QUEENSLAND FLOOD COMMISSION OF INQUIRY

REPORT TO THE QUEENSLAND FLOOD COMMISSION OF INQUIRY

FINAL REPORT

MAY 2011

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Project Report to the Queensland Flood Commission of Inquiry	**Project Number** 111024
Client QLD Flood Commission of Inquiry	**Client's Representative** Lisa Hendy
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Date 11 MAY 2011	**Verified by** [redacted]

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REPORT TO THE QUEENSLAND FLOOD COMMISSION OF INQUIRY

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1. INTRODUCTION

1.1. Scope of the Report

1 Following the flooding of the Brisbane River and its tributaries in January 2011 the Queensland Flood Commission of Inquiry (The Commission) requested that Mark Babister of WMAwater prepare a report providing advice on the operation of Wivenhoe and Somerset Dams and the resultant flooding downstream.

2 The Commission requested the following reports be considered:

- January 2011 Flood Event Report on the operation of Somerset Dam and Wivenhoe Dam, 2 March 2011 (Seqwater);
- January 2011 Flood Event: Report on the operation of Somerset Dam and Wivenhoe Dam Review of Hydrological Issues, dated 11 March 2011 (SKM);
- Review of Seqwater Document "January 2011 Flood Event - Report on the operation of Somerset Dam and Wivenhoe Dam 2 March 2011", 9 March 2011 (Emeritus Professor Colin Apelt);
- Review of the Operation of Wivenhoe and Somerset Dams During the January 2011 Flood Event, 9 March 2011 (WRM Water & Environment Pty Ltd);
- Flood event of January 2011- Wivenhoe Dam water releases - compliance with Manual, 10 March 2011 (Mr Leonard McDonald);
- Flooding in the Brisbane River Catchment January 2011, 20 February 2011 (ICA Hydrology Panel); and
- Impact of January 2011 South-east Queensland Weather Event at Brisbane and Ipswich (WorleyParsons, for IAG),

and that this report outline any differences in methodology or approach in these reports and identify differences in findings and opinions within these reports. The Commission requested that an evaluation be undertaken of the methodology, findings and opinions included within each report.

3 The Commission requested that the following questions be addressed:

- To what extent was flooding (other than flash flooding) in the Brisbane, Ipswich and the Lockyer Valley caused by releases from the Somerset and Wivenhoe Dams?
- To what extent did the manner flood waters were released from the Somerset and Wivenhoe Dams avoid or coincide with peak flows from the Bremer River and Lockyer Creek?
- To what extent did the manner in which flood releases were made from Somerset and Wivenhoe Dams avoid or coincide with high tides in the Brisbane River?
- Were the releases from the Somerset and Wivenhoe Dams in accordance with the flood manual?
- What were the consequences of not more rapidly escalating releases from the Wivenhoe and Somerset Dams between 6 and 11 January 2011?

- Does the flood manual adequately address needs for flood management during a major flood?
- In relation to releases from the Somerset and Wivenhoe system, was the reliance on short term weather forecasts by the Flood Operations Centre appropriate?
- Did the absence of modelling for the combined Somerset/Wivenhoe, Brisbane, Ipswich and Lockyer catchments impact on the capacity of those controlling the Flood Operations Centre to make fully informed assessments as to flood releases? If so, how? and
- Had the levels in Somerset and Wivenhoe Dams been reduced to 75% of full supply level by the end of November 2010 what impact would this have had on the extent of flooding within Brisbane, Ipswich and the Lockyer Valley in January 2011?

1.2. Outline of the Report

4 Sections 1 to 3 of this report details the scope, author qualifications and data relied upon. Section 4 of this report covers background technical information on how a dam operates, rainfall and streamflow data collection systems, rainfall forecasting and design hydrology. Section 5 provides a summary and analysis of the 2011 event. Section 6 details issues requiring consideration which have come to light when reviewing the documents and which are discussed in detail in Section 7. Section 8 provides answers to The Commission's questions, based upon the material presented in this report. Section 9 summarises the key recommendations and conclusions.

2. QUALIFICATIONS, EMPLOYMENT HISTORY AND EXPERIENCE

5 Mark Babister is a practicing flood hydrologist with over 25 years of experience in water engineering studies. He is the managing director of WMAwater a specialist flood consultancy with over 20 staff.

6 Mark has been awarded the following qualifications:

- Bachelor of Engineering (Civil) Honours University of NSW, 1988;
- Master of Engineering Science (Hydrology) University of NSW, 1993; and
- Graduate Diploma in Management Deakin University, 1997.

7 Mark has the following professional affiliations:

- Member of the Institution of Engineers Australia;
- Chartered Professional Engineer (CPEng);
- Registrant on the National Professional Engineers Register (NPER); and
- Registered Professional Engineer of Queensland (RPEQ).

8 Mark takes an active role in the profession and is the current Chair of the National Committee on Water Engineering, and member of the Steering and Technical Committees that are overseeing the updating of Australian Rainfall & Runoff (ARR). Published by Engineers Australia, ARR is the national guideline used for the estimation of design floods. It is used for the determination of flood levels for land use planning and designing infrastructure for appropriate flood risk. Mark is the ARR Project Manager for the Temporal Patterns of Rainfall, Losses for Design Flood Estimation and Two-Dimensional Simulation projects for the revision. Appendix B contains a full CV of relevant experience and a list of publications.

9 Mark has considerable experience in hydrologic investigations involving runoff-routing models, flood frequency and joint probability analyses. He has worked on numerous flood and floodplain management studies (over 50) ranging from small catchments subject to flash flooding to large catchments where thousands of people are at risk. Mark was the project manager for a range of investigations into Warragamba Dam in Western Sydney. Warragamba Dam is the main water supply for Sydney. Up to 60,000 people live within the dam break zone including a significant number below the 100 year flood level. This was an extensive study with a duration of over 5 years that looked at gate operations, dam failure and mitigation strategies and their impact on flood warning, flood levels and evacuation.

2.1. WMAwater

10 WMAwater was established in 1983. The Firm has over 20 employees, all but one of whom have a core practice area of flood hydrology and floodplain management.

2.2. Assistance

11 Due to the short timeframe allowed for the preparation of this document and the large amount of data, reports and information to be processed, Mark Babister has been assisted in technical investigations and report preparation by the following hydrologists:

- Rhys Hardwick Jones;
- Monique Retallick; and
- Ivan Varga

12 Additional assistance with review and preparation of the report was provided by:

- Erin Askew;
- Stephen Gray;
- Richard Dewar; and
- Erika Taylor.

3. AVAILABLE INFORMATION

3.1. Documents Relied Upon

13 Documents that have been considered in the preparation of this report, and the numbers by which they are referenced, are listed in Table 1.

14 Witness statements submitted to The Commission have also been considered. Where information from witness statements has been relied upon, specific references are provided.

3.2. Data Relied Upon

15 Raw data as used for preparation of reports by Seqwater and BoM were provided for the purposes of preparing this report.

3.3. Reliance Statement

16 Due to the limited time available to produce this report, it has not been possible for the author to check the reliability of all information in the documents considered. Information and data provided by The Commission and other sources have been presumed to be accurate. Due to the time constraints it has not been possible to conduct thorough independent checks of the work of others or to conduct our own modelling work, except where otherwise stated in this report.

17 A considerable amount of hydrologic analysis has been carried out prior to the construction of Wivenhoe Dam, as well as numerous studies post construction. The authors have attempted to read and digest as much as possible of this information in the timeframe available. Every attempt has been made to attribute work we have relied upon to the original source and author.

18 We have attempted to include background information for non hydrologists to assist The Commission and public in understanding many of the technical issues addressed in this report.

19 This report has been prepared on behalf of The Commission, and is subject to, and issued in accordance with, the provisions of the agreement between WMAwater and The Commission.

Table 1: Documents Considered

Document Number	Report Title	Author	Date
1	Brisbane River Flood Study	City Design - Brisbane City Council	Jun-99
2	Review of Brisbane River Flood Study	Independent Review Panel - Russell Mein, Colin Apelt, John Macintosh, Erwin Weinmann	3-Sep-03
3	Response to Hedley Thomas Questions on 4 July 2003	-	4-Jul-03
4	Crime & Misconduct Commission Investigation - Brisbane River Flood Levels	CMC	Mar-04
5	Joint Flood Taskforce Report	Joint Flood Taskforce / Prof. Colin Apelt	8-Mar-11
6	Flood Fact Sheet	Brisbane City Council	8-Mar-11
7	Manual of Operational Procedures for Flood Mitigation at Wivenhoe Dam and Somerset Dam	Seqwater	Nov-09
7b	Manual of Operational Procedures for Flood Mitigation at Wivenhoe Dam and Somerset Dam - Uncontrolled	Seqwater	Nov-09
8	Wivenhoe Dam infographic	Seqwater	
9	Report on the operation of Somerset Dam and Wivenhoe Dam	Seqwater	2-Mar-11
10	Flooding in the Brisbane River Catchment January 2011 Volume 1 An Overview	WRM, Water Matters International, Worley Parsons	20-Feb-11
11	Flooding in the Brisbane River Catchment January 2011 Volume 2 Flooding in Brisbane City LGA	WRM, Water Matters International, Worley Parsons	20-Feb-11
12	The Nature and Causes of Flooding in Toowoomba 10 January 2011	WRM, Water Matters International, Worley Parsons	14-Feb-11

Document Number	Report Title	Author	Date
13	Flooding in the Brisbane River Catchment January 2011 Volume 3 Flooding in Ipswich City LGA	WRM, Water Matters International, Worley Parsons	20-Feb-11
14	Manual of Operational Procedures for Flood Mitigation for Wivenhoe Dam and Somerset Dam	Seqwater	4-Oct-04
15	Manual of Operational Procedures for Flood Mitigation for Wivenhoe Dam and Somerset Dam	Seqwater	20-Dec-04
16	Natural Hazards and the risks they pose to South-East Queensland	AGSO / BoM	
17	Somerset - Wivenhoe Interaction Study	Seqwater	Oct-09
18	Flood Procedure Manual - Uncontrolled Copy	Seqwater	Jan-10
19	Manual of Operational Procedures for Flood Mitigation at North Pine Dam - Uncontrolled	Seqwater	Aug-10
20a	January 2011 Flood Event: Report on the Operation of Somerset Dam and Wivenhoe Dam	SKM	11-Mar-11
20b	Review of Seqwater Document "January 2011 Flood Event - Report on the operation of Somerset Dam and Wivenhoe Dam" 2 March 2011	UniQuestion	9-Mar-11
20c	Review of the Operation of Wivenhoe and Somerset Dams During the January 2011 Flood Event	WRM	9-Mar-11
20d	Flood Event of January 2011 - Wivenhoe Dam Water Releases - Compliance with Manual	Leonard A McDonald	10-Mar-11
21	Design Discharges and Downstream Impacts of the Wivenhoe Dam Upgrade	Wivenhoe Alliance	Sep-05
22	Wivenhoe Dam - Draft Report on Safety Review	GHD	Apr-97
23	Report on the Feasibility of Making Pre-Releases from SEQWC Reservoirs	SEQWC	Aug-01
24	Flood Control Centre -Event Log		Jan-11
25	Wivenhoe Dam - Assessment of Wivenhoe Dam Full Supply Level on Flood Impacts	SunWater	Dec-07
26	Hydrology report for Manual of Operational Procedures for Flood Mitigation for Wivenhoe Dam and Somerset Dam Volume 1 and 2	K.L Hegerty and W.D Weeks	Jan-85

Document Number	Report Title	Author	Date
27	Brisbane River Flood Study - Further Investigation of Flood Frequency Analysis Incorporating Dame Operations and CRC-Forge Rainfall Estimates - Brisbane River	SKM	18-Dec-03
28	Report: Assessment of the Flood Impacts of Raising the Full Supply Level in Wivenhoe Dam	SunWater	Mar-06
29	Brisbane River Flood Study draft	SKM	Jun-99
30	*Number not allocated*	SKM	Jun-99
31	*Number not allocated*	SKM	Feb-98
32	*Number not allocated*	SKM	1996
33	*Number not allocated*		
34	City Design Flood Modelling Services FINAL - Recalibration of the MIKE11 Hydraulic Model and Determination of the 1 in 100 AEP Flood Levels	SKM	5-Feb-04
35	City Design Flood Modelling Services DRAFT - Recalibration of the MIKE11 Hydraulic Model and Determination of the 1 in 100 AEP Flood Levels	SKM	23-Dec-03
36	City Design Flood Modelling Services FINAL - Calculation of Floods of Various Return Periods on the Brisbane River	SKM	6-Jul-04
37	Feasibility and Final Report For Brisbane Valley Flood Damage Minimisation Study	Brisbane City Council	29-Jun-07
38	Brisbane River Flood Study Review of Hydrological Aspects	Monash University	9-Dec-98
39	Further investigations for Brisbane River Flood Study	Brisbane City Council	Dec-99
40	Preliminary Risk Assessment Wivenhoe, Somerset and North Pine Dams	SKM	Mar-00
41	Report To Queensland Floods Commission of inquiry	BoM	Mar-11
42	Brisbane River and Pine River Flood Study - Report Number 7a	Water Resources Commission	Sep-92
43a	Brisbane River and Pine River Flood Study - Report Number 8a	Water Resources	Mar-93

Document Number	Report Title	Author	Date
43b	Brisbane River and Pine River Flood Study - Report Number 8b	BoM	Mar-93
43c	Brisbane River and Pine River Flood Study - Report Number 8c	Water Resources	Mar-93
43d	Brisbane River and Pine River Flood Study - Report Number 8d	Water Resources	Mar-93
44	Brisbane River and Pine River Flood Study - Report Number 13	Water Resources	Aug-93
45	A Comprehensive Evaluation of the Proposed Wivenhoe Dam on the Brisbane River	For the Coordinator-General's Department by T.J. Grigg	Jun-77
46	Discussion Paper - Change in Operation of Wivenhoe Dam	Connell Wagner	12-Dec-06
47	Somerset Dam - Maximum Flood Level Estimates for Various Gate Operation Scenarios	Wivenhoe Alliance	25-Feb-04
48	Report on the Hydrology of Wivenhoe Dam	QLD Irrigation and Water Supply Commission	Sep-77
49	Wivenhoe Design Flood Study	QLD Water Resources Commission	May-83
50a	Future Brisbane Water Supply and Flood Mitigation Volume 1	Co-Ordinator General's Department	Jun-71
50b	Future Brisbane Water Supply and Flood Mitigation Volume 2	Co-Ordinator General's Department	Jun-71
51	Impact of January 2011 South East Queensland Weather Event	Worley Parsons	17-Feb-11

4. BACKGROUND TECHNICAL INFORMATION

20 This section provides generalised information about the use of dams to mitigate flooding and the various constraints and objectives that must be balanced when optimising gate operational strategies during floods. Background technical information on data networks, hydrology and hydraulics is also provided.

4.1. Conflicts Between Flood Mitigation and Water Supply Objectives

21 Many dams built in Australia are for the dual purpose of water supply and flood mitigation and can be thought of as removing some of the extremes in streamflow variability we see in Australia. They perform this function by capturing flow during high flow periods and storing this water so it is available during low flow periods. It is normal practice to dedicate the lower part of the dam storage for water supply and using storage above this level for the temporary storage of floodwaters. This level is usually called Full Supply Level (FSL).

22 The dual roles of flood mitigation and water supply are generally demarcated by the FSL, however when a dam is below FSL there will be additional storage available to partially or completely capture flood waters, as occurred at Wivenhoe in 1999. Because of the dual nature of many dams there is often a public sentiment that the FSL should be raised during drought periods or lowered during flood periods, both of which have been suggested at Wivenhoe. There are major economic trade-offs when any issues concerning the FSL are considered, as the economic and humanitarian consequences of both flooding and running out of potable water can be very high.

23 Nearly every major investment in water supply and mitigation dams occurs in a catch-up mode in the aftermath of either a major flood occurring or water supply running very low, and there is rarely any spare capacity to adjust either without changing flood or drought risk. Lowering FSL means that an implicit decision has been made either to accept reduced level of water security or to invest in alternative and usually more expensive sources of water supply. Raising the FSL means making an implicit decision that people who have built houses and businesses with a certain level of flood risk (whether it has been quantified properly or not) should be accepting of a higher level of risk.

4.2. Mitigation Basics

24 The operation of a mitigation dam is a complex multi-objective problem. Even once the decision is made of what portion of the dam will be used for flood mitigation, there are conflicting objectives regarding how the temporary storage space should be used. These objectives may include:

- the safety of the dam;
- maximising peak flood mitigation; and
- maximising warning time before downstream flooding occurs.

25 Safety of the dam is extremely important and should be the overriding objective of any flood mitigation strategy. The failure of the dam wall can have catastrophic consequences, releasing an uncontrolled discharge of water generally greater than the dam inflow, and resulting in downstream damages far in excess of controlled discharge scenarios.

26 Maximising peak flood mitigation involves use of the dam to reduce the peak flow downstream of the dam by storing as much of the peak inflow as possible within the dam, then subsequently releasing the water at a sustained lower rate.

27 Warning time is very important to many communities as it gives them time to plan for the arrival of flooding. This is conceptually demonstrated in Figure 1 where all the storage is used to delay the onset of flooding. The benefits of increased warning time include:

- allowing time for evacuation before cutting key transport links;
- allowing time for picking up family members and moving to safe ground;
- allowing time for moving stock and equipment;
- providing enough time that people are not stranded on the wrong side of the river;
- minimising the interference in day-to-day life; and
- the possible reduction of deaths and accidents by minimising chances of people getting stranded or driving through flood waters.

28 Maximising warning time can be counter-productive if flood water subsequently rises at a very fast rate. It is often beneficial to allow flood waters to rise at a very slow rate so that individuals are not caught out. Because of the need for warning time the dam operators are often unable to carry out substantial pre-releases immediately prior to the arrival of flood inflows.

29 Figure 1 shows how a dam can be hypothetically used to solely increase warning time by storing the initial inflows for as long as possible before allowing a dam release, and then allowing all flow to pass through once levels are high enough to threaten dam safety. While this type of operation is theoretically possible, it is unadvisable as it results in a sudden increase in flow once water is released and will not mitigate the peak flow in the river if the flood is large enough to use up all available mitigation storage. Usually only a small amount of a dam’s storage is devoted to increasing warning time.

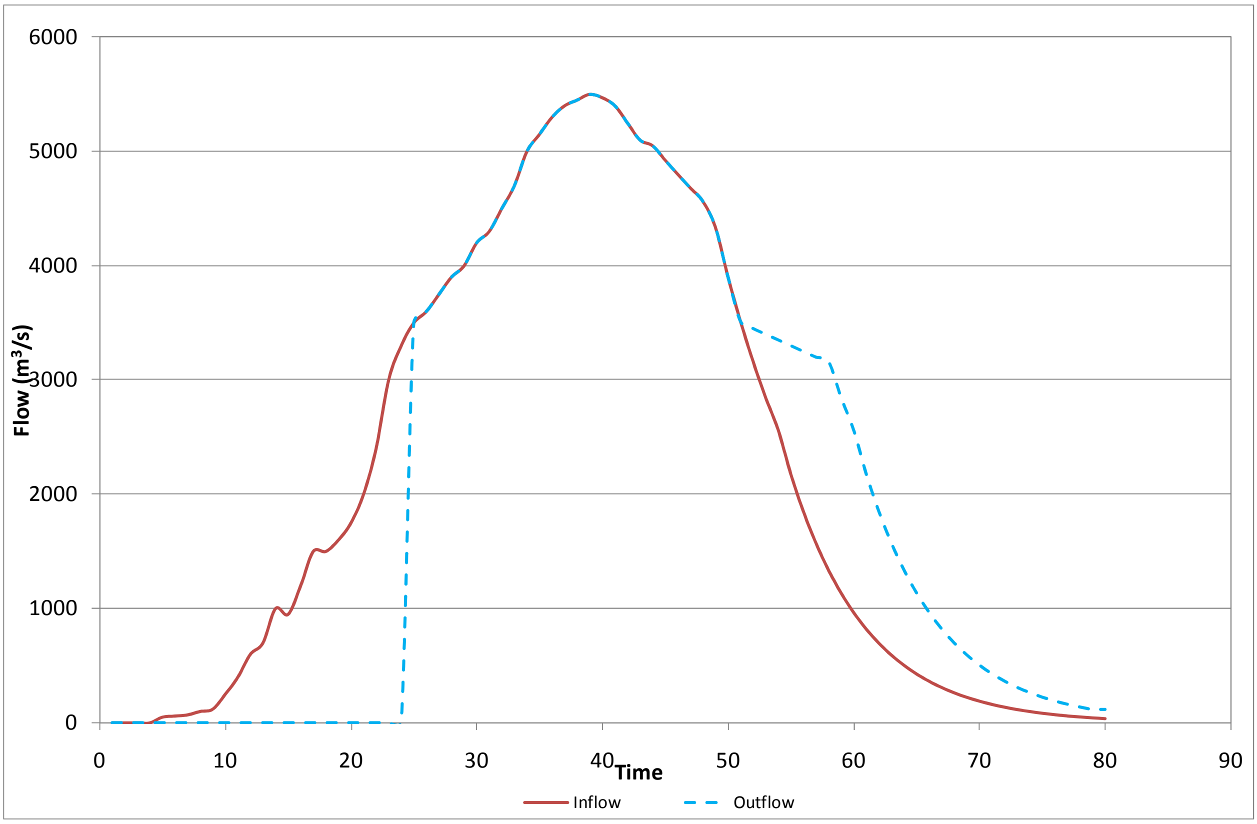

Figure 1: Operation strategy of a dam solely for maximum warning time

30 An idealised mitigation strategy for minimising peak outflow would utilise the dam storage available for flood mitigation only during the peak inflow to the dam (Figure 2). Such a strategy can only be achieved with accurate foreknowledge of the timing, duration and magnitude of the inflow hydrograph peak, and if the gates can be operated in a flexible manner. This is clearly an unrealistic expectation.

31 A significant problem with trying to maximise the mitigation for a given design flood through a highly optimised strategy is that it may not produce a robust solution for a wide range of real floods exhibiting variability of key characteristics (such as spatial and temporal patterns and flood duration). A slight increase or decrease in assumed inflow results in sub-optimal performance for an overly complex mitigation strategy, potentially threatening dam safety or resulting in under-mitigation. Predicting an inflow is quite complex and predictions become less accurate the further ahead they are made. Reasonably robust predictions can be made using observed rainfall but heavy reliance on predicted rainfall is required for longer time horizons.

32 Most dam operating strategies are therefore designed to be robust for a range of inflows where a reliable amount of mitigation is achieved for all events. This is also why a mitigation strategy should not be changed based on one event but should be tested for a large number of events with a broad range of characteristics. Figure 3 shows a typical mitigation strategy, offering both increased warning time and reduction of the flood peak discharge.

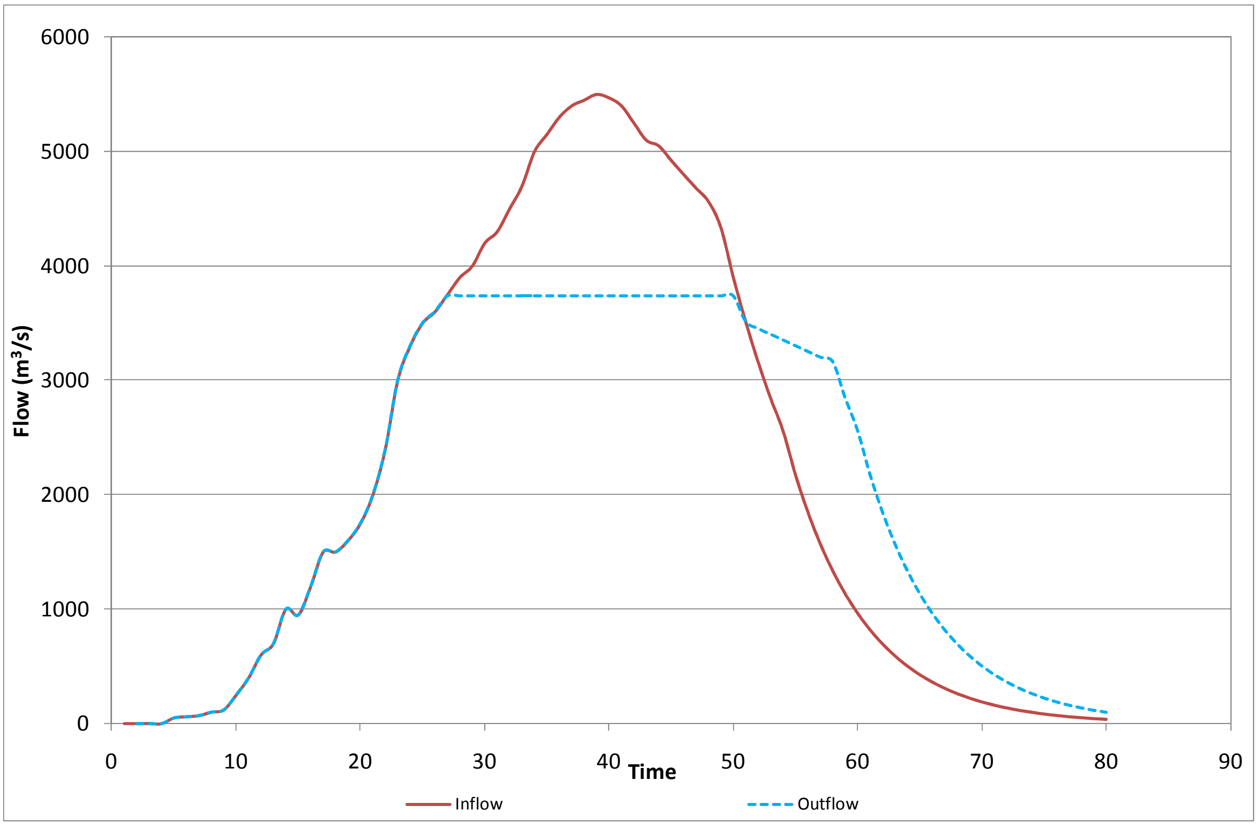

Figure 2: Operation of a dam solely for maximum mitigation of peak flow rate

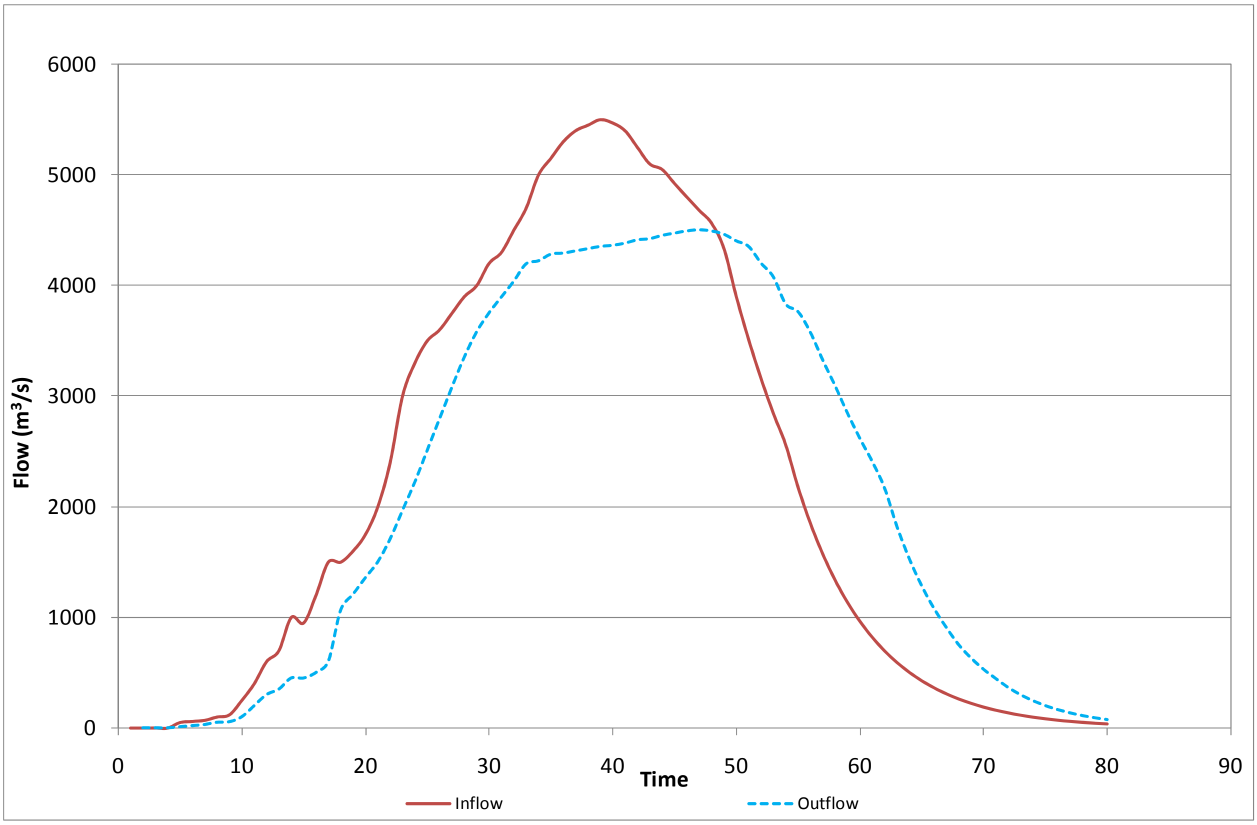

Figure 3: Typical dam flood mitigation strategy

33 Maximising the safety of a dam requires a strategy to ensure that the temporarily stored water does not overtop the dam or reach a level that would likely cause failure. Failure of a dam usually results in a dam break wave which travels downstream very quickly with devastating consequences. Under this scenario all the water in the dam including the temporarily stored water is released over a very short time and the dam discharge exceeds the inflow by a significant amount.

34 Flood operational procedures must therefore strike a balance between storing some of the incoming floodwaters as inflows increase, while ‘saving’ some of the finite available storage to retain floodwaters later should they continue to rise. Extensive testing is required to determine an effective and robust strategy, which performs well under a range of plausible inflows. Over-optimisation of the strategy for a limited selection of design floods should be avoided.

4.3. Measurement of Rainfall and Streamflow Data

35 The operation of a dam during a flood is reliant on the data collection network. This network needs to measure rainfall and streamflow and supply this information to a flood forecasting system. These systems need to be robust and have sufficient redundancy under extreme conditions to be used during a flood.

36 While point rainfall is relatively easy to measure it is difficult to extrapolate this point information to catchment rainfall. Even with a relatively dense rainfall gauge network it is possible for the more intense part of the storm to miss the gauges. There is also a more practical problem with gauges being placed in the more accessible lower parts of valleys (often co-located with stream gauges) where rainfall tends to be slightly lower.

37 Discharges in a river are measured by a proxy of water level. This measurement poses several challenges, and subsequent conversion to streamflow is complex. This is carried out using a relatively simple relationship between level and flow (known as a rating curve) that only approximates the relationship. Other than at spillways and chock points the real relationship tends to vary with event size and during the rising and falling stages of the flood.

38 The rating curve is a particularly important characteristic of a streamflow gauge. The rating curve is generally developed by collecting “gauging” measurements, whereby one visits the gauge during flow events, and collects manual measurements to estimate flow discharges over a range of water levels. Traditional techniques for undertaking these gaugings can be extremely hazardous during high flow, and high flow events are relatively rare, leading to a dearth of measurements at the upper end of the rating curve (which is the critical areas for flood estimation). Rating curves are often extended for high flows via extrapolation and/or supplementary modelling.

39 For these reasons there is always some uncertainty in catchment rainfall and streamflow estimates.

40 Typical components of the data collection network include:

- Gauges – including rainfall, streamflow, and dam levels;
- Telemetry system – the means of communicating recordings back to base. Newer systems will typically use the phone, mobile and radio networks; and
- Power supply – required for both the gauges (in most cases) and telemetry systems.

41 Maintenance of the system is essential to the reliable operation of the data collection network during an event.

4.4. Data Collection Network Challenges

42 Issues which can undermine the data collection network's reliable and accurate function include the following:

- the network is highly distributed;
- gauges are often sited in isolated and unsupervised locations. Streamflow gauges are often at risk of being be damaged or destroyed during large flows due to their proximity to the watercourse;
- the overall data collection network can be a mixture of different gauge types and in some cases even various different telemetry systems; and
- there is a reliance on telemetry during events (when physical access to gauges can be unavailable).

43 As a result of these fundamental issues it is highly likely that some element of system failure exists at any one given time. However, a well designed data collection network copes with this eventuality by incorporating redundancy. Redundancy is relatively easily achieved in both the rainfall and streamflow networks, as long as enough gauges exist per catchment. Redundancy of all important telemetry systems is more difficult to achieve.

44 Various issues can arise that undermine the data collection network's ability to provide accurate and timely data.

- *Obvious gauge failure.* At any given time a gauge may cease to operate due to a variety of reasons. Ongoing maintenance programs will limit this however unless duplicate redundant gauges are operated at all sites such an outcome is likely. In rainfall gauge networks failure of an individual gauge is tolerable as long as the gauge network is sufficiently dense. Similarly if one streamflow station ceases to operate then as long as other gauges exist on the watercourse up and downstream results can be inferred at that location. Examples of mechanisms of total gauge failure could include the following:
    - power failure at the gauge;
    - lack of required consumables at the gauge; and
    - a faulty mechanism at the gauge.

As a result of the above failure mechanisms no data are transmitted back to base.

- *Non-obvious gauge failure.* This is a key risk, particularly during events when there's no time to confirm data inputs. In such a situation the gauge is no longer making accurate observations of on-ground behaviour, but that fact is unknown. Streamflow stations are far more prone to this than rainfall stations. During a non-obvious gauge failure, data are being transmitted back to the base, but those data are wrong. Sometimes the errors will be obvious but more insidiously in some cases they will not. Examples include:
  - for a rainfall gauge the inlet is blocked (rainfall underestimate) or rainfall is intercepted above the gauge and funnelled into the gauge (rainfall overestimate); and
  - for streamflow gauges a variety of issues may arise. The stream cross-section can change dramatically during a large event due to bank collapse/erosion and/or sedimentation, downstream blockage due to debris can increase pool level (exaggerating flow readings), or the rating may be deficient and thus flow estimates are based on a non-rated stage flow relationship which is inaccurate.

- *Loss of telemetry.* Loss of the telemetry system is a significant threat to the overall function of a data collection network. As such there is a need for redundancy in the telemetry system with a parallel system, based on the same technology or linkage points being the least preferred type of redundancy. The ultimate backup system will tend to be a site visit to each gauge for manual reading or download, however given most data collection networks will service relatively large catchments such work would likely be prohibitively time consuming during an event as well as requiring significant resources (for example site access may be compromised and as such vehicular access may not be possible).

45 There are significant advantages in different organisations maintaining separate data collection networks and sharing data. This practice adds an additional level of redundancy.

4.5. Rainfall Forecasting

46 There have been considerable advances in the reliability of forecasting of streamflow and rainfall over the last 10 years. Forecasts rely on increasingly accurate computer models of the atmosphere and meteorological processes. These increases in reliability have been driven by dramatic improvements in the type and amount of data available for these models and by increases in computer power.

47 The Bureau of Meteorology (BoM) is the lead national agency for forecasting and weather services and provides a range of forecasting products from 24 hour rainfall estimates to 3 month seasonal forecasts of rainfall and streamflow. All these products have different

degrees of reliability and are not 100% accurate. The reliability of these products will continue to increase with time but will never be 100% accurate. It is only in recent times that the information value in these forecast products has had enough utility for it to be considered in a quantitative way in decision making.

48 While forecast rainfall is not accurate it presents the opportunity to look further ahead in forecasting dam inflows, with the acknowledgement of a level of uncertainty. For example using 24 hour forecast rainfalls can give a significant increase in lead time for many important flood evacuation and management decisions. The alternatives to not using forecast rain in such a situation are usually "do nothing", assume the rainfall stops instantly or assume the rainfall continues at its current rate.

49 While 24 hour rainfall forecasts are currently issued as a best estimate with a limited quantification of the associated uncertainty it would be possible to quantify some of this uncertainty by issuing to flood forecasting agencies an ensemble (set of) of estimates based on the different weather models. If all estimates are similar or the resultant flood levels or flows are similar when the forecasts are used in a flood forecasting model, greater confidence can be had in the results. The major operational challenges for organisations that could make use of forecast rain are:

- the difficulty in quantifying the uncertainty of forecasts, and incorporating this uncertainty into operational procedures. This in turn makes is difficult to decide at what point in time rainfall forecasts become sufficiently robust that they should be used, and
- limited opportunity to test the utility of using forecast rainfall because very few large rainfall events occur in a particular area.

4.6. Design Hydrology

50 Australian Rainfall and Runoff (ARR) provides national guidelines for flood estimation. The current version was published in 1987, with one of the fourteen chapters being updated in 1999. ARR is currently undergoing a significant revision and subject to funding is scheduled to be released in 2013.

51 One of the major changes that will occur as part of the ARR revision is the move from deterministic to stochastic methods. When Wivenhoe Dam was designed, hydrologists were very limited in computational power and had to use a single representation of temporal and spatial rainfall patterns, and losses that produce floods. The new version of ARR is recommending for most flood estimation problems that stochastic methods be used. This will involve using an ensemble or distribution of temporal patterns, spatial patterns, losses and other key parameters for flood estimation. This type of approach is beginning to be adopted by practitioners and is particularly useful for the investigation of gate operations.

52 The "temporal pattern" is the sequence in which rainfall falls over the catchment during the event. The rainfall also varies spatially across the catchment (and this spatial variation

changes with time). The term “losses” in flood hydrology refers to rainfall that does not flow to the bottom of the catchment as runoff within the timeframe of the flood, and includes infiltration to groundwater, as well as rainfall that remains stored in localised depressions or is captured by vegetation in the upper catchment.

4.7. Undertaking Dam Flood Operations

53 The task of running a dam operations centre during a flood is extremely demanding. A typical flood study takes several months to analyse a flood event and calibrate hydrologic models. This gives the flood hydrologist time to carefully consider all data, assumptions and try various alternatives as well as visiting measuring sites to investigate possible causes of inconsistencies. This is in contrast to a flood forecasting environment where this task is carried out in real-time so that major operational decisions can be made. This task is more difficult when a very large event occurs as many of the data sources and forecasting tools are operating outside the range of tested performance.

54 This is further compounded when a dam is subject to a larger flood than has occurred before. Many of the components are being subject to loads and operated under circumstances that have not occurred before. This is particularly crucial to the spillway and gate operations.

55 During an event the flood engineers need to carefully check all incoming data, discard any data that appear anomalous, remove discarded stations from models, and calibrate losses in a sufficiently robust way to make informed decisions. The complex parts of this process cannot be reduced to a set of rules, but need to be considered decisions based upon experience and insight.

4.8. Flood Forecasting

56 Flood forecasting for dam operations is based upon data collection networks providing streamflow and rainfall data for use in rainfall runoff-routing models.

57 The usual steps in this process are:

- obtaining rainfall and streamflow data from gauges in the network;
- checking the data at each gauge for anomalies and assign alternatives for problem gauges;
- determining the spatial rainfall extent using the accepted gauges;
- converting stream height data to streamflow using rating curves;
- adjusting losses (the proportion of rainfall that does not runoff) in the rainfall runoff-routing model to reproduce streamflows calculated to observed flows; and
- routing these flows through the dam and comparing the calculated levels with observed dam levels.

58 Each of these steps requires a level of hydrological skill and familiarity with the catchment behaviour. Due to the level of uncertainty in the spatial extent of rainfall over the

catchment and the uncertainty in the conversion of levels to flow, the calculation of losses is rarely certain.

59 Rainfall runoff-routing models have been well researched in Australia and been in use for over 30 years. They are used to convert rainfall into flow and route these through a stream network. They are a robust and reliable way of calculating runoff for both forecasting and flood studies. The basic algorithms have not changed during this period and they remain the principal tool used by the hydrologist for this purpose in Australia.

60 The application of losses in rainfall runoff-routing models are one of the weakest links in flood hydrology in Australia. Despite extensive research, reliable methods of predicting losses during floods have not been developed. One of the major reasons for this is that even minor errors in the estimation of streamflow and catchment rainfall can have a big influence on calculated losses. For these reasons most rainfall runoff-routing models use conceptualised losses processed in a very simple way. Investigations into loss methods are currently being undertaken as part of the updating of ARR.

61 Hydrodynamic (or hydraulic) models are used for conversion of flows into flood levels and the routing of floods along river systems. These are regularly used in flood studies and to produce flood maps and are often used in forecasting systems. Hydrodynamic models can accurately quantify the complicated flow interactions that occur at major tributary confluences, such as backwater effects, which are not well represented by runoff-routing models

4.9. Reverse-Routing Method of Dam Inflow Estimation

62 “Reverse-routing” is a technique for at-site estimation of dam inflow, which relies on the principle of water volume conservation. The difference between the total inflow and outflow volumes for the dam over a given period is equal to the change in total water volume stored in the dam, as expressed by the following equation:

$$\Delta S = Volume_{in} - Volume_{out}$$

63 The storage characteristics of the dam can be relatively well quantified from survey of the dam geometry. Outflow rates can also be reasonably well estimated based on the theoretical relationships with the measured depth of flow over the dam spillway crest, as well as prior analysis/modelling of gate configurations specific to the dam. Therefore the equation above can be solved to give inflow volume over a given period, which can be converted to an inflow rate.

64 This method forms one of two primary methods for estimating dam inflows at Somerset and Wivenhoe Dams. The other method uses hydrologic modelling of runoff-routing processes, which uses observed rainfall on the catchment as an input to a model calibrated against previous floods. Reverse-routing can therefore be used to provide a

good at-site observational correction to forecast inflows from real-time rainfall runoff-routing modelling techniques.

65 Reverse-routing is a reliable method for estimating the general shape of the inflow hydrograph, and the total inflow volume. However, the estimated flow rate during any given time period of the calculations can be unreliable, because it can be highly sensitive to measurement errors such as:

- current dam outflow rate;
- estimated rate of change of lake level (and hence storage volume); and
- accumulated errors from inflow estimates at previous steps.

66 These factors can result in a "spiky" oscillatory shape for the estimated inflow hydrograph, and even estimates of negative inflow, whereas the hydrograph is in reality likely to be smoother and generally not negative during floods.

67 Discussion of the role of reverse-routing specifically in dam operations during the January 2011 flood is provided in Section 5.9.

5. ASSESSMENT OF JANUARY 2011 FLOOD EVENT

In this section the methodologies and findings of key reports relating to the January 2011 Flood Events are discussed. Additional analysis relating to the severity of the event is also presented.

5.1. Overview of Available Reports

68 The Commission identified a list of key reports, by various organisations and individuals, which provide a record of the events of the January 2011 Brisbane River flood (Section 1.1). This section summarises the methodologies, findings and opinions of these key reports, with a view to identifying significant differences between the reports. Where opposing or conflicting views are found, some discussion of the perceived reasons for the differences is provided.

69 The reports can generally be divided into three categories. The three reports by Seqwater, Insurance Council of Australia (ICA) and Insurance Australia Group (IAG) had a similar primary focus to provide an account of the January 2011 flooding (Documents 9, 10 and 51 respectively). These studies include descriptions of meteorological conditions, recorded rainfall and stream gauge data, and assessments of the rarity of rainfall and flooding in various areas. The Seqwater report additionally provides a record of dam operations undertaken during the flood, including event logs and modelling undertaken to inform decision-making.

70 The report by SKM (Document 20a) contains a review of hydrological aspects of the Seqwater report, as well as an assessment of the adequacy of the data collection network and real-time modelling tools available for flood operations.

71 The remaining three reports specifically nominated by The Commission for consideration specifically address whether releases from Wivenhoe and Somerset Dams were undertaken in accordance with The Manual (Documents 20b, 20c and 20d).

5.2. Reports Describing the January 2011 Flood Event

72 The Seqwater, ICA and IAG reports use similar methodologies to investigate the causes and severity of flooding. Each report broadly describes the temporal and spatial characteristics of the rainfall experienced in the Brisbane River catchment over the week prior to January 13. Each report compares point rainfall data from specific gauges against design Intensity-Frequency-Duration (IFD) data to ascertain the rarity of the peak rainfalls for various durations.

73 The reports contain a significant amount of analysis at individual sites that it would be impractical to scrutinise in detail in this report. It is noted that the Seqwater and ICA reports find that for durations greater than 48 hours, several stations in the upper Wivenhoe Dam catchment recorded rainfall greater than an ARI of 100 years, with isolated

locations recording significantly higher rainfall intensity (estimated as close to an ARI of 2000 years). However the IAG report finds that the most intense rainfall was recorded at Toowoomba and had an ARI of between 50 and 100 years. It is noted that the Seqwater and ICA reports are more comprehensive than the IAG report, and include data from a significantly larger number of stations, therefore increasing the likelihood that more extreme rainfalls would be recorded. Additionally, the methodology for assessing rainfall severity and the sources of rainfall data are more clearly described in the Seqwater and ICA reports.

74 Apart from this issue, significant differences in findings or opinions were not identified in the overall findings of these reports. The Seqwater and ICA reports in particular provide a thorough record of pertinent data from the event.

5.3. Further Comments on Seqwater Report

75 It is noted that there is a disconnect between the estimated severity of rainfall in the catchment (between 100 year and 200 year ARI) and the comparison of runoff volume with total volumes from design flood hydrographs. The Seqwater report suggests that the total inflow volume for the event is comparable to the volume from the 2000 year ARI design event. This is not considered to be a reasonable comparison, as the design flood hydrographs are developed from a framework that focuses on estimating peak flows from isolated peak rainfall bursts, and does not consider rainfall antecedent or subsequent to the burst. The result is that design hydrographs frequently have low total runoff volumes compared to real floods. It is considered that estimates of flood severity from comparison of total flood volume against design flood volumes should be viewed with caution, and that comparison with observed historic flood volumes (using a flood frequency approach) is likely to give a more reliable estimate of overall flood severity.

5.4. Further Comments on ICA Report

76 The ICA report defines a “dam release flood” as being caused by “caused by the rapid release of large volumes of water from a dam, typically as an emergency response to an incoming flood. If sufficiently large, the release can overtop the banks of receiving waterways and inundate downstream communities.” The report identifies that this definition does not include any reference to dam inflows nor the level of mitigation of the inflow provided by the dam, and therefore by this definition any release of water from the dam must be a “dam release flood.”

77 The Somerset and Wivenhoe Dams attenuated the peak flood discharge in the lower Brisbane River, resulting in lower flood levels and reduced flood inundation extent downstream of Wivenhoe Dam than would have been experienced without the existence of the dams. Damage to urban areas in particular was reduced by the presence and operation of the dams during the January 2011 flood.

78 The term “dam release flood” implies that the dam is the primary cause of flood discharges, rather than rainfall in catchment areas upstream of the dam. The application of the term “dam release flood” to the Brisbane River flooding in January 2011 is therefore misleading and has the potential to cause the general public to form an incorrect understanding of the causes and management of the flooding in this instance. This term should be reserved for situations where discharge from a dam is greater than the discharge would naturally have been without the dam.

5.5. SKM Review of Hydrological Issues

79 SKM completed a thorough review of hydrological issues from the Seqwater report. The review praised the performance of the data collection network and real-time modelling system, although some possible areas of improvement were identified. In particular, SKM observed that the existing deterministic framework for hydrologic analysis of the dam catchment, while consistent with established practice, has significant limitations for including uncertainty in various inputs (particularly spatial and temporal variation of rainfall. It is suggested that the use of a stochastic hydrological simulation framework be considered.

80 The review supported most of the findings of the Seqwater report, stating:

> *“The conclusions drawn by Seqwater are considered to be broadly defensible. It is considered that the annual exceedance probability of the rainfalls for the whole dam catchment is around 1 in 100 to 1 in 200, though the annual exceedance probability of the most extreme point rainfalls that occurred in the centre of the Brisbane River catchment is likely to be between 1 in 500 and 1 in 2000. When compared with historic events, flood volumes indicate the volume of the January 2011 event was almost double the 1974 flood, and rivals the February 1983 flood. Peak water levels at gauges in the Brisbane River above Wivenhoe Dam were the highest on record. In the Lockyer Valley, peak water levels exceeded the 1974 levels and may well have been larger than those of 1893. A comparison of the recorded peaks, volumes and peak levels at Somerset and Wivenhoe Dams indicate the January 2011 flood event exceeds 1 in 100 AEP.”*

81 The SKM report raises similar reservations as those outlined above about the validity of comparisons against design flood characteristics to estimate flood severity. The assessment in the SKM report that the January 2011 flood event “exceeds 1 in 100 AEP” is considered the most reasonable estimate based on available information until more detailed analysis can be undertaken.

82 The SKM review report is considered to provide an excellent summary of hydrological issues and a balanced assessment of severity of the January 2011 flood event, and its findings are endorsed.

5.6. Reports Assessing Compliance of Dam Releases with The Manual

83 Three separate assessments (by Emeritus Professor Colin Apelt, WRM Water & Environment Pty Ltd, and Mr Leonard McDonald) have been undertaken answering the following two questions:

- *"Was the release of water from Wivenhoe Dam and Somerset Dam during the January 2011 Flood Event in accordance with The Manual of Operational Procedures for Flood Mitigation at Wivenhoe Dam and Somerset Dam (Revision 7)?"* and
- *"Based on the information obtained in [Seqwater] report, were there any aspects relating to the operation of Wivenhoe Dam and the operation of Somerset Dam during the January 2011 Flood Event not in accordance with The Manual of Operational Procedures for Flood Mitigation at Wivenhoe Dam and Somerset Dam (Revision 7)?"*

84 The three assessments found in the affirmative for the first question, that dam releases were undertaken in accordance with The Manual.

85 Mr Leonard McDonald identified a possible exception relating to the time at which the decision was made to implement Strategy W2. Mr McDonald identifies an internal ambiguity in The Manual relating to whether predicted or observed flows at Lowood/Moggill should be used to make the decision to implement Strategy W2, and determined that The Manual gives the dam operators some latitude in this regard.

86 The report by WRM identified two "minor deviations" from The Manual, one relating to ambiguity in the use of forecast or predicted lake levels to implement Strategy W4, and the other relating to gate closure sequences after the flood peak had passed. WRM note that the two deviations "may be due to a lack of clarity in The Manual rather than non-compliance."

87 Emeritus Professor Apelt did not identify any issues of non-compliance.

88 The consensus finding of the three assessments of compliance was that the dam releases were in accordance The Manual. Some possible non-compliance issues were identified, but on each occasion these issues were attributed to ambiguity or inconsistency within The Manual.

5.7. Rainfall & Streamflow Data

89 Within the Brisbane River catchment three authorities operate gauges: These authorities are:

- Brisbane City Council;
- Bureau of Meteorology - Seqwater, and;
- Department of Environment and Resource Managment (QLD).

90 Seqwater operates a network of rainfall and streamflow gauges with the purpose of providing flood warning service. Seqwater operates a combined total of 146 rainfall and streamflow gauges within the Brisbane River catchment. From the 149 stations, 129 belong to the ALERT network and 17 are telephone telemeter stations. Prior to the January 2011 flood event, 4 rainfall and 6 streamflow gauges were not available for recording data. The flood event caused damages in further streamflow gauges, namely 4 rainfall and 10 streamflow gauges.

91 After collecting and analysing the rainfall data provided the following observations are made with regards to the following rainfall gauges:

- Kalbar TM (40867) - No records for the period of interest
- Tenthill Alert (540152) - No records for the period of interest
- Lindfield (540491) – No data collected for this station
- Peachester (540059) – No data collected for this station
- Lowood Pump Stn Alert-B (540183) - No records for the period of interest
- Moogerah Dam (40135) – No records between 13/01/2011 to 17/01/2011
- Wivenhoe Dam (40763) - No records between 12/01/2011 to 13/01/2011 and 15/01/2011 to 19/01/2011
- O'Reilly's Weir Alert (540153) - No records after 11/01/2011 20:25
- West Woodbine Alert (540166) - No records after 9/01/2011 18:37
- Wivenhoe Dam TW Alert-B (540179) - No records after 11/01/2011 22:31
- Kuss Rd Alert (540194) - No records after 8/01/2011 14:16
- Hume Lane Alert (540341) - No records after 6/1/2011 14:52
- Gatton TM (540363) – No records after 15/01/2011 02:06

5.8. Rainfall Intensity Frequency Analysis

92 In order to assess the magnitude of a rainfall event at various locations, WMAwater have undertaken further comparison of observed rainfall intensity plots against design rainfall estimates at each location.

93 Figures showing comparisons of recorded rainfall intensity with IFD information from BoM are provided in Appendix C. The figures show the highest rainfall intensity measured at a point location for a given duration. IFD data were derived using the nearest grid point from a 0.025° grid (~2.5 Km). The range of durations is from 5 minutes to 72 hours and the ARI curves are from 1 to 100 years ARI. A summary of the durations for which the maximum rainfall severity was experienced at each station is given in Table 2.

Table 2: Rainfall intensities at ALERT stations

Station	Maximum Rainfall Intensity Frequency (years ARI)	Duration (hours)
Adams Bridge Alert (540157)	20	9, 36
Amberley Alert-P (540180)	5 – 10	48 - 72
Amberley Alert-B (540181)	5	48 - 72
Atton TM (540363)	50	48 – 72

Station	Maximum Rainfall Intensity Frequency (years ARI)	Duration (hours)
Baxters Creek Alert (540189)	>100	2 – 24
Blackbutt Alert (540493)	50 – 100	36 -72
Boat Mountain Alert (540141)	100	9 to 36
Brisbane City Alert (540198)	1 – 2	24 – 72
Caboonbah Alert (540155)	100	48 – 72
Cooyar Creek Alert (540146)	20 – 50	36 - 72
Cressbrook Dam Alert (540142)	10 – 20	36 to 72
Crows Nest Alert (540161)	20 – 50	36 – 72
Devon Hills Alert (540188)	20 – 50	12 - 72
Enoggera Dam Alert (540119)	5 – 10	48 to 72
Ferris Knob Alert (540190)	50	72
Gatton Alert (540156)	20 – 50	48 – 72
Glenore Grove Alert (540149)	100	9 – 12
Gold Ck Reservoir Alert (540107)	5 – 10	1
Greenbank (Thompson Rd) Alert (040794)	2	48 to 72
Gregor Ck Alert (540139)	100	6 to 72
Harrisville Alert (540154)	5 – 10	36
Jimna Alert (540167)	10 – 20	48 - 72
Jindalee Alert (540192)	1 – 2	48 – 72
Jingle Down Alert (40786)	2	1
Kalbar Weir Alert (540151)	2 – 5	36 – 72
Kilcoy Alert (540163)	50	48 – 72
Kluvers Lookout Alert (540168)	>100	5 - 18
Linville Alert (540261)	20	72
Little Egypt Alert (540170)	10	1
Lyons Bridge Alert (540174)	>100	3 - 72
Lyons Bridge Alert (540175)	>100	3 – 72
Moggill Alert-P (540200)	1 – 2	6 – 18, 36 - 72
Mt Binga Alert (540494)	50 – 100	36 – 72
Mt Castle Alert (540171)	>100	36 - 72
Mt Crosby Alert (540199)	2 – 5	48 – 72
Mt Glorious Alert-P (540138)	>100	3 - 24
Mt Mee Alert-B (540246)	50 – 100	48 - 72
Mt Mee Alert-P (540185)	50 – 100	48 - 72
Mt Pechey Alert (541057)	10	48 - 72
Nukinenda Alert (540172)	20 – 50	48 - 72
O'Reilly's Weir Alert (540153)	>100	4 – 72
Oogerah Dam (040135)	5 – 10	48 – 72
Rosentreters Bridge Alert (540148)	20 – 50	36 - 72
Rosewood Alert (540193)	>100	7 – 12
Savages Crossing Alert (540150)	>100	1 - 72
Showground Weir Alert (540158)	50	9 - 12
Somerset Dam HW Alert (540160)	>100	48 - 72
St. Aubyns Alert (540144)	20 – 50	4 – 9
Tallegalla Alert (040503)	>100	2 to 72
Tarome Alert (540173)	5 – 10	9 - 72
Thornton Alert (540169)	50	12
Toogoolawah Alert (540165)	50 -100	24 -72
Toowoomba Alert (540162)	20 – 50	1
Top of Brisbane Alert (540164)	>100	5 - 18

Station	Maximum Rainfall Intensity Frequency (years ARI)	Duration (hours)
Walloon Alert (540196)	10 – 20	6 – 24, 48 - 72
Washpool Alert (540195)	2	36 – 72
West Bellthorpe Alert (540191)	>100	12 - 72
Wilsons Peak Alert (040876)	2 – 5	7 - 72
Wivenhoe Dam (040763)	50 – 100	24 to 72
Wivenhoe Dam HW Alert (540177)	>100	4 - 72
Wivenhoe Dam TW Alert (540178)	>100	4 - 72
Wivenhoe Dam TW Alert-B (540179)	>100	4 - 72
Woodford Alert-B (540338)	50 – 100	2 – 3
Woodford Alert-P (540337)	50 – 100	2 - 3
Yarraman Alert (540145)	50 – 100	2 – 9 , 36 – 72

94 There are suggestions that over 800 mm fell in the Wivenhoe Dam catchment over a 12-hour period to 3:00pm on January 10 (68mm/hr for 12 hours, Document 9, pp 146-147), based on the observed rapid rise in Wivenhoe Dam lake levels during this period. This is an estimate resulting from "closing-the-loop" in various error sources for inflow estimates from rainfall runoff-routing models. The radar images show that a substantial storm passed over the storage, and the rain gauges only picked up the edges of this burst. This estimate would rank with some of the most extreme rainfall events ever recorded in Queensland, as listed in Table 3.

Table 3: Historical extreme rainfall observations close to the Brisbane River catchment

Duration in minutes [hours]	Rainfall Intensity (mm/hr)	Location
18 [0.3]	270	Tambourine Village
53 [0.9]	265	Gatton-Lawes
65 [1.1]	217	Gatton-Lawes
203 [3.4]	609	Nobby
100 [1.7]	240	Enoggera
102 [1.7]	245	Benarby
90 [1.5]	180	Gatton-Lawes
152 [2.5]	304	Wamuran
176 [2.9]	235	Townson (Laidley)
356 [5.9]	119	Kumbia
864 [14.4]	62	Duck Creek
1417 [23.6]	30	Beerwah (Crohamhurst)

95 However, an extreme storm event over the immediate dam catchment is only one possible explanation of the errors. While there is no doubt the storm dumped a large amount of rainfall directly into the storage it is possible that less than 800 mm of rain fell in this location and part of the rise in levels was caused by rainfall that fell elsewhere on the catchment, and arrived at the time of the local storm. A small error in estimated depth of rainfall over the upper dam catchment area, resulting from an underestimation of total rainfall due to spatial averaging or location bias effects, could account for part of the rapid lake level rise observed.

96 The above explanation illustrates there are more likely sources of error than the 800 mm localised rainfall estimate in twelve hours, which is possible but improbable. Figure 4 shows how the 800 mm 12-hour rainfall ranks on BoM list of extreme Queensland rainfalls (triangular marker). Figure 4 also shows the rainfall depth of 410 mm in 12 hours recorded at the Mt Glorious gauge (square marker).

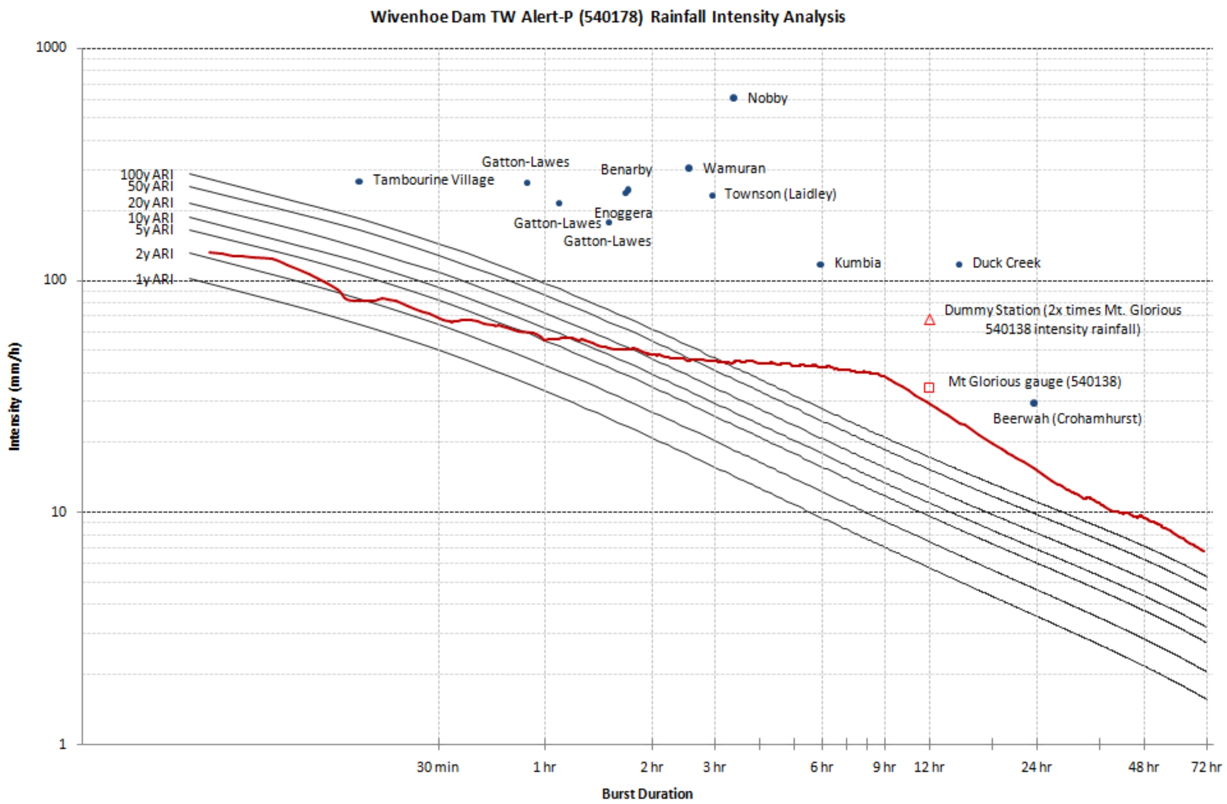

Figure 4: Severity of Wivenhoe Dam TW ALERT gauge rainfall readings, in comparison with extreme QLD rainfall events

5.9. Dam Inflow Estimates

97 The Seqwater estimate of peak inflow to the dam (Document 9) was obtained using reverse-routing techniques as described in Section 4.9. In the early stages of the flood, the dam operators were relying on real-time runoff-routing model estimates for dam inflows, but switched to reverse-routing at around 1pm on Tuesday 11 January (Supplementary Witness Statement of Robert Arnold Ayre, pp 56, paragraph 157) as the estimates from the runoff-routing models were divergent from what was being observed at the dam.

98 The decision to switch to reverse-routing as the primary method of estimating current dam inflows during the flood operations was a sensible one. However there is some uncertainty relating to the peak flow estimates as reported in Document 9, as there is evidence of oscillations in the hourly estimated flow rates. Table 4 shows estimated peak inflow rates close to the peaks as estimated by Seqwater (Document 9, pp156):

Table 4: Seqwater estimates of peak dam inflow

Date and Time	Seqwater Inflow Esimate (m^3/s)	Date and Time	Seqwater Inflow Estimate (m^3/s)
FIRST PEAK		SECOND PEAK	
10/01/2011 05:00	8933	11/01/2011 10:00	10376
10/01/2011 06:00	9312	11/01/2011 11:00	9606
10/01/2011 07:00	9351	11/01/2011 12:00	10120
10/01/2011 08:00	10095	11/01/2011 13:00	11561
10/01/2011 09:00	9731	11/01/2011 14:00	9739
10/01/2011 10:00	7267	11/01/2011 15:00	9055
10/01/2011 11:00	8059	11/01/2011 16:00	8947

99 It can be seen that the estimated peak inflow rates are only for a single hourly calculation point in each instance, and that the flow rates for the hourly periods immediately before and after the peak are significantly lower.

100 These calculations can be sensitive to slight changes in inputs, which are subject to some measurement error. Measured lake levels in particular are important, as a one-centimetre rise can represent a very large volume of water, but in any given hourly period the rise will generally be recorded as only a few centimetres, or even as no rise. Measurement can also be complicated by wave setup, prevailing winds, and oscillations. These errors (and others) can accumulate from one time-step to the next, requiring correction in subsequent steps.

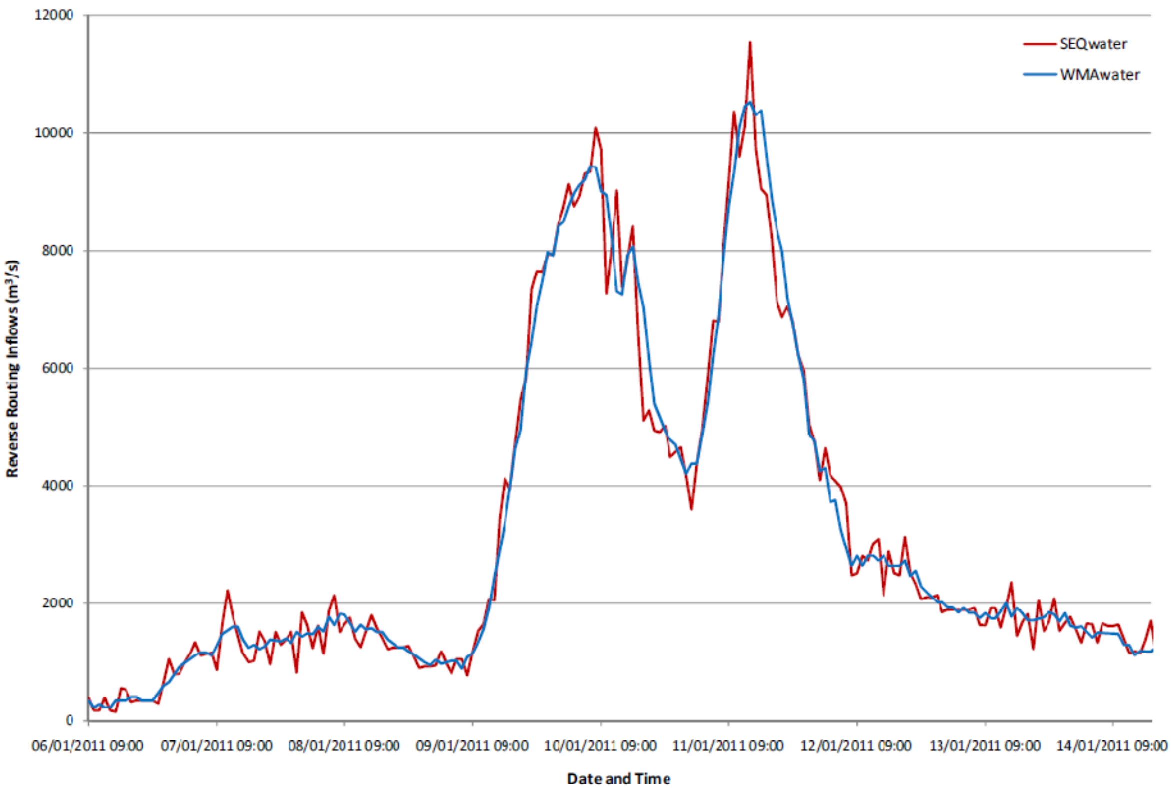

Figure 5: Comparison of alternative reverse-routing dam inflow estimates

101 Figure 5 shows the results of an alternative reverse-routing analysis undertaken by WMAwater, using Seqwater measurements, but with some slight smoothing of recorded lake levels, to dampen the effects of this uncertainty on lake storage and outflow measurements. The Seqwater inflows are shown for comparison. Figure 6 shows a closer view of the peak inflow values.

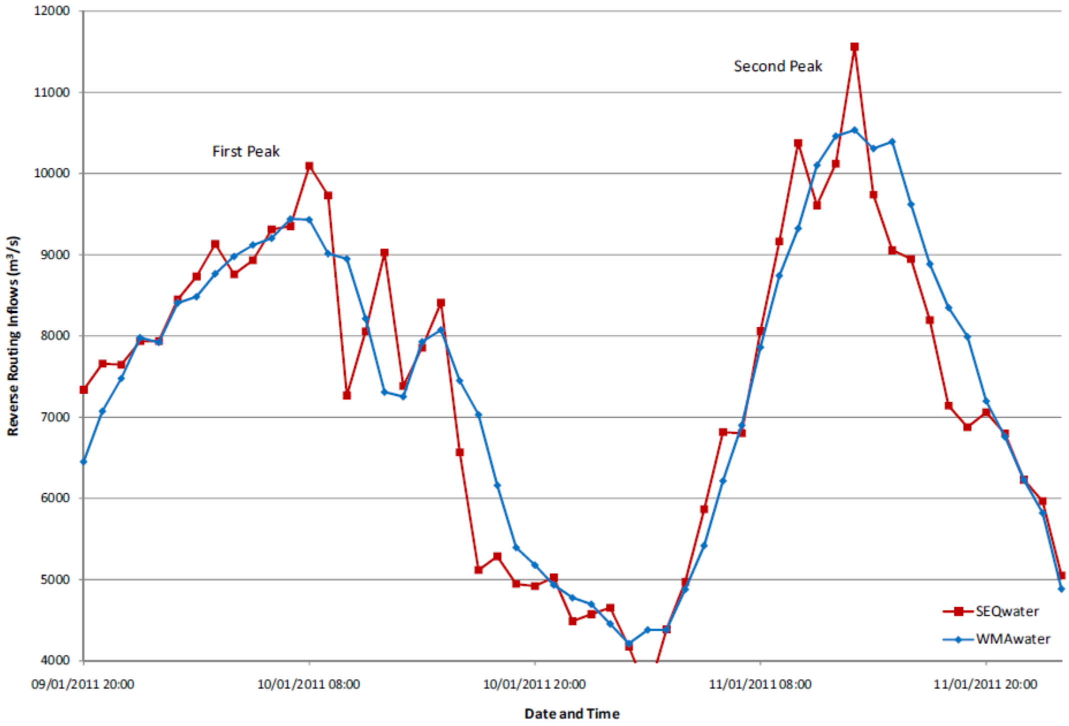

Figure 6: Comparison of alternative reverse-routing dam inflow estimates at flood peaks

102 The peak inflow rate from WMAwater alternative reverse-routing analyses (adopting different levels of smoothing for lake level measurements) ranges from approximately 10,500 m^3/s to 11,100 m^3/s, between 4% and 9% lower than the Seqwater estimate. There are limitations to both approaches, and both WMAwater and Seqwater estimates have uncertainty, however the purpose of this comparison is to highlight that some caution should be exercised in adopting the Seqwater estimate as an "official" peak inflow rate.

103 This is an important consideration as peak flow estimates are often used as a primary indicator of flood severity, and the ratio of inflow to outflow rate is often used as a measure of the mitigation effectiveness of the dam. For example, using the Seqwater estimate, Wivenhoe Dam mitigated the peak flood flow by 35%. Using the WMAwater estimates, the mitigation effectiveness was between 29% and 33%.

5.10. Relative Contributions to Lower Brisbane River Flooding

104 Large flood discharges in both the Wivenhoe Dam catchment and in Lockyer Creek and the Bremer River (which bypass the dams) contributed to flooding in the lower Brisbane River. Flow releases from Wivenhoe Dam were the major component of the flood peak.

105 Figure 7 shows the location of key stream gauges in the Lockyer and Bremer Valleys.

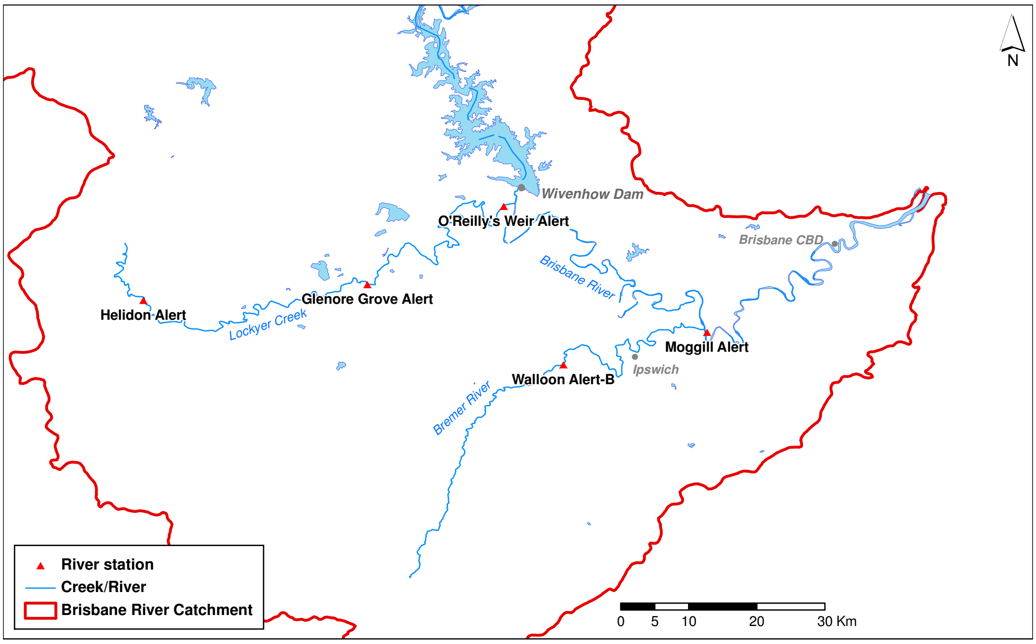

Figure 7: Location of streamflow gauges downstream of Wivenhoe Dam

106 Flooding in Ipswich resulted from the combined effects of the flow releases from the dam and the flows in the Bremer River. Figure 8 indicates that the flows from Brisbane River coincided with the falling limb of the flow in the Bremer River. Earlier releases of dam flow may have increased the peak flood level and inundation extent at Ipswich.

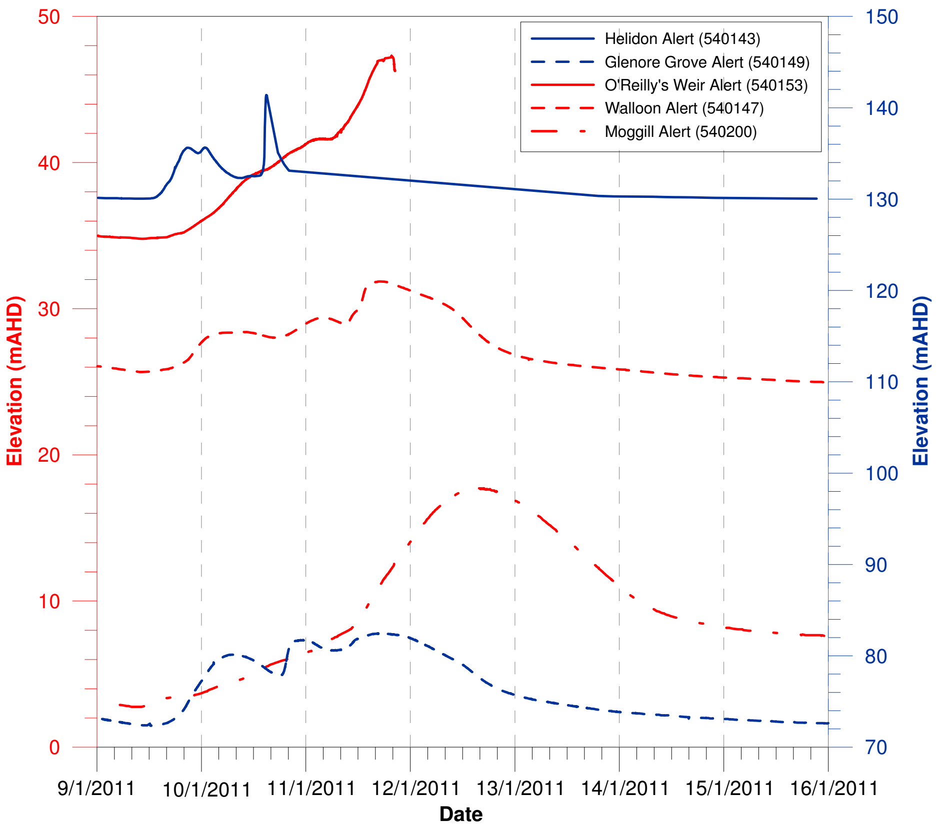

Figure 8: Timing of flood peak at various streamflow gauges

6. OTHER ISSUES FOR CONSIDERATION

107 The main focus of this section of the report is to identify the important questions about the suitability of the current operational procedures that have arisen from analysis of the January 2011 flooding. Each of the issues raised in this section is treated in detail in later sections of this report.

108 The natural question arising from the flood event, as to whether better mitigation performance could have been achieved or could be achieved in the future, is a complex question requiring consideration of many factors:

a. Understanding of the system through scientific analysis;
   i. Data collection;
   ii. Design hydrology;
   iii. Flood mapping (through hydraulic modelling);
   iv. Estimation of flood damages for various levels of flooding;
   v. Interaction of dam releases with downstream influences such as the Lockyer/Bremer tributary inflows, and ocean tides;
b. Strategic considerations for developing mitigation procedures;
   i. The method of transition from prioritising mitigation to prioritising the structural integrity of the dam;
   ii. The relative reliance on incorporation of forecast rainfall and model estimates as opposed to current data measurements;
   iii. Methods of estimating dam inflows in real-time;
   iv. The decision whether to prioritise mitigation for smaller more frequent floods over larger, rarer events (as it is unlikely that any given strategy will be fully effective over the entire range of flood extremities);
   v. Attempting dam drawdown prior to floods arriving to increase the available storage for flood mitigation;
c. Other considerations;
   i. The level of discretion for key personnel during flood operations, and the legal implications of exercising this discretion;
   ii. The working conditions provided for flood operations personnel; and
   iii. The frequency and scope of review of The Manual.

109 The Manual plays a central role in the unification of these issues. The first group of factors relating to scientific understanding are a vital pre-requisite to the development of operational procedures. The procedures themselves are formalised by The Manual, and development of the procedures presents an opportunity for a wide range of stakeholders to have input into the overall strategy eventually adopted. It is considered that the other influences identified must also be considered in the formulation of the Manual. The expected outcomes of the adopted strategy must be effectively communicated to the public, as there will always be some level of flood risk from the dam. Detailed discussion of these issues is provided in the following section.

7. DISCUSSION OF OTHER ISSUES

7.1. Data Collection Requirements

110 The available raw measurement data are generally sufficient both for detailed investigation and development of operational procedures, and real-time estimation as part of flood mitigation operations. However there are isolated locations where deficiencies in the data network exist.

111 This event illustrated that additional rain gauges are needed in some areas of the Wivenhoe Dam catchment where the gauge network is relatively sparse. However it is recognised that the most intense part of a storm will not always be picked up even by a very dense rain gauge network.

112 Continuity and reliability are among the most important aspects of hydrological data. It is therefore imperative that the current data collection network is maintained to least at the current level, and augmented where possible as new technologies become available. It is also vital that the redundancy in the current system is maintained.

113 Streamflow gauging is important for model calibration to increase certainty in real-time flood forecasting for dam operations. Effort should be directed at the gauging of key stations to improve the associated rating curves. It is not clear whether any gauging was undertaken during this event. A number of key gauges used in this system are not gauged or only gauged to a very low flow.

114 Most upper Brisbane River streamflow gauges were recording levels in the extrapolation zone of the rating curve. Given the importance of these gauging data in generating reliable estimates of flood discharge, it is recommended that the rating curves of critical gauges (such as at Moggill, Lowood and Gregors Creek) be assessed for suitability for purpose. Where lacking, these rating curves should be improved if possible. Hydraulic modelling techniques may also assist the development of the rating curves.

7.2. Review Practices for The Manual

115 The fundamental approach in the operational procedures has not changed significantly since the initial development, as documented by K. L. Hegerty and W. D. Weeks (Document 26, 1985), shortly after Wivenhoe Dam was completed in 1984. Although Revision 1 for the Manual was not completed in 1992, Hegerty & Weeks developed a draft of the original procedures based on their 1985 investigations, which is included as an attachment to Document 26.

116 The Draft Manual (dated 29 January 1985) has several features that form the basis of the current operational strategy, including the following key aspects:

- Four procedural modes were specified for Wivenhoe Dam that correspond closely to the strategies W1 to W4 in the current Manual;
- Procedure 4 stipulated that releases should increase until the storage level begins to fall, and identified a Wivenhoe Storage Level of 74.0 mAHD as a trigger above which other lower level objectives become secondary to the safety of the dam, which is broadly similar to the current Strategy W4.
- Procedure 3 identified a maximum release at the Moggill gauge of 4,000 m^3/s, which has been maintained in subsequent revisions, although in the current Strategy W3 it is recognised that if there are high natural flows in the Lockyer and Bremer catchments it *'may not be possible to limit the flow at Moggill to below 4000 m^3/s.'*
- Procedure 2 identified a target maximum release equivalent to the maximum natural discharge expected from the Lockyer or Bremer catchments, up to maximum of 3,500 m^3/s. This is similar to the current Strategy W2 targets at Lowood.

117 The Draft Manual stipulated that the Manual should be reviewed *'at intervals not exceeding five years, and otherwise after every significant flood event. The review is to take into account the continued suitability of the hydrologic and hydraulic engineering assessments of the operational procedures.*'

118 Weeks & Hegerty identified that there were significant limitations on their original hydrologic analyses. In particular, they noted that:

> *"Time, manpower and data constraints limited the extent of some components of the hydrologic investigations described in this report. The components of the investigation listed below should be further investigated in the review required by the manual.*
>
> a. *"Calibration of the downstream model – This was the most unsatisfactory component of the investigation and one of the most critical since evaluation of the procedures and the flood frequency study were dependent on the results of the model.*
> b. *"Spatial distribution of rainfall - Mean catchment rainfalls were uniformly distributed over the various subcatchments affecting the timing and the magnitude of the design floods.*
> c. *"Duration of the floods – Only 2-day design rainfalls were used since these produced the peak inflows. However, these rainfalls were not used as part of longer duration storms.*
>
> *...*
>
> *"These procedures* [for the draft Manual] *were satisfactory for these design floods but, the peak discharge/flood volume characteristics of these floods may have been significantly affected by the above limitations."*

119 The above recommendations of Hegerty & Weeks are remarkably prescient, and highlight some important limitations in the design hydrology. The recommendations have not been sufficiently addressed as part of subsequent revisions of The Manual, which have primarily

involved fine tuning of the existing overall strategy for operational procedures, without critical review of various aspects of the underlying analysis methodology.

120 The 5-year periodic review process is an important aspect of The Manual, and should go further than fine tuning of the existing operational procedures. The review should consider high-level aspects of the gate operations, such as the design hydrology methodology, updating of models and inclusion of new historical data in assessment of alternative mitigation strategies.

7.3. Design Hydrology

121 The limitations in the design hydrology, particularly the flood durations used, have led to a set of operational procedures that are optimised for the design flood assumptions, but are susceptible to real floods that deviate substantially from the design assumptions.

122 The January 2011 Brisbane River catchment flood had several attributes that challenged the implicit assumptions of the design hydrology and subsequent development/assessment of the operational strategies, including:

- a long duration;
- a large total volume;
- a double peak;
- "back-loaded" volume characteristics (a large part of the total flood volume arrived towards the end of the flood event); and
- the relatively late arrival of large downstream tributary inflows (which under design assumptions would pass prior to the Wivenhoe Dam release peak).

123 Substantial revision of the design hydrology methodology should be considered, preferably including a stochastic framework that can reproduce reasonable natural variability in the flood characteristics identified above, through the use of a suite of plausible temporal and spatial rainfall patterns.

7.4. Consideration of Downstream Contributions for Dam Release Timing

7.4.1. Interaction with Lower Tributary Inflows

124 Given the emphasis placed on downstream flow targets for Wivenhoe Dam releases, more effort needs to be put into understanding the interaction between the Lockyer Creek, Bremer River, Lower Brisbane River and the outflows of Wivenhoe Dam. Better modelling tools and data will provide an opportunity to compare observed and modelled stage at Moggill. The new models that are being developed by Seqwater need to target this outcome.

125 The current suite of forecasting models does not include a functional hydrodynamic model. Such models have the advantage that they properly account for the interactions that occur at the confluence of major tributaries.

126 The rainfall runoff-routing models currently in use do not account for these effects, however they are still an important component of the tools used to assess flood mitigation strategies and for real-time flood estimation. They are particularly useful for the rapid assessment of the relative results of numerous alternative design flood scenarios and/or flood mitigation strategies. Rainfall runoff-routing models should therefore be retained, but should be assessed against results from a calibrated hydrodynamic model.

127 It is recommended that a calibrated hydrodynamic model based on current survey be implemented into the flood forecasting system. The model should include the Lower Brisbane River and major tributaries. Such a model would be helpful for understanding the relative consequences of elevated discharges above damaging levels during flood operations.

128 A discharge of 4,000 m^3/s at Moggill is specified in The Manual as the threshold for significant urban damages in the lower Brisbane River. However there is very little information about the consequences of higher discharges in The Manual.

129 The recent study into Brisbane Valley Flood Damages (Document 37) provides an assessment of the economic damages expected for various discharges thresholds. The modelling and mapping used to undertake this assessment should be developed further, and consideration of these damage estimates should be incorporated into an update of the Manual.

7.4.2. Tidal Influences

130 Flood levels in the lower reaches of the Brisbane River are affected by river flow and tides. It has been suggested by various sources that dam releases should be timed to coincide with the low tides to reduce flooding.

131 Figures 9 to 12 show the tidal effect in the Brisbane River at Moggill, Jindalee Bridge, Brisbane City and Whyte Island. The following can be seen in the figures:

- Tides can be seen on all 4 figures at the beginning of the plots. The peaks take time to travel upstream into the estuary;
- The tides at Moggill and Jindalee are drowned out by the higher flows and velocities of the flood wave. The tidal signature is still observable at the Brisbane City gauge, however the amplitude is significantly reduced.

132 Releasing pulses to coincide with low points in the tidal cycle is difficult because:

- both the tidal wave and the flood wave are moving, often in opposite directions;
- they would not coincide at all locations, and releases would have to target a specific highly localised area;
- the pulsing of the dam discharge may make flooding worse at other locations;
- rainfall in the lower reaches after the release could affect the outcome;

- the pulse would be attenuated as it travels downstream;
- releases would have to be made in extremely accurately-timed bursts. The releases would only be able to occur at approximately 12-hour intervals. Meanwhile the situation at the dam may change dramatically and it may not be possible to wait till the next appropriate part of the tide to release; and
- the travel time of the pulse will change with flood level.

133 Therefore releasing flood waters in pulses in order to coincide with low tides is impractical, unlikely to provide a substantial widespread benefit, and could worsen flood severity if timing estimates were inaccurate. It should not be considered for flood operation procedures at Wivenhoe Dam.

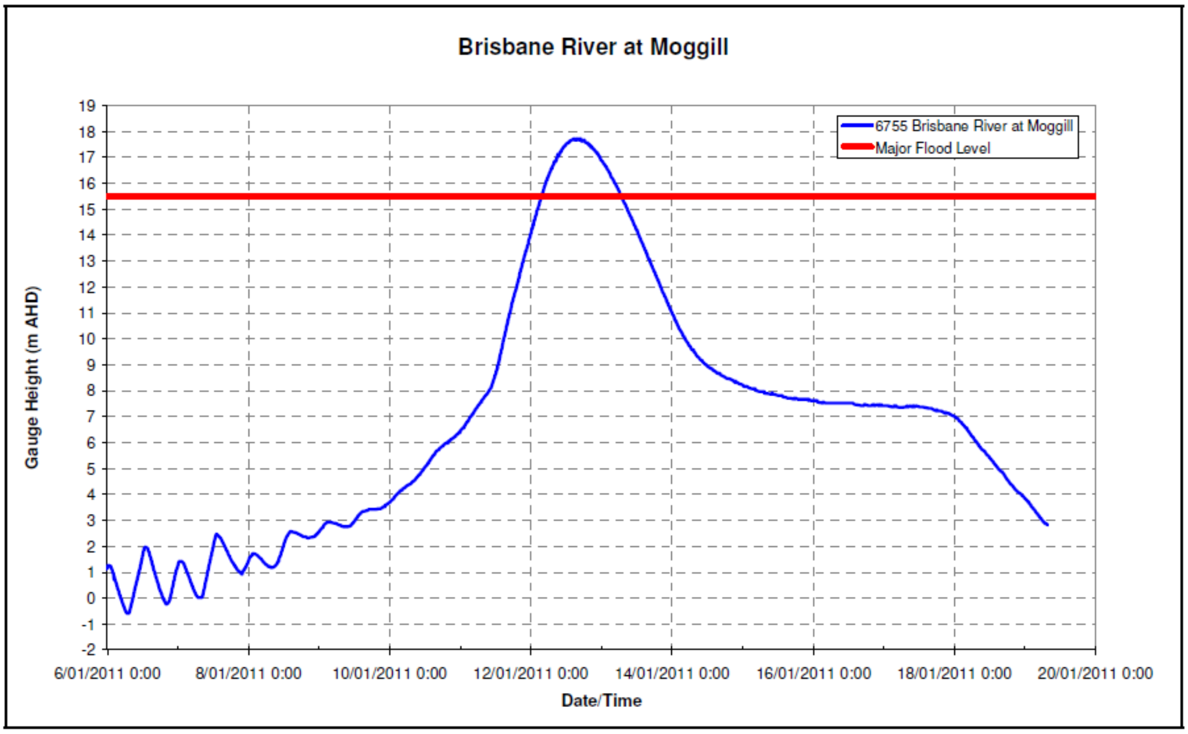

Figure 9: Flood Levels – Brisbane River at Moggill (Source: Seqwater, 2011)

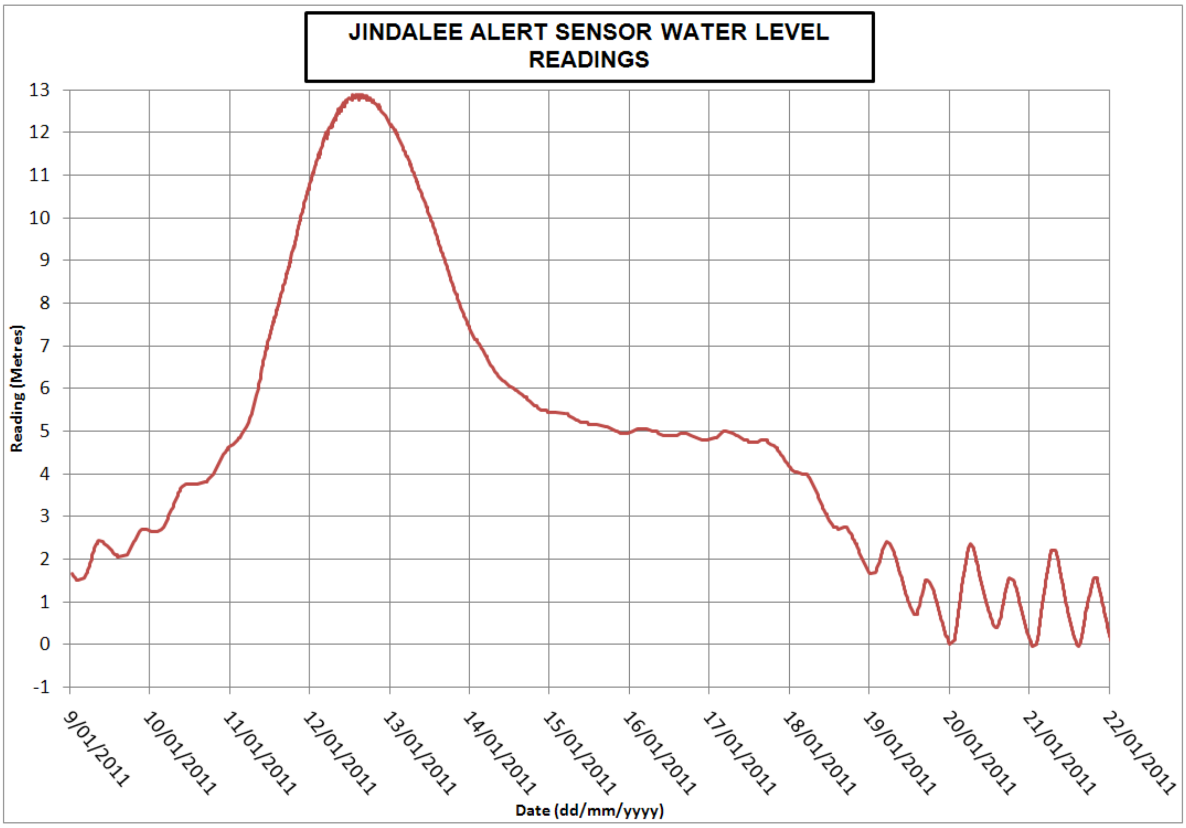

Figure 10: Flood Levels – Brisbane River at Jindalee Alert

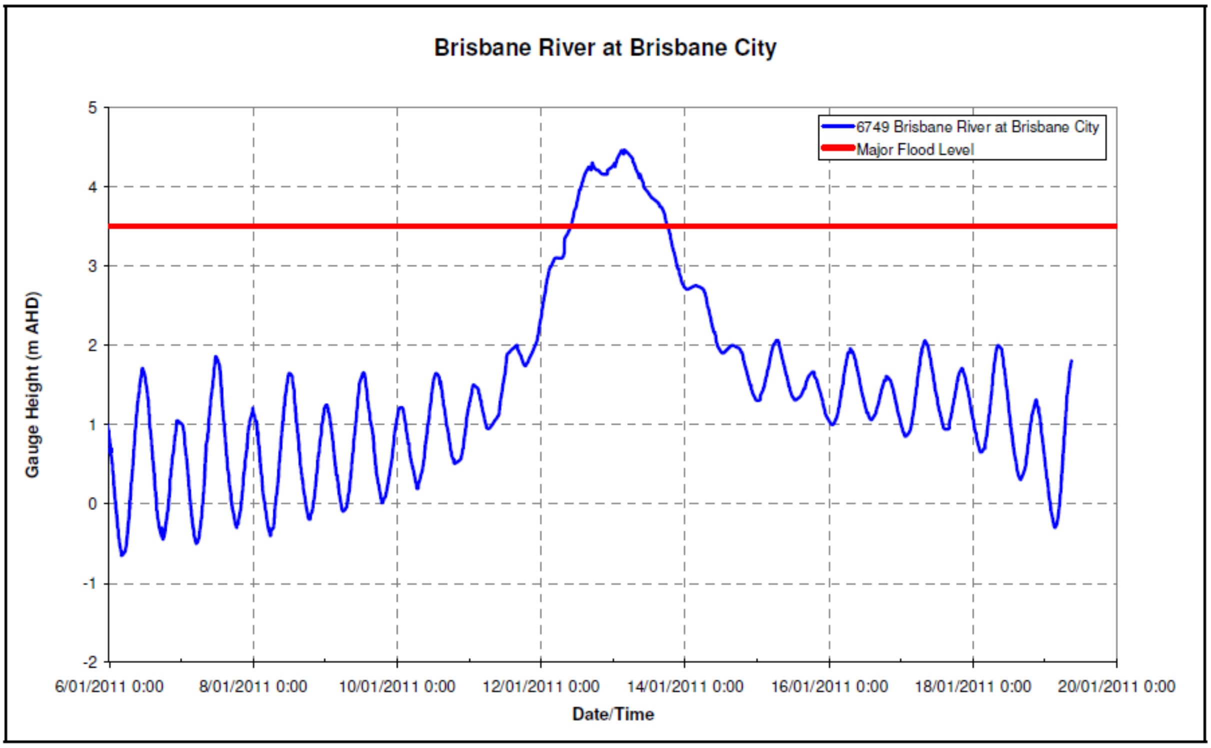

Figure 11: Flood Levels – Brisbane River at Port Office Gauge Height (Source: Seqwater, 2011)

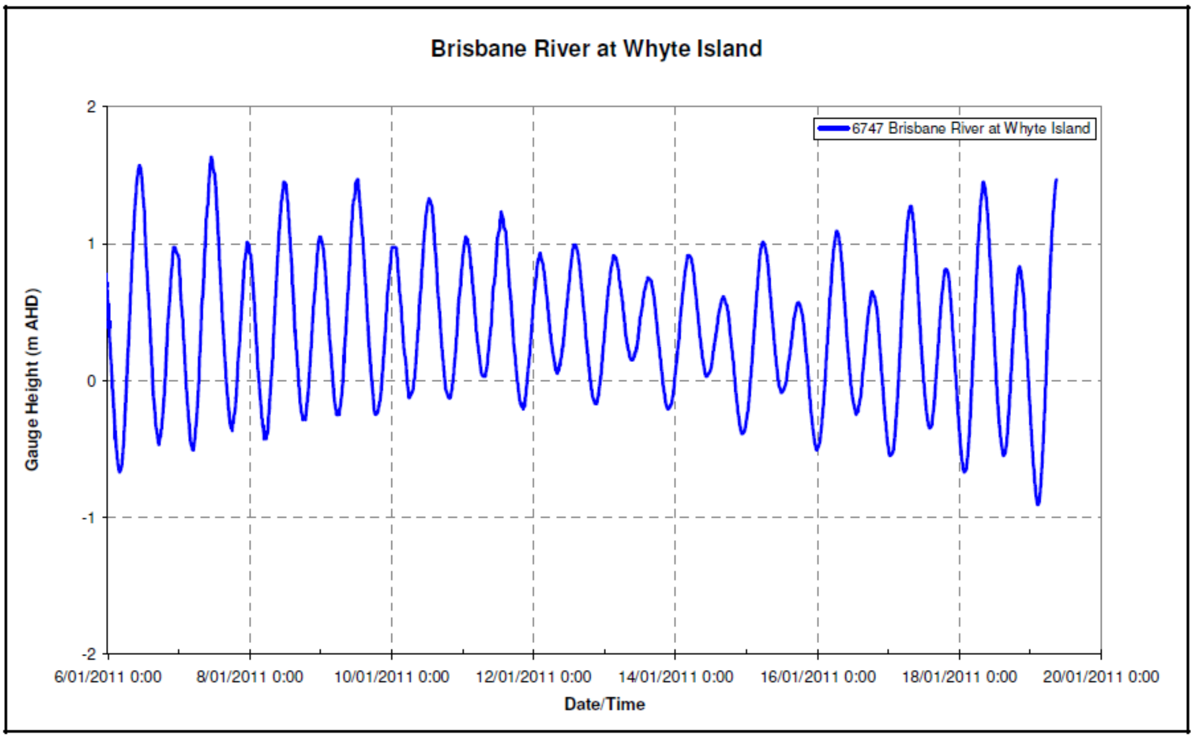

Figure 12: Flood Levels – Brisbane River at Whyte Island (Source: Seqwater, 2011)

7.5. Transition from Prioritising Mitigation to Prioritising Dam Safety

134 The primary overriding objective of The Manual is to ensure the structural safety of the dams. Secondary objectives, in order of importance, include protection of urban areas from inundation, and minimising disruption of rural life in areas downstream of Wivenhoe Dam.

135 As discussed in Section 4.2, these objectives would dictate different and somewhat opposing strategies if considered alone. A policy concerned solely with protecting the dam structural integrity would dictate larger early dam releases to preserve a protective buffer against later inflows that might threaten to overtop the dam, whereas a policy biased more towards protection of downstream areas might withhold dam releases until absolutely necessary.

136 The Manual describes four operational strategies for Wivenhoe Dam (W1 to W4) and three strategies for Somerset Dam (S1 to S3). Strategies W1 to W3 and S1 to S2 are used when the risk of a fuse plug failure at Wivenhoe Dam is assessed to be unlikely, and the mandates to minimise urban inundation and disruption of rural life in downstream areas become the primary consideration. Once storage levels in Wivenhoe Dam approach the upper limits of available flood mitigation capacity, strategies W4 and S3 may be triggered, under which the structural integrity of the dam is the overriding focus.

137 The procedures outlined in The Manual generally provide a reasonable balance between the objectives of preserving dam safety while mitigating the damage and disruption of flooding in downstream area. As mentioned above, the dams successfully reduced the

peak flood flow in the Lower Brisbane River below what would have naturally occurred without the dams in place. However the January 2011 flooding has illustrated some possible areas of weakness with the current procedures.

138 Under some circumstances the current trigger criteria for transition from Strategy W3 to W4 can result in a sudden switch in primary objective, resulting in dramatic escalation of dam releases. This scenario occurred on Tuesday 11 January 2011 (Document 9, pp 158-159). From midnight until 8:00am, outflows from Wivenhoe Dam were held reasonably constant at around 2750 m^3/s, in line with the target maximum flow for Strategy W3 of 4,000 m^3/s at Moggill (presumably in combination with estimated contributing flows from other catchments of approximately 1250 m^3/s at Moggill at that time).

139 Rising lake levels in Wivenhoe Dam caused Strategy W4 to be triggered, with the release from Wivenhoe Dam reaching a peak of almost 7,500 m^3/s at 7:00pm that evening, at which time lake levels began to subside. This represents an almost threefold increase in outflow over an 11-hour period once Strategy W4 was executed.

140 With the benefit of hindsight, it is clear that an earlier escalation of the dam outflow rate would have reduced the ultimate peak release discharge downstream of Moggill, including at the Brisbane CBD. However it appears that earlier releases could have exacerbated flooding at Ipswich and the lower Lockyer Valley. It is questionable whether the Flood Engineers had sufficiently reliable information to justify an earlier transition to Strategy W4 or to increase releases to greater than the target allowed under Strategy W3.

141 It must be remembered that no operational procedure can produce the optimal outcome for all floods. However this event suggests that a smoother transition between maximising mitigation and ensuring dam safety would provide benefits for certain larger floods. Methods for achieving the smoother transition may include a scheduled increase in target flow as dam levels increase towards the trigger for Strategy W4, variation of the trigger lake level, and variation of the maximum allowable flow rate under Strategy W3.

7.6. Inclusion of Forecast Rainfall in Operational Strategies

7.6.1. Use of Forecast Rain in Gate Operations for January 2011 Floods

142 It is apparent from the Flood Operation Engineer statements (Witness Statement of Robert Arnold Ayre) that the forecast rain was not considered sufficiently reliable to be used to inform operational decisions and was only used to provide possible insight into the operational situation they would be in at a later time.

143 With the quality of the forecast information getting more reliable over time, a process should be developed to determine to what extent forecast rainfall should be used in the operation of the dams. Table 5 and Figure 13 (plotted in the same plotting format as Document 20a, SKM, 2011) shows that all the predictions up to and including the peak were either under estimates or within 20 mm of the forecast.

Table 5: Forecast vs Observed Rainfall (mm)

Date/Time of issue	Forecast for 24 hours to:	24-hour Catchment average forecast rainfall (mm)	24-hour Catchment average actual rainfall (mm)	Error (mm)	% error if error greater than 20mm and is an over-prediction	% error if error greater than 20mm and is an under - prediction
Mon 03/01/2011 11:36	Tue 04/01/2011 09:00	8	5	3		
Mon 03/01/2011 16:00	Tue 04/01/2011 15:00	15	4	11		
Tue 04/01/2011 11:30	Wed 05/01/2011 09:00	15	0	15		
Tue 04/01/2011 16:00	Wed 05/01/2011 15:00	10	2	8		
Wed 05/01/2011 10:03	Thu 06/01/2011 09:00	25	26	-1		
Wed 05/01/2011 16:00	Thu 06/01/2011 15:00	40	44	-4		
Thu 06/01/2011 10:21	Fri 07/01/2011 09:00	40	38	2		
Thu 06/01/2011 16:00	Fri 07/01/2011 15:00	25	43	-18		
Fri 07/01/2011 10:03	Sat 08/01/2011 09:00	25	26	-1		
Fri 07/01/2011 16:04	Sat 08/01/2011 15:00	25	6	19		
Sat 08/01/2011 10:03	Sun 09/01/2011 09:00	40	28	12		
Sat 08/01/2011 16:00	Sun 09/01/2011 15:00	40	80	-40		50%
Sun 09/01/2011 10:03	Mon 10/01/2011 09:00	50	149	-99		34%
Sun 09/01/2011 16:00	Mon 10/01/2011 15:00	65	125	-60		52%
Mon 10/01/2011 10:03	Tue 11/01/2011 09:00	75	120	-45		63%
Mon 10/01/2011 16:00	Tue 11/01/2011 15:00	38	129	-91		29%
Tue 11/01/2011 10:13	Wed 12/01/2011 09:00	100	51	49	196%	
Tue 11/01/2011 16:00	Wed 12/01/2011 15:00	75	12	63	625%	
Wed 12/01/201110:03	Thu 13/01/2011 09:00	10	2	8		
Wed 12/01/2011 16:00	Thu 13/01/2011 15:00	5	1	4		
Thu 13/01/2011 14:25	Fri 14/01/2011 09:00	5	0	5		
Thu 13/01/2011 16:00	Fri 14/01/2011 15:00	5	0	5		
Fri 14/01/2011 10:03	Sat 15/01/2011 09:00	3	0	3		
Fri 14/01/2011 16:00	Sat 15/01/2011 15:00	3	0	3		

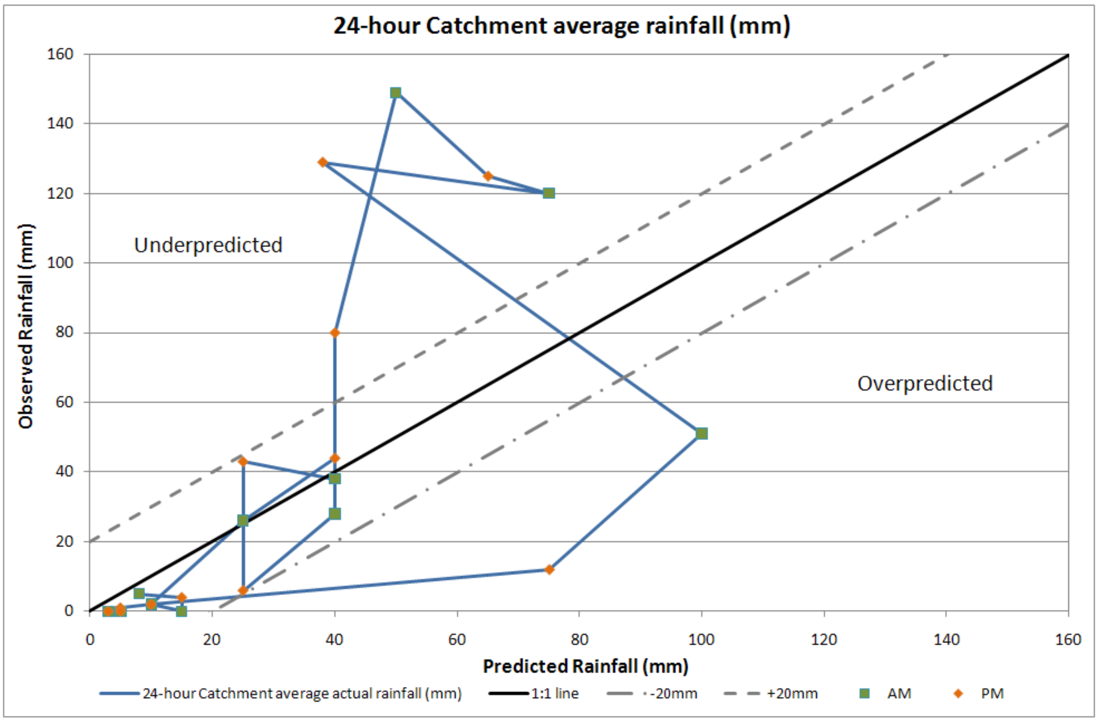

Figure 13: 24 hour Catchment Average Rainfall - Predicted vs Observed

7.6.2. Incorporation of Rainfall Predictions in Operational Strategies

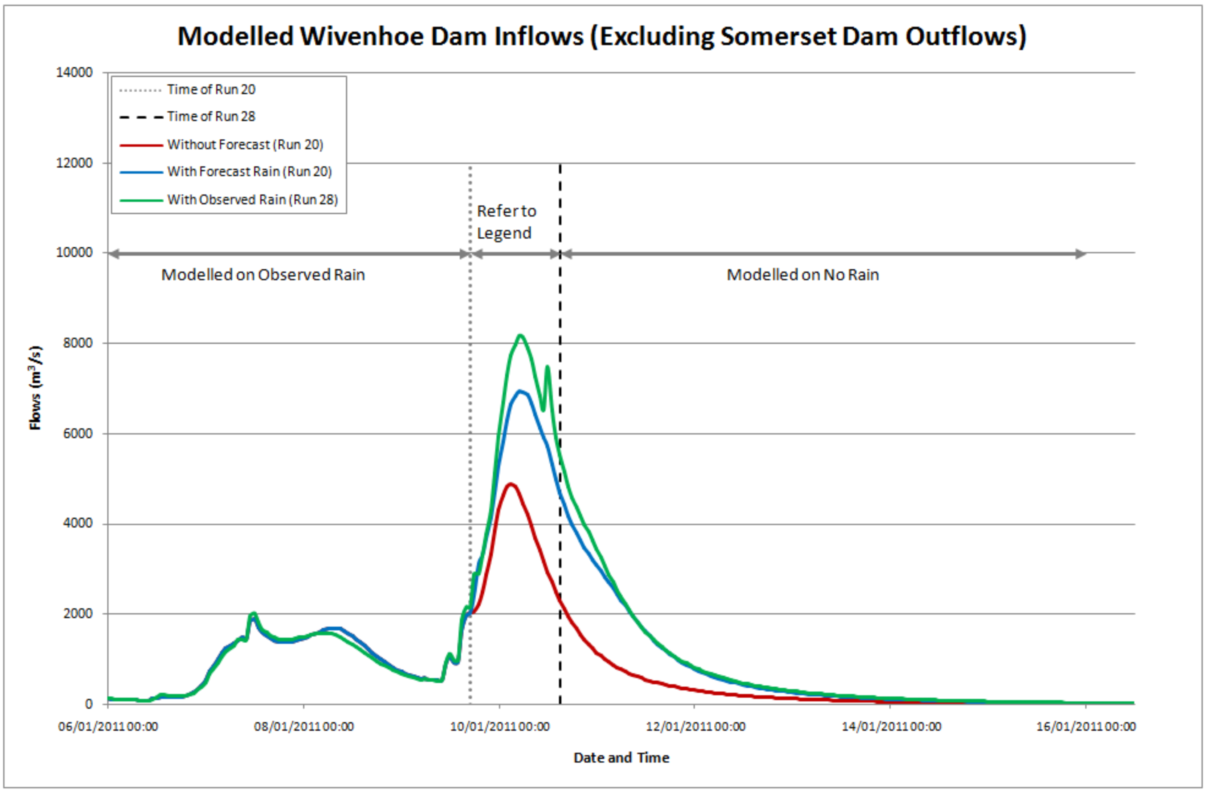

Figure 14: Modelled Wivenhoe Dam Inflows – Runs 20 and 28

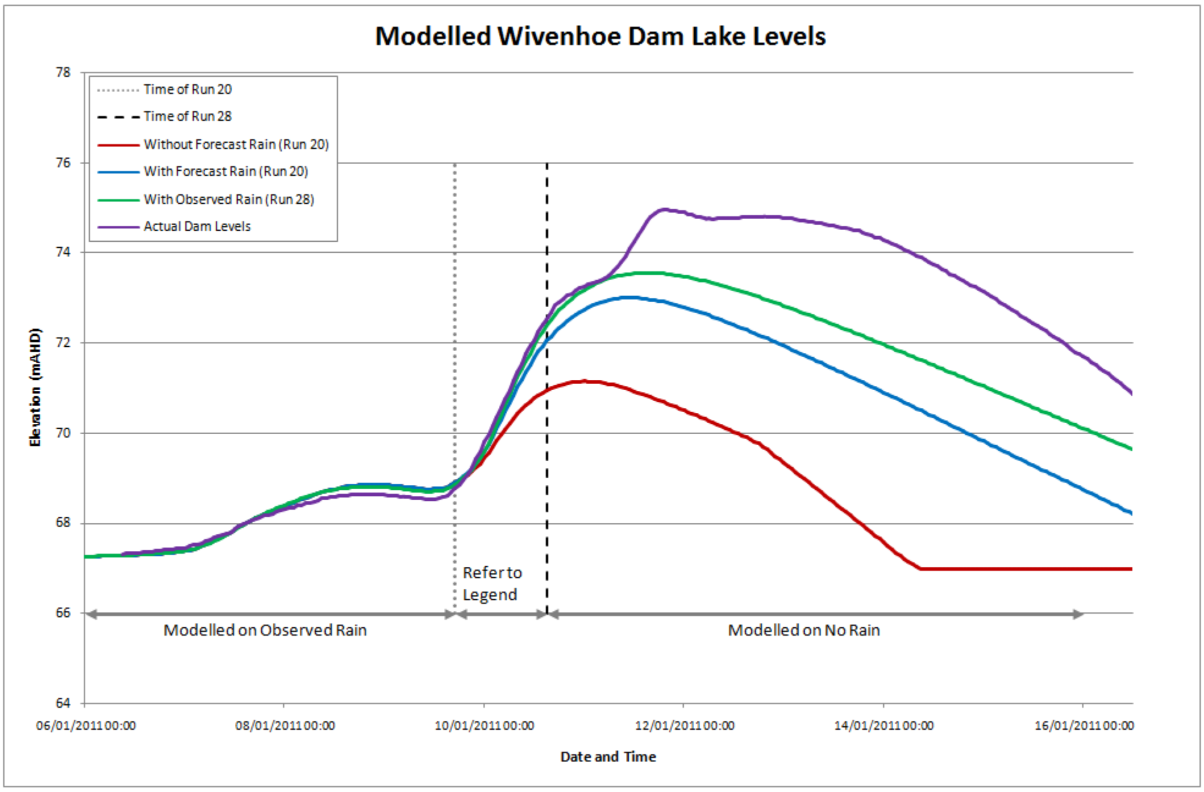

Figure 15: Modelled Wivenhoe Dam Lake Levels – Runs 20 and 28

144 When rainfall forecasts are reliable they can provide significant benefit in estimating how the flood will proceed. Figure 14 and Figure 15 show the predicted dam inflow and lake level respectively for "Run 20" (Document 9, Appendix A) with and without forecast rain. Results for "Run 28" are also plotted, which provide an indication of the actual inflows that occurred in the 24 hours subsequent to the predictions from "Run 20." Figure 15 also shows the measured dam water level for the entire event. In this case it is clear that the incorporation of the forecast rainfall would have provided a better estimate.

145 It is noted that up until the peak of the January 2011 forecast rainfalls were generally less than what was actually recorded (refer to Section 7.6.1). If the forecasts had been over-predictions, the model results incorporating predicted rain may have been less accurate than those assuming no further rain.

146 Incorporation of predicted rainfall into the decision-making process for The Manual should be considered.

147 Predicted rainfall could have some discount applied for input into flood-forecasting models to account for uncertainty. This is likely to provide a more reasonable estimate than assuming no additional rain at all times.

148 Incorporation of predicted rainfall might take such a form as "the decision to move to Strategy W4 should be taken when the actual lake level exceeds 73.5m, or the predicted lake level (using predicted rainfall with a 50% discount factor) exceeds 74.5m, whichever occurs first."

149 Simulation of such a strategies involving predicted rainfall can be complex, as erroneous rainfall forecasts must be generated to properly simulate the effects of being wrong. However the statistical tools to undertake such modelling are available.

7.7. Real-Time Estimation of Dam Inflows

150 During the event problems arose with flood-forecasting model. At around 1pm on Tuesday 11 January, about the time of "Run 39" (Document 9, Appendix A), the engineers were unable to tune the rainfall runoff-routing model to match increases in observed water levels in the dam, and switched to reverse-routing as the basis for dam releases (Supplementary Witness Statement of Robert Arnold Ayre, pp 56, paragraph 157).

151 This is not unexpected during a large event as the ability to tune the rainfall runoff-routing model to observed levels becomes more difficult if the model has not been calibrated to events of this magnitude. There are also problems with rating curves being extrapolated beyond the reliable range and any errors in the dam stage storage relationship can make tuning difficult. These errors may also accumulate. It is clear from the radar images that the rain gauge network struggled to pick up some intense parts of the storm. The operator's principal calibration tool is the adjustment of losses to match observed flows

and volume and is discussed in Document 20a (SKM, 2011) where it is referred to as "closing the loop." This process assumes all model parameters and measurements are correct.

152 Data from the January 2011 flood event will provide an opportunity to fine tune the calibration of the rainfall runoff-routing model for large events, rating curves and spatial interpolation of rainfall from the gauge network. The relative contribution of each to the discrepancy between modelled and observed flow should be quantified. Since it is the first large event since the construction of Wivenhoe Dam the rating of the gates and the dams stage storage relationship should be considered. While no evidence has been found to suggest there is an issue with the rating of the gates or the dam storage relationship it is considered necessary to confirm the reliability, particularly if reverse-routing is going to be relied upon in the future.

7.8. Dam Drawdown in Anticipation of Flooding

153 Under the current operational strategy, it is unlikely that having the dam drawn down prior to January 6 would have made any substantial difference to peak outflow released from the dam, as the extra dam volume would have been filled during the early part of the flood, well before the second peak.

154 Any decision to change the FSL of the dams or to undertake drawdown based on seasonal forecasts needs to look at trade-offs in economic and humanitarian cost of increased flood mitigation at the expense of water supply security.

7.9. Discretion in Flood Operations

155 The Manual bestows discretionary authority on the Senior Flood Engineer to depart from the specified operational procedures, provided that reasonable attempts are made to "consult with the Chairperson and Chief Executive." The Manual does not provide any guidance on circumstances under which it is foreseen discretion maybe necessary.

156 The provision for such discretion is important as it allows flexibility should circumstances arise that were not foreseen in the development of operational procedures, such as flood behaviour well outside assumed parameters, or in situations where aspects of the data collection network or gate control systems have failed.

157 It appears from statements in the original Draft Manual (1985) that the allowance for discretion was also expected to result in improved flood mitigation performance.

> *"The floods of February 1893 and January 1974 would be reduced to approximately 4 metres and 4.6 metres on the Brisbane City Gauge respectively if the procedures in the manual were strictly followed. However, these levels can be reduced to 3.4 metres and 4 metres respectively using the discretionary powers of the Engineer.*

"The procedures were designed to ensure the safety of the dams whilst reducing the magnitude of downstream flooding. For floods of magnitudes similar to 1893 and 1974, there is ample storage available for the Engineer to use his discretionary powers."

158 There is an implication that in large floods, the Senior Flood Engineer may decide that early escalation of dam releases is advantageous, and will have the authority to act on this assessment. However it is worth considering the circumstances under which the Senior Flood Engineer is likely to invoke such discretionary powers. It may be unrealistic to assume that the Senior Flood Engineer will have the confidence to increase outflows above target levels in the knowledge that such a decision will result in an increase in flood damage downstream (at least in the short term), even if he/she believes the eventual peak outflow would be reduced based on current forecasts. Such a decision must necessarily be taken based on forecast information with a high level of uncertainty, and could produce an adverse rather than a beneficial result if the forecasts are incorrect.

159 It is less likely that discretion will be exercised by the Senior Flood Engineer to escalate dam releases (and less likely that such a decision will be supported by the approving authority), as opposed to a scenario when it is desirable to reduce outflows below standard procedure on the expectation that rainfall/inflows are easing and forecast inflows can be safely captured by the dam.

160 This view is supported by the Witness Statement of Robert Arnold Ayre (paragraph 271, page 56) regarding flood operations for the January 2011 flood:

"During the January 2011 Flood Event, the only occasion on which I considered exercising my discretion under section 2.8 (at approximately 9pm on Monday 10 January 2011) was in proposing not to invoke strategy W4 at a time when Wivenhoe Dam was approaching the 74.0m AHD level ..."

161 This is an important issue for consideration during a review of The Manual. The natural inclination to exercise discretion to withhold dam releases, rather than increasing dam releases, should be recognised in the development of operational procedures. For example, in investigating options for transition from maximising flood mitigation to ensuring dam safety, it may be sensible to adopt an outflow strategy that targets higher and earlier outflows than those currently specified. This would be expected to result in slightly reduced mitigation performance in moderate-sized floods, but potentially significant improvements in mitigation of very large floods.

162 The Manual could be improved by providing some guidance on foreseeable circumstances whereby discretion might be employed.

7.10. Working Conditions for Flood Operations

163 The working conditions under which flood operations personnel performed their duties during the January 2011 floods were very demanding. It is recommended that where possible, changes be implemented that would enable Flood Operations Engineers to focus on tasks requiring their particular skills, training and responsibilities.

8. RESPONSES TO QUESTIONS FROM THE COMMISSION

Brief answers to the specific questions asked by The Commission are provided below. These answers rely on the information presented in this report for context.

To what extent was flooding (other than flash flooding) in the Brisbane, Ipswich and the Lockyer Valley caused by releases from the Somerset and Wivenhoe Dams?

164 Flooding occurred due to runoff from each of the Brisbane, Ipswich and Lockyer Valley catchments. The releases from Wivenhoe Dam were the major component of the flood peak in the Brisbane River.

To what extent did the manner flood waters were released from the Somerset and Wivenhoe Dams avoid or coincide with peak flows from the Bremer River and Lockyer Creek?

165 When the Wivenhoe Dam operational strategy is primarily concerned with flood mitigation (Strategy W1 to W3), there is an objective to prevent the combined flow of dam releases with flows from the Bremer River and Lockyer Creek exceeding damaging levels. This objective was fulfilled while operating under Strategies W1 to W3. When the primary focus of the dam gate operations changed from mitigation (W3) to dam security (W4) water was released without consideration of timing with flow from other catchments in order to preserve the structural integrity of the dam and avoid potential fuse plug failure or breaching of the dam wall. By this stage it was inevitable that releases from Wivenhoe Dam would coincide with peak discharges from other catchments. Once the dam levels were stabilised, the total downstream flow became a primary consideration again, and efforts were made to reduce flows within target levels as soon as was feasible.

To what extent did the manner in which flood releases were made from Somerset and Wivenhoe Dams avoid or coincide with high tides in the Brisbane River?

166 The releases from the dam coincided with high tides in Brisbane River. This outcome was unavoidable as the period of high discharge spanned more than the time between two high tides. The high tides during this period were however relatively low. Further discussion is provided in Section 7.4.2.

Were the releases from the Somerset and Wivenhoe Dams in accordance with the flood manual?

167 Three independent reviews found that the dam releases were in accordance with The Manual. Minor deviations were observed that were attributed to ambiguity within The Manual. Further discussion is provided in Section 5.6.

What were the consequences of not more rapidly escalating releases from the Wivenhoe *and Somerset Dams between 6 and 11 January 2011?*

168 Escalating flows earlier would have resulted in lower peak discharges and flood levels in the Brisbane River at Brisbane. It is possible that earlier escalation of flows may have increased flood levels at Ipswich. The extent to which levels would have changed can only be determined using modelling that is not currently available. Optimal mitigation of any given flood can only be achieved with accurate foreknowledge of the dam inflow hydrograph. It should be remembered that no mitigation strategy can produce the optimal outcome for all floods.

Does the flood manual adequately address needs for flood management during a major flood?

169 The Manual is broadly effective for the mitigation of large floods, however the January 2011 flood event highlighted some potential areas where it could be improved. These issues are discussed in Sections 6 and 7.

In relation to releases from the Somerset and Wivenhoe system, was the reliance on short term weather forecasts by the Flood Operations Centre appropriate?

170 Rainfall forecasts were not significantly relied upon in making decisions about releases from the Somerset and Wivenhoe system. Short term rainfall forecasts have only recently become sufficiently reliable that it appropriate to consider using them in operational decisions. Incorporation of predicted rainfall into the flood-forecasting and decision-making process for dam flood operations should be considered, perhaps with a discount applied to account for uncertainty. This is likely to provide a more reasonable estimate than assuming no additional rain at all times. Discussion is provided in Section 7.6.

Did the absence of modelling for the combined Somerset/Wivenhoe, Brisbane, Ipswich and Lockyer catchments impact on the capacity of those controlling the Flood Operations Centre to make fully informed assessments as to flood releases? If so, how?

171 This event significantly tested the modelling (forecasting) system and exposed some limitations. Discussion is provided in Section 7.4 Despite these limitations it is unlikely the way the dam was operated for the January 2011 flood event would have changed significantly with an improved modelling system.

Had the levels in Somerset and Wivenhoe Dams been reduced to 75% of full supply level by the end of November 2010 what impact would this have had on the extent of flooding within Brisbane, Ipswich and the Lockyer Valley in January 2011?

172 Under the current operational procedure it is unlikely that reducing the dam to 75% of FSL would have had a significant impact on flood levels downstream of the dam. The amount flood levels would be reduced can only be determined by detailed modelling that has not been undertaken.

9. RECOMMENDATIONS AND CONCLUSIONS

9.1. Design Hydrology

173 The design modelling that was first developed in 1983 should be updated to take full advantage of new techniques for design hydrology and improvements in computing power. This should include an investigation of longer duration floods and larger inflow volumes, preferably using an ensemble or stochastic modelling process where a range of plausible temporal and spatial patterns are considered for a full range of flood events. The modelling process needs to replicate the historical timing differences between the dam inflows and other tributaries upstream of Moggill.

9.2. Gate Operation Strategies for Flood Mitigation

174 Alternative gate operation strategies for flood mitigation should be reviewed using the revised hydrology for a full range of flood events, with consideration of average annual flood damages resulting from each strategy.

175 The review of gate operations should place particular emphasis on the hard transition between the W3 and W4 strategies. Modifications that specify an increasing target discharge at Moggill once key criteria are either reached or predicted to be reached should to be investigated.

9.3. Predicted Rainfall

176 The reliability of using 24 hour forecast rainfall should be assessed and the utility of predicted rainfall for flood-forecasting during an event should be investigated. This assessment should be compared to the default current assumption of assuming no further rain.

177 Methods of treating forecast rainfall could include discounting predicted rainfall to reduce the likelihood of over prediction. The use of ensemble forecasts should also be investigated. The utility of incorporating predicted rainfall into operation decisions could be tested by using a stochastic approach.

9.4. Data network and Modelling

178 Additional rainfall gauges should be added to the rainfall network in catchment areas where the gauge density is relatively low. The data network should be maintained at least to the current standards for future operations.

179 The rating of all streamflow gauges should be reviewed and causes for the forecasting model not matching observed water levels should be quantified. This will require some recalibration of the models.

180 Downstream of the dam the existing rainfall runoff-routing model should be complemented by a calibrated hydrodynamic model so that flood levels and inundation extents corresponding to various discharges in the Brisbane River can be estimated more accurately.

9.5. Discretionary Powers

181 The Manual should include guidance of foreseeable circumstances under which discretionary powers are likely to be exercised, and in what manner.

9.6. Flood Operations

182 It is recommended that where possible, changes be implemented that would enable Flood Operations Engineers to focus on tasks requiring their particular skills, training and responsibilities.

10. REFERENCES

1. Pilgrim H (Editor in Chief)

Australian Rainfall and Runoff – A Guide to Flood Estimation
Institution of Engineers, Australia, 1987.

Appendix A

APPENDIX A: GLOSSARY

Taken from the NSW Floodplain Development Manual (April 2005 edition)

Annual Exceedance Probability (AEP)	The chance of a flood of a given or larger size occurring in any one year, usually expressed as a percentage. For example, if a peak flood discharge of 500 m^3/s has an AEP of 5%, it means that there is a 5% chance (that is one-in-20 chance) of a 500 m^3/s or larger event occurring in any one year (see ARI).
Australian Height Datum (AHD)	A common national surface level datum approximately corresponding to mean sea level.
Average Annual Damage (AAD)	Depending on its size (or severity), each flood will cause a different amount of flood damage to a flood prone area. AAD is the average damage per year that would occur in a nominated development situation from flooding over a very long period of time.
Average Recurrence Interval (ARI)	The long term average number of years between the occurrence of a flood as big as, or larger than, the selected event. For example, floods with a discharge as great as, or greater than, the 20 year ARI flood event will occur on average once every 20 years. ARI is another way of expressing the likelihood of occurrence of a flood event.
catchment	The land area draining through the main stream, as well as tributary streams, to a particular site. It always relates to an area above a specific location.
discharge	The rate of flow of water measured in terms of volume per unit time, for example, cubic metres per second (m^3/s). Discharge is different from the speed or velocity of flow, which is a measure of how fast the water is moving for example, metres per second (m/s).
effective warning time	The time available after receiving advice of an impending flood and before the floodwaters prevent appropriate flood response actions being undertaken. The effective warning time is typically used to move farm equipment, move stock, raise furniture, evacuate people and transport their possessions.
emergency management	A range of measures to manage risks to communities and the environment. In the flood context it may include measures to prevent, prepare for, respond to and recover from flooding.
flash flooding	Flooding which is sudden and unexpected. It is often caused by sudden local or nearby heavy rainfall. Often defined as flooding which peaks within six hours of the causative rain.
flood	Relatively high stream flow which overtops the natural or artificial banks in any part of a stream, river, estuary, lake or dam, and/or local overland flooding associated with major drainage before entering a watercourse, and/or coastal inundation resulting from super-elevated sea levels and/or waves overtopping coastline defences excluding tsunami.
flood awareness	Flood awareness is an appreciation of the likely effects of flooding and a knowledge of the relevant flood warning, response and evacuation procedures.

flood education	Flood education seeks to provide information to raise awareness of the flood problem so as to enable individuals to understand how to manage themselves an their property in response to flood warnings and in a flood event. It invokes a state of flood readiness.
flood liable land	Is synonymous with flood prone land (i.e. land susceptible to flooding by the probable maximum flood (PMF) event). Note that the term flood liable land covers the whole of the floodplain, not just that part below the flood planning level (see flood planning area).
flood mitigation standard	The average recurrence interval of the flood, selected as part of the floodplain risk management process that forms the basis for physical works to modify the impacts of flooding.
floodplain	Area of land which is subject to inundation by floods up to and including the probable maximum flood event, that is, flood prone land.
Flood Planning Levels (FPLs)	FPL's are the combinations of flood levels (derived from significant historical flood events or floods of specific AEPs) and freeboards selected for floodplain risk management purposes, as determined in management studies and incorporated in management plans. FPLs supersede the "standard flood event" in the 1986 manual.
flood proofing	A combination of measures incorporated in the design, construction and alteration of individual buildings or structures subject to flooding, to reduce or eliminate flood damages.
flood prone land	Is land susceptible to flooding by the Probable Maximum Flood (PMF) event. Flood prone land is synonymous with flood liable land.
flood readiness	Flood readiness is an ability to react within the effective warning time.
flood risk	Potential danger to personal safety and potential damage to property resulting from flooding. The degree of risk varies with circumstances across the full range of floods. Flood risk in this manual is divided into 3 types, existing, future and continuing risks. They are described below. **existing flood risk:** the risk a community is exposed to as a result of its location on the floodplain. **future flood risk:** the risk a community may be exposed to as a result of new development on the floodplain. **continuing flood risk:** the risk a community is exposed to after floodplain risk management measures have been implemented. For a town protected by levees, the continuing flood risk is the consequences of the levees being overtopped. For an area without any floodplain risk management measures, the continuing flood risk is simply the existence of its flood exposure.
flood storage areas	Those parts of the floodplain that are important for the temporary storage of floodwaters during the passage of a flood. The extent and behaviour of flood storage areas may change with flood severity, and loss of flood storage can increase the severity of flood impacts by reducing natural flood attenuation. Hence, it is necessary to investigate a range of flood sizes before defining flood storage areas.
	Those areas of the floodplain where a significant discharge of water occurs during

floodway areas	floods. They are often aligned with naturally defined channels. Floodways are areas that, even if only partially blocked, would cause a significant redistribution of flood flows, or a significant increase in flood levels.
freeboard	Freeboard provides reasonable certainty that the risk exposure selected in deciding on a particular flood chosen as the basis for the FPL is actually provided. It is a factor of safety typically used in relation to the setting of floor levels, levee crest levels, etc. Freeboard is included in the flood planning level.
habitable room	**in a residential situation:** a living or working area, such as a lounge room, dining room, rumpus room, kitchen, bedroom or workroom. **in an industrial or commercial situation:** an area used for offices or to store valuable possessions susceptible to flood damage in the event of a flood.
hazard	A source of potential harm or a situation with a potential to cause loss. In relation to this manual the hazard is flooding which has the potential to cause damage to the community. Definitions of high and low hazard categories are provided in the Manual.
hydraulics	Term given to the study of water flow in waterways; in particular, the evaluation of flow parameters such as water level and velocity.
hydrograph	A graph which shows how the discharge or stage/flood level at any particular location varies with time during a flood.
hydrology	Term given to the study of the rainfall and runoff process; in particular, the evaluation of peak flows, flow volumes and the derivation of hydrographs for a range of floods.
local overland flooding	Inundation by local runoff rather than overbank discharge from a stream, river, estuary, lake or dam.
local drainage	Are smaller scale problems in urban areas. They are outside the definition of major drainage in this glossary.
mainstream flooding	Inundation of normally dry land occurring when water overflows the natural or artificial banks of a stream, river, estuary, lake or dam.
major drainage	Councils have discretion in determining whether urban drainage problems are associated with major or local drainage. For the purpose of this manual major drainage involves: • the floodplains of original watercourses (which may now be piped, channelised or diverted), or sloping areas where overland flows develop along alternative paths once system capacity is exceeded; and/or • water depths generally in excess of 0.3 m (in the major system design storm as defined in the current version of Australian Rainfall and Runoff). These conditions may result in danger to personal safety and property damage to both premises and vehicles; and/or • major overland flow paths through developed areas outside of defined drainage reserves; and/or • the potential to affect a number of buildings along the major flow path. •

mathematical/computer models	The mathematical representation of the physical processes involved in runoff generation and stream flow. These models are often run on computers due to the complexity of the mathematical relationships between runoff, stream flow and the distribution of flows across the floodplain.
minor, moderate and major flooding	Both the State Emergency Service and the Bureau of Meteorology use the following definitions in flood warnings to give a general indication of the types of problems expected with a flood: **minor flooding:** causes inconvenience such as closing of minor roads and the submergence of low level bridges. The lower limit of this class of flooding on the reference gauge is the initial flood level at which landholders and townspeople begin to be flooded. **moderate flooding:** low-lying areas are inundated requiring removal of stock and/or evacuation of some houses. Main traffic routes may be covered. **major flooding:** appreciable urban areas are flooded and/or extensive rural areas are flooded. Properties, villages and towns can be isolated.
peak discharge	The maximum discharge occurring during a flood event.
Probable Maximum Flood (PMF)	The PMF is the largest flood that could conceivably occur at a particular location, usually estimated from probable maximum precipitation, and where applicable, snow melt, coupled with the worst flood producing catchment conditions. Generally, it is not physically or economically possible to provide complete protection against this event. The PMF defines the extent of flood prone land, that is, the floodplain. The extent, nature and potential consequences of flooding associated with a range of events rarer than the flood used for designing mitigation works and controlling development, up to and including the PMF event should be addressed in a floodplain risk management study.
Probable Maximum Precipitation (PMP)	The PMP is the greatest depth of precipitation for a given duration meteorologically possible over a given size storm area at a particular location at a particular time of the year, with no allowance made for long-term climatic trends (World Meteorological Organisation, 1986). It is the primary input to PMF estimation.
probability	A statistical measure of the expected chance of flooding (see AEP).
risk	Chance of something happening that will have an impact. It is measured in terms of consequences and likelihood. In the context of the manual it is the likelihood of consequences arising from the interaction of floods, communities and the environment.
runoff	The amount of rainfall which actually ends up as streamflow, also known as rainfall excess.
stage	Equivalent to “water level”. Both are measured with reference to a specified datum.
stage hydrograph	A graph that shows how the water level at a particular location changes with time during a flood. It must be referenced to a particular datum.
water surface profile	A graph showing the flood stage at any given location along a watercourse at a particular time.

Appendix B

[redacted]

Mark Kenneth BABISTER

POSITION: Managing Director

DATE OF BIRTH: [redacted]

NATIONALITY: Australian

PROFESSION: Civil Engineer

QUALIFICATIONS:

$ Bachelor of Engineering (Civil) Honours
University of NSW, 1988

$ Master of Engineering Science
University of NSW, 1993

- Graduate Diploma in Management
Deakin University, 1997

MEMBERSHIP & COMMITTEES:

$ Engineers Australia (CPEng, NPER)

$ Registered Professional Engineer of Queensland (RPEQ)

$ Chair of Engineers Australia, National Committee on Water Engineering

$ AR&R Revision Steering and Technical Committees

$ Former Chair of Sydney Division Water Engineering Panel, Engineers Australia

$ Chair of Organising Committee for 2003 International Hydrology & Water Resources Symposium

SPECIAL FIELDS OF COMPENTENCE

- ***Community Engagement on Major Water Resource Projects***
- ***Hydrologic Modelling***
- ***Hydraulic Modelling***
- ***Floodplain Management***
- ***Flood Frequency, Joint Probability Analysis and Risk Assessments***
- ***Computer Programming***
- ***Data Collection, Analysis and Presentation***

PROFESSIONAL EXPERIENCE

WMAwater (formerly Webb, McKeown & Associates Pty Ltd)
September 1988 - to Date

Hydrological Studies

$ Project Director - State of the Darling Basin Report for MDBC
$ Project Director - Coxs River IQQM Review for Delta Electricity
$ Project Director - Coxs River Mass Balance Review for DIPNR
$ Project Manager - Hawkesbury-Nepean Water Use Study for DLWC
$ Project Manager - Impact of Farm Dams on Streamflow in Hawkesbury-Nepean Catchment for DLWC
$ Project Manager - Assessment of the Homogeneity of Streamflow on Hawkesbury-Nepean Catchment for DLWC
$ Project Manager - Macquarie Marshes RUBICON programming for DLWC
$ Project Engineer - HMAS Kuttabul
$ Project Engineer - Buttonderry Landfill for Wyong City Council
$ Project Manager - Review of the Bellinger, Kalang and Nambucca River Catchments Hydrology

Floodplain Management

$ Project Manager - Riverstone Bypass Flood Study for RTA
$ Project Manager - Penrith Lakes Development Flood Management Options for Bowdens
$ Project Manager - Lord Howe Island for Lord Howe Island Board
$ Project Manager - Investigation of Hawkesbury/Nepean Floodplain for Sydney Water Board
$ Project Manager - Lochinvar for Maitland City Council
$ Project Manager - Investigation of Floodplain Management Measures in Hawkesbury River for Hawkesbury-Nepean Flood Management Advisory Committee
$ Project Manager - Wolli Creek Station Flood Study for NSR Transfield/Bouygues
$ Project Engineer - Hunter River for Maitland Council
$ Project Manager - Parramatta Rail Link for Maunsell McIntyre
$ Project Manager - Cooks Cove for Maunsell McIntyre
$ Project Manager - Upper Yarraman Creek FPM Plan for DLWC

$ Project Manager - Wagga FPM Study for Wagga City Council
$ Project Manager - Carroll Boggabri FPM Plan for DIPNR
$ Project Manager - Kempsey Flood Study
$ Project Manager - Newry Island Flood Study
$ Project Manager - Deep Creek Flood Study
$ Project Manager - Kurnell Flood Study, Floodplain Risk Management Study and Plan

Hydraulic Modelling

$ Project Manager - M5 Motorway Cooks River Crossing Flood Study for Hyder Consulting
$ Project Manager - Warragamba Dam Inter Departmental Committee Study for NSW Government
$ Project Manager - Wooyung/Mooball Flood Investigation for Tweed and Byron Councils
$ Project Manager - Warriewood Wetlands - Henroth Pty Ltd
$ Project Engineer - Wombarra Hydraulic Study for State Rail Authority
$ Project Engineer - Illawarra Railway Culvert Upgrading for State Rail Authority
$ Project Engineer - Macleay River Flood Gate Operation for Kempsey Shire Council
$ Project Manager - Emu Plains Local Hydraulics for DLWC
$ Project Manager - Kempsey to Eungai Pacific Highway Upgrade for PPK Environment & Infrastructure
$ Project Manager - Lane Cove River Crossing for Parramatta Rail Link Company
$ Project Manager - Riverview Road Levee Gradient for DLWC
$ Project Manager - New Southern Railway Cooks River Crossing for Transfield Bouygues Joint Venture
$ Project Manager - Warragamba Dam Side Spillway for AWT
$ Project Manager - Bethungra Dam PMF and Dambreak for DLWC
$ Project Manager - South Creek High Level Crossing for DLWC
$ Project Manager for various studies in Hawkesbury - Nepean catchment for DLWC
$ Project Manager - Kempsey to Frederickton Pacific Highway Upgrade - Project Implementation
$ Project Manager - Australian Rainfall and Runoff Research Project 15 - Two Dimensional Simulation

Design Flood Estimation

$ Project Manager - Bethungra Dam PMF and Dambreak Assessment for DLWC
$ Project Engineer - Review of Lower Hastings Design Flood Levels for Hastings Shire Council
$ Project Manager - Lord Howe Island Design Rainfall Assessment for DLWC
$ Project Manager - NSW - FORGE Project Data Compilation for DLWC
$ Project Manager - Warragamba Mitigation Dam for Sydney Water Board
$ Project Manager - Warragamba Dam Side Spillway, Freeboard, Dambreak and Sunny Day Failure Studies
$ Project Engineer - Moruya River Flood Study for Eurobodalla Shire Council
$ Project Engineer - Lord Howe Island Flood Study for Lord Howe Island Board
$ Project Manager - Wombarra Drainage for RSA
$ Project Manger - Australian Rainfall and Runoff Research Project 3 - Temporal Patterns of rainfall – Testing of an alternative temporal pattern approach

Stormwater Management

$ Project Engineer - Sheas Creek for Sydney Water Board

Coastal & Estuarine Studies

$ Project Engineer - Batemans Bay Coastal Management Study
$ Project Engineer - Lake Cathie/Lake Innes Management Study for Hastings Council and National Parks
$ Project Manager - Development of an Eroding Entrance Model for Breakout of Coastal Lagoons

Legal Proceedings

$ Court Appointed Expert - Oceanic Developments vs Minister for Planning
$ Expert Witness for the following:
    $ Primo Estates vs. Wagga City Council
    $ Kurnell Lodge
    $ McGirr & Xenos - Woodford Street, Longueville
$ Project Manager - EPA vs Camilleri=s Stockfeeds Pty Ltd for NSW Environment Protection Authority
$ Project Manager - EPA vs ADI Murray River for NSW Environment Protection Authority
$ Project Manager - Warriewood Valley Pty Ltd vs Pittwater Council
$ Project Manager - Davis-Firgrove Estate, Dubbo for North & Badgery
$ Project Manager - Bourne ats Kurnell Lodge Pty Ltd

SYDNEY WATER BOARD
Southern Region - Systems Planning Group
July 1983 to August 1988

Involved in various aspects of water supply and sewer investigation. This included performance assessment of sewerage pumping systems and investigation, design and operation of reticulation and trunk watermains, modelling of network performance and water hammer, water supply operation and maintenance, reservoir design and stormwater construction. Construction experience included onsite supervision of stormwater channels at Woolloomooloo and Double Bay.

PUBLICATIONS

1993 RUBICON - An Unsteady Flow Branched Model

1993 Dealing with the Zero Depth Problem within the PIPENET Solution Algorithm

1994 A Review of Numerical Procedures for Routing Unsteady Flows Along a Dry Bed

1998 Batemans Bay Coastal Management: A Sustainable Future

1999 The Influence of the Illawarra Escarpment on Long Duration Design Rainfalls – Implications for Floodplain Management

2003 Editor 28th International Hydrology & Water Resources Symposium Proceedings

2005 Adding Value to Bureau of Meteorology Flood Prediction

2008 31st Hydrology & Water Resources Symposium Proceedings: *Can Fixed Grid 2D Hydraulic Models be used as Hydrologic Models*, joint authors with J. Ball and K. Clark

2008 Comparison of Two-dimensional modelling approaches used in current practice, *9th National Conference on Hydraulics in Water Engineering*, Joint author with M.Retallick

2009 A Hydroinformatic approach to development of design temporal patterns, *Hydroinformatics in Hydrology and water resources (Proc. Of Symposium JS.4 at the Joint IAHS and IAH Convention Hyderabad India,* Joint author with C.Varga and J.Ball

2009 Estimation of design flood flows considering climate change, *IAHR Congress Vancouver,* Joint author with J.Ball and B. Phillips

2009 An alternative approach for developing temporal patterns, *Proceedings of the 32nd Hydrology and Water Resources Symposium Newcastle 2009,* Joint author with C.Varga and J.Ball

2009 Two dimensional simulation in urban areas, *Proceedings of the 32nd Hydrology and Water Resources Symposium Newcastle 2009,* Joint author with M.Retallick and J.Ball

2009 Do filtered temporal patterns resemble real patterns? *Proceedings of the 32nd Hydrology and Water Resources Symposium Newcastle 2009,* Joint author with M.Retallick, C.Varga, J.Ball, and E. Askew

2010 Considering the impacts of Climate Change on flood risk *Practical Responses to Climate Change National Conference*, Joint author with D. McLuckie and R. Dewar

2011 Consideration of Sea Level Rise in Flood and Coastal Risk Assessments, *51st Annual Floodplain Management Authorities Conference* D.McLuckie, P. Watson and M. Babister.

2011 Revisiting the Design Flood Problem *Proceedings of the 34th IAHR World Congress* Joint author with J.Ball, and M. Retallick

2011 The Ineptitude of Traditional Loss Paradigms in a 2D Direct Rainfall Model *Proceedings of the 34th IAHR World Congress* Joint author with F.Taaffe and S.Gray

In Print *Australian Rainfall and Runoff Research Project 15: Two dimensional simulation in urban areas*, Editor