (SDCC) at 1:00 pm on 10 January to inform them that a, "pulse of really heavy rainfall was moving over the Toowoomba town area with expected flash flooding over the next hour or two. During the conversation with the SDCC, the Bureau expressed the view that the expected flash flooding could soon result in calls for assistance" (Australian Government Bureau of Meteorology, 2011f, p. 53). Although this message was issued about 45 minutes later than the earliest such time that a message of this type could have been issued for Toowoomba, it was at least issued at around the time that increases in stream levels would have started to have been observed in East and West Creeks and was therefore reasonably timely. It would be reasonable to expect that communications between the Bureau of Meteorology and the State Disaster Coordination Centre would be recorded but not transcripts of these conversations were made available for the author to prepare this report. The author is not aware whether the information supplied in the 1:00 pm 10 January 2011 message was relayed from the State Disaster Coordination Centre to Toowoomba Regional Council or Lockyer Valley Regional Council.

5.7 Assessment of the Performance of Warnings Issued Prior to and During the 10 and 11 January 2011 Event

The Bureau of Meteorology released a large number of warnings relevant to the Lockyer Valley and Toowoomba in January 2011. These warnings fall into three categories:

- severe weather warnings of heavy rainfall leading to localised flash flooding;
- flood warnings for Lockyer Creek, which often also discuss flood conditions in the rest of the Brisbane River basin; and
- flood warnings for the Condamine Balonne River system.

This section of the report assesses the performance of severe weather, flash and non-flash flood warnings for Toowoomba and communities in the Lockyer Valley issued by the Bureau of Meteorology prior and during the 10 January flood event. It also separately assesses the prospect for Toowoomba Regional Council to have provided its own advice to emergency agencies prior to and during the flash flood event in Toowoomba.

5.7.1 Severe Weather Warnings

Severe weather warning had been in place for Southeast Queensland (including the Lockyer Valley and Toowoomba) since 5 January 2011. On the days of 9, 10 and 11 January 2011, the Bureau of Meteorology issued sixteen separate warnings with warnings titled "SEVERE WEATHER WARNING for heavy rainfall leading to localised flash flooding and potentially worsening of the existing river flood situation" pertaining to either the Lockyer Valley or Toowoomba (Australian Government Bureau of Meteorology, 2011e).

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The wording for each of these severe weather warnings was similar throughout the entire period between 9 and 11 January 2011 inclusive. None of the sixteen severe weather warnings refer to specific towns or locations, instead the only spatial reference provided in these forecasts is to the Bureau of Meteorology's "southeast coast" and the Darling Downs and Granite Belt forecast districts. The Lockyer Valley, being on the eastern side of the Great Dividing Range, falls within the "southeast coast" forecast district, although none of the severe weather forecasts provide any specific mention of the Lockyer Valley or any towns or locations within the Lockyer Valley. Toowoomba is within the Darling Downs and Granite Belt forecast district and although some of the severe weather warnings specifically refer to the "eastern parts" of the district, no specific mention is made of Toowoomba.

Each of the severe weather warnings provide similar wording about the nature of the meteorological threat, using words such as, "Heavy rain areas and thunderstorms are expected to increase / continue," and "Heavy falls may lead to localised flash flooding and/or worsen existing river flooding." The warnings also contain advice from the State Emergency Service that, "people in the affected area should: avoid driving, walking or riding through flood waters; take care on the roads, especially in heavy downpours; avoid swimming in swollen rivers and creeks." The warnings do not give specific advice regarding evacuation.

The use of the terminology "southeast coast" forecast district is potentially misleading with regard to residents and visitors to the Lockyer Valley, which is located approximately 100 km from the coast. Many ordinary people hearing a warning for the "southeast coast" forecast district in the Lockyer Valley may have heard this warning and mistakenly thought that the warning pertained to areas closer to the coast and not to them. In providing severe weather warnings, the Bureau of Meteorology should consider using forecast areas that more closely align with geographic areas that are immediately known to residents and visitors to an area, such as Local Government Area boundaries. Ideally, severe weather warnings would mention specific towns and cities that are subject to the severe weather threat at that time.

The use of the Darling Downs in the name of the forecast district is in common use and would be more apparent to residents and visitors to the area. Use of more specific locations in severe weather warnings, such as Local Government Areas and the names of towns and cities would enhance those in potentially affected areas to understand and respond to the warnings issued.

5.7.2 Bureau of Meteorology Flash Flood Warnings Issued for Upper Lockyer Creek (Grantham and tributaries upstream)

Between 9 and 11 January 2011 inclusive, the Bureau of Meteorology issued nine flood warnings for Lockyer Creek, which also included warnings for the Brisbane River below Wivenhoe Dam and other tributaries of the Brisbane River. The Bureau of Meteorology also issued five Flash Flood Warnings specifically for Lockyer Creek during this same period.

The first flash flood warning was issued for Lockyer Creek at 5:00 pm on Monday 10 January 2011. This warning states that, “Very heavy rainfalls have been recorded in the Toowoomba area and caused extreme flash flooding. This rainfall is also causing extreme rises in the Upper Lockyer Creek at Helidon with very fast and dangerous rises possible downstream at Gatton in the next few hours. Rises will extend downstream of Gatton during tonight.”

The most upstream gauging station on Upper Lockyer Creek is located at Helidon. Water levels started to rise abruptly at the streamflow gauge on Lockyer Creek at Helidon at 2:30 pm on Monday 10 January 2011 (Insurance Council of Australia Hydrology Panel, 2011a). The streamflow gauge at Helidon failed at 2:53 pm and “anecdotal evidence suggests that the flood at Helidon township peaked around 1530 hours” (Insurance Council of Australia Hydrology Panel, 2011a).

Evidence from streamflow gauges in the catchment is that flood levels had already peaked in Helidon between one and two hours before the first flash flood warning was issued for Lockyer Creek by the Bureau of Meteorology at 5:00 pm on 10 January. On the basis of amateur video footage shot mid-way between Murphys Creek and Helidon and radar observations of rainfall across the upstream catchments (discussed in Section 4.5.2), rapid rises in water levels are almost certain to have commenced in Spring Bluff, Murphys Creek and Postmans Ridge before 2 pm, although it is difficult to estimate the exact time. All of the flash flood warnings for Lockyer Creek were therefore not sufficiently timely to be of any practical use to people that were in Helidon, Grantham or the other communities upstream.

It would reasonably be expected that the severe weather meteorologists should have been informing the Flood Warning Centre of the high rainfall intensities forecast and observed for the upper Lockyer Creek catchment over the period between 12:15 pm and 2:30 pm, which should have alerted the Flood Warning Centre to the prospect of rapid rises in water level.

The Bureau of Meteorology has a number of automated quality control procedures that are run to detect apparently erroneous data returned from telemetered water level and rainfall recording stations.

The automated procedure flagged the water level returns from the Helidon streamflow gauge on the rapid rising limb of the hydrograph on 10 January 2011 as erroneous (Australian Government Bureau of Meteorology, 2011f, p. 45). This masked evidence of actual streamflow rise that was occurring from personnel in the Bureau of Meteorology Flood Warning Centre until 4:16 pm, when they were alerted of intense rainfalls in the upper Lockyer Valley that could give rise to flash flooding (Australian Government Bureau of Meteorology, 2011f, p. 45). This lack of communication between the Severe Weather Meteorologists and the Flood Warning Centre during the afternoon of 10 January about the intense rainfall that the severe weather meteorologists could reasonably have been observing is likely to have prevented the issue of timely warnings. Previously recorded flood levels from the Helidon gauge were manually flagged as valid data by Flood Warning Centre staff sometime between 4:30 and 4:50 pm (Australian Government Bureau of Meteorology, 2011f, p. 45). The Bureau of Meteorology could reasonably have reviewed the algorithm that is used to filter potentially erroneous water level recordings and update the computer software to reduce the likelihood of a similar occurrence in future.

The Bureau of Meteorology using its current systems and procedures could have been in a position to issue a flash flood warning for Grantham at 2:45 pm, on the basis of the very rapid rises in flow that had been observed at the Helidon gauge in addition to the other evidence of high rainfall totals from weather radar and raingauges to that time. Although this would have provided very little lead time prior to the commencement of rapid streamflow rises in Grantham it would have provided more than 2 hours of lead time to the estimated peak level at Grantham.

The Bureau of Meteorology did not contact Lockyer Valley Regional Council to specifically communicate the message about the prospect of heavy rainfall and flash flooding (Australian Government Bureau of Meteorology, 2011f). Specific information about heavy rainfall leading to the prospect of flash flooding in the two local government areas could have been provided and may have assisted the two local authorities to monitor and provide advice to their local communities about imminent flash flooding.

Davidson (2011) notes that the telephone call from the Bureau of Meteorology to the State Disaster Coordination Centre at 1:00 pm on 10 January mentioned heavy rainfall to the west of Wivenhoe Dam (which would include the upper Lockyer Creek catchment), storm spotter reports from Cressbrook Dam advising of multiple landslides and specifically drew attention to the prospect of imminent flash flooding in Toowoomba. Davidson (2011) admits that the telephone call did not specifically discuss the prospect of flash flooding in the Lockyer Valley, nor did it mention specific towns within the Lockyer Valley. The author is not aware whether this information was relayed from the State Disaster Coordination Centre to Lockyer Valley Regional Council.

Section 6 of this report discusses recent developments in technology that would allow for more specific, timely and accurate flash flood warnings. If a flash Flood Warning Centre, using these advanced technologies had been in place, it is likely that specific flash flood warning could have been provided for individual communities in the upper Lockyer Valley by 12:15 pm. A warning issued using these advanced technologies would have provided more than two hours of lead time before rapid water level rises commenced in Helidon, Postmans Ridge and Grantham. Available warning lead times for Spring Bluff and Murphys Creek would have been considerably shorter than two hours.

5.7.3 Bureau of Meteorology Flash and Non-Flash Flood Warnings for Lower Lockyer Creek (Downstream of Grantham)

Between 9 and 11 January 2011 inclusive, the Bureau of Meteorology issued nine flood warnings for Lockyer Creek, which also included warnings for the Brisbane River below Wivenhoe Dam and other tributaries of the Brisbane River. The Bureau of Meteorology also issued five Flash Flood Warnings specifically for Lockyer Creek during this same period.

The flash flood warning released at 5:00 pm on 10 January was at the time that flood levels would have commenced to rise again in Gatton and about three hours prior to the expected peak of flood levels in Gatton. The flood warning issued for Lockyer Creek at 6:12 pm on 10 January 2011 also warned that, "Severe record major flooding is expected in areas downstream of Gatton overnight and during Tuesday." These warnings were released in a sufficiently timely manner that if the time to disseminate the warning was short, at least some people at threat of flooding in Gatton could have had sufficient time to evacuate to safety. This is notwithstanding that a specific flash flood warning issued for Gatton at an earlier time could have allowed more time for that warning to be disseminated to emergency agencies and people under threat, which could have allowed more time for those people affected to evacuate themselves and possibly some possessions.

As noted earlier, if there had been more effective communications between the Severe Weather Forecasters and the Flood Warning Centre, flash flood warnings specifically mentioning Gatton could have been issued by 2:45 pm, which would have provided at least 2 hours prior to the commencement of rapid water level rises at Gatton.

At Glenore Grove, there is a first peak in flooding at 11:34 pm on 10 January 2011 at 14.62 metres gauge height but this is later exceeded by a peak of 15.34 metres recorded for the period between 5:00 and 6:22 pm on 11 January 2011.

The Bureau of Meteorology issued a flood warning for Lockyer Creek at 12:06 am on 11 January 2011 that forecast peaks in flood levels above 15 metres gauge height at Glenore Grove and between 16 and 16.5 metres gauge height at Lyons Bridge. Flood levels peaked at Glenore Grove at 15.34 metres. Flood levels peaked at Lyons Bridge at 17.25 metres at 6:00 pm on 11 January 2011, which is likely to have been consistent with information that the Bureau of Meteorology flood forecasters could have had available at that time. Later increases in flood levels along Lockyer Creek at Lyons Bridge and locations downstream were influenced by releases from Wivenhoe Dam and it would have been difficult at the time that this warning was prepared (12:06 am on 11 January 2011) for Bureau of Meteorology flood forecasters to foresee releases from Wivenhoe. The flood warning released at 9:28 am on 11 January 2011 revised the forecast peak for Lyons Bridge up to 17 metres, which was reasonably consistent with the actual peak (17.25 metres gauge height) observed more than eight hours later. The flood warnings issued for Glenore Grove and Lyons Bridge during this event demonstrates the appropriateness and accuracy of the Bureau of

Meteorology Flood Warning Centres data collection, flood modelling and procedures for non-flash flood situations in the Lockyer Valley.

5.7.4 Bureau of Meteorology Flood Warnings Issued pertaining to Toowoomba

Between 9 and 11 January 2011 inclusive, the Bureau of Meteorology issued thirteen warnings pertaining to the Condamine and Balonne River System. Although Toowoomba is located in the upper parts of the Condamine River basin, there was no mention made in any of these warnings to Toowoomba, Gowrie Creek or East or West Creeks in Toowoomba. In the warning issued at 10:53 am on 10 January 2011 there is mention of, "Renewed rises and flooding is likely in tributary creeks..." although it would be difficult to specifically attribute this to Toowoomba, Gowrie, East or West Creeks. The warning issued for 10:53 am on 10 January was the last warning issued by the Bureau of Meteorology for the Condamine-Balonne prior to the peak of the flood in Toowoomba which peaked between 2:00 and 2:15 pm in the Toowoomba CBD and at about 2:30 pm at the Cranley streamflow gauge on Gowrie Creek (Insurance Council of Australia Hydrology Panel, 2011c).

Across the set of warnings issued as both severe weather warnings and the flood warnings for the Condamine-Balonne River system in the period between 9 and 11 January 2011 inclusive, there is no specific guidance for Toowoomba, Gowrie, East or West Creeks. There is no specific guidance in any of these warnings that residents and visitors to Toowoomba at that time should take any specific action, other than the three points of guidance provided by the State Emergency Service about avoiding entry to creeks and taking care whilst driving during heavy downpours. Since virtually the same guidance is provided in all severe weather warnings of this type issued by the Bureau of Meteorology, it would be difficult for residents to determine which events are more dangerous and provide a more immediate level of threat than others. Clearly, the flash flood event that unfolded in Toowoomba on the afternoon of 10 January 2011 presented a much higher level of threat than other thunderstorms that typically occur in South East Queensland.

5.7.5 Assessment of Warnings and Actions Taken by Lockyer Valley Regional Council

Lockyer Valley Regional Council operates just two telemetered raingauges: on Sandy Creek at Sandy Creek Road and in Upper Sandy Creek. The council operates one telemetered streamflow gauge, located with the raingauge on Sandy Creek at Sandy Creek Road.

Both of these rainfall gauges were located to the east of the intense rainfall cell that moved across the catchments of the upper Lockyer Creek on the afternoon of 10 January 2011. Monitoring of these two gauges on their own could not have provided any indication of the higher rainfall intensities that were occurring in the upper Lockyer Creek catchment to the east.

The streamflow gauge on Sandy Creek at Sandy Creek Road recorded a rise in water levels. Analysis of data post the event, as discussed in Section 4.5.3, reveals that it is likely that this rise was contributed to by flood waters from Lockyer Creek backing up underneath the railway bridge at Grantham and flowing over the railway line in Grantham. It is unreasonable to expect during the event that Lockyer Valley Regional Council could have interpreted that the rise in water levels recorded at the Sandy Creek Road gauge were cause by flooding from Lockyer Creek.

Lockyer Valley Regional Council would not have been in a position to accurately forecast a flash flood in the upper Lockyer Valley prior to the peak of the flood passing through Grantham.

5.7.6 Assessment of Warnings and Actions Taken by Toowoomba Regional Council

Toowoomba Regional Council operates a network of eleven recording raingauges, which are located in and near the catchment of Gowrie Creek (Insurance Council of Australia Hydrology Panel, 2011c, p. 23). On 10 January 2011, two of these rainfall stations malfunctioned and the remaining nine gauges recorded rainfall during the event. The numbers and locations of these stations are reported in Insurance Council of Australia Hydrology Panel (2011c, pp. 18, 23). In addition, the Bureau of Meteorology operates two recording rainfall gauges in and near the catchment of Gowrie Creek (Insurance Council of Australia Hydrology Panel, 2011c, pp. 18, 23). The rainfall gauges operated by Toowoomba Regional Council reported accumulated rainfall in 15 minute increments. The data from the Bureau of Meteorology rainfall gauge was provided as the time when the rainfall tipping bucket tips to record an additional 1 mm of rainfall.

The recording raingauge network operated in Toowoomba by the Toowoomba Regional Council and the Bureau of Meteorology has a much higher density of gauges than is typical over the rest of Australia. Networks of raingauges of comparable density would typically only be established in urban areas.

Toowoomba Regional Council measured rainfall when that rainfall had been collected by a ground based rainfall gauge. Rainfall intensities of less than 4 mm/h, which were the rates measured in the Toowoomba Regional Council raingauge network for the period prior to 12:00 noon on 10 January 2011, would not have prompted any immediate concern for flash flooding in Gowrie Creek or its tributaries. Even the rainfall intensities (less than 12 mm/h) observed at the gauges for the period between noon and 12:45 pm would not have indicated that a flash flood of the magnitude observed later on 10 January would occur. It was only once the rainfall had intensified, over the period between 12:45 pm and 2:15 pm, that Toowoomba Regional Council could have observed rainfall of sufficient intensity for the Council to be in any position to forecast the occurrence of a flash flood. The flood peaked between 2:00 pm and 2:15 pm in the Toowoomba CBD and at about 2:30 pm at the Cranley streamflow gauge on Gowrie Creek (Insurance Council of Australia Hydrology Panel, 2011c).

Ground based raingauges only observe the rainfall that has occurred at the point where the gauge is located. Thunderstorms and rainfalls exhibit spatial variability that is at a finer resolution than even a very dense raingauge network, such as the one operated by Toowoomba Regional Council, could detect. The thunderstorm on 10 January 2011 was moving at approximately 30 km/h, being typical of intense thunderstorms, which also complicates forecasting of rainfall rates using a network of ground based raingauges. Making consistently accurate forecasts of future rainfall using a ground based raingauge network alone for catchments of the size of East and West Creeks in Toowoomba is virtually impossible.

Toowoomba Regional Council would not have been in a position to forecast a flash flood in Toowoomba on the basis of the raingauge data that they had at the time until between 1:30 and 2:00 pm. The recorded water level at the Cranley streamflow gauge rose by almost a metre between 1:00 and 1:30 pm and peaked at about 2:30 pm. Toowoomba Regional Council could have had insufficient time to issue a warning based on data from its own raingauge recording network that could have been communicated prior to rapid rises in flow and water levels in Gowrie, East and West Creeks.

Although the rain gauge network was of limited use to Toowoomba Regional Council as a basis for real-time forecasting of flash flooding in Toowoomba, the network of rain gauges provides data to assist in calibration of hydrological models of the Gowrie Creek and other nearby catchments, which will be valuable in revision of floodplain management studies for Toowoomba and in the assessment and design of potential flood mitigation measures. If the Bureau of Meteorology were to take on a role in providing flash flood forecasts for Toowoomba, access to data from Toowoomba Regional Council's network in real-time would be useful as validation of rainfall data inferred from other sources, such as weather radar.

5.8 Assessment of Toowoomba Regional Council's Management of the January 2011 Flood Event in its Role as Owner of Cooby Dam

Under the Emergency Action Plan (Toowoomba Regional Council, 2010a), Toowoomba Regional Council are required to notify all residents within 5 km of the Cooby Dam wall once the water level in the dam reaches 479.04 m AHD, which equates to 0.50 m above the spillway crest or an outflow rate from the dam of approximately 100 m³/s. This level was reached at approximately 9:00 pm on Sunday 9 January 2011. Toowoomba Regional Council's log of events (Toowoomba Regional Council, 2011a) notes that by 10:10 pm on 9 January 2011, "Confirmation received that downstream residents within 5 km zone of Cooby Dam OK and notified."

Water levels in the Dam continued to rise and a minor peak in water level in the dam was observed at 479.32 m AHD (0.78 m above the spillway level) at about 2:00 am on 10 January 2011. The water level in Cooby Dam receded over the next several hours. The water level in Cooby Dam rose rapidly from about 1:00 pm on 10 January 2011 and peaked at a level of approximately

479.8 m AHD (about 1.3 metres above the spillway level) at about 4:30 pm on 10 January 2011. The flow rate over the spillway for this second peak would have been approximately 200 m^3/s. The second peak in water levels in Cooby Dam was contributed to by heavy rainfall from the intense thunderstorm cell that resulted in flash flooding in Toowoomba and the Upper Lockyer Valley on the afternoon and evening of 10 January 2011. Water levels in Cooby Dam receded from this second peak over the following period of several hours.

Further heavy rainfall over the catchment of Cooby Dam during the early hours of 11 January 2011 caused further inflows to the Dam, which resulted in water levels in the Dam rising to a third peak. Water levels in the Dam rose at a relatively constant rate from about 2:00 am on 11 January 2011 until the third and highest of the three peaks was observed at 480.09 m AHD at 7:43 am on 11 January 2011. There is evidence that Toowoomba Regional Council continued to monitor water levels in accordance with the Emergency Action Plan during this period (Toowoomba Regional Council, 2011a). The maximum water level was almost three metres below the crest of the main dam embankment and almost four metres below the crest of the wave wall. A flood more extreme than the event observed in January 2011 would therefore be required to compromise the safety of Cooby Dam.

Under the Emergency Action Plan (Toowoomba Regional Council, 2010a), Toowoomba Regional Council are required to seal the door of the dam intake tower, initiate closure of roads downstream of the dam and initiate evacuation of all residents within 5 km of the Cooby Dam wall once the water level in the dam reaches 480.04 m AHD, which equates to 1.50 m above the spillway crest. The water level in Cooby Dam reached 480.04 m AHD just after 7:00 am on 11 January 2011, peaked just 50 mm above this level at about 7:43 am and then subsided to be below 480.04 m AHD before 8:30 am (Toowoomba Regional Council, 2011a). The structural integrity of the Dam was not at immediate threat from the flood during the relatively short period when water levels were above the trigger level of 480.04 m AHD. Water levels and outflows from the Dam receded from this final peak over several days.

Toowoomba Regional Council may have broader responsibilities in emergency management of flash and non-flash flooding, including warning and forecasting for communities in the Toowoomba Regional Council area, separate from Toowoomba Regional Council's responsibilities as a dam owner.

Toowoomba Regional Council issued two media releases on 10 January 2011, the first advising of the prospect of flooding in Oakey and the second advising of the closure of public access to Cooby Dam as a result of overflows from Cooby Dam (Toowoomba Regional Council, 2011d) (Toowoomba Regional Council, 2011f). No specific times of day has been provided for the media releases or are mentioned on either media release. A further media release from Toowoomba Regional Council on 11 January 2011 notes that discharges were still occurring from the spillway of Cooby Dam but that water levels were falling at that time (implying a reduction in flows over the Cooby Dam spillway) and that the contribution of flows from the catchment of Cooby Dam were, “minor compared to other inflows due to the extreme rainfall event” (Toowoomba Regional Council, 2011e). Toowoomba Regional Council confirmed in a media release on 12 January 2011 that outflows from Cooby Dam were continuing to fall and that water leves in Oakey Creek at Oakey had also continued to fall (Toowoomba Regional Council, 2011b).

6 Possible Improvements to Flash Flood Warning and Response in Australia

6.1 Summary of Recent Review

Hapuarachchi et al. (2011) recently published a "Review of Advances in Flash Flood Forecasting." This review paper was funded under the Water Information Research and Development Alliance, which is a joint initiative CSIRO Water for a Healthy Country Flagship and the Bureau of Meteorology's Water Division.

Hapuarachchi et al. (2011) provides a relatively comprehensive summary of the "state of the art" in operational flash flood forecasting. Some of the key findings of Hapuarachchi et al. (2011) that are relevant to the development of an effective flash flood warning system for Australian conditions are:

- "Effective flash flood forecasting with useful lead times is one of the most challenging areas in hydrology, particularly due to the uncertainties associated with rainfall forecasts" (Hapuarachchi, Wang, & Pagano, 2011).
- Technology to facilitate flash flood warning has developed rapidly over the last few decades. Hapuarachchi et al. (2011) state that the major advances that have increased the possibilities of issuing effective warnings for flash flood events have included:
  - More accurate methods for quantitative estimation of rainfall across catchment areas, built on increasing accuracy and availability of radar and satellite based remote sensing technologies;
  - Improvements in merging rainfall data derived from different sources (rain gauges, radar, satellite and numerical weather prediction);
  - More reliable estimates of quantitative rainfall forecasts available from extrapolation of remotely sensed rainfall estimates and improved numerical weather prediction models;
  - Increasing availability of high resolution and accurate digital terrain models across large areas;
  - Increasing availability, at high spatial resolution, of other remotely sensed information that influences flooding, including land use, vegetation cover, impervious areas, soil types, soil moisture, evapotranspiration and snow cover.
  - Advances in flow forecasting models, driven by a move to more spatially distributed models;
  - Increasing computer processing power to facilitate the use of more sophisticated and spatial data-intensive flow forecasting models; and
  - Methods for more explicitly including forecast uncertainty in estimates.

- Hapuarachchi et al. (2011) reviewed three different methods were reviewed for deciding on where flash flooding would occur:
  - Comparing estimated and forecast rainfalls with critical thresholds for rainfall;
  - Forecasting flows at locations using hydrological models and comparing those flow forecasts with critical thresholds; and
  - Use of a qualitative risk assessment approach to identify conditions that represent a high risk of flash flooding.
- Hapuarachchi et al. (2011) identified that a major challenge still exists in including uncertainties in the flash flood forecasts, dominated by uncertainty in quantitative rainfall forecasts, into the decision making process of whether to issue a warning for a particular location or not. If uncertainty is not adequately considered, there is a risk of either too many misses of flood events (not predicting a flash flood event with adequate lead time prior to that event actually occurring) or false alarms (predicting a flash flood event that then does not eventuate).
- Urban areas are highly vulnerable to flash floods but Hapuarachchi et al. (2011) concluded that no hydraulic models currently exist that have sufficient computational speed and that are sufficiently accurate to be used in real time flash flood forecasting for urban catchments.

6.2 Possible Improvements to a Flash Flood Warning System for Australia

Although Hapuarachchi, Wang and Pagano are Australian authors and their research was funded by Australian organisations, their paper was published in an international journal and may have had a more general and less urgent focus than the specific and current needs of Australians for an effective flash flood warning system. This section addresses the current situation in Australia in regard to systems to support flash flood warning and systems that could be implemented within the next few years, assuming that adequate resources were put in place to support the implementation.

As set out in section 3 of this report, the Bureau of Meteorology and other agencies already operate an extensive observing network for rainfall and streamflow that is amenable to producing forecasts for flash floods, even though the network may have been established for other purposes. The existing observing network consists of a widely distributed network of rainfall and streamflow gauges that report rainfall and water levels to the Bureau of Meteorology Flood Warning Centres in real-time. Local, State and Territory government agencies and other organisations also collect their own rainfall and streamflow gauging data, some of which is telemetered to provide real time information.

The existing modelling platform operated by the Bureau of Meteorology for most catchments, including the Lockyer Creek catchment and the Upper Condamine catchment, is based upon the URBS rainfall runoff routing model (Malone, 1999). The Bureau of Meteorology obtains the input data for its URBS models from the telemetered raingauge and streamflow gauge network. Model runs are initiated manually for each individual catchment where flood forecasts are required, with the flood forecaster having the opportunity to make manual adjustments to the model parameters and manual quality checking of the input data for each run so that there is an acceptable level of consistency between model outputs and observed flows. Observed flow data and model outputs are then interpreted by the flood forecasters and they manually prepare customised flood warnings for each basin.

Quantitative estimates of rainfall derived from radar or other remote sensing are not normally used by the Bureau of Meteorology for operational flood forecasting, although information from radar may be manually inserted to the flood models on an ad-hoc basis by flood forecasters. Similarly, forecasts of future catchment rainfall are manually input to the models on an ad-hoc basis by flood forecasters, typically following consultation with meteorologists on duty at the time.

The existing forecasting systems used by the Bureau of Meteorology for non-flash flooding have been demonstrated over many years and many flood events as producing, in most cases, flood forecasts of non-flash flooding that are understandable, accurate and timely. The analysis of the flood warnings produced for the lower part of the Lockyer Valley, from Glenore Grove and downstream, for the January 2011 event demonstrated that the existing system produced useful forecasts for a flooding situation that was a non-flash flood.

The system currently used by the Bureau of Meteorology for forecasting of non-flash floods is not suitable in its current form for flash flood forecasting. The author agrees with the Bureau of Meteorology’s statement that to provide a site specific flash flood warning service, “would require a different systems and service model scaled to deal with flash flooding at state and national scale” (Australian Government Bureau of Meteorology, 2011f, p. 46). The existing modelling approach used by the Bureau of Meteorology is currently unsuitable for flash flood warning because:

- The current system requires too much manual intervention by flood forecasters to be workable for providing customised flash forecasts for a very large number of small catchment areas;
- The system lacks automated input of quantitative rainfall estimates from radar that have been ground calibrated using the reporting raingauge network;
- Manual intervention is required to insert quantitative rainfall forecasts for each catchment; and
- Forecasts produced by the modelling system need to be manually interpreted and converted into a warning.

An effective flash flood warning system would need to overcome the above limitations. Specifically a flash flood warning system providing useful lead times would require:

- A greater degree of automation, with model runs initiated automatically at a regular frequency without any forecaster intervention;

- Consideration of the possible implementation of a different hydrological model, such as a spatially distributed model, more amenable to automated production of accurate forecasts for small catchments without forecaster intervention;
- Spatially and temporally distributed quantitative rainfall estimates, which are most likely to be obtained from a combination of weather radar and reporting raingauges;
- Insertion of quantitative rainfall forecasts with limited or no manual intervention; and
- Automated production of pro-forma forecasts and warnings for specific locations, with appropriate systems put in place for the forecaster to review and approve the automated warning prior to its issue.

Fortunately, the review by Hapuarachchi et al. (2011) (as discussed in Section 6.1) suggests that technology has evolved over recent years such that a system with these characteristics could be put in place.

The coverage of telemetered rainfall and streamflow gauges and weather radar across Australia is sufficient that an effective flash flood warning service could be provided for much of the population susceptible to flash flooding, provided investment is made in the development, implementation and operation of such a system. Any system implemented would need to be sufficiently robust that it could continue to function, in the event that some of the critical data inputs became unavailable. Alternative procedures would need to be developed in particular to cover loss of data for a period of time from one or more of the weather radar in the network and/or from a large number of the reporting raingauges.

Quantitative rainfall forecasts are required as a critical input to flash flood warning to provide a reasonable lead time for forecasting of flash flooding that would allow for a sufficiently timely warning for people to safely evacuate. Whilst there are several algorithms that have been developed for this purpose, one algorithm that has been demonstrated to successfully provide quantitative rainfall forecasts was jointly developed in research by the Bureau of Meteorology (Bowler, Pierce, & Seed, 2006). Hapaurachchi et al. (2011) lists a number of alternative algorithms that could also be considered.

A flash flood forecasting and warning system will require spatial information on catchment topography and drainage at an appropriate spatial scale. The Bureau of Meteorology produced its first release of the Australian Hydrological Geospatial Fabric in October 2010 (Australian Government Bureau of Meteorology, 2011). This would provide the underpinning arrangement of catchments, terrain data and stream network to provide the basis for a flash flood forecasting system.

Whilst incorporation of uncertainty into the forecasting process is important (as identified by Hapaurachchi et al. (2011), it should not be over-emphasised in a flash flooding situation that the cost to the community of a missed flash flood forecast, in terms of loss of life, injuries and high value property, may outweigh the cost to the community of responding to one or more false alarms of flash flooding.

It should be noted that a significant investment would be required to develop, implement, operate and maintain an effective and specific flash flood warning system for Australia as outlined above. As demonstrated by the events of 10 January 2011, the potential to save lives and property from improved flash flood warning capability may justify that investment. Consideration should therefore be given to the development of such a system.

6.3 Institutional Capacity to Implement Flash Flood Warning

The previous section has outlined a high level conceptual design of an effective flash flood warning system for Australia. A flash flood warning system of this nature would require real-time access to large quantities of data and sophisticated and robust computer networks to implement and operate the system. Most importantly, access to a sufficiently large resource pool of personnel with meteorological and hydrological expertise would be required to operate and maintain the system on a 24 hours per day, 7 days per week basis. These people would require on-going professional development and training in the meteorology and hydrology associated with flash flood forecasting. It is unlikely for most places in Australia that any organisation, other than the Bureau of Meteorology, could invest the resources required to develop and maintain the institutional capacity required to operate an effective flash flood warning system for their jurisdiction.

7 Options Other than Warning for Mitigation of Flood Risk in Toowoomba and the Lockyer Valley Regions

There are likely to be a large number of options, other than warning, available for the mitigation of flooding risk in Toowoomba and the Lockyer Valley Regional Council areas.

The communities affected by flooding in January 2011 have specifically raised a number of flood risk mitigation options since the event. This section addresses some of those specific issues raised by these communities. It is not a comprehensive assessment of flood risk mitigation options for Toowoomba and the Lockyer Valley Regional Council areas.

Options for mitigation of flood risk should be comprehensively assessed, considering the costs and benefits associated with each option, in studies performed using detailed calibrated hydrological and hydraulic models for each specific floodplain area**.** In many of the communities affected by the January 2011 floods there are no calibrated hydraulic models with sufficient detail and these would need to be established as the first stage in assessing flood risk mitigation measures.

7.1 Modification of Cooby Dam to Provide for Increased Flood Mitigation Capacity

Some residents downstream of Cooby Dam have argued that Cooby Dam should be raised or modified in some other way to provide increased flood mitigation capacity for downstream communities, including Oakey. During the January 2011 event, Cooby Dam provided flood mitigation for downstream communities, although it is difficult to quantify at this stage the magnitude of the flood mitigation benefit delivered by the Dam for this particular flood event at particular downstream locations. Although modification of Cooby Dam is one option that could be considered to provide flood mitigation for Oakey and other communities downstream of the dam, there are likely to be many other options for management and mitigation of flooding that could also be considered. A detailed study considering a wide variety of options for flood mitigation, including modifications to Cooby Dam, should be conducted that considers the costs and flood mitigation benefits delivered by each option. This should be included in a wider review of flood plain management and planning for Oakey and other potentially flood affected communities in the catchments of Oakey and Gowrie Creeks.

The media and some residents downstream of Cooby Dam identified what they consider to be maintenance issues with regard to the low level scour outlet from the dam (Toowoomba Regional Council, 2011c). The 600 mm diameter cast iron pipe is for the purpose of inspecting the dam and outlet works. It is not designed to be operated during a flood event and would have made no difference to flows passing into Oakey Creek downstream of the dam even if it had been operated, since any flows from this conduit would have joined with the much larger flows via the spillway and continued down Oakey Creek. Maintenance of the outlet conduit is not material with regard to operation of the dam during the January 2011 flood event.

7.2 Modifications to the Railway Line between Ipswich and Toowoomba

The railway between Ipswich and Toowoomba has been in existence for more than 140 years (Cole, 1944) and would pre-date virtually every other house or structure located on the floodplain in Grantham and other towns in the Lockyer Valley. The railway embankment therefore represents a latent feature of the floodplain that should be taken into account as a part of prudent floodplain planning and management.

It would be unusual to expect an owner of existing infrastructure, in this case QR National, to provide additional culverts or bridges underneath the railway to allow for movement of flood waters underneath the railway line, unless they were undertaking works to increase the height of the railway embankment from its existing level. Furthermore, if additional culverts or bridges had been installed in the railway embankment then this may have the detrimental effect of increasing the flood exposure for properties on the northern side of the railway line that are, at least partially, protected from Lockyer Creek flooding by the existing configuration of the railway line. If additional culverts or bridges through the railway line were to be considered for flood mitigation purposes, they should be considered along with consideration of a number of other floodplain management options for Grantham and the surrounding area, following the establishment of a detailed calibrated hydraulic model, which is required to make a robust assessment of all flood mitigation options.

QR National has undertaken repair works to an 1100 metre section of the railway line in Grantham since the flood event (Insurance Council of Austalia Hydrology Panel, 2011b, p. 59), which has involved reinstatement of ballast underneath railway sleepers and tracks. Some Grantham residents have expressed concern that these works have increased the height of the railway line and embankment, which would have the effect of increasing flood risk on the southern side of the railway line from the conditions that existed prior to the January 2011 flood event. On the basis of information currently at hand, it is not possible to determine whether the level of the railway embankment has changed following the restoration works undertaken since the flood. An "as built" survey of the railway embankment would be required to determine this, which could then be compared against survey data available from prior to the flood event, such as LIDAR data collected for the area in 2009. A survey of the railway line since its restoration should be undertaken and a comparison performed to embankment levels determined from the latest reliable available survey undertaken prior to the January 2011 flood event.

7.3 Removal of existing vegetation from stream beds, banks and floodplains

Hydrological and hydraulic modelling is required to assess the specific impact of vegetation along a particular part of a stream or floodplain. This section provides a general discussion of the likely impacts of vegetation on flooding.

During minor and moderate flooding, dense in-stream and riparian vegetation will reduce flow velocities in the vicinity of that vegetation and it will increase flood levels upstream of where the vegetation is located from the levels that would have been observed if the vegetation were not present. Grasses, even where the grass is relatively long, will normally bend over with the velocity of flood waters and their relative hydraulic impact on flood levels and velocities reduces for moderate and major floods.

During large and extreme flooding, it is common for vegetation to be bent over, broken or even completely removed by the velocity of flood water. It is also common during large and extreme flood events for sediment, including sand, cobbles and boulders, to be mobilised by the velocity of flood water. Vegetation detached from in-stream, riparian and floodplain zones will travel downstream with the flood water, becoming part of the debris load for the flood event. The January 2011 flash flood event was sufficiently large that much of the vegetation removed from in-channel and riparian zones would have been stripped during the early stages of the flood event, well before the occurrence of the peak flow.

Large and extreme floods are also often associated with landslides in the affected catchments, which occur on hill slopes outside of areas that are normally considered as waterways. Several landslides occurred during the January 2011 flood and there would have been considerable volumes of vegetation transported from those landslide areas that would have reached streams and been transported to form a sizeable fraction of the overall debris load for the event.

Debris transported by the January 2011 flood event become caught at some culvert and bridge crossings of waterways. As stated earlier, some of this debris was vegetation generated from within waterways but it is also likely that much of the debris was transported from landslide areas outside of waterways or vegetation and structures (including houses and cars) removed from floodplain areas that are well outside the normal waterway and riparian zone. In general, it is unlikely that for most parts of the Lockyer Valley catchment that removal of trees and shrubs from waterways and riparian zones would have had any appreciable impact on flooding during the January 2011 event. There may be specific locations where removal of in-stream or riparian vegetation prior to the flood event may have had an impact but detailed hydrological modelling of those particular locations would be required to confirm this.

Vegetation in the bed and along the banks of streams performs a number of important functions that are beneficial to the ecological health of the stream. Vegetation provides: shading, regulating the temperature of the water; habitat; inputs of organic material; inputs of large woody debris, which provide important fish habitat; filtering of runoff, hence reducing loads of nutrients and pathogens and they stabilise the stream bed and banks against erosion (Rutherford, Jerrie, & Marsh, 2000). The impact on flood levels and velocities of vegetation should never be the only consideration when potential removal of vegetation is under discussion (Rutherford, Jerrie, & Marsh, 2000).

Designers of culverts and bridges crossing waterways should consider that in large flood events there will be significant volumes of vegetation and other debris transported by the event. As part of the current revision of *Australian Rainfall and Runoff*, a report has been produced on *Blockage of Hydraulic Structures* (Weeks, Barthelmess, Rigby, Witheridge, & Adamson, 2009) that should be consulted by crossing designers and those undertaking floodplain modelling.

7.4 Maintenance of drains in Forest Hill

The majority of streets and roadways in Forest Hill have open table drains on each side. These v-shaped table drains are normally vegetated with grass. The table drains are designed to cope with runoff generated during local storm events in Forest Hill. It is understood that some residents had expressed concern, prior to and after the January 2011 flood, that grass in the table drains had grown to excessive lengths thereby impairing the hydraulic performance of the drains. Excessive grass growth in the drains is also aesthetically unpleasing. Grass was observed in some places within the table drains in Forest Hill to be about 0.5 metres high, during a field inspection on 5 April 2011. There was evidence during the field inspection that Lockyer Valley Regional Council had cleaned some of the drains post the January 2011 flood event.

The January 2011 flood event was a major creek flooding event and it is most likely that the water that flooded Forest Hill came from breakouts of flows from Sandy and Laidley Creeks. Aerial photography from 18 January 2011 shows that flood water spread out over a width of more than 2 km across the floodplain at Forest Hill. Reduction in the height of vegetation and cleaning of table drains in Forest Hill would have made negligible difference to the overall hydraulic roughness of the entire floodplain and therefore had negligible influence on flood depths in Forest Hill during the January 2011 flood.

Maintenance of drainage infrastructure may have a larger influence on more frequent local runoff events in Forest Hill. This report concentrates on the January 2011 flood event and broader consideration of the impact of drain maintenance on local runoff flood events in Forest Hill is therefore beyond the scope of this report.

8 Conclusions and Recommendations

8.1 Arrangements for Flash Flood Warning in Australia

8.1.1 Conclusions

Australian Government Bureau of Meteorology (2011b) acknowledges that, "In some areas, the Bureau is working with local councils to install systems to provide improved warnings for flash flood situations," but they stop short of transferring the responsibility for flash flood forecasting and warning to local government or other agencies. Australian Government Bureau of Meteorology (2011e) states in their submission to the Commission that, "The Bureau does not routinely issue location specific flash flood warnings because it does not have the knowledge of local conditions at individual locations." The Bureau of Meteorology states that it has arrangements in place whereby specific guidance about flash flooding is provided by local agencies.

As a result of the current arrangements, the Bureau of Meteorology has organised itself internally in each region with a Flood Warning Centre that provides warnings of non-flash floods and a severe weather meteorology section that provides generalised warnings of situations that may cause flash flooding, but not specific flash flood forecasts. These two forecasting teams operate independently to issue warnings and although they are co-located in the Brisbane regional office there is no documented process for communication between the Flood Warning Centre and severe weather meteorologists during an event.

Providing clear, timely and accurate forecasts of flash flooding for specific locations is difficult because the intense thunderstorms that typically cause flash floods develop and move very quickly and there are many thousands of locations across Australia fed by small catchments, with times of concentration less than 6 hours, that could be afflicted by flash flooding if the right meteorological conditions were to occur.

The Bureau of Meteorology's Flood Warning Centres have developed their data collection, modelling and warning preparation systems to forecast and warn of non-flash floods. In a flash flooding situation the data collection and forecasting systems are set up in such a way that rapid rates of water level rise and flash flooding are likely to have already commenced, and possibly even peaked, at locations in upper catchments before the Flood Warning Centre have adequate evidence to forecast the flash flood.

It would be expected that the severe weather meteorologists would be monitoring outputs from numerical weather prediction, reporting raingauges, weather radar and other meteorological data during severe weather events that would alert them to the existence, development and movement of storms with intense rainfall. The severe weather meteorologists currently lack the forecasting systems and hydrological expertise to provide flash flood forecasts for specific locations. What they can do, even under existing arrangements, is initiate communication with the Flood Warning

Centre about the location and movement of thunderstorms with high rainfall intensities. The severe weather meteorologists could also make contact with local authorities that under current arrangements have the responsibility for alerting about flash floods.

Toowoomba Regional Council only had access to its own reporting raingauge network for the urban area of Toowoomba. Lockyer Valley Regional Council have only two rainfall gauges and one streamflow gauge that translate objective data in real time. Both Toowoomba Regional Council and Lockyer Valley Regional Council are typical of Australian local governments in that they do not have the expertise in flash flood warning or severe weather meteorology nor sufficient access to quantitative radar data from the Bureau of Meteorology to provide advice or warnings, even if they had the regulatory authority to do so, with sufficiently useful lead time.

Technological developments over recent years appear to have made it possible to provide a more specific flash flood warning service for much of the populated areas of Australia that are exposed to a significant threat of flash flooding. A significant investment would be required to develop, implement, operate and maintain an effective and specific flash flood warning system for Australia of this type. As demonstrated by the events of 10 January 2011, the potential to save lives and property from improved flash flood warning capability may justify that investment. It is unlikely for most places in Australia that any organisation, other than the Bureau of Meteorology, could invest the resources required to develop and maintain the institutional capacity required to operate an effective flash flood warning system for their jurisdiction.

8.1.2 Recommendations

The Bureau of Meteorology should rectify the imprecise definitions in its own publicly available materials of flash flooding by providing a clear public statement on its website of what it considers the difference between a flash and a non-flash flood.

Communication protocols between severe weather meteorologists and the Flood Warning Centre during events should be reviewed so that the two teams can complement one another in delivery of clear, accurate and timely warnings.

Communication protocols between severe weather forecasts at the Bureau of Meteorology and local agencies, which have the current responsibility for flash flood response, should also be reviewed.

Investment in forecasting and warning systems to provide clear, timely, accurate and location specific forecasts of flash floods, based upon recent technological advances, should be considered.

Responsibilities for flash flood warning and provision of forecasts to emergency agencies in Australia could reviewed in the light of recent technological developments that may make cost effective delivery of a specific flash flood warning system possible for Australia. An investment of resources is required to develop and maintain the institutional capacity required to operate an effective flash flood warning system.

Local government agencies in general, with the exception of large local government agencies, do not currently and are unlikely to have in the near future the access to data, flood warning and meteorological expertise and institutional capacity to issue effective warnings of flash floods. Bureau of Meteorology are more likely to be able to develop this capacity on a national basis than local government authorities and transferring future responsibility for flash flood warning to the Bureau of Meteorology should be considered.

8.2 Capacity of local government agencies to issue advice to emergency authorities

8.2.1 Conclusions

Making consistently accurate and timely forecasts of future rainfall using a ground based raingauge network alone for catchments of the size of East and West Creeks in Toowoomba is virtually impossible.

It was unlikely that Toowoomba Regional Council would have been in a position to forecast a flash flood in Toowoomba on the basis of the raingauge data that it had at the time until sometime between 1:30 and 2:00 pm. The recorded water level at the Cranley streamflow gauge rose by almost a metre between 1:00 and 1:30 pm and peaked at about 2:30 pm. Toowoomba Regional Council may have had insufficient time to issue a warning based on data from its own raingauge recording network that could have been communicated prior to rapid rises in flow and water levels in Gowrie, East and West Creeks.

Although it was of limited use for forecasting the 10 January 2011 flash flood, the network of rain gauges in Toowoomba provides data to assist in calibration of hydrological models of the Gowrie Creek and other nearby catchments, which will be valuable in revision of floodplain management studies for Toowoomba and in the assessment and design of potential flood mitigation measures.

The Bureau of Meteorology did not have access to Toowoomba Regional Council's network of real-time reporting rainfall gauges prior to or on 10 January 2011. It is unlikely that data from this gauge network on its own would have improved the timeliness of flood warnings for Toowoomba. If the Bureau had access to this data in real time it may have improved the capacity for the Bureau of Meteorology to make accurate and timely flash and non-flash flood forecasts for other parts of the Condamine-Balonne basin and to validate rainfall intensity estimates made using weather radar in the Toowoomba area.

The Bureau of Meteorology has had a program running since the 2007/08 financial year and continuing into the 2011/12 financial year for modernisation and extension of hydrologic monitoring systems, which includes activities such as providing the Bureau of Meteorology with real-time access to data collected by other organisations, such as local government authorities (Australian Government Bureau of Meteorology, 2011c).

The actions of Toowoomba Regional Council in operating Cooby Dam during the January 2011 event were in broadly in accordance with their Emergency Action Plan, albeit that there was a short period of an hour and a half when water levels in the dam peaked 5 cm above the trigger level in the Emergency Action Plan for initiation of road closures and evacuation of residents within 5 km of the dam wall. The structural integrity of the dam was never at immediate threat from the flood during this relatively short period when water levels were above the trigger level.

Lockyer Valley Regional Council only operates a network of two raingauges and one water level gauge in the catchment of Sandy Creek. Monitoring of these gauges, on their own, could not have provided any indication of the higher rainfall intensities that were occurring in the upper Lockyer Creek catchment to the east. Lockyer Valley Regional Council would not have been in a position to accurately forecast a flash flood in the upper Lockyer Valley prior to the peak of the flood passing through Grantham.

8.2.2 Recommendations

The Bureau of Meteorology should be provided with access to telemetry from Toowoomba Regional Council rainfall gauges in real-time to support its forecasting and warning services, which could be funded under the current funding program for modernisation and extension of hydrologic monitoring systems.

Over time, real-time access should be provided to the Bureau of Meteorology for rainfall and streamflow data from other local government agencies that have similar networks to Toowoomba, which could be funded under the current funding program for modernisation and extension of hydrologic monitoring systems.

Bureau of Meteorology appears more likely to be able to develop this capacity on a national basis than local government authorities such that it could be given future responsibility for flash flood warning in Australia.

8.3 Effectiveness of warnings issued by the Bureau of Meteorology for Toowoomba and the Lockyer Valley on 10 January 2011

8.3.1 Conclusions

Use of the name “southeast coast” forecast district could be confusing for use in severe weather warnings, particularly for visitors and residents in the western parts of the district, such as the Lockyer Valley.

Severe weather warnings issued during the entire period between 5 and 12 January 2011 and typical severe weather warnings issued provide virtually identical advice, which did not reasonably characterise the specific level of threat posed by flash flooding to specific communities, when it may be possible to provide more urgent and specific advice in some situations. Each of the severe weather warnings provide similar wording about the nature of the meteorological threat, using words such as, “Heavy rain areas and thunderstorms are expected to increase / continue,” and “Heavy falls may lead to localised flash flooding and/or worsen existing river flooding.” The warnings also contain advice from the State Emergency Service that, “people in the affected area should: avoid driving, walking or riding through flood waters; take care on the roads, especially in heavy downpours; avoid swimming in swollen rivers and creeks.” At no stage did any of these severe weather warnings advise people in affected areas to consider evacuation in response to the threat of flash flooding.

On the basis of the evidence available to severe weather meteorologists by sometime between 12 noon and 12:15 pm on Monday 10 January, they should have been alerting the Flood Warning Centre and local authorities with responsibilities under current arrangements for flash flooding of the meteorological situation. Weather radar collected by 11:48 am and that would have been available to forecasters before 12 noon on 10 January 2011 showed a thunderstorm with rainfall intensities of more than 50 mm/h across an area approximately 40 km in diameter, moving at a relatively consistent speed of approximately 30 km/h toward Toowoomba and the Lockyer Valley. Soils in the catchments in the area were saturated and losses would be expected to be low, which indicated that flash floods produced from this rainfall would have a lower AEP than 1 in 10. An experienced meteorologist could reasonably have been able by 12:15 pm to predict that rainfall intensities would increase as the rainfall approached the Toowoomba Range due to orographic enhancement and Doppler radar data demonstrating the likely presence of strong updrafts on the south-eastern side of the storm from radar scans available at the time.

Had the Toowoomba Regional Council been provided with advice by the Bureau of Meteorology severe weather forecasters at 12:15 pm, this would have provided at least 30 minutes of lead time before the on-set of heavy rainfall in the Gowrie Creek catchment and associated rapid rises in streamflow in East and West Creeks and approximately 1 hour and 45 minutes of lead time before flows are expected to have peaked in the Toowoomba Central Business District. The Bureau of Meteorology contacted the State Disaster Coordination Centre (SDCC) at 1:00 pm on 10 January to inform them of the high rainfall intensities expected for Toowoomba. Although this message was issued about 45 minutes later than the earliest such time that a message of this type could have been issued for Toowoomba, it was at least issued at around the time that increases in stream levels would have started to have been observed in East and West Creeks.

Intense rainfall would have commenced at about 12 noon in the northern most part of the Lockyer Creek catchment and was widely spread through the upper Lockyer Creek catchment by 12:42 pm. Because of the saturated condition of the catchment and the steep terrain present in the upper tributaries of Lockyer Creek, it is most likely that runoff and rapid increases in overland flow and flows in watercourses would have commenced in these tributaries within minutes after the commencement of intense rainfall.

There is evidence that the time of the peak at Grantham was at approximately the same time as when the first flash flood warning was issued (around 5:00 pm). All of the flash flood warnings for Lockyer Creek were therefore not sufficiently timely to be of any practical use to people that were in Helidon, Grantham or the other communities upstream.

It would reasonably be expected that the severe weather meteorologists should have been informing the Flood Warning Centre of the high rainfall intensities forecast and observed for the upper Lockyer Creek catchment over the period between 12:15 pm and 2:30 pm, which should have alerted the Flood Warning Centre to the prospect of rapid rises in water level.

An automated procedure flagged the water level returns from the Helidon streamflow gauge on the rapid rising limb of the hydrograph between 2:30 and 2:53 pm on 10 January 2011 as erroneous, and masked the evidence of the actual streamflow rise occurring from personnel in the Bureau of Meteorology Flood Warning Centre for about 90 minutes. The absence of a communication protocol between the Severe Weather Meteorologists and the Flood Warning Centre during the afternoon of 10 January regarding the intense rainfall prevented severe weather meteorologists from being able to make appropriate observations and therefore issue appropriate warnings.

The Bureau of Meteorology using its current systems and procedures should have been in a position to issue a flash flood warning for Grantham at 2:45 pm, on the basis of the rapid rises in flow observed at the Helidon gauge, in addition to the other evidence of rainfall totals from weather radar and raingauges to that time. Although this could have provided little lead time prior to the commencement of rapid streamflow rises in Grantham it could have provided 2 hours of lead time to the estimated peak level at Grantham.

If a specific flash Flood Warning Centre had been established using recent technological developments, it is likely that specific flash flood warning could have been provided for individual communities in the upper Lockyer Valley by 12:15 pm. A warning issued using these advanced technologies would have provided more than two hours of lead time for these two communities.

The Bureau of Meteorology did not issue a specific flash flood warning for Lockyer Creek until 5:00 pm. If these warnings were released in a sufficiently timely manner, provided that the time to disseminate the warning was sufficiently short, it is possible that at least some people at threat in

Gatton could have had sufficient time to evacuate themselves to safety. This is notwithstanding that a specific flash flood warning issued for Gatton at 2:45 pm would have allowed more than 2 hours prior to the commencement of water level rises at Gatton and almost 5 hours prior to the peak at Gatton, allowing more time for those people affected to evacuate themselves and possibly some of their possessions.

Warnings issued for Glenore Grove and communities downstream were understandable, reasonably timely and accurate. Time from commencement of intense rainfall to rise was more than 6 hours at Glenore Grove, which suggests that the Bureau of Meteorology was equipped to forecast for non-flash floods in the Lockyer Valley catchment.

Peak water levels during this event for Lockyer Creek downstream of about Glenore Grove occurred on 11 and 12 January and were influenced by flows down the Brisbane River, including the influence of releases from Wivenhoe Dam and inflows from Lockyer Creek and other tributaries of the Brisbane River that enter downstream of Wivenhoe. Bureau of Meteorology forecasts were reasonably understandable, timely and accurate for this lower part of Lockyer Creek.

8.3.2 Recommendations

The name of the “southeast coast” forecast district should be reconsidered and/or the district needs to be split into smaller areas for the purpose of issuing severe weather and flash flood warnings, such as local government areas.

When severe flash flooding is forecast, the warnings issued should include advice for those in properties that could be affected by an unusually large flood to move themselves and potentially also their high value, easily moved possessions to higher ground or a higher level in their own or another structure.

The Bureau of Meteorology should review the algorithm that is used to filter potentially erroneous water level recordings and update the computer software to reduce the likelihood in future of telemetered data that shows rapid rises in water level that are real as being flagged as erroneous.

The Bureau of Meteorology should develop protocols to improve communication between severe weather meteorologists and the Flood Warning Centre during thunderstorms and other severe weather events.

8.4 Options for Mitigation of Flash Flood Risk Other than Improvements to Warnings

8.4.1 Conclusions

There are likely to be a large number of options, other than warning, available for the mitigation of flooding risk in Toowoomba and the Lockyer Valley Regional Council areas. The communities affected by flooding in January 2011 have specifically identified a number of flood risk mitigation options since the event. Some of those specific issues raised by these communities were discussed in this report but it is not a comprehensive assessment of flood risk mitigation options for Toowoomba and the Lockyer Valley Regional Council areas.

The Cooby Dam low level scour outlet pipe is not designed to be operated during a flood event and would have made no difference to flows passing into Oakey Creek downstream of the dam even if it had been operated. Maintenance of the outlet conduit is not a material issue with regard to operation of the dam during the January 2011 flood event.

The railway embankment between Ipswich and Helidon has been in operation for more than 140 years and pre-dates virtually every other structure on the floodplain at Grantham. It would be unusual to expect an owner of existing infrastructure, in this case QR National, to provide additional culverts or bridges underneath the railway to allow for movement of flood waters underneath the railway line at Grantham, unless they were undertaking works to increase the height of the railway embankment from its existing level.

The January 2011 flash flood event was sufficiently large that much of the vegetation removed from in-channel and riparian zones would have been stripped during the early stages of the flood event, well before the occurrence of the peak flow. In general, it is unlikely that for most parts of the Lockyer Valley catchment that removal of trees and shrubs from waterways and riparian zones would have had any appreciable impact on flooding during the January 2011 event. There may be specific locations where removal of in-stream or riparian vegetation prior to the flood event may have had an impact but detailed hydrological modelling of those particular locations would be required to confirm this.

Reduction in the height of vegetation and cleaning of table drains in Forest Hill would have made negligible difference to the overall hydraulic roughness of the entire floodplain and therefore had negligible influence on flood depths in Forest Hill during the January 2011 flood. Maintenance of drainage infrastructure may have a larger influence on more frequent local runoff events in Forest Hill.

8.4.2 Recommendations

If options for flood risk mitigation are to be assessed, this should be done by considering the costs and benefits associated with several possible flood mitigation options, in studies performed using detailed calibrated hydrological and hydraulic models for each specific floodplain area.

The railway line between Ipswich and Toowoomba represents a latent feature of the Lockyer Valley floodplain that should be taken into account as a part of prudent floodplain planning and management, particularly for in Grantham and Forest Hill where it is likely to have a significant effect on flows during large and extreme floods.

An "as-built" survey of the railway line since the repair works should be undertaken and a comparison performed to embankment levels determined from the latest reliable available survey undertaken prior to the January 2011 flood event.

Designers of culverts and bridges crossing waterways should consider that in large flood events there will be significant volumes of vegetation and other debris transported by the event. As part of the current revision of *Australian Rainfall and Runoff*, a report has been produced on *Blockage of Hydraulic Structures* (Weeks, Barthelmess, Rigby, Witheridge, & Adamson, 2009) that should be consulted by crossing designers and those undertaking floodplain management and modelling.

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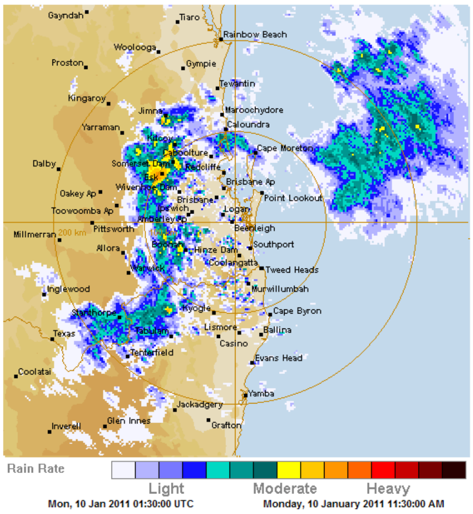
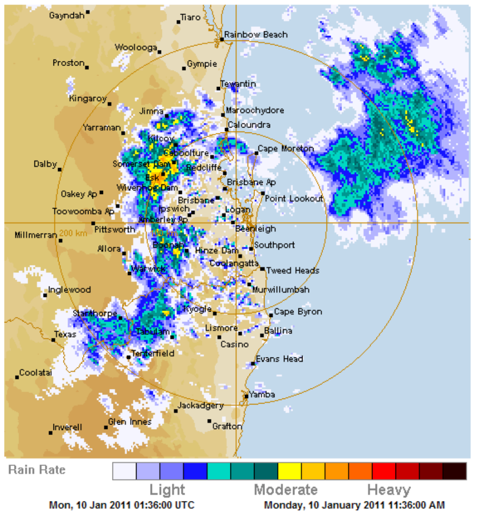
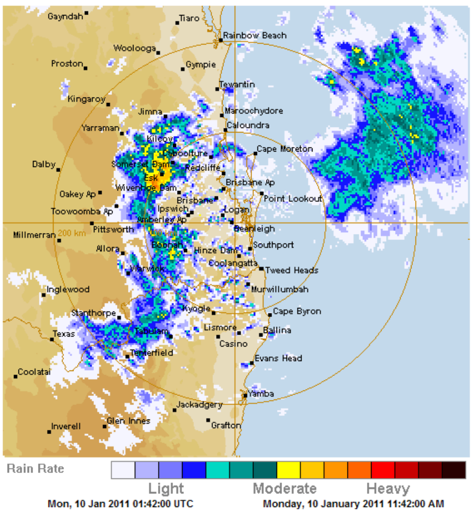
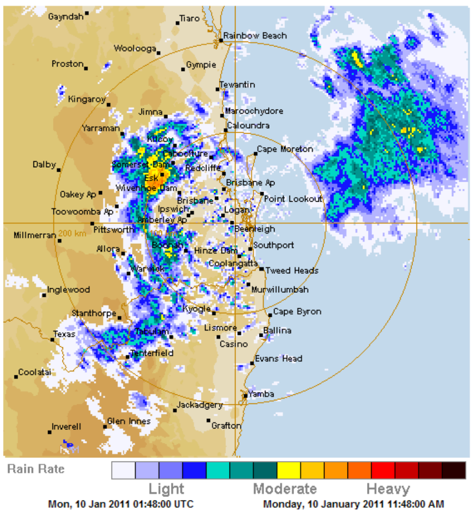
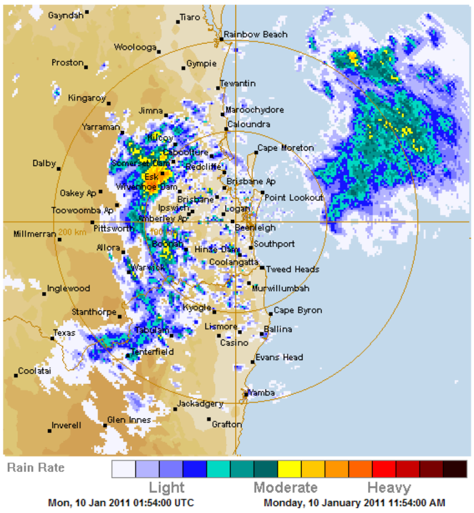
Appendix A Images from Mount Stapylton Bureau of Meteorology Weather Watch Radar for 11:30 am to 2:54 pm on 10 January 2011







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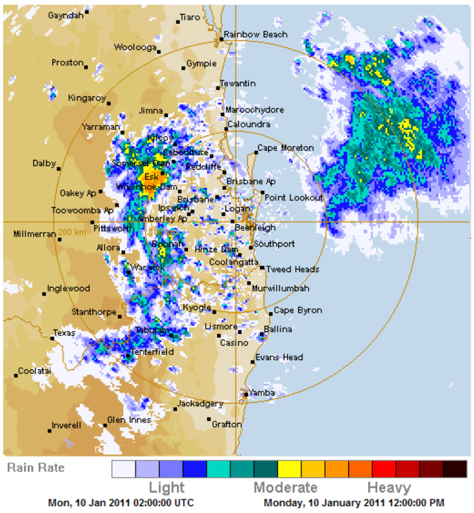
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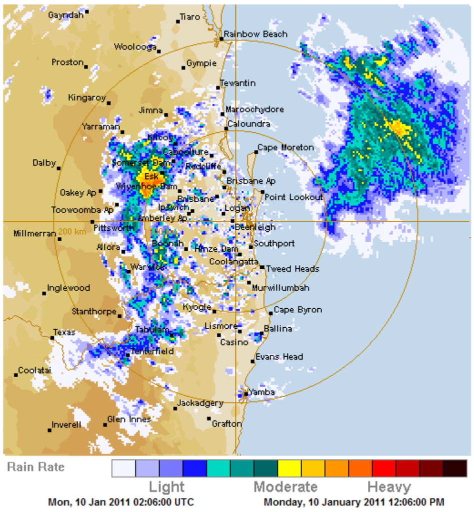
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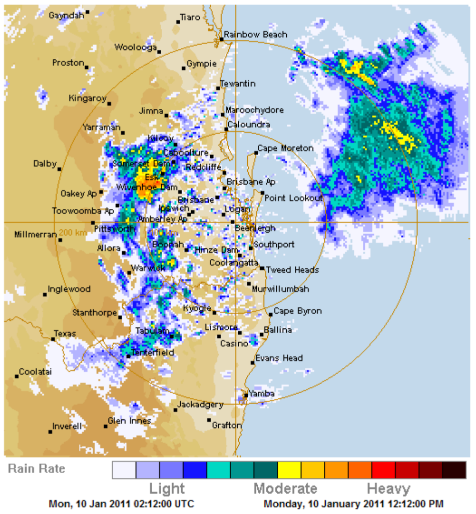
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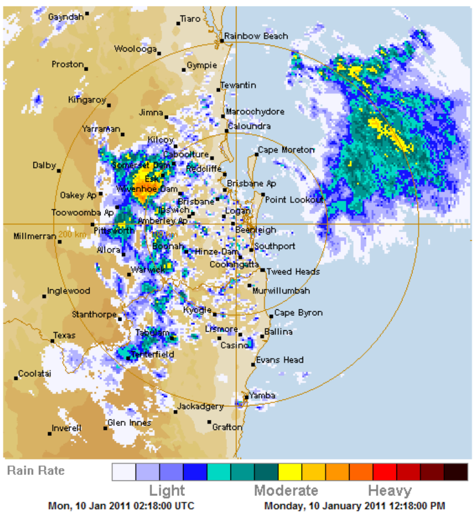
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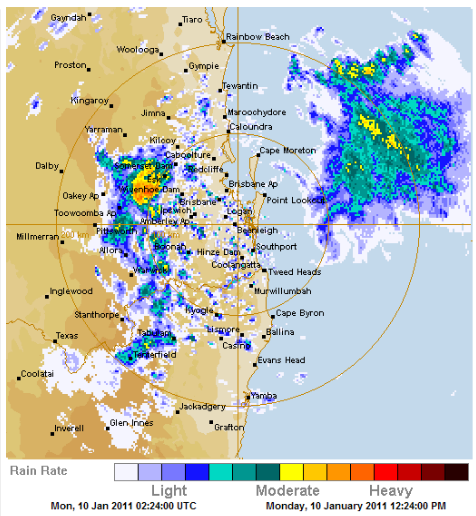
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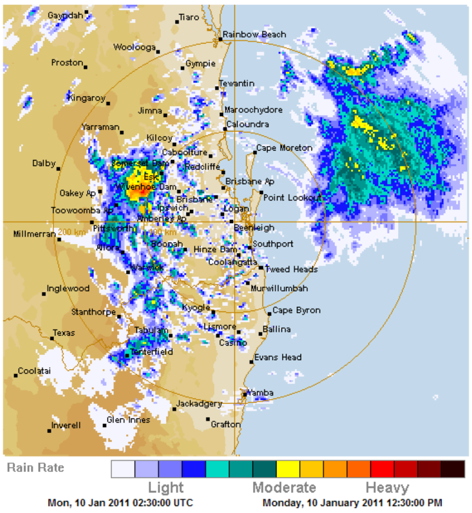
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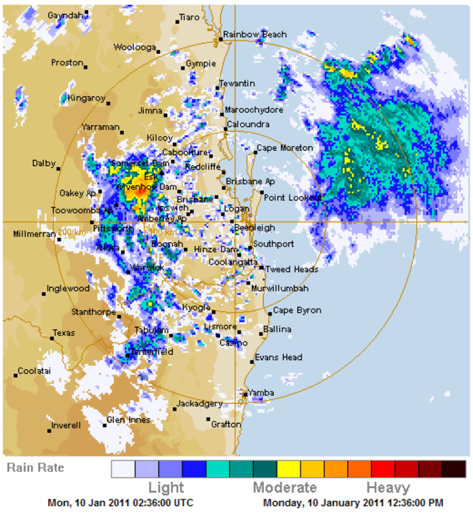
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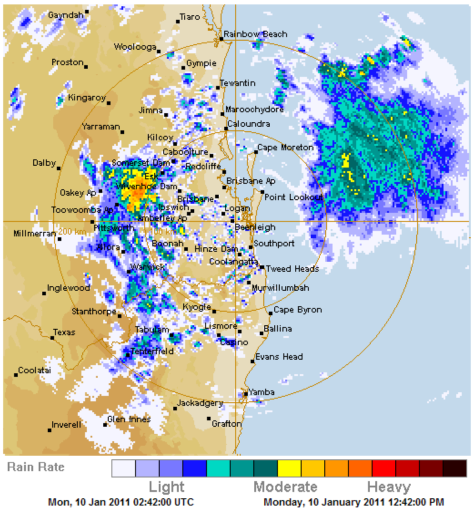
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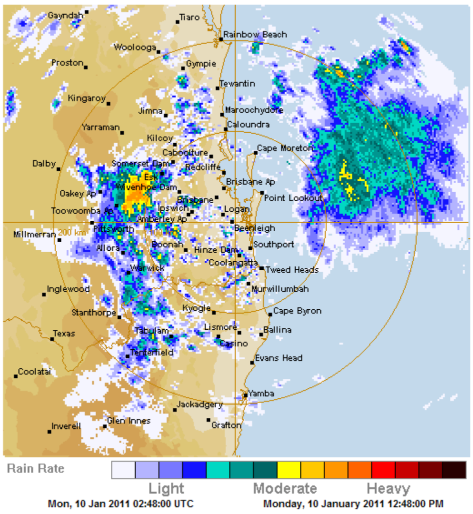
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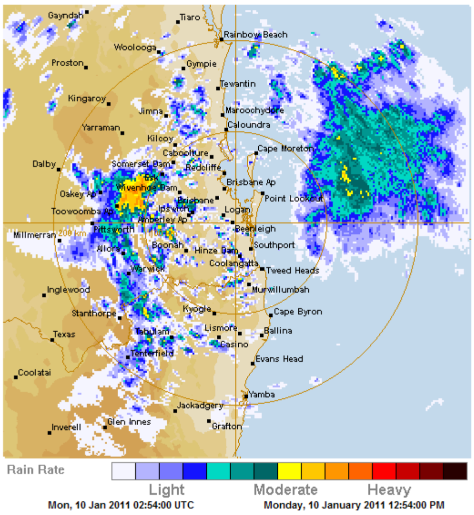
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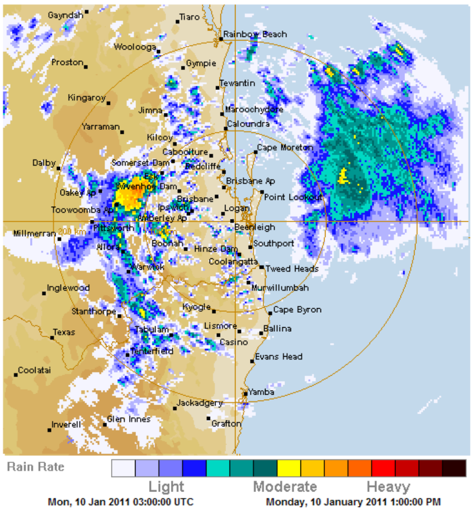
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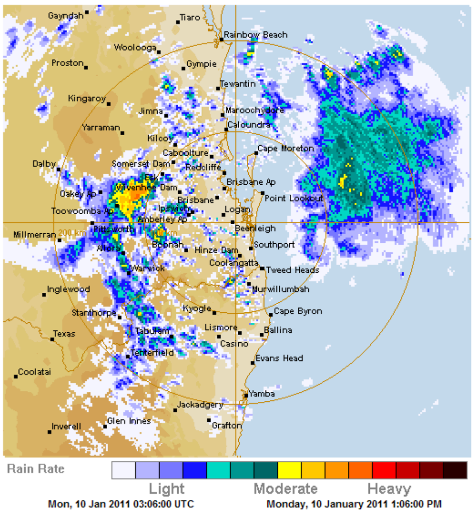
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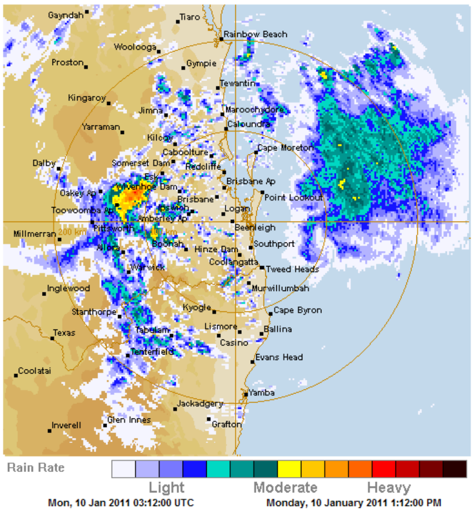
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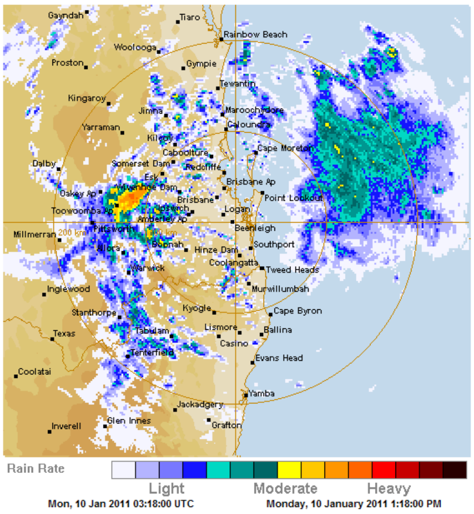
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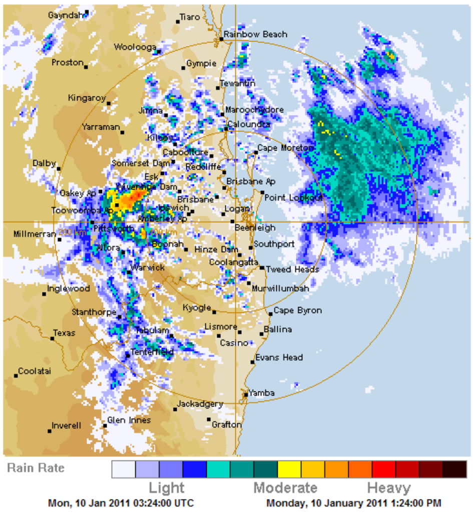
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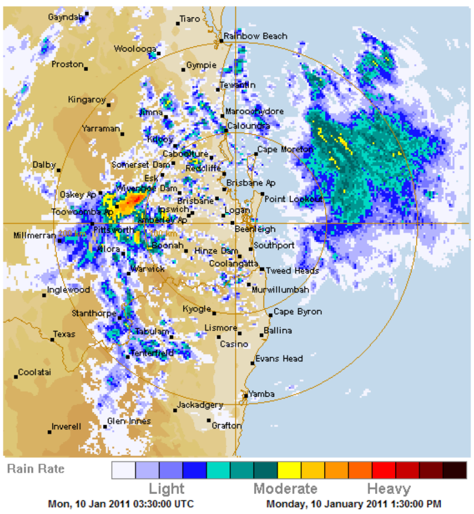
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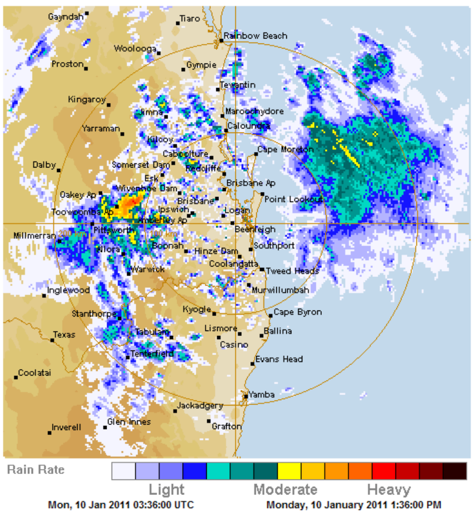
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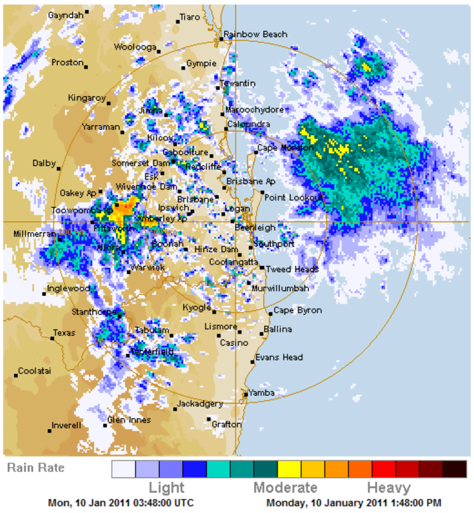
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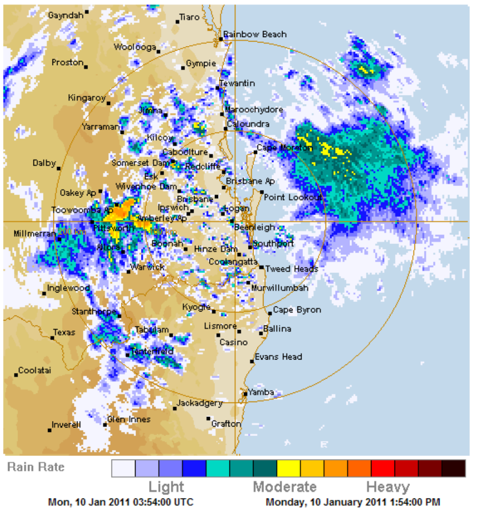
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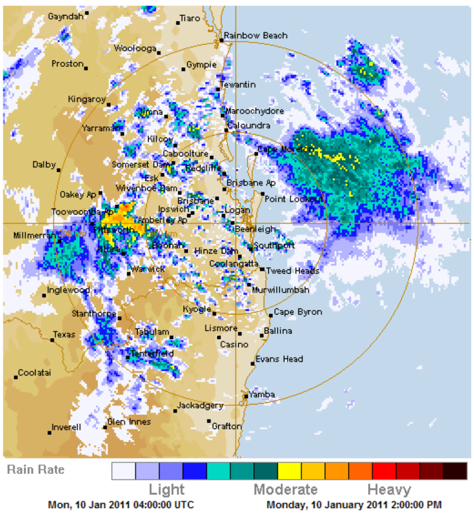
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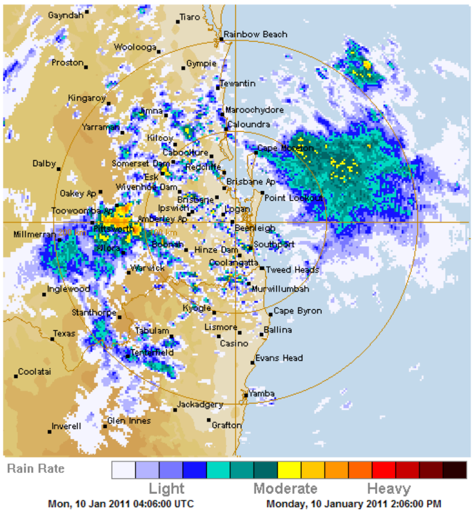
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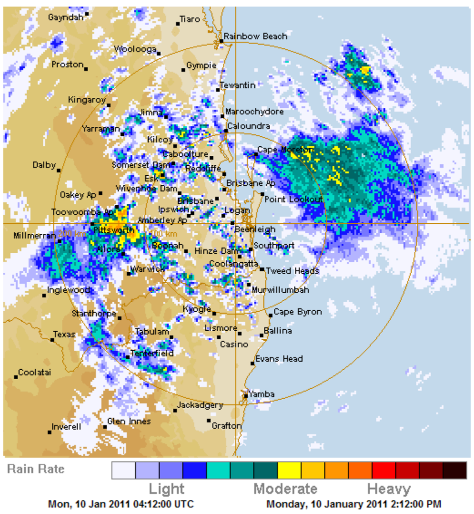
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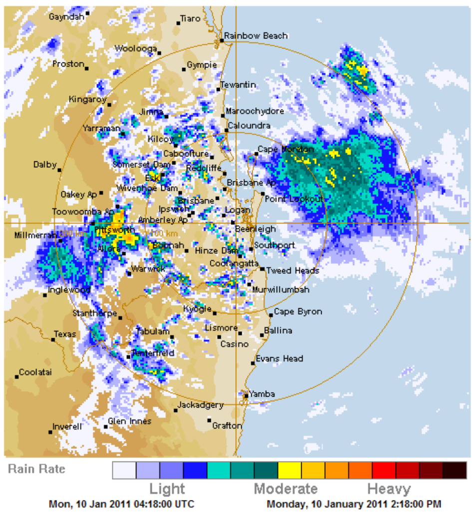
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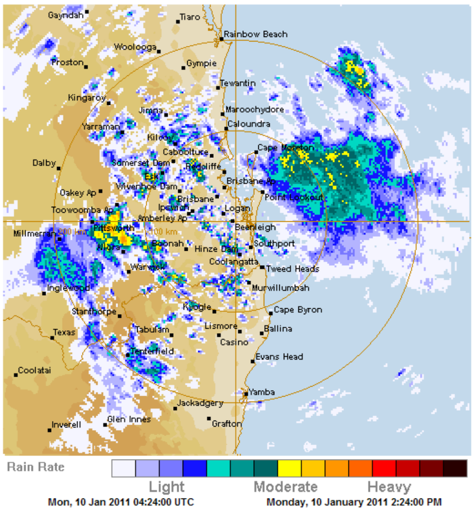
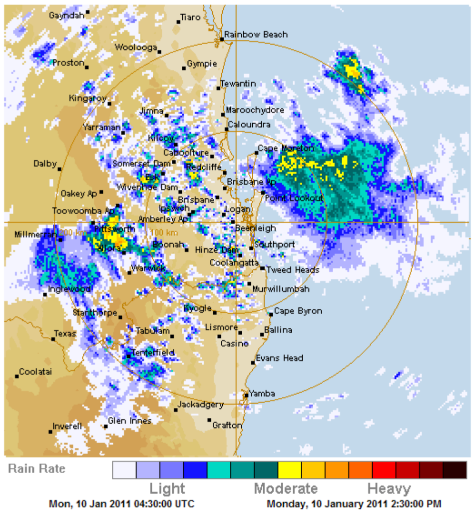
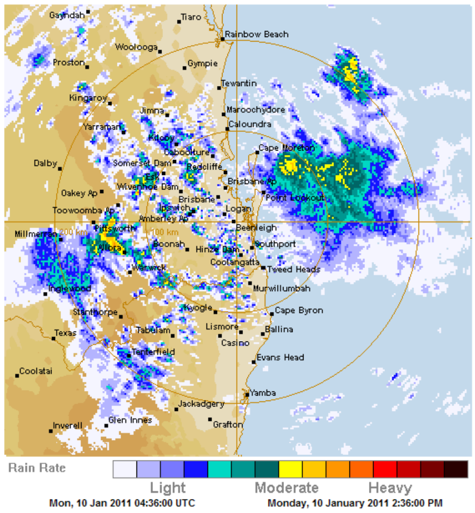
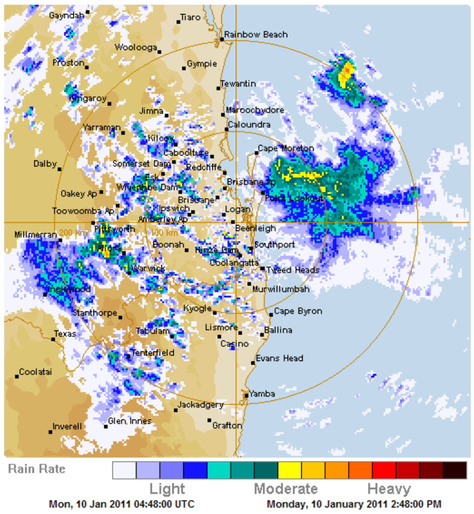
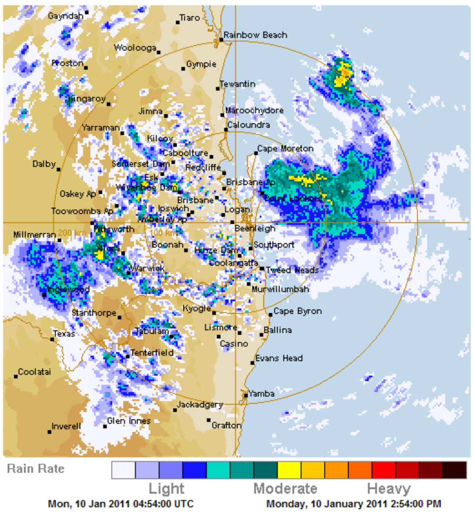
SINCLAIR KNIGHT MERZ
SKM







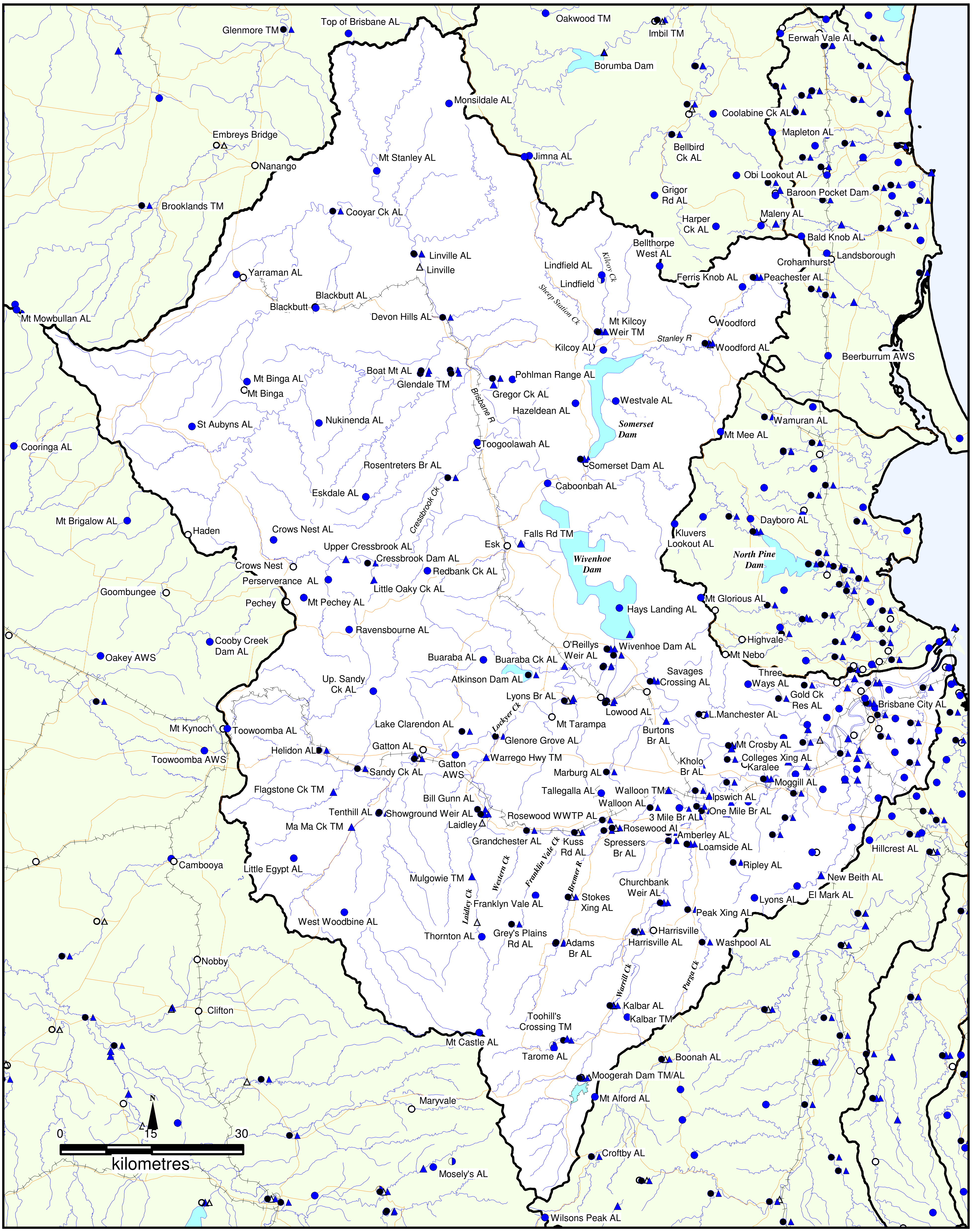




Appendix B Bureau of Meteorology Maps of Real-Time Flood Warning Networks in Brisbane River Basin

Australian Government
Bureau of Meteorology

MAP 143.1



◑	Manual Heavy Rainfall Station
○	Daily Reporting Rainfall Station
△	Manual River Station
●	Telemetry Rainfall Station
▲	Telemetry River Station

BRISBANE, BREMER & STANLEY RIVERS

FLOOD WARNING NETWORK

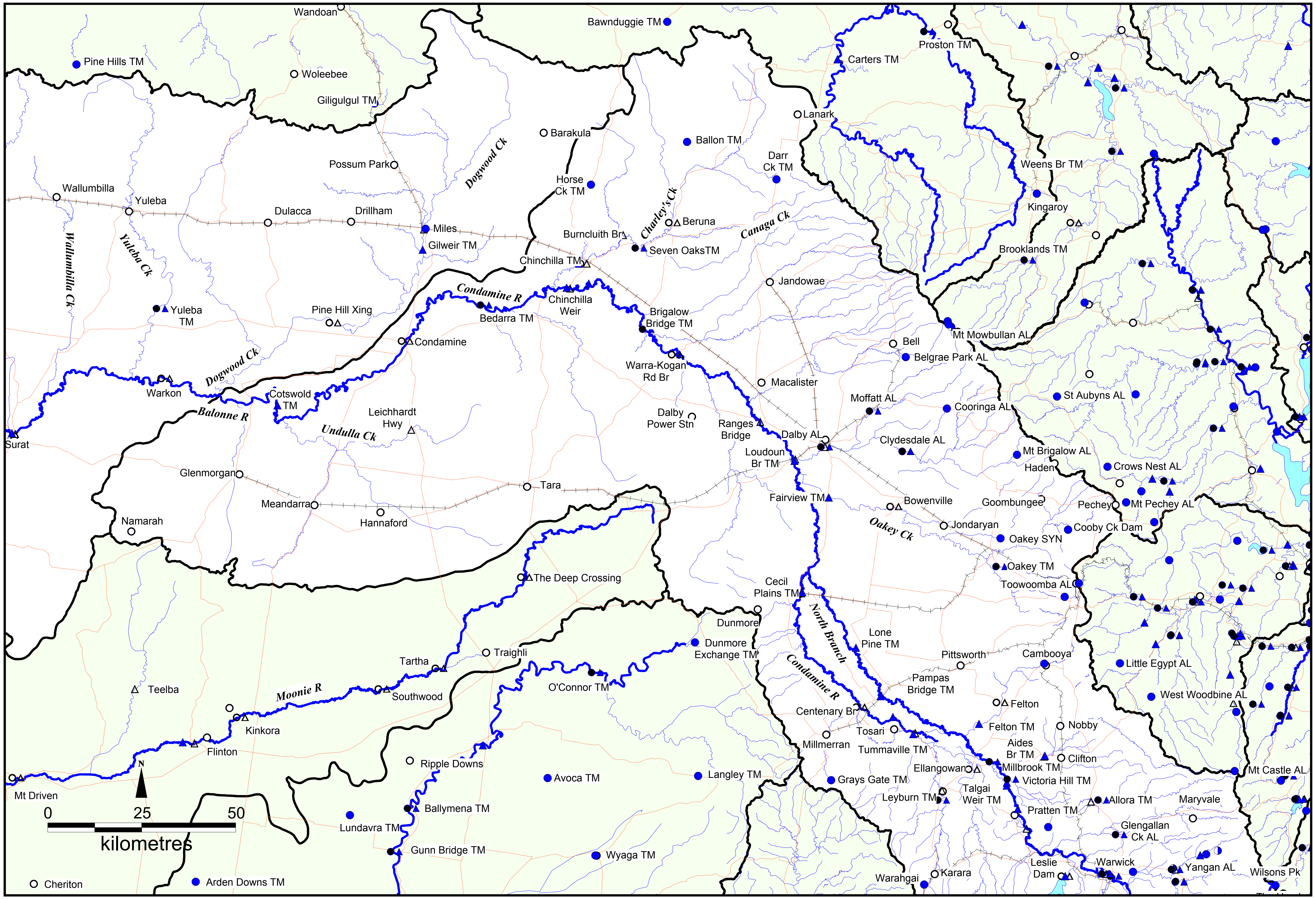
Major Roads

Railway

Revised: April 2010

r:/pub/maps/map03/map143_1.wor

Appendix C Bureau of Meteorology Maps of Real-Time Flood Warning Networks in Condamine River Basin



- Manual Heavy Rainfall Station
- Daily Reporting Rainfall Station
- Manual River Station
- Telemetry Rainfall Station
- Telemetry River Station

CONDAMINE RIVER - WARWICK TO COTSWOLD

FLOOD WARNING NETWORK

- Major Roads
- Railway

Revised: Nov 2009