QUEENSLAND FLOOD COMMISSION OF INQUIRY

SUPPLEMENTARY REPORT – IPSWICH FLOOD FREQUENCY ANALYSIS

FINAL REPORT

OCTOBER 2011

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Project Supplementary Report Ipswich Flood Frequency Analysis	**Project Number** 111024
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1. INTRODUCTION

1.1. Overview

1 This report documents an assessment of flood frequency at Ipswich resulting from Brisbane and Bremer River flows. WMAwater have estimated the 1% AEP (100 year ARI) flood level at Ipswich, as well as the probability of the January 2011 flood event.

2 This report is supplementary to a previous WMAwater report, "*Brisbane River 2011 Flood Event – Flood Frequency Analysis*" (Reference 1), which documented similar investigations on the Brisbane River below the Bremer River confluence, from Moggill to the Brisbane River mouth. The analysis presented in this report should be read in conjunction with Reference 1, which contains general discussion of central concepts of flood frequency analysis and flood planning levels (FPLs), and also documents assumptions and limitations which are relevant to this study.

3 Determining design flood levels at Ipswich is a particularly complex task that has a considerable level of uncertainty. The prime cause of the uncertainty is the difficulty in quantifying the interaction between the Brisbane and Bremer Rivers, both of which exert a strong influence on flood behaviour in and around Ipswich and Moggill. The design flood estimates undertaken to date at Ipswich have not thoroughly addressed the joint probability of these two main flood mechanisms.

4 WMAwater have developed a flood frequency approach which incorporates a consideration of the joint probability effects of Brisbane/Bremer River floods at Ipswich. The approach can also be used to assess the influence of Wivenhoe and Somerset Dams on the frequency of flooding at Ipswich, via modification of the Brisbane River flow record as per Reference 1.

5 There are significant limitations to the analysis, particularly in the present understanding of backwater effects at the Brisbane/Bremer confluence and the conditional probability relationship of flooding between the two systems. WMAwater have attempted to identify the most important limitations and methods by which confidence in the results can be improved. The results from this preliminary analysis appear reasonably robust and consistent with historical data. Further efforts to reduce uncertainties in various parts of the analysis would be worthwhile.

1.2. Scope of the Report

6 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.

7 The Commission has requested that Mark Babister of WMAwater undertake the following:

a. Conduct a flood frequency analysis and determine the 1% AEP flood level for key locations on the Brisbane River below its junction with the Bremer River and on the Bremer River in the vicinity of Ipswich using information available prior to the January 2011 event. This work should be used to determine 1% AEP flood levels at up to 8 key locations in the Brisbane and Bremer Rivers and to produce 1% AEP flood profiles. This work should include a review of the SKM 1% AEP flood profile.

b. Repeat task 1 with the 2011 event included in the historical dataset.

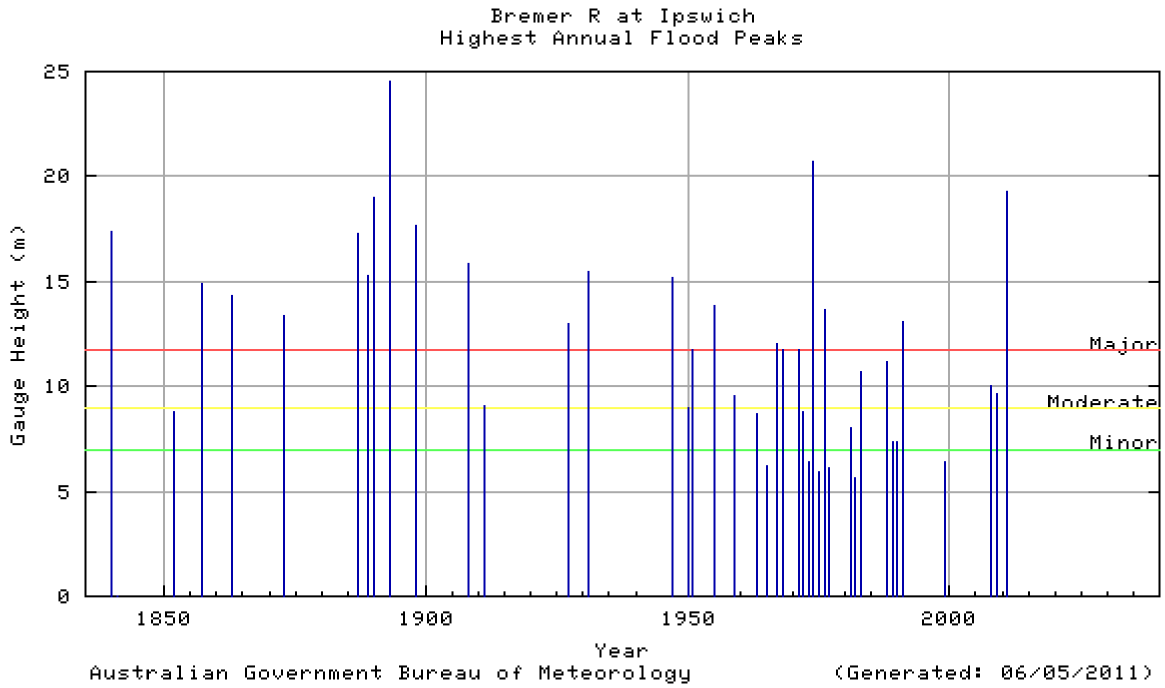
c. Using results of tasks (a) and (b) determine the ARI and AEP of the January 2011 floods at particular points along the Brisbane River and Bremer River.

2. BACKGROUND

2.1. Bremer River Catchment

8 The city of Ipswich lies approximately 40 km west of Queensland's State Capital, Brisbane, and has a population of 155,000. Ipswich can be impacted by floodwaters from the Brisbane and Bremer valleys and has a history of suffering significant flood events with 19 events having exceeded the "Major" flooding classification in the past 170 years (Figure 1).

Figure 1: Bureau of Meteorology Peak Flood Level Record and Classifications at Ipswich



9 The Bremer River passes through the southern and eastern suburbs of Ipswich, and its headwaters are in the Macpherson Ranges. The Bremer's total catchment area to the confluence with the Brisbane River is approximately 1,790 km^2 (Reference 15) of which Warrill Creek (also known as the Fassifern Valley) constitutes approximately two thirds at 1,150 km^2, entering the Bremer River approximately 10 km upstream of Ipswich.

2.2. Ipswich Flood History

10 Reasonably reliable flood records extend back as far as 1893, with other less reliable observations of large events from as far back as 1825 (Reference 34). The peak flood level record provided to WMAwater by the Bureau of Meteorology (BoM) dates back to 1840. Floods have traditionally been gauged at David Trumpy Bridge, which is also known as the Ipswich City Gauge.

11 The largest flood on record at Ipswich occurred in 1893 when the Bremer River reached a level of 24.5 mAHD. The largest flood of the 20th century was the 1974 event, reaching 20.7 mAHD at David Trumpy Bridge. This led to the inundation and partial or complete destruction of many homes. The January 2011 flood reached 19.25 mAHD, which caused significant residential and commercial damage. Each of the three highest recorded events at Ipswich (1983, 1974 and 2011) involved significant Bremer River flood flows occurring concurrently with major flooding of the Brisbane River.

2.3. Joint Probability of Brisbane/Bremer Flood Mechanisms

12 There are significant difficulties in estimating the frequency of a given flood level at Ipswich. The primary difficulty arises because whilst Ipswich is on the Bremer River and significant flooding can occur as a result of flows from the Bremer catchment alone, flooding may also occur as backwater from Brisbane River flooding (with or without concurrent elevated flows from the Bremer catchment).

13 Generally, the peak flood level experienced at Ipswich will be a result of the combined influence of the Brisbane and Bremer flood mechanisms, although the relative contribution may vary. It would generally be expected that the likelihood of significant concurrent flooding in both systems will increase for larger floods, as the large-scale meteorological systems that will generally produce large Brisbane River floods are also likely to produce considerable rainfall and runoff in the Bremer catchment.

14 This situation is a classic joint probability problem and while it is not uncommon that different mechanisms contribute to flooding, often the influence of the smaller catchment or secondary flood mechanism is relatively minor compared with the primary source of flooding. In such cases it is possible to assess flood behaviour from the dominant mechanism and use a reasonably simple assumption to account for the weaker supplementary mechanism. Such an approach is not suitable at Ipswich as the Bremer River has a substantial catchment size, and both sources of flooding (Bremer and Brisbane Rivers) have the potential to cause significant flooding.

15 The importance of the flood interaction is evidenced by the largest floods recorded at Ipswich, such as the January 2011 flood, when the recorded David Trumpy flood level was approximately 1.4 m higher than the level at Moggill near the confluence of the two rivers. From available data it appears that both the Brisbane and Bremer River flood mechanisms alone can produce flooding well above the “Major” level of 11.7 mAHD, and coincident Bremer River and Brisbane River flows can add in the order of 5 m on top of the level from Brisbane River backwater alone.

2.4. Use of Flood Frequency Analysis at Ipswich

16 Flood Frequency Analysis (FFA) is a preferred method to directly estimate flood probability in areas where variability in flood-producing mechanisms is hard to quantify. As discussed

in Reference 1, the at-site flood record includes all the variability in factors that influence flood behaviour such as rainfall intensity, runoff volume, storm characteristics, and relative contribution of tributaries.

17 Difficulties arise in undertaking traditional flood frequency analysis at Ipswich because the backwater influence from the Brisbane River makes the development of a rating curve (which is a difficult process for a non-backwatered gauge) even more challenging. Furthermore, a frequency analysis based solely on flows in the Bremer River will only estimate the probability of flood discharges in the Bremer River alone and will not capture the critical influence of the Brisbane River on the eventual flood level, and therefore will not be particularly useful for estimating flood height probabilities.

18 As a result, it is tempting to undertake FFA directly on observed flood heights. However there are pitfalls to such an approach as flood heights are dependent on localised topography in the vicinity of the gauge, and can therefore be subject to discontinuities. For example, a location with a narrow channel and a relatively wide flat floodplain will have a discontinuity at the level where flow breaks out into the floodplain, which can invalidate the fitting of a distribution to these data.

19 If a long record is available a meaningful estimate of flood probabilities can still be obtained by drawing a fit "by eye" through a plot of the recorded flood heights against their most likely probability, based on their rank in the historical record. However such an approach can be invalid in locations (such as Ipswich) where a major catchment change such as construction of a flood mitigation change introduces a substantial change to the at-site flood frequency.

2.5. Floodplain Management Challenges

20 In addition to the above challenges in estimating design flood levels at Ipswich, floodplain management at Ipswich is further complicated by the relatively large variation in observed flood levels. For example whilst the definition of "Major" flooding at Ipswich is a level above 11.7 mAHD at Ipswich City Gauge, the 1893 event reached a peak flood height of 24.5 mAHD whilst the recent January 2011 event reached 19.25 mAHD. Variation of this magnitude at the upper end of recorded flood levels is relatively uncommon for Australian catchments.

21 Another location where large variation in behaviour of extreme flood events occurs is at Windsor, located downstream of Warragamba Dam on the Hawkesbury-Nepean system in New South Wales. At Windsor under normal river conditions the river is tidal with an average level just above mean sea level (similar to Ipswich). In contrast the 1% AEP flood level is 17.3 mAHD, while the 0.5% AEP (200 year ARI) flood level is approximately two metres higher. This means that a house with a floor level at the standard flood planning level (FPL) of the 1% AEP plus 0.5 m freeboard will still be flooded in an event slightly larger than the 1% AEP.

22 From a planning and floodplain management perspective, particularly with regards to emergency response management, such large variation in flood levels is a major concern. Risk management involves consideration of both the likelihood and consequences of an event. In locations such as Ipswich and Windsor, the consequences of floods larger than the adopted FPL (such as the 1% AEP) can be far more severe than elsewhere, as the increased depths of water above the FPL can increase the risk of injury or death for inhabitants of the floodplain, and of structural failure of buildings built at the FPL.

23 As a result, Windsor has been identified as a location where traditional floodplain management methods need to be reconsidered and it is likely that such considerations are also applicable to Ipswich. Several variations to standard floodplain management measures have been proposed at Windsor, although consensus has not been achieved, which is partially a reflection of the magnitude of the challenges posed. Proposed measures include an increased focus on flood events larger than the 1% AEP event, and particularly on floodplain evacuation routes and procedures considering flooding up to and including the Probable Maximum Flood (PMF), to ensure that evacuated residents do not become stranded by rising floodwaters. Such areas may require:

a. higher flood planning levels to be used for certain types of development;

b. larger amounts of freeboard;

c. requiring two-storey dwellings for residences below the 0.5% AEP flood planning level, with flood compatible double-brick construction for the lower storey;

d. requiring buildings to have openings to reduce the likelihood of structural failure from differential flood level pressures; and

e. the incorporation of additional features to help manage the flood risk, such as dwellings with reinforced structures designed to withstand the forces of flooding, and the use of marine ply bracing that does not degrade and fail following extended periods of inundation.

3. PREVIOUS STUDIES

3.1. List of Key Reports

24 The following is a chronological list of key studies and reports relating to determination of design flood levels at Ipswich, and reviewed by WMAwater as part of this investigation.

- Queensland Survey Office (1975) – Maps of Inundation for Brisbane and Bremer Rivers as well as presentation of limited FFA analysis and damage estimates;
- Ipswich Council (Late 1970s) “Gamble” Maps – based on observations from the 1974 and 1955 events;
- SKM (2000) Ipswich Rivers Flood Studies – Phase 1 and 2 prepared for Ipswich Rivers Improvement Trust and Ipswich City Council
- Halliburton KBR (2002a) Ipswich Rivers Flood Studies – Lower Bremer River Flooding Report prepared for Ipswich City Council
- Halliburton KBR (2002b) Ipswich Rivers Flood Study Phase 3 – Final Report prepared for Ipswich City Council
- Sargent Consulting (2002a) Brief Review of Flood Frequency Analysis and Discharge Rating Curve for Brisbane River at Moggill Gauge prepared for Ipswich City Council
- Sargent Consulting (2002b) Composite Mapping for 20 Year ARI – Review and Recommendations prepared for Ipswich City Council
- KBR (2004) Bremer River Catchment Flood Risk Management Study – Final Report - prepared for Ipswich Rivers Improvement Trust
- DHI Water and Environment (2005) MIKE 11 Model Review Ipswich Rivers – Final Report prepared for Ipswich City Council
- DHI Water and Environment (2006) Ipswich River MIKE 11 Model Upgrade – Final Report prepared for Ipswich City Council
- Sargent Consulting (2006a) Ipswich Rivers Flood Study Rationalisation Project - Phase 3 “Monte Carlo” Analysis of Design Flows – Final Report prepared for Ipswich Rivers Improvement Trust and Ipswich City Council
- Sargent Consulting (2006b) Ipswich Rivers Flood Study Rationalisation Project - Re-estimation of Design Flows – Final Report prepared for Ipswich Rivers Improvement Trust and Ipswich City Council
- Sargent Consulting (2006c) Ipswich Rivers Flood Study Rationalisation Project - Re-estimation of Design Flood Levels – Hydraulic Model Calibration Report prepared for Ipswich Rivers Improvement Trust and Ipswich City Council
- Sargent Consulting (2006d) Ipswich Rivers Flood Study Rationalisation Project - Re-estimation of Design Flood Levels – Final Report prepared for Ipswich Rivers Improvement Trust and Ipswich City Council

3.2. Summary of Previous Studies

25 In 1975, following the large flood of 1974, the Queensland Survey Office published flood maps for the Brisbane and Bremer River systems. At a similar time Ipswich Council staff developed the "Gamble" maps for use in defining flood liable areas for development purposes. According to Sargent (2002b, Reference 13) no reports have been located documenting these maps and the maps have not been sighted by WMAwater for review. Reference 13 indicates that the 20 year ARI levels in the Gamble maps may have been based on observations of the 1955 event, which reached a level of 13.82 mAHD at the Ipswich gauge.

26 In 2000, SKM completed Phases 1 and 2 of the Ipswich Rivers Flood Studies (Reference 11). The study utilised models developed SKM Brisbane River work (1998, Reference 8), which were used to define Brisbane River flood levels. The study established, via flood frequency analysis conducted on flood levels rather than flows, a 1% AEP level at David Trumpy Bridge of 18.6 mAHD. SKM also undertook rainfall-runoff and hydraulic modelling work, resulting in an estimated 1% AEP level of 18.65 mAHD.

27 In 2002, Halliburton KBR completed a review (Reference 14) of the SKM 2000 report, which questioned the validity of the SKM (2000) design levels. KBR raised a number of issues primarily related to the hydraulic modelling work, including:

a. the use of an inappropriate hydraulic radius formulation, resulting in exaggerated conveyance (flow capacity);

b. excessively high roughness values;

c. poor model scaling;

d. a large proportion of cross-sections along the Bremer River reach (~70%) not extending to fully contain flood levels; and

e. an estimated reduction in modelled levels of approximately 1 m for events less than the 1% AEP when the above issues were addressed.

28 Sargent (2002b, Reference 13) made recommendations for generating composite maps from the Gamble maps, SKM (2000) and KBR (2002b) results (Phases 1, 2 and 3 of the flood study work). The report states that mapping of the 5% AEP event is far from straightforward since agreement between the studies from 2000, 2002 and the Gamble maps is poor (Table 1, Reference 13). A similar exercise was undertaken by KBR in 2004 (Reference 19).

29 In 2005 DHI (Reference 20) peer reviewed Ipswich City Council's hydraulic model (from SKM 2000 for the lower Bremer/Brisbane Rivers and from KBR (2002b) for the upper Bremer River). DHI were engaged to work on the model, and in 2006 DHI submitted a report detailing the changes made to the model and the impact of these on modelled calibration events (Reference 21). Recalibration is stated as being required and as per

other previous reports (Sargent 2002a, KBR 2002a) model schematisation was highlighted as an issue requiring further attention. In particular, DHI recommended separate schematisation of overbank and river flowpaths, and highlighted sensitivity analysis as a key issue (Reference 21).

30 In 2006, the Ipswich Rivers Improvement Trust undertook the Ipswich Rivers Flood Rationalisation Project, which led to a series of four reports from Sargent Consulting. These reports document the review and revision of hydrologic and hydraulic modelling to better define design flood levels in Ipswich. The main issue driving the project was the redefinition of the Q100 (1% AEP) flow estimate in the Brisbane River resulting from review and revision of SKM's Brisbane River study in 2003 (Reference 17). The progression of the Brisbane River work is discussed in detail in WMAwater's main report (Reference 1).

31 Sargent's first report (2006a, Reference 22) looked at Monte Carlo modelling of hydrology using CRC FORGE rainfall datasets. A finding from this work was that SKM (2003, Reference 17) had used underestimates of design rainfall depths for all durations except the 72-hour event. This discrepancy in the rainfalls could possibly explain the discrepancy that SKM (Reference 17) were finding between the flow estimates for Savages Crossing derived from the two different methods used – hydrologic modelling and flood frequency analysis. These discrepancies were also discussed by the Independent Review Panel headed by Mein (2003, Reference 16). Sargent queried the suitability of the RAFTS hydrologic modelling methodology used by SKM (2000, Reference 11), specifically the use of conceptual storages in RAFTS to emulate attenuation typically associated with flood routing.

32 Sargent's fourth report (2006d, Reference 25) re-defined design levels at the David Trumpy Bridge Gauge (Table 1) and indicated that a suitable freeboard for design flood levels may be one to two metres. The report also noted that the schematisation of the hydraulic model still required revision in order to reduce uncertainty associated with Ipswich design flood levels.

3.3. History of Design Flood Estimates

3.3.1. Ipswich

33 Several of the studies discussed above defined design flood levels and extents for Ipswich and surrounds. The design flood levels for the 5% AEP (20 year ARI) and 1% AEP (100 year ARI) events are summarised in Table 1.

Table 1: Summary of Previous Design Flood Estimates at Ipswich

Year	Author	ARI	Level (mAHD)
1975†	Queensland Survey Office	110 year	16.4
2000	SKM	100 year	18.60 / 18.65
2002	Halliburton KBR	100 year	18.65
2006	Sargent	100 year	15.28
1975†	Queensland Survey Office	28 year	12
Late 1970s	Ipswich City Council (Gamble)	20 year	13.5
2000	SKM	20 year	15.11
2002	Halliburton KBR	20 year	15.43
2006	Sargent	20 year	11.36

Notes:
† Results from the 1975 study do not consider tailwater (Brisbane River flooding) and therefore are not comparable with the other estimates.

3.3.2. Savages Crossing

34 Over time the Savages Crossing stream gauge location has shifted and hence each of the stations Lowood, Vernor and Savages Crossing all have the same gauge number of 143001 however the records are differentiated by suffix. Lowood is 143001A, Vernor is 143001B and Savages Crossing is 143001 or 143001C. Each of the stations has a similar upstream catchment area of approximately (10,100 km^2) and Vernor is 1.1 km downstream of Lowood whilst Savages is a further 200 m downstream of Vernor. (Table B.2, Reference 35). The Lowood gauge has a record of 41 years (1909-50), Vernor 8 years (1950-58) and Savages Crossing 33 years (1958 to 1991).

35 In 1993, the then Department of Natural Resources undertook at-site FFA for a variety of stations including downstream of the Brisbane River/Lockyer Creek confluence at Savages Crossing, Vernor and Lowood (Reference 35). The study estimated a 1% AEP flow of 5,633 m^3/s (pre-Somerset Dam), with an increased flow estimate of 9,511 m^3/s using the post-Somerset Dam record. This unexpected result is most likely explained by the relatively short record lengths used (as a result of splitting the record into pre- and post-dam series), and also the occurrence of the large 1974 flood in the post-dam series, but no floods above 6,000 m^3/s in the pre-dam series.

36 In 1998, SKM (Reference 8) undertook more detailed FFA work at Moggill, Lowood (Savages Crossing) and Port Office on the Brisbane River. In order to adjust the flow series to remove the effect of Somerset Dam, a relationship was derived between Woodford and Silverton. The study estimated a 1% AEP flow of 8,200 m^3/s at Savages Crossing (no dams) based on 75 years of record. This analysis did not include the flood of record (1893).

37 In 2003, SKM (Reference 17) revised the FFA work to make use of prior historical floods and regional information. The study used a Bayesian maximum likelihood approach with a range of at-site and regional methods, consistent with current best practice in FFA. Case 3 (using a record from 1890 to 2000 adjusted to remove dam effects), gave an estimated 1% AEP flow of 11,900 m^3/s using a Generalised Pareto fit, and that dataset forms the basis of flood frequency work at Savages Crossing in this assessment. Based on this work SKM gave 12,000 m^3/s as a best estimate within bounds of 10,000 m^3/s to 14,000 m^3/s.

Table 2: Summary of Previous 1% AEP flow estimates at Lowood/Savages Crossing

Report	Q100 Estimate (m^3/s)	Distribution	Continuous Record	Historic Period	Comments
SKM 2003	6,690	GP	1909-1951	1909-1951	Ignores data post Somerset, post Wivenhoe and the historical 1893 event. Excludes information from regional analysis.
	14,070	GP	1909-1951	1847-1951	Includes the best estimate of 1893 historic peak (13,000 m^3/s). Ignores data post Somerset and post Wivenhoe. Excludes regional information
	11,970	GP	1909-1951	1847-1951	As per previous case including prior regional information.
	15,690	GP	1909-1951	1825-1951	No prior regional information. 1825 and 1893 peak flows of 13,200 m^3/s. Plotting position of 1825 event is outside 90% confidence interval. Magnitude is highly questionable
	13,720	LP3	1909-1951	1847-1951	No prior regional information. Includes the best estimate of 1893.
	12,660	GP	1909-1951	1847-1951	1893 peak of 14,500 m^3/s estimated by BoM. Includes prior regional information
	11,560	GP	1909-1951	1847-1951	1893 peak of 12,000 m^3/s taken from BoM URBS modelling. Includes prior regional information
	7,667	LP3	1909-1951	1847-1951	Includes best estimate of 1893 historic peak (13,000 m^3/s). Q100 determined using ARR87 method for including historical data.
	7,870	GP	1909-1982	1909-1982	Includes prior regional information. Excludes best estimate of 1893. No correction for Somerset Dam
	11,500	GP	1909-1982	1847-1982	Includes prior regional information. Includes best estimate of 1893. No correction for Somerset Dam
	11,900	GP	1890-2000	1890-2000	Analysis of "No Dams". Excludes prior regional information.
	13,150	LP3	1890-2000	1890-2000	Analysis of "No Dams". Excludes prior regional information.
	3,590	GP	1909-2000	1890-2000	Analysis of "Post Dams". Excludes prior regional information
	4,920	LP3	1909-2000	1890-2000	Analysis of "Post Dams". Excludes prior regional information
SKM 1998	8,200	LP3	1910-1985	-	No Dams. FFA Fit by eye estimate. Annual series adjusted for those years with low or no-recorded flows.
	9,190	LP3	1910-1985	-	With Dams. Peak flow derived from RAFTS modelling
SEQWater 1993	5,633	LP3	1909-1942	-	No Dams.
	9,511	LP3	1943-1978	-	With Somerset Dam only. It is understood from this report that the FFA analysis was carried out based on observed flows post construction of Somerset Dam. Report concludes that post dam flows are higher than pre dam flows due to the post dam period being wetter than the pre dam period.

3.4. Comments on Previous Studies

38 The previous studies have tended to treat design flood estimation on the Brisbane and Bremer Rivers separately. SKM (Reference 11) recognised that backwater from the Brisbane River is the dominant flood mechanism at Ipswich. This was reflected in hydraulic modelling work undertaken for the assessment, which used an envelope approach, taking the design flood level at a given location as the maximum flood level obtained from either Brisbane River, Bremer River, or local catchment critical storm durations.

39 However, such methods generally require an assumption of the likely joint probability (for example by modelling a 5% AEP tailwater in the Brisbane River in conjunction with a 1% AEP design flood on the Bremer River), and a thorough assessment of appropriate joint probability assumptions has not generally been undertaken.

40 SKM (2000) undertook flood frequency based on recorded flood heights at the Ipswich gauge. However that analysis is subject to the limitations discussed in Section 2.4 above, and the historical data are not shown on the probability plot (Figure 7.6 of Reference 11) so the appropriateness of the distribution fitted to the data cannot be assessed.

41 The issues identified by Sargent with regards to the RAFTS modelling completed by SKM are important. If the rainfalls for durations other than 72-hours are indeed underestimates as suggested, the follow-on effects of the mistake may be considerable, as this body of hydrological modelling work has been used as an input for key assessments of design flood levels in the Brisbane River system, as well as investigations into the flood-mitigation effects of Wivenhoe and Somerset Dams.

42 The use of a small number of concentrated conceptual storages to emulate routing in the SKM (2000) RAFTS modelling (also identified by Sargent (2006a)) is highly unorthodox and WMAwater do not consider it to be an appropriate method in the context of the Brisbane River system.

43 For the task of estimating design flood levels at Ipswich, the modelling issues identified by DHI (2005b) and Sargent (2006a), while needing to be addressed, are likely to have less influence on the outcomes at Ipswich than a comprehensive treatment of the joint probability issues on flood behaviour.

4. FLOOD FREQUENCY ANALYSIS

4.1. Available Data

44 The following datasets were utilised for this analysis:

- Savages Crossing gauge continuous flow record, for which a composite record of the Lowood (143001A), Vernor (143001B) and Savages Crossing records (143001C) was created, received from DERM on 21 September 2011;
- The Savages Crossing annual maximum flow series, adjusted for the influence of Somerset Dam from SKM (Reference 17);
- Amberley gauge (143108A) continuous flow record, received from DERM on 21 September 2011;
- Walloon gauge (143107A) continuous flow record, received from DERM on 21 September 2011;
- Discontinuous peak flood height record at Ipswich gauge (040101), received from BoM on 29 September 2011; and
- Mike 11 model of the Brisbane and Bremer Rivers (Version 2), received from SKM on 6 July 2011 (refer to References 31 and 32).

45 Where flows records have been required, WMAwater have relied upon the flows provided by DERM, and have not checked the conversion of the gauge water level record against the applicable rating curve for the gauge.

4.2. Selection of Gauges

46 Previous studies have included flood frequency analysis at various gauges, and in the process have made an assessment as to the usefulness of the gauge record, accuracy of the rating, and other considerations. These assessments regarding the suitability of various gauge records were comprehensive and have been used by WMAwater to inform the selection of gauges for the present analysis.

47 The Moggill gauge was excluded from the analysis, as Sargent (References 24 and 25) indicated major issues with unstable channel shape at Moggill. Additionally, the continuous flow record provided to WMAwater is relatively short (1992 to present) and also contained spurious measurements (above 70 mAHD), which limited the usefulness of this gauge for this analysis.

48 Walloon and Loamside were also identified as being stations with relatively unreliable hydraulic characteristics and/or poor ratings by Sargent (2006d, Reference 25). The primary gauges selected for use in the flood frequency analysis were:

- Warrill Creek at Amberley (143108A); and

- Savages Crossing on the Brisbane River (143001A/B/C).

4.3. Methodology

4.3.1. Joint Probability Approach

49 The interaction between the Bremer and Brisbane River flood mechanisms at Ipswich is critical, and therefore was a central consideration in determining an appropriate methodology for the present assessment.

50 The approach used is based on an analytical technique proposed by Eric Laurenson (1974, Reference 5). The technique has a broad range of hydrologic applications, and its suitability for flood frequency analysis at locations where joint probability is important (such as a river confluence) was specifically acknowledged by Laurenson. Essentially, the approach allows for an at-site flood frequency analysis on one branch of the system to be transposed to another location, provided there is a sufficient understanding of:

a. the correlation between flows on the two contributing river branches (i.e. for a given flow on one branch, an estimate of the probability distribution of flow on the other branch); and

b. the physical interaction of the two branches at the confluence (i.e. an understanding of the flood level produced by coincident flows at varying magnitudes).

51 The data required to undertake this analysis at Ipswich are therefore:

a. a long continuous flood record on both the Brisbane and Bremer Rivers upstream of the confluence;

b. the gauges should preferably be far enough upstream from the confluence to be relatively free of backwater influence, but close enough to the confluence to capture a large percentage of the upstream catchment for the tributary, and

c. a series of rating curves giving flood heights at Ipswich for varying combinations of flow in the Bremer and Brisbane River systems.

52 For this analysis, the Savages Crossing gauge was selected as most appropriate for the Brisbane River component, and the Amberley gauge for the Bremer River component. It is possible that the Mt Crosby gauge could be used in place of Savages Crossing, as both gauges have a similar length of record. Savages Crossing was selected in this instance as considerable attention has already been given to FFA at this gauge in previous studies. The Amberley gauge on Warrill Creek was considered more suitable than the Walloon gauge, as it captures a larger proportion of the Bremer River catchment and is recommended by Sargent as having the more reliable rating curve.

53 Savages Crossing and Amberley represent good locations for the inputs into the joint probability analysis as they satisfy the criteria identified above. Savages Crossing also provides a good primary probability input as it has a relatively long record and the FFA work undertaken to date by SKM (Reference 17) has been comprehensive.

54 The relationship between flood level at Ipswich and the Brisbane/Bremer flows requires a large amount of data in order to be well defined across a broad range of flood magnitudes. As the gauge at Ipswich is non-continuous and only a limited number of historical data were available, the relationship was developed by supplementing the available historical data with hydraulic modelling results, using the Mike11 model provided to WMAwater by SKM (reviewed by WMAwater in Reference 31). While problems have been acknowledged with the Bremer River schematisation in the model, this was considered the most appropriate method to undertake the required analysis in the available timeframe.

55 A detailed description of the application of Laurenson's methodology to flood frequency analysis at Ipswich is provided in Appendix B.

56 The adopted FFA methodology combines the contribution of Brisbane River and Bremer River flooding. Additionally, the influence of Wivenhoe and Somerset Dams can be included in the analysis via appropriate adjustment of the Brisbane River data (at Savages Crossing in this instance) to represent "no dams" or "with dams" conditions.

4.3.2. Savages Crossing FFA

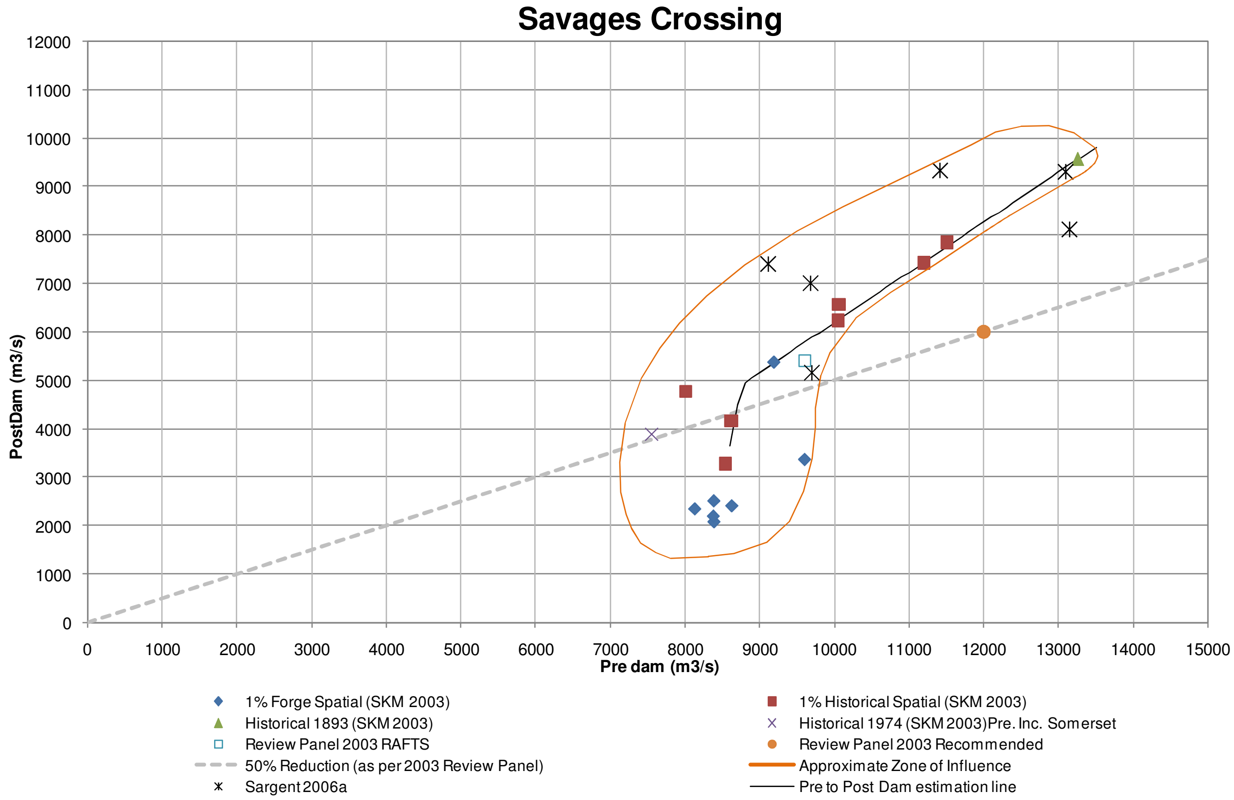
57 Under the adopted methodology, flood frequency curves at Savages Crossing are a key input for obtaining flood frequency estimates at Ipswich. Previous studies have investigated flood frequency at Savages Crossing using at-site and regional approaches under a wide range of assumptions, as summarised in Section 3.3.2.

58 For the purposes of this study, WMAwater utilised the annual maximum flow series provided to SKM by DNRM and utilised in the SKM (2003) study (Appendix D, Reference 17). The data series extracted from that Appendix was for the period from 1890 to 1955. The annual series from the SKM (1998) study (Appendix E, Reference 8) was used for the period after this, but prior to Wivenhoe Dam construction, from 1956 to 1985. The effect of Somerset Dam was already removed from this SKM (1998) dataset. Recorded flows from the DERM gauge data were used to complete the annual series period from 1985 to 2011. These data were adjusted by WMAwater to account for the influence of Wivenhoe Dam. The adjustment factor was determined by fitting a line to historical and modelled data points estimating the dam effects at Savages Crossing (Figure 2). The full annual series used by WMAwater is given in Appendix C along with the relevant sources.

59 Figure 2 is similar to Figure 5 of Reference 1 with additional points from Sargent 2006a (Reference 22). The additional Sargent data is consistent with the original SKM data and is based upon the same model. While the graph shows there is considerable scatter in the

mitigation of peak flow, it was necessary for this simplified joint probability assessment to assume a single relationship for flows above 3,600 m^3/s to represent average expected behaviour.

Figure 2: Flow Adjustment for Wivenhoe and Somerset Dam at Savages Crossing



60 WMAwater used the FLIKE program to undertake the FFA at Savages Crossing. The data were tested against the LP3 and GEV distributions, and the analysis was repeated with and without the January 2011 flood event.

4.4. Limitations

61 There are significant limitations for the application of the adopted Laurenson methodology at Ipswich, as follows:

a. The three-way relationship between flood level at Ipswich, discharge in the Bremer River, and discharge in the Brisbane River is not well-defined, particularly for larger floods. This relationship could be better understood via further hydraulic modelling, and the implementation of a continuous water level recorder at the Ipswich gauge.

b. The Savages Crossing gauge has been moved on two occasions, being originally located at Lowood and then briefly at Vernor before being placed at the current position. These moves may have interfered with the continuity of the gauge record. Additionally, the construction of Wivenhoe and Somerset Dams introduces discontinuities in the record.

c. The uncertainty surrounding the effect of the dams on flow at Savages Crossing is compounded by the Lockyer Creek component of flow, which is not subject to attenuation from the dams. Methods to address this uncertainty (such as Monte Carlo approaches) have been discussed in previous reports to the Commission (Reference 33 and 36).

d. As is generally the case for flood frequency analysis, there is some uncertainty regarding the rating curves for the gauges, as the stage-discharge observations that have been used to generate the ratings often do not cover very high levels of flow. These ratings can also be supplemented by hydraulic modelling; and

e. The length of record at Amberley (dating from 1961) is relatively brief.

4.5. Results

62 Figure 3 and Figure 4 display the results of flood frequency analysis at Savages Crossing with and without January 2011 data respectively for the "no dams" case. The estimated flows for various return probabilities are summarised in Table 3.

Figure 3: Flood Frequency at Savages Crossing including January 2011 data (GEV) – No Dams

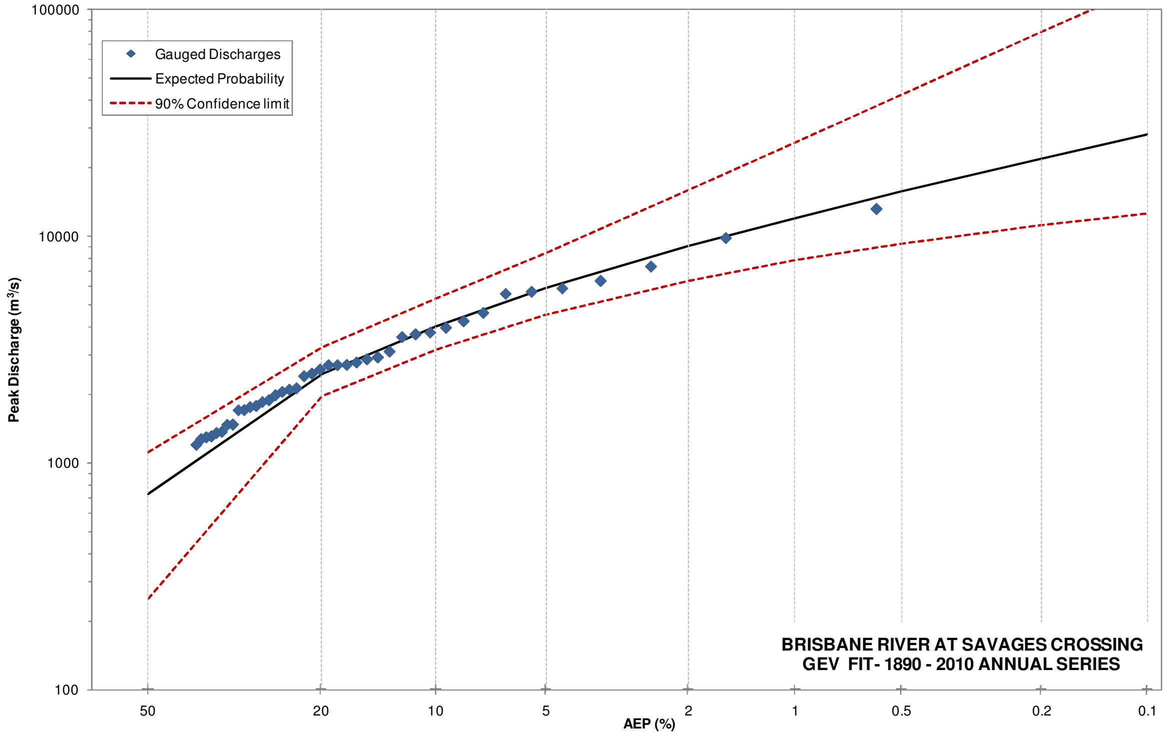


Figure 4: Flood Frequency at Savages Crossing without January 2011 data (GEV) – No Dams

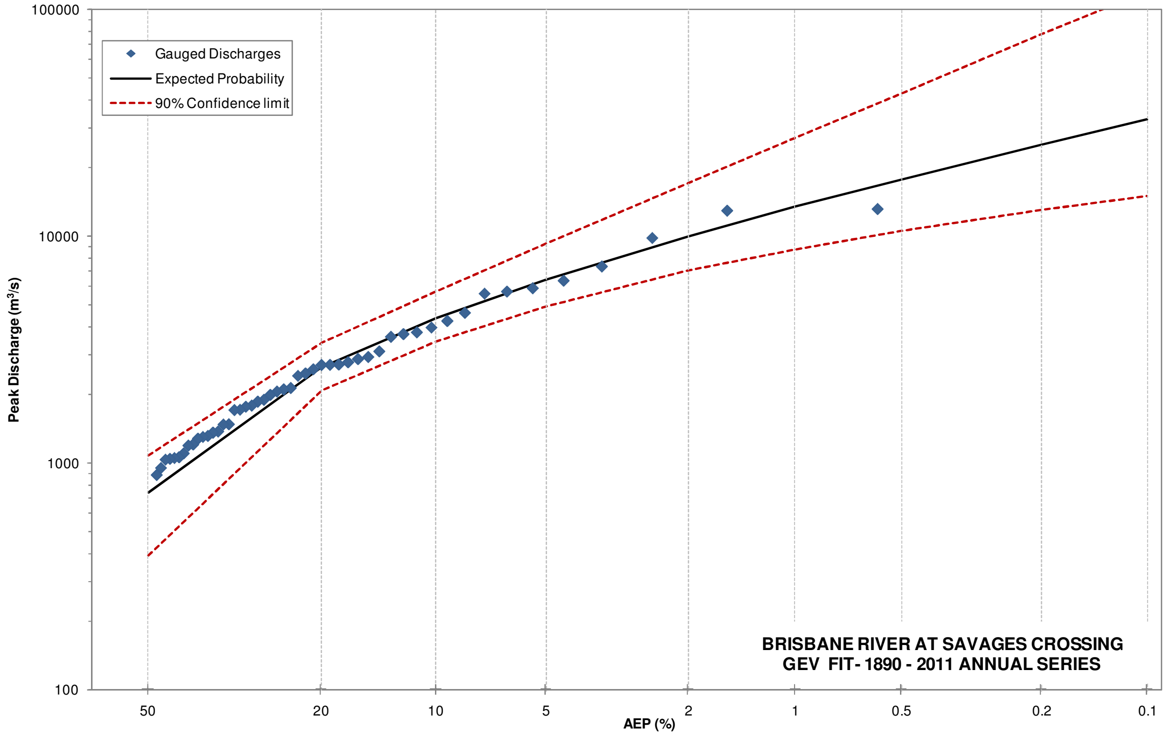


Table 3: Design flow estimates (m^3/s) from flood frequency at Savages Crossing

ARI	Excluding January 2011 Data		Including January 2011 Data	
	No Dams	With Dams	No Dams	With Dams
200 year	15,700	12,100	17,800	14,000
100 year	12,000	8,300	13,500	9,800
50 year	9,000	5,200	10,000	6,200
20 year	5,880	2,560	6,430	2,780
10 year	4,020	1,810	4,340	1,942
5 year	2,470	1,190	2,630	1,254

63 The adjusted annual series used for the Savages Crossing analysis is provided in Appendix C, along with LP3 fits to the data.

64 The flood frequency curves for both “no dams” and “with dams” scenarios obtained at Ipswich (David Trumpy Bridge), including information from the January 2011 flood, are presented in Figure 5.

65 Historical flood heights are also plotted on Figure 5, in two separate series. In water years (July to June) with multiple floods, only the annual maximum is included. The points marked with triangles represent floods with no mitigation from Wivenhoe or Somerset Dams, while squares indicate flood heights with both Wivenhoe and Somerset Dams in place. Solid markers indicate a recorded level at David Trumpy bridge, while hollow markers indicate that the recorded level has been adjusted to account for the removal/introduction of the dams. Adjustments were made based on the relationships developed in Figure 2 and Figure B6 (Appendix B). Error bars are provided as an indication of uncertainty involved with this procedure.

66 The flood frequency curves at Ipswich obtained without using the January 2011 flood data are plotted on Figure 6. Note that the plotting position of the historical data (particularly the larger events) also changes slightly as a result of the removal of the highly ranked January 2011 event.

Figure 5: Flood Frequency Curves at David Trumpy Bridge including January 2011 data

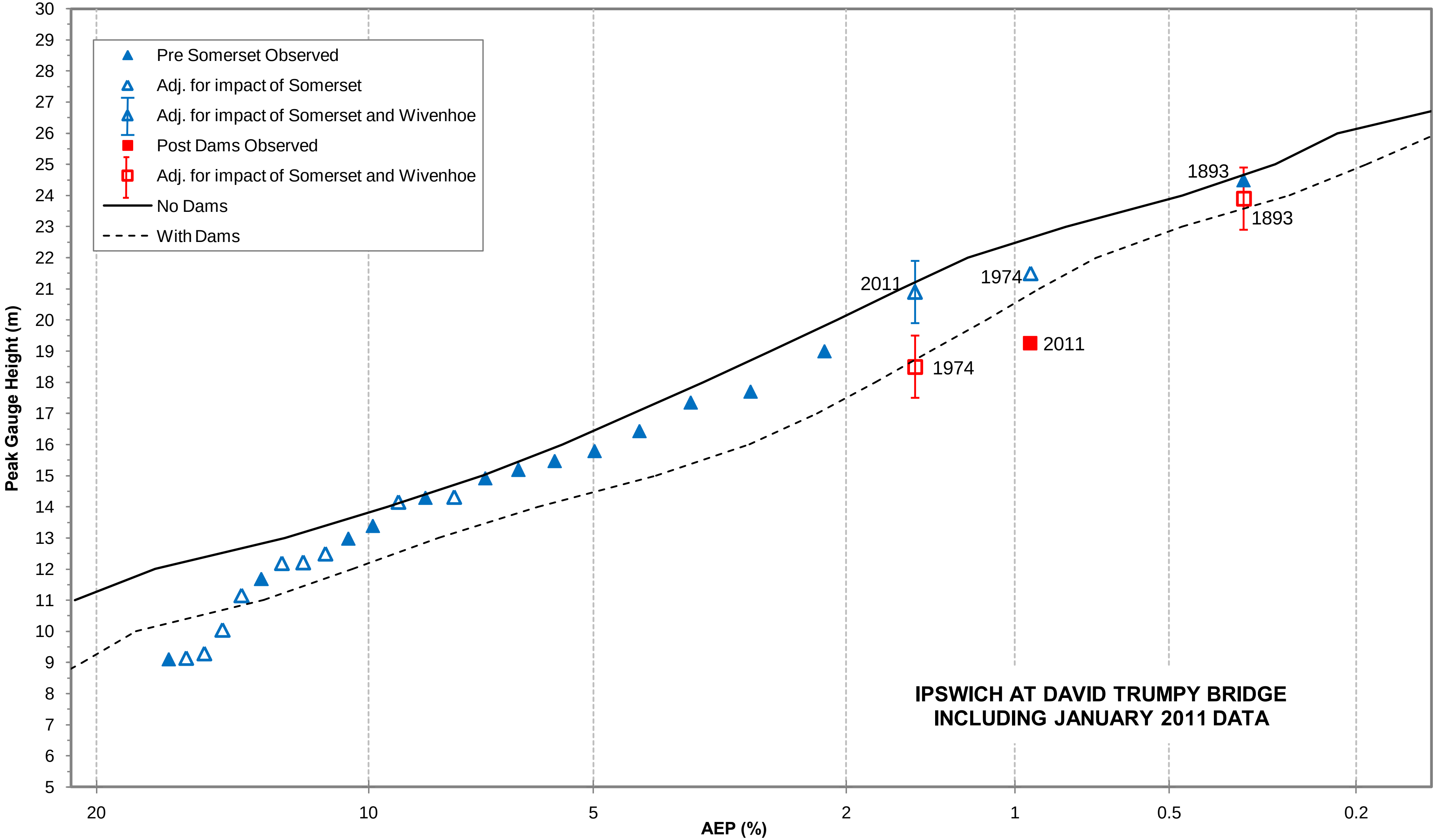
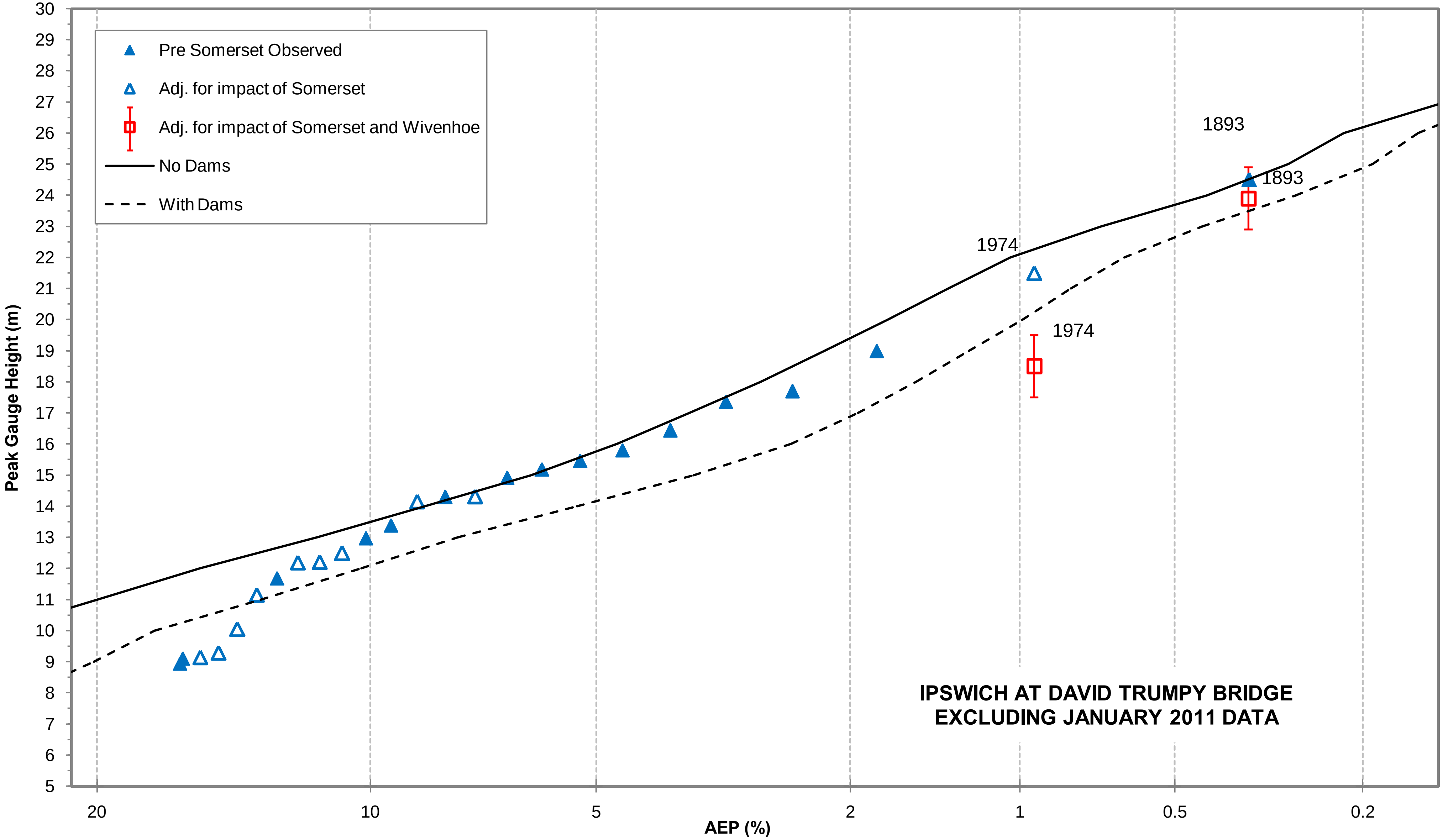


Figure 6: Flood Frequency Curves at David Trumpy Bridge without January 2011 data



67 It is important to note that on Figure 5 and Figure 6, the flood frequency curves are not actually derived from a distribution fitted to the plotted historical data points, as would typically be the case for FFA. The fact that the curves produce a reasonable match with the historical data provides some confidence that the methodology described in Appendix B is appropriate and robust, despite the limitations in the available data (as discussed in Section 4.4).

68 Another important observation is that the estimates at the rarer end of the flood frequency curve (such as the 1% AEP level) are not heavily influenced by the estimates for more frequent events (such as the 20% AEP to 5% AEP events). Therefore the results for the 1% AEP flood level are insensitive to the assumptions made about the influence of Wivenhoe and Somerset Dams on Savages Crossing flows below about 9,000 m^3/s (pre-dams). That is, although the effects of the dam are relatively uncertain below this level (Figure 2), the assumptions made in this flow range do not significantly affect the 1% AEP flood level estimate, which is primarily driven by the 1% AEP flow estimate at Savages Crossing (about 12,000 m^3/s for no dams without 2011 data), and by the correlation relationship with Bremer River flows.

69 The design flood levels at David Trumpy Bridge estimated from the analysis are summarised in Table 4.

Table 4: Design flood level estimates (mAHD) at Ipswich

ARI	Excluding January 2011 Data		Including January 2011 Data	
	No Dams	With Dams	No Dams	With Dams
200 year	23.7	22.7	23.9	22.9
100 year	22.1	20.0	22.5	20.6
50 year	19.4	16.9	20.2	17.5
20 year	15.8	14.2	16.5	14.5
10 year	13.5	12.1	13.8	12.2
5 year	11.0	9.1	11.3	9.3

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Summary

70 Estimation of design flood levels at Ipswich is a complex task, primarily due to the difficulty in quantifying the joint probability and physical interaction of the Brisbane and Bremer River flood mechanisms, both of which have the potential to produce major flooding at Ipswich. The difficulties are further compounded by the wide range of flood levels experienced historically.

71 Substantial effort was devoted to the estimation of design flood levels at Ipswich between 1998 and 2006. These studies included the development of hydrologic and hydraulic models, which appear to have been generally used to consider the Brisbane and Bremer River flood mechanisms independently when estimating design flood levels.

72 The most recent studies by Sargent (Reference 25) and DHI (Reference 21) recommended that further work was required, including substantial revision of both hydrological and hydraulic models (due to issues identified with the modelling methodology), recalibration of models, and re-estimation of design flood levels and extents.

73 The issues identified with the modelling work undertaken to date casts doubt on the validity of the design flood estimates, particularly in light of the lack of attention given to the crucial issue of joint probability.

74 WMAwater have presented a methodology for flood frequency analysis at Ipswich that can be used to address the joint probability issues identified above. The methodology has been used to estimate the probability of various flood levels at Ipswich, taking into account the mitigation effects of Wivenhoe and Somerset Dams. The estimated flood levels are generally higher than those estimated in previous studies, mainly due to higher design flows adopted for the Brisbane River.

75 The limitations of the adopted methodology are outlined in Section 4.4, and are primarily related to issues with the available data. WMAwater have attempted to identify methods for reducing these uncertainties, and in particular where data mining or modelling techniques could be used to supplement the data used for this assessment.

76 Despite the limitations identified, the adopted methodology directly assesses the crucial issue of joint probability of Brisbane River and Bremer River flood mechanisms at Ipswich, and produces a flood frequency curve that plots well against the likely probabilities of historical data.

77 The FFA work undertaken by SKM (Reference 17) at Savages Crossing is comprehensive and reflects best practice. While it would have been preferable to have access to these data for direct use in this assessment, the results were reproduced reasonably well with the relatively simple flow adjustment relationship indicated in Figure 2.

5.2. Ipswich 1% AEP Flood Level

78 The analysis undertaken by WMAwater gives an estimated 1% AEP flood level at Ipswich (David Trumpy Bridge) of 20.6 mAHD. Without the inclusion of data from the January 2011 flood event, the 1% AEP flood level estimate is reduced to 20.0 mAHD. A full range of flood levels from the analysis are presented in Section 4.5.

79 Due to limitations with the data used for the analysis, and recognising that Ipswich is subject to large variability in flood levels, these flood estimates have a relatively wide range of uncertainty. It would be reasonable to consider the estimates for the 2% AEP and 0.5% AEP flood levels (i.e. 17.5 mAHD to 22.9 mAHD) as an indicative range for the 1% AEP flood level.

80 Based on direct interpolation of the flood frequency analysis, the January 2011 event would be equivalent to approximately a 1.35% AEP (75 year ARI) flood at Ipswich (David Trumpy Bridge). The curve obtained appears to be somewhat high compared to the plotted historical data for rarer events, and therefore a more detailed analysis is likely to produce an estimate closer to the 1% AEP level.

81 Flood profiles within Ipswich and levels at locations of interest identified by The Commission were not produced as part of this assessment, as the available modelling tools and data were insufficient to complete such an analysis.

5.3. Recommendations

82 WMAwater have identified strategies to reduce the uncertainty of Ipswich design flood level estimates, which are generally consistent with the recommendations from previous WMAwater reports to The Commission (References 1, 31 and 33).

83 A high quality two-dimensional hydraulic model with a practical run time and a calibration focus on a range of recent events, including the 2011 flood, is required for the Brisbane and Bremer River systems to better understand their interaction. The model should be built using detailed and up to date bathymetric and topographic survey data.

84 Uncertainty associated with various aspects of the joint probability analysis undertaken for this assessment could be substantially reduced by further work. The physical relationship between Brisbane and Bremer River flows and levels at Ipswich could be better defined with access to reliable hydraulic modelling tools of this area (preferably two-dimensional).

85 The mitigation effect of Wivenhoe and Somerset Dams on flow at Savages Crossing has been treated deterministically for this study, although Figure 2 suggests there is significant variation in the attenuation factor. This aspect of the system could be incorporated into the analysis as a probabilistic variable to represent this variability.

86 Timing of flow in the Brisbane and Bremer systems has been implicitly accounted for in the flow correlation method. While this approach was sufficient for this analysis, the timing between flood peaks at Savages Crossing and Amberley could possibly be introduced into the analysis as another probabilistic variable to assess whether this is an important consideration. It is likely this could be undertaken with data already available from the gauge records, but this step was not undertaken in light of the time constraints on this project.

87 It should be investigated whether a better understanding of the correlation structure between flows on Bremer and Brisbane systems can be developed by considering historical catchment average rainfalls. Historical flow and rainfall data could be used in conjunction with calibrated models to investigate the relative timing of flows on the Bremer and Brisbane systems. The resolution of theses issues would allow flooding at Ipswich to be assessed in a Monte Carlo framework, and independently checked against the joint probability method used in this report.

88 As recommended by the Commission in its Interim Report, Stochastic/Monte Carlo analysis should be used to better understand the impact of Wivenhoe and Somerset dams on flows at Savages Crossing and (by extension) flooding at Ipswich.

89 The FFA work undertaken for Savages Crossing by SKM (Reference 17) should be updated to include the January 2011 event.

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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

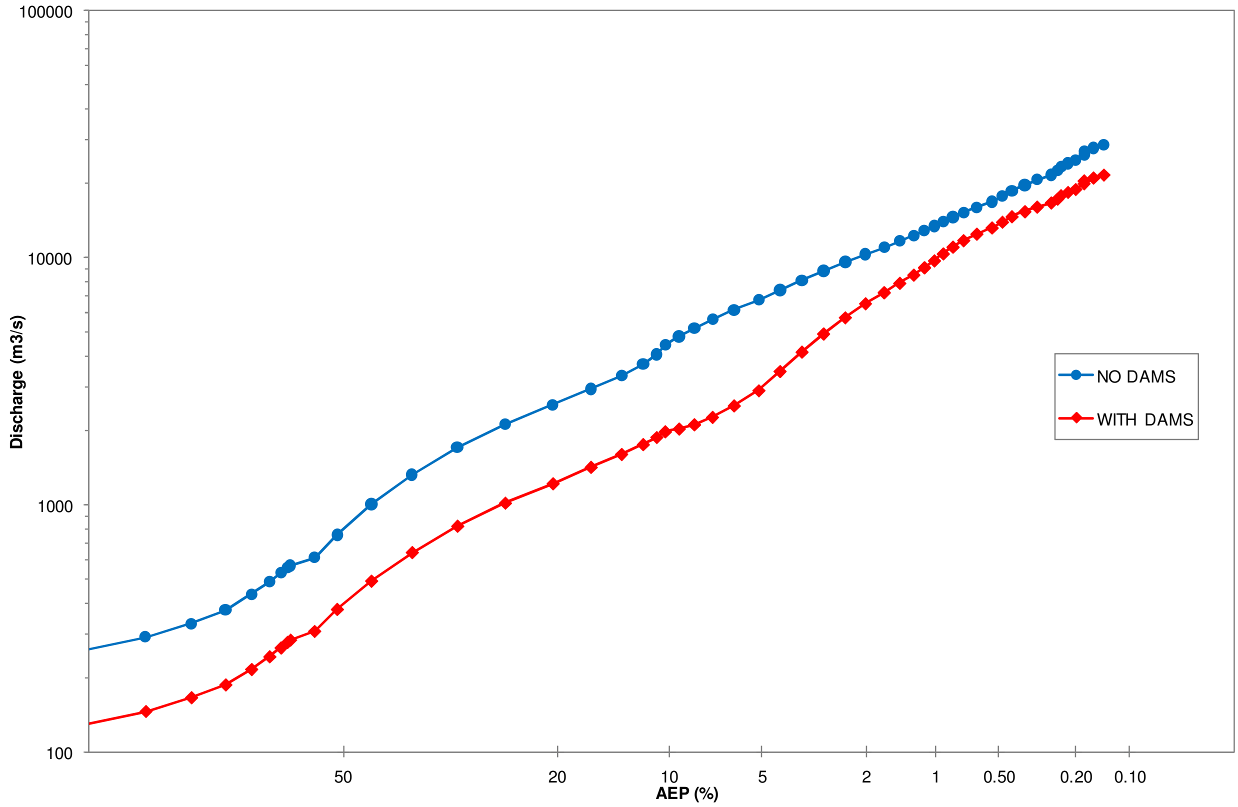
APPENDIX B: Ipswich Flood Frequency Methodology

B1 The methodology used to conduct the joint probability flood frequency analysis as applied at Ipswich is recounted step-by-step in this section. The methodology is adapted from Laurenson (1974), and particularly *Example 4* from the method published in Water Resources Research (Reference 5). The notation conventions from that paper are also utilised here.

B2 Step 1 – Estimate Flood Frequency Curve at Savages Crossing. This step was undertaken using a standard Bayesian flood frequency approach (implemented using the Flike program). The flood frequency curve was first estimated for "no dams" conditions using the adjusted annual series from Appendix C, for flows greater than 1,000 m^3/s.

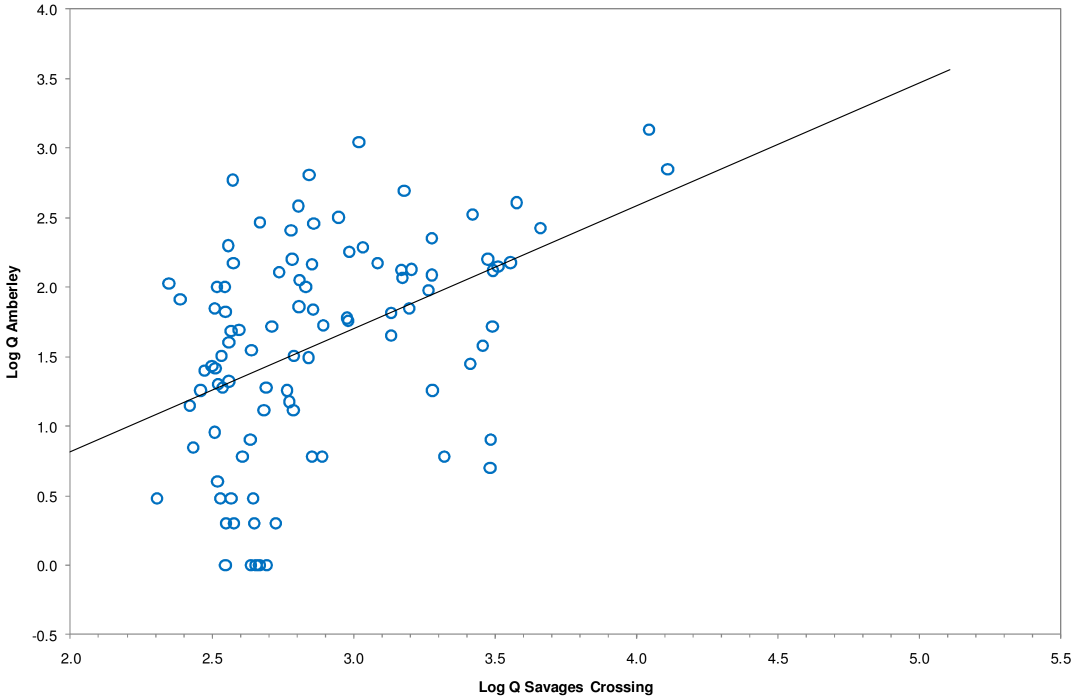
B3 The "no dams" curve was then adjusted to represent "with dams" conditions based on the relationship illustrated in Figure 2.

Figure B1: Input flood frequency curves at Savages Crossing



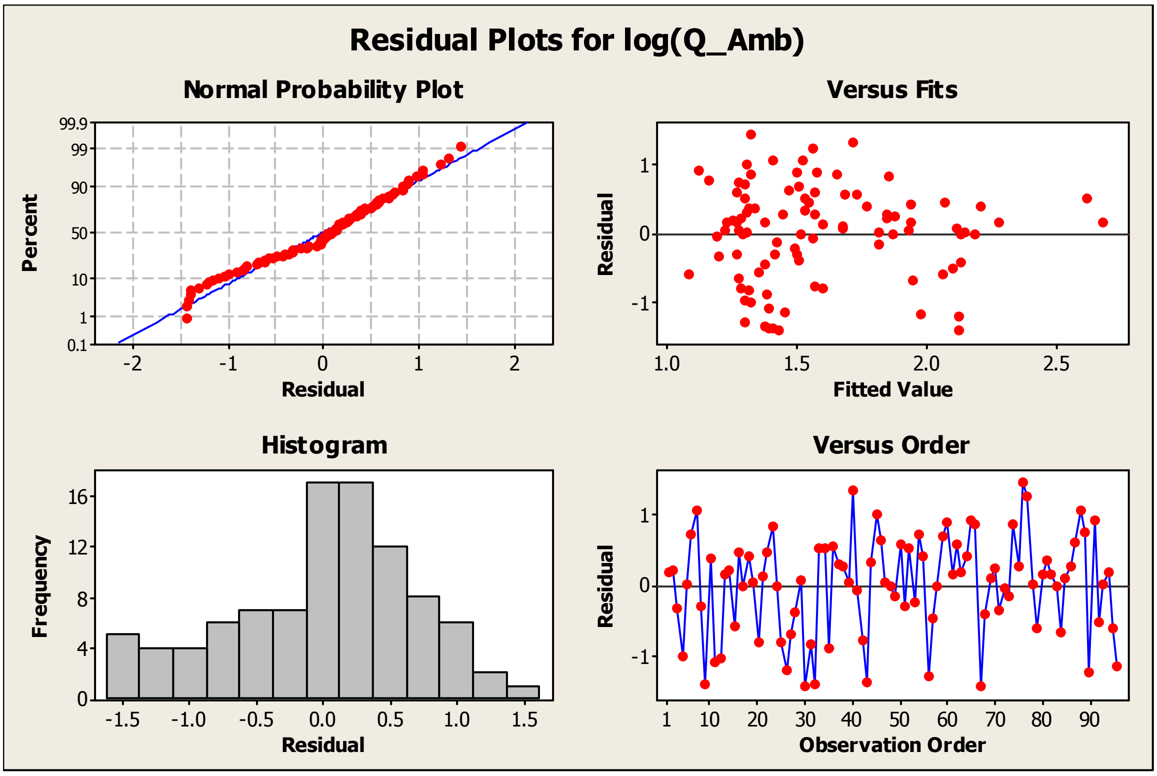
B4 Step 2 – Develop conditional flood frequency curves. The analysis requires a probabilistic description of the likelihood of various flows at Amberley (Q_{Amb}) being exceeded for a given flow at Savages Crossing (Q_{Sav}). First a series of flow pairs was extracted from the continuous gauge records. Flow peaks at Savages Crossing greater than 100m^3/s and separated by more than 5 days were identified. The continuous flow record at Amberley was then searched for flow peaks occurring within 12 hours of the Savages Crossing peak. 259 events meeting the criteria were identified at Savages Crossing, but of these only 96 had matching flows at Amberley, mainly as a result of the much shorter flow record. The flow pairs were log-transformed and a linear regression was fitted, as plotted in Figure B2.

Figure B2: Regression of Amberley discharge against Savages Crossing discharge



B5 The residuals of the log-log regression were found to be reasonably well represented by a normal distribution (Figure B3, upper left). When plotted against $\log(Q_{Sav})$, the variation in the residuals appears to reduce with increasing flow at Savages Crossing (Figure B3, upper right). If these data are representative of the general flow correlation between Amberley and Savages Crossing, this observation is consistent with the expectation that more closely correlated flow behaviour can be expected for larger floods (see Paragraph 13).

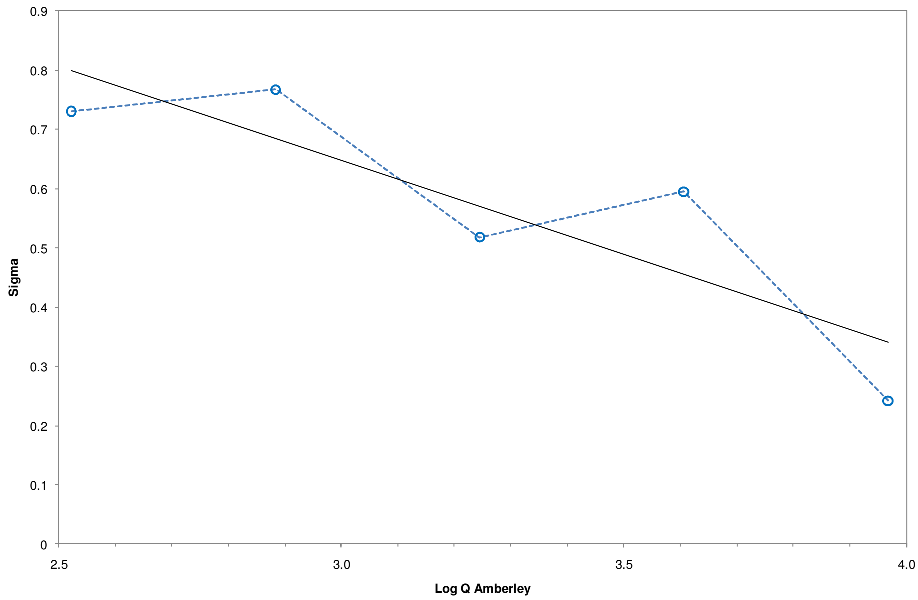
Figure B3: Residuals plots for regression of Q_{Amb} using Q_{Sav} as a predictor



B6 Based on the above findings, it was considered reasonable to separate the residuals into five bins based on Q_{Sav}, and estimate the change in standard deviation of the residuals based on the samples in each bin. The calculated standard deviations were then used to define a log-normal probability distribution of Q_{Amb}, conditional on Q_{Sav}:

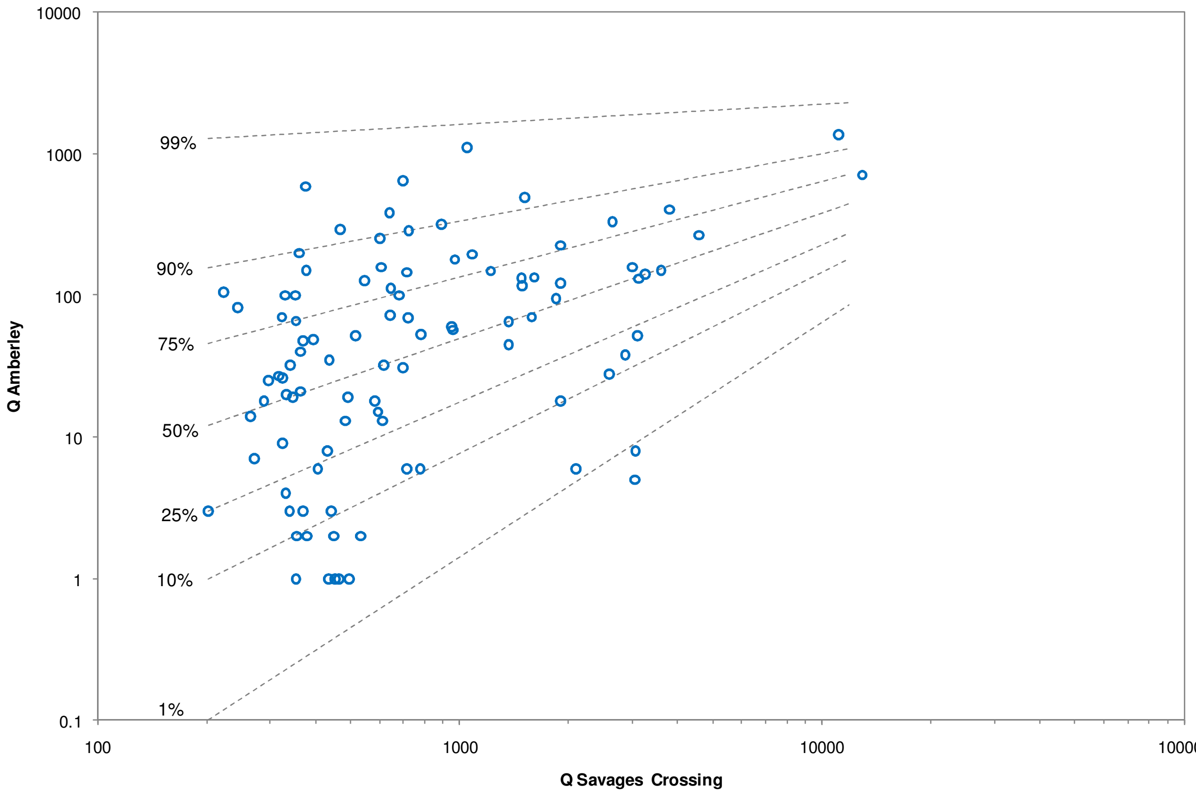
$$Q_{Amb}|Q_{Sav} \sim \log N(\mu, \sigma^2)$$

Figure B4: Trend of standard deviation of Q_{Sav}/Q_{Amb} regression residuals



B7 The mean (μ) of this conditional distribution is estimated from the log-log regression, and the standard deviation (σ) is estimated from the binned residuals described above. The conditional probability thus obtained is presented graphically in Figure B5, with dotted lines indicating the 99th, 90th, 75th, 50th, 25th, 10th, and 1st percentile respectively (top to bottom) of Q_{Amb} for a given observed value of Q_{Sav}.

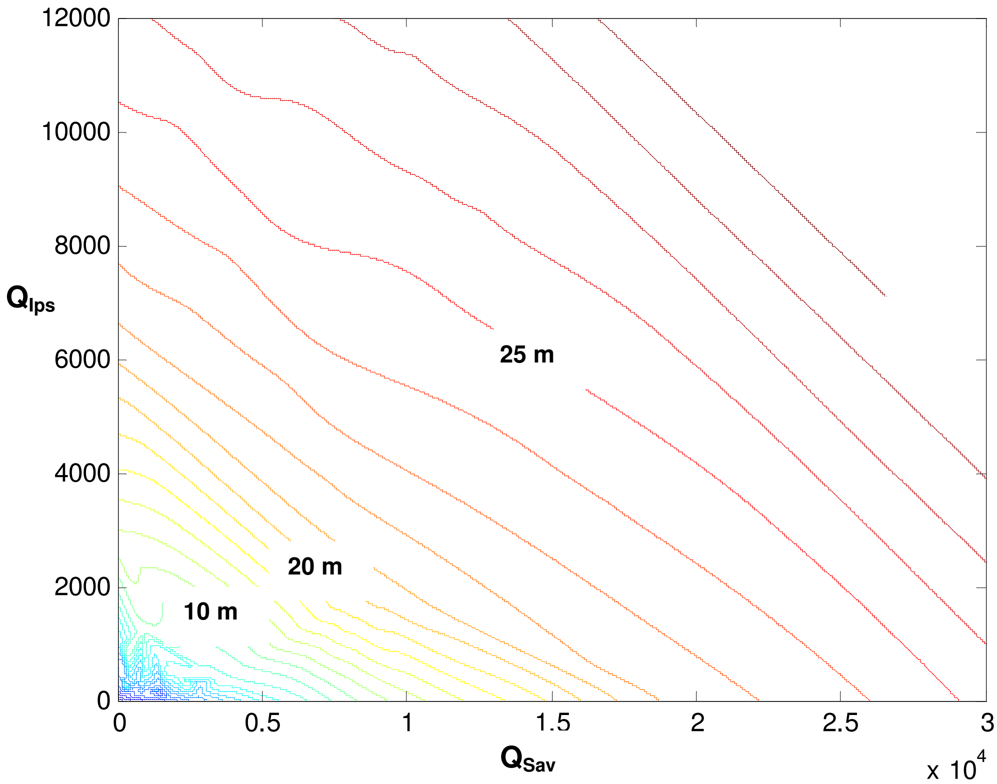
Figure B5: Probability curves for Amberley discharge conditional on Savages Crossing



B8 Step 3 – Develop backwater relationship at Ipswich. In addition to the correlation from Step 2, which represents the likelihood that flood producing rainfall on the Brisbane River system will produce a flood of various magnitudes on the Bremer River (using Warrill Creek at Amberley as a proxy), a relationship representing the physical interaction of Brisbane and Bremer River flows at the confluence is required.

B9 There is a paucity of historical data to develop this relationship, as water levels at Ipswich are not recorded continuously. 78 observations of peak height at Ipswich (H_{Ips}) are available in the period from 1840 and 2011, and of these only 45 concurrent observations are available for Q_{Sav} and Q_{Amb} or Q_{Wal} (flow at the Walloon gauge). There are only two events higher than 14 mAHD at Ipswich with recorded values at all relevant gauge stations (1974 and 2011). It was therefore necessary to supplement the data with results from the MIKE11 model. The model was used to estimate H_{Ips} for various values of Q_{Ips} and Q_{Sav}, particularly higher flows. The combined historical and modelled dataset was gridded to develop a relationship between flow at Savages Crossing, flow at Ipswich (based on flows at Walloon and Amberley for historical data), and flood height at Ipswich. Contours of the relationship developed are shown in Figure B6.

Figure B6: Contours of Ipswich flood level relationship with Q_{Sav} and Q_{Amb}



B10 Note that this relationship assumes coincident timing of flows at the Brisbane/Bremer confluence, as correlation of timing is implicitly included in the relationship developed at Step 2.

B11 Step 4 – Develop transformation matrix. A range of levels for the flood frequency curve at Ipswich was specified (from 0 mAHD to 28 mAHD in increments of 1 m). For each of the ordinates of Q_{Sav} in the Savages Crossing flood frequency curve, the relationship in Figure B6 was used to determine the required coincident value of Q_{Ips} that would result in each of the specified values of H_{Ips}.

B12 Each value of Q_{Ips} was factored to a corresponding flow at Amberley based on a simple relative catchment area relationship (assumed Q_{Amb} = 0.6*Q_{Ips}) The conditional flood frequency relationships developed at Step 2 were then used to estimate the probability of these values of Q_{Amb} being exceeded for the specified value of Q_{Sav}.

B13 For example, for a value of Q_{Sav}=10,000 m^3/s, the flow at Ipswich that would result in an Ipswich flood level of 21 mAHD is estimated to be approximately 2,000 m^3/s (Figure B6), which corresponds to an estimated flow at Amberley of 1,200 m^3/s. Based on the conditional flood frequency relationships, the probability of this flow being exceeded at Amberley for a Savages Crossing flow of 10,000 m^3/s is approximately 6%.

B14 Using this methodology a matrix, *A*, was established giving the conditional probability of Q_{Amb} based on Q_{Sav}, resulting in the specified values of H_{Ips}. The Savages Crossing flood frequency curve was sampled at 66 ordinates, giving a matrix with 29 rows (corresponding to the specified values of H_{Ips}) and 66 columns (corresponding to the ordinates of Q_{Sav}).

B15 The flood frequency curve at Ipswich $P(H_{Ips})$ was then obtained by matrix multiplication of the Savages Crossing flood frequency curve:

$$P\left(H_{Ips}\right) = A \times P(Q_{Sav})$$

B16 The analysis was repeated with and without the data from the 2011 flood event, and for both the “no dams” and “with dams” scenarios.

Additional Comments

B17 The flow correlation relationship developed at Step 2 suffers from complications for the “with dams” scenario, for two reasons. First, the underlying physical basis for the correlation is that flooding in the Brisbane and Bremer river catchments is often caused by rainfall from the same broad-scale meteorological systems. After the dam is constructed, this correlation does not necessarily change. That is, although the peak discharge at Savages Crossing may be reduced from say 13,000 m^3/s to 10,000 m^3/s by mitigation from the dams, the weather system which produced the “no dam” flow of 13,000 m^3/s would suggest a larger expected flow in the Bremer River. From this perspective, the conditional probability should always be determined using adjusted “no dams” flows at Savages Crossing.

B18 However the second consideration is that the Wivenhoe Dam flood mitigation procedures contain an explicit objective to avoid peak releases that coincide with peak Bremer River flows. The degree to which this objective can be achieved will vary with every flood.

B19 To some extent these two considerations will cancel each other out, suggesting that under "with dams" conditions the conditional probability of Q_{Amb} can be estimated using the reduced value of Q_{Sav} from dam mitigation. For this analysis, this approach was adopted for larger Brisbane River floods (greater than 6,000 m^3/s), as these floods are more likely to have "peakier" hydrographs that can be released with more favourable timing with regards to avoiding peak Bremer River flows. However it is recognised that this aspect of the analysis needs further attention.

B20 Another aspect of the analysis that could be substantially improved by further investigation is the physical backwater relationship developed at Step 3. In particular, further hydraulic modelling based on up to date topography between Savages Crossing, Amberley and Moggill could improve the definition of this relationship, as well as clarifying timing considerations for the flood peaks.

B21 Finally, although the method of implicitly incorporating timing considerations in the flow correlations at Step 2 was considered sufficient for this analysis, the timing between flood peaks at Savages Crossing and Amberley could possibly be introduced into the analysis as another probabilistic variable. It is likely this could be undertaken with data already available from the gauge records, however this step was not undertaken in light of the time constraints on this study.

Appendix C

APPENDIX C: Savages Crossing Flood Frequency Information

Year	Flow No Dams (m^3/s)	Source
1890	7343	SKM 2003
1891	1790	SKM 2003
1892	3953	SKM 2003
1893	13156	SKM 2003
1894	1060	SKM 2003
1895	1194	SKM 2003
1896	3699	SKM 2003
1897	432	SKM 2003
1898	5889	SKM 2003
1899	211	SKM 2003
1900	313	SKM 2003
1901	885	SKM 2003
1902	142	SKM 2003
1903	1717	SKM 2003
1904	351	SKM 2003
1905	816	SKM 2003
1906	745	SKM 2003
1907	302	SKM 2003
1908	6356	SKM 2003
1909	325	SKM 2003
1910	706	SKM 2003
1911	1316	SKM 2003
1912	461	SKM 2003
1913	416	SKM 2003
1914	234	SKM 2003
1915	1035	SKM 2003
1917	375	SKM 2003
1918	522	SKM 2003
1922	1280	SKM 2003
1924	173	SKM 2003
1925	778	SKM 2003
1927	2715	SKM 2003
1928	4225	SKM 2003
1929	2064	SKM 2003
1930	749	SKM 2003
1931	5574	SKM 2003
1934	614	SKM 2003
1935	120	SKM 2003
1936	139	SKM 2003
1937	1102	SKM 2003
1938	1052	SKM 2003
1939	460	SKM 2003
1940	697	SKM 2003
1941	425	SKM 2003
1942	1360	SKM 2003
1944	1207	SKM 2003
1946	1377	SKM 2003
1947	1302	SKM 2003
1948	613	SKM 2003
1950	2930	SKM 2003
1950	1043	SKM 2003
1951	2704	SKM 2003
1953	1863	SKM 2003
1954	2111	SKM 2003
1955	5692	SKM 2003
1956	2141	SKM 1998
1958	1770	SKM 1998
1962	152	SKM 1998
1963	502	SKM 1998
1964	258	SKM 1998
1966	2481	SKM 1998
1967	2706	SKM 1998
1968	3766	SKM 1998
1971	2779	SKM 1998
1972	1995	SKM 1998
1973	531	SKM 1998
1974	9807	SKM 1998
1975	407	SKM 1998
1976	1712	SKM 1998
1978	436	SKM 1998
1979	298	SKM 1998
1980	44	SKM 1998
1981	1478	SKM 1998
1982	2873	SKM 1998
1983	2420	SKM 1998
1984	456	SKM 1998
1985	166	SKM 1998
1986	623	Figure 2
1987	32	Figure 2
1988	1898	Figure 2
1989	3103	Figure 2
1990	1482	Figure 2
1991	375	Figure 2
1992	2588	Figure 2
1993	55	Figure 2
1994	47	Figure 2
1995	40	Figure 2
1996	4590	Figure 2
1997	87	Figure 2
1998	23	Figure 2
1999	3597	Figure 2
2000	195	Figure 2
2001	951	Figure 2
2002	39	Figure 2
2003	47	Figure 2
2004	515	Figure 2
2005	86	Figure 2
2006	24	Figure 2
2007	15	Figure 2
2008	109	Figure 2
2009	715	Figure 2
2010	244	Figure 2
2011	12926	Figure 2

Figure C1: Flood Frequency at Savages Crossing with January 2011 data (LP3) – No Dams

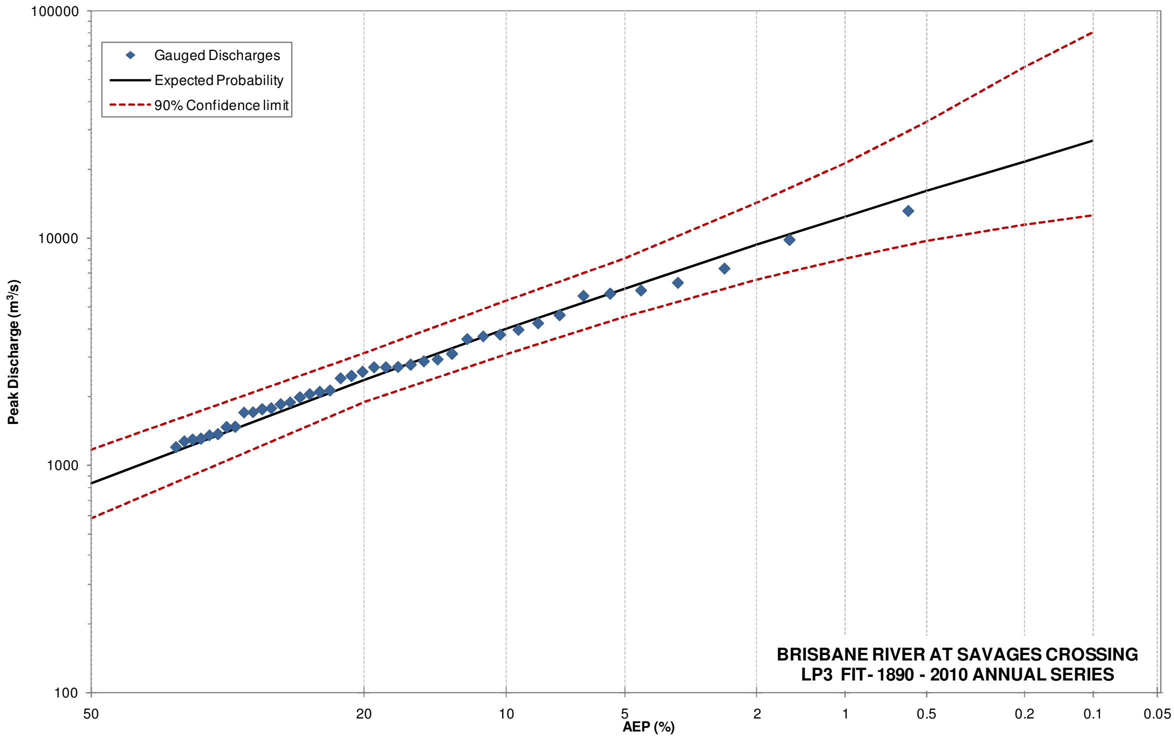


Figure C1: Flood Frequency at Savages Crossing without January 2011 data (LP3) – No Dams