Review of Supplementary Report, Ipswich Flood Frequency Analysis

PREPARED FOR

QLD Flood Commission of Inquiry

October 2011

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Executive Summary

This document is a review of the "WMA Ipswich Report" (WMA, 2011c) pertaining to flooding in the region of Ipswich (which incorporates flood frequency analysis of the Bremer and Brisbane rivers). It is a supplement to the "WMA Brisbane Report" (WMA, 2011a). The terms of reference are the same for both reports.

Since Ipswich is near the confluence of the Bremer and the Brisbane it is jointly influenced by both rivers. There are two aspects to this joint influence,

(i) the hydraulic join - where backflow from an elevated Brisbane River will cause higher water levels in Ipswich based on its proximity to the confluence and channel properties, and

(ii) the hydrologic join - because the flows down the Bremer and Brisbane Rivers are not independent of each other. Their correlation is due to the coincidence of rainfall on both catchments across the variety of storm events.

As the design levels at Ipswich are not independent of the flows down the Brisbane River, parts of the analysis are contingent on accepting the results of the WMA Brisbane Report. In fact, the WMA Ipswich Report presents significant additional reasoning on matters relating to the Brisbane River flows. This additional information requires discussion of the Brisbane River flows to be revisited. In short, they identify that data entry errors on a number of input rainfalls presented in the SKM report (2003) cause a significantly different interpretation of the results. The corrected input rainfalls support a higher post-dam estimate of flow than the SKM (2003) report.

Numerous studies of the Bremer River and flooding in the Ipswich region have been conducted previously. Putting aside questions over Brisbane River flows, there is a significant development in the methodology of the WMA Ipswich report. Where earlier studies have required limiting assumptions on the hydrologic coupling of the Brisbane and Bremer rivers, WMA have performed a joint probability analysis. This methodology is reviewed in detail because of the additional assumptions required beyond that of a standard flood frequency analysis. This review is not exhaustive on these matters, but is intended to highlight those assumptions which appear more critical.

The main short-coming of the WMA Ipswich report, as with the WMA Brisbane report, is dictated by the short time frame available to WMA: that a stochastic (Monte Carlo) assessment is required to provide the fullest assessment on the role of the dams. It is expected that modelling the variability in the dam conversion will cause significant additional uncertainty in the Q100 estimates. It is possible that this additional uncertainty is sufficiently large that any difference in the best-estimate from competing hypotheses is drowned by the variability in their resultant estimates. Such an analysis would favour greater conservatism from a risk-based analysis point of view in contrast to methods that use a deterministic dam conversion which can overstate the certainty in the resulting design estimate.

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1. Introduction

The scope of work requested by the Queensland Flood Commission of Inquiry to Mark Babister of WMA water was to:

1. 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.
2. Repeat Task 1 with the 2011 event included in the historical dataset.
3. Using results of Task 1 and 2 determine the ARI and AEP of the January 2011 floods at particular points along the Brisbane River and Bremer River.

The supplement (WMA, 2011c) is referred to here as the "WMA Ipswich report" whereas the main report (WMA, 2011a) is referred to as the "WMA Brisbane report". This report is best read in conjunction with the WMA Ipswich report. The terminology "the authors" or “WMA” is used to reference analyses expressed in either of these reports and "the reviewer" references analysis presented here or in the prior review of the WMA Brisbane report (Leonard, 2011). A summary of the reviewer’s qualifications are provided in Appendix A.

The statistical methodology requires consistency in the catchment conditions such that conversions between the two must be made to account for the influence of the dams. This conversion is a central issue. A common terminology is that flow estimates as referred to as either being ‘pre-dam’ or ‘post-dam’ (similarly ‘without-dams’ or ‘with dams’). Also note, that the term “dam” is typically used in the singular by the reviewer to refer to the combined behaviour of two dams (Wivenhoe and Sommerset). The terms Monte Carlo and stochastic analysis are used interchangeably, as both can be thought of generically even though they may taken on specific meanings in some contexts.

Another important term is the Q100. This is a design flow that will be exceeded 1% of the time in a *long run* average (1% AEP, annual exceedance probability). It is synonymous with the term 100 year ARI (average recurrence interval). While it is the 1% AEP flood height at any given point that is of interest, the design methodology requires the 1% AEP flow be defined and that 1% AEP heights are subsequently obtained from this flow. In the case of Ipswich which is influenced by both the Bremer and the Brisbane rivers, there is no single pair of flows that give the 1% AEP, rather it is determined from joint combinations of flows on both rivers. It is not appropriate to use the separately determined Q100 of the Brisbane River and the Q100 on the Bremer River as inputs. This is because the joint coincidence of two rare events implies the resulting combined event is even rarer.

1.1 Summary of WMA Brisbane Report

The claims of the WMA Brisbane report and the reviewer's response are summarised briefly here as background material. Given further reflection on the WMA Brisbane Report, some additional clarification and commentary is provided not otherwise made before.

WMA conducted a flood frequency analysis for the Port Office gauge and provided a Q100 flow estimate (pre-dam) of 13,000 m^3s^{-1}. The reviewer considers this estimate to be robust. A major reason for this is because it agrees well with the SKM (2003) estimate, yet it was based on a different methodology (equally valid) and a different set of data. The WMA preference of methodology is a pragmatic one. While questions over the reliability of the Port Office data are proper and the possibility of incorporating more detailed analysis along the lines of SKM (2003), these complexities take on a diminished importance because the pre-dam agreement is strong.

The pre-dam Q100 90% confidence limits provided by WMA of 10,000 m^3s^{-1} to 20,000 m^3s^{-1} are excessive. The reviewer demonstrated one method that reduces them to 10,000 m^3s^{-1} to 16,000 m^3s^{-1}. Incorporating regional techniques (as per SKM, 2003) offers another avenue for potential reduction. There is additional uncertainty due to the rating curve on top of this estimate. WMA suggest this issue is significant. Based on a qualitative analysis, the reviewer's opinion is that while this issue is important, it is not as significant as the pre-dam to post-dam conversion. A further clarification that was not given earlier is that the earlier analysis of rating curve errors was demonstrated for the case where they are equally likely to be positive or negative (Leonard, 2011). This causes the overall best estimate to remain unchanged but increases the uncertainty. If rating curve errors can be demonstrated to be significantly biased then the importance of this issue is reinstated.

The main discrepancy between the earlier SKM best estimate of 6500 m^3s^{-1} and the WMA best estimate of 9500 m^3s^{-1} comes down to assessment of the variability and average performance of the dams. There is considerable difficulty in this task as a rigorous assessment requires the input of a large variety (preferably 1000s) of large storms, whereas the historical record offers only a few. The method for achieving this is known as a Monte Carlo assessment or a stochastic method and the chief difficulty in its construction is showing that the relative occurrence rates of the storms are representative. This task is non-trivial and beyond the feasibility of the timeline imposed on WMA, yet the terms of reference require WMA to provide a post-dam Q100 best estimate. In lieu of a stochastic analysis, WMA have provided a loading curve which converts the response (post-dam flow) for a given load (pre-dam flow). The authors argue this should better match the true (but unknown) long-run average performance of the dam in contrast to prior estimates of approximately 50% reduction. Their argument, as presented in the Brisbane Report, rests on the observation that the 1893, 1974 and 2011 floods all have lesser reductions than a 50% curve and also on the inference that dam capacity to mitigate flooding should diminish for increasing flood sizes. Short of a stochastic analysis, the reviewer is persuaded that the WMA arguments for a higher estimate of 9500 m^3s^{-1} is suitable

The authors noted significant issues in determining the pre-dam post-dam conversion which revolve around unusually low estimates from rainfall methods. The authors had originally suggested climatic variability and issues constructing areal average estimates as likely reasons to explain the discrepancy. The reviewer has noted that either explanation is plausible but essentially unverified. The Ipswich report readdresses the issue of rainfall methods being biased low and they present significant additional evidence on this issue. This is discussed further in Section 2.

1.2 Overview of the WMA Ipswich Report

The authors note the complexity of inferring design levels for the Ipswich region and cite Windsor (NSW) as a precedent where sensitive changes in the AEP of the event (e.g. between a 1% AEP and a 0.5% AEP) are known to give large variation in the range of extreme events (~2 m). The authors point out the long record of events at the David Trumpy Bridge and that the three highest recorded events (1893, 1974, 2011) all have significant flows in the Bremer river that co-occurred with significant flows in the Brisbane River. The observation here is that the weather mechanisms that generate the flows in both catchments cause a level of correlation between the two that must be accounted for (i.e. a joint probability problem). The issue is relevant only for the region of the confluence of the two rivers such that elevated flows in one river will cause elevated levels upstream on the other branch (known as a backwater effect). The authors rightly point out that role of both rivers is significant to the Ipswich region, that floods can be caused either by the Bremer River alone, by the Brisbane River alone or by combinations of the two. For this reason, simplifying assumptions that ignore the dual behaviour are inappropriate (as noted in para. 38 and 39). There are two alternatives (i) perform flood frequency analysis on the observed river heights or (ii) perform a flood frequency analysis that accounts for probabilities of co-occurring flows.

The authors note that there can be pitfalls directly applying flood frequency analysis to observed river heights as the heights can be biased by localised effects. The authors instead use a flood frequency analysis of flows at two sites: Warrill Creek at Amberley and Savages Crossing on the Brisbane River. A hydraulic model is then used to account for local effects at the site of interest and determine the response heights for input flows. The quality of this model is a crucial element of the procedure and the authors highlight the need for model improvements and a better understanding of the backwater effects and timing effects.

As the heights at Ipswich are dependent on the Brisbane River, the estimates are therefore influenced by the assumed performance of the dams. For this reason the WMA estimates are tied to the assumptions presented in the WMA Brisbane report. In particular, that the reduction in flow provided by the dams is significantly less than in previous studies. This topic is reviewed further in the following section.

2. Biases in rainfall estimation

The WMA Ipswich report highlights a finding by Sargent (2006a) that earlier RAFTS modelling contained several spurious values of rainfall input (WMA, para. 31). This is a significant discovery as the low bias in rainfall estimates has been a confounding factor at the heart of understanding the behaviour of the Brisbane River dams. Since the Brisbane River system has myriad complexities to weigh up (tides, channel changes, catchment changes, gauge issues) and the number of assumptions in rainfall based analyses is large, it is not surprising that this source wasn't identified earlier. Standard flood frequency analysis is not dependent on rainfall analyses, but the presence of the dams requires rainfall based modelling techniques to determine the degree of mitigation. This degree has significant scatter depending on the incident rainfall patterns. Even floods not otherwise influenced by the dam are not immune to questioning (such as the 1893 flood) as the overall assessment must hold competing flow-based and rainfall-based information together. Either the discrepancy between the two can be explained or the reliability of one source over another is discounted. It should also be noted that this observation does not preclude other suggested possibilities for rainfall causing lower estimates (e.g. climate or rainfall gauge density).

This issue is pertinent to the Bremer in the vicinity of Ipswich as the backwater effects are a dominant flooding mechanism (WMA, para. 38). WMA observe that the corrected values, as verified by Sargent (2006a) cause higher post-dam flows than previously assumed. This supports the argument proposed by WMA in the Brisbane report that the attenuation of the dam should be less than previously assumed. While this observation gives a strong support for their argument there is still a significant degree of variability in the dam behaviour. The question is not whether one can point to a flood that was highly attenuated (e.g. 1999) or another that was poorly attenuated (e.g. 2011) but that if a great many storms were realised over the catchment, to know where does the overall average density of those storms lie? The average dam conversion performance is what defines the long-run average of the Q100. However, if the scatter of many hypothetical storms were known (and that those storms had representative occurrence rates) then more important questions could be answered regarding not just the long-run average, but the variability of flows down the Brisbane River and questions of the vulnerability in the event of a future flood. In short, the additional source of information is compelling for the argument of higher post-dam flows, but as noted from many sources, a stochastic method is needed to fully address questions over dam performance.

The reviewer accepts the estimation line and the zones of influence denoted by WMA in Figure 2. However. the revised estimates by Sargent (2006a) do not end all questions over the dam influence. Aside from debate over the significance of individual data points, the reviewer's opinion is in part due to a speculation that even if the estimation line were ultimately proven to be lower (with a stochastic analysis) that same analysis will reinforce the high level of variability and uncertainty – warranting higher greater conservatism in risk analysis. Nonetheless, some observations are made about the zone of influence in Figure 2 to indicate that judgements are still required about the dam behaviour,

- it has a significant range of post-dam flows, so questions over variability of attenuation remain
- it has been drawn skewed to suggest that the scatter may be more likely to go higher than the estimation line than below. This is only partly supported by the limited sample of data (even including revised information) as skewness is notorious for requiring a large number of points to estimate reliably.
- It has also been drawn with a sharp drop-off in the pre-dam flow vicinity of 8000 m^3s^{-1}. This is perhaps reflecting the data availability rather than a definitive statement on the physical function of the dam.

The review of WMA's joint probability analysis pursued in the following section makes use of the estimation line in Figure 2. However the methodology is generic so that it could be repeated with a 50% line, or some other functional form. The point being made is that any comparison of this nature should be done in an uncertainty framework so that any delineation of the confidence limits between the methods can be assessed (this informs whether you can statistically support one estimation line over another).

3. Joint flood frequency analysis review

A joint probability analysis is a complex task which rests on a large number of assumptions. Appendix B details a review of the WMA analysis for the purposes of testing some of these assumptions, but also to demonstrate a means for obtaining confidence inervals. The WMA report has not provided confidence intervals, no doubt due to a combination of the short time line and the computational demand involved. The reviewer feels that being able to provide confidence intervals is important for a number of reasons, amongst others (i) it causes one to assess assumptions, model parameters and their relative magnitudes of variability in detail (ii) it tests the model under a wide range of conditions (iii) it naturally cautions against over-confidence in the line of best fit by pointing to the range of possible scenarios.

To this end an attempt has been made here to determine uncertainty limits, but has fallen short because of time constraints and because of not having access to the underlying hydraulic model. An indication of the confidence limits has been determined for:

- a very small sample of 10 realisations (due to computational demand)
- a small AEP range aprox. 2% - 0.5% (due to hydraulic model approximation error)
- only the ‘without dams’ scenario, due to poor hydraulic model approximation

Thus the method would need to be revisited. The main benefit of an uncertainty analysis is to formally incorporate the variability implied by the pre-dam to post-dam conversion process which has otherwise assumed to be deterministic. The impact of different hypothesized conversion functions could be compared in light of the sensitivity on the final estimates. Where a significant increase in variability of the best estimate is determined this can be used to inform decision making and risk analysis.

Data files were obtained from WMA corresponding to the composite flow record at Savages Crossing (Q_{Sav}), the flow record at Amberley (Q_{Amb}) and the conversion functions used to account for the dams (Table C.1 and Table C.2). A number of datasets were extracted from these records including

- Amberley annual maximums (Table C.3),
- Coincident flows at Amberley for annual maximums at Savages Crossing (Table C.4)
- Entire record of Savages Crossing annual maximums (Table C.5)
- Peak over threshold (POT) flows at Savages Crossing with coincident Amberley flows (Table C.6)

Additionally the data underlying WMA Figure B2 and WMA Figure B6 was manually digitized based on their report,

- POT data (Figure B.6 and Table C.7) with little loss of precision
- Hydraulic model approximation (Figure B.10 and Table C.8) with significant impact on quality of results for heights less than 18m.

Two minor adjustments were made to the methodology of WMA, including

- Use of log-normal distribution (less parameters and more convenient to model)
- Formal implementation of standard deviation regression (facilitates parameter uncertainty)

A number of technical issues are raised in Appendix B, but none are considered to invalidate the general approach of WMA. A brief summary is listed here:

- 2 out of 47 of heights at Ipswich seem to be caused by annual maximums of Amberley flows rather than Savages Crossing. The issue is not significant enough to model formally as other assumptions are more critical and it is less likely to impact high flows.
- At least 3 out of 47 flows would cause a higher water level if timing considerations were given more attention

- The reviewer obtained more data points that WMA for the POT analysis although their scatter agrees well.
- An explanation for the 0.6 flow conversion factor is not given
- The Amberley flows modelled by WMA are likely to be underestimated in the lower tail. This should have little impact on the Q100 height estimates.
- Any ongoing work using a joint probability approach should present results for several alternative formulations regarding the correlation structure. The WMA model appears adequate, but the assumed correlation structure is likely to be a critical factor in controlling the exceedance estimates.

The output of the analysis in Appendix B is shown in Figure 3.1. This Figure validates the best estimate WMA results (cf. WMA Figure 5) for the region of 2% AEP to 0.2% AEP. For the method used here, AEP less than 0.2% start to have numerical precision issues and AEP greater than 2% are unreliable because the reviewer used a hydraulic approximation. The results are considered reasonable for the indicated region because the hydraulic approximation was suitably reproduced in this region. At the 1% level the simulation of 10 samples produced a range of approximately 4 m for the pre-dam scenario.

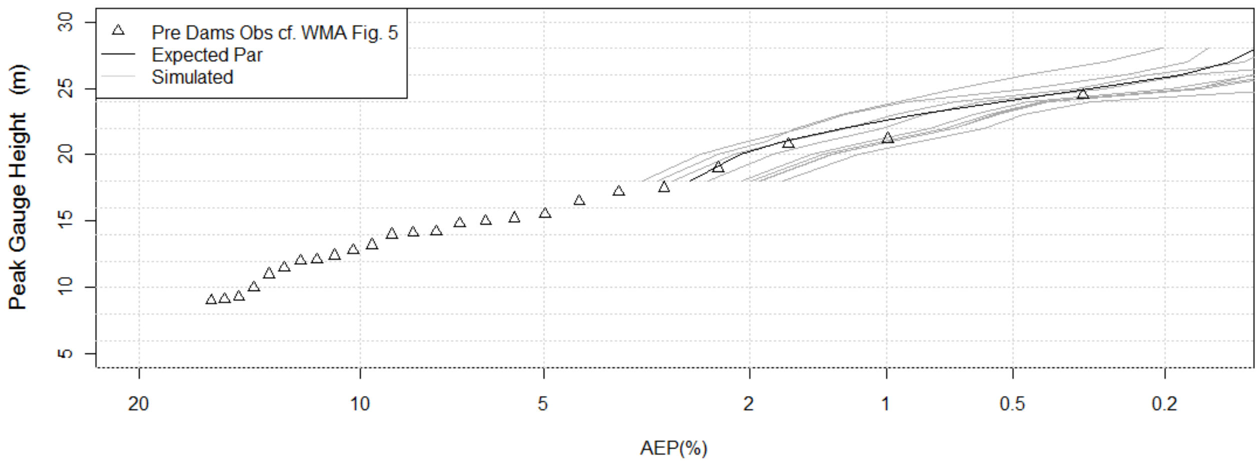

Figure 3.1 Modelled heights at the Ipswich gauge. The best estimate parameters similar to WMA water give the solid black line. 9 samples are presented (a very low amount for interpretation) which demonstrate variability in the method due to parameter uncertainty. The simulated lines have been clipped at a height of 18 m because approximations in the method below this level were unreliable (the estimated and simulated lines drop too quickly).

Other than verifying the general procedure by WMA, Figure 3.1 is of limited use because the "with dams" scenario is of greater interest. Unfortunately for this analysis, the nature of the dam conversion is to cause lower flows and this pushes more of the underlying probability distribution into the region where the hydraulic approximations were unreliable. Nonetheless, the method could be repeated with accurate knowledge of the hydraulic model and used to construct variability estimates[1]. The issue of the hydraulic approximation serves to show the centrality of the hydraulic model to the joint probability method (though, any alternate method would also require a strong reliance on this same model), so the model's quality is important.

[1] The without dams scenario should also be repeated because the flows since the dams were built require conversion to pre-dam estimates

The main aim of an uncertainty analysis should be to assess the statements made regarding the influence of the dams (WMA, Figure 2). Even though the Bremer River is not dammed, the backwater effects of the Brisbane River imply that the 'with dams' scenario will strongly influence the variability of the estimates in the Ipswich region. A method to do this would be to allow a multiplier on the error that scales with the magnitude of the pre-dam flow. The mean function could be either the 50% line or the estimation line suggested by WMA. Short of using a spatiotemporal Monte Carlo analysis to populate the scatter about the conversion line, it is not possible to know the true character of the conversion. So any analysis of this type would need to make stand-in assumptions, for example, that the variation is factored at 20% of the predam flow, that the errors follow a normal distribution and therefore that the scatter is not skewed or biased about the best-estimate of the mean line.

4. Conclusions

The aim of this review is to highlight the need for uncertainty in design estimates. WMA have adopted a joint probability approach to provide a best estimate of exceedance probabilities at Ipswich. This represents a significant advance on earlier methods, but it also rests on a large number of assumptions and can have high levels of uncertainty. Due to the imposed constraints WMA have been unable to provide formal uncertainty analysis of their estimate. The reviewer supports the WMA estimate but also notes that a variety of assumptions need to be tested in more detail and that uncertainty estimates need to be quantified. A method to achieve this which builds upon the joint probability framework has been demonstrated here, but results were only for a very limited case. The results presented here at least partially confirm the work by WMA, but significant additional work is required to demonstrate that the results are not sensitive to the joint dependence structure and to allow for the variable function of the dams (as already pointed out by WMA para. 85 and 87). The authors highlighted that their estimates will likely have a wide range of uncertainty and recommend a range based on the 2% AEP to the 0.5% AEP which is over 4.4m. Given the limited analysis presented here this estimate seems reasonable.

WMA have highlighted the two key problems in determining design estimates for the Ipswich region (i) understanding the hydraulic effects and (ii) understanding the joint hydrologic effects. There is a heavy reliance upon a hydraulic model in coming up with a design estimate in the confluence zone so that any improved understanding of the physical link will translate into better estimates. However, the reviewer’s main concern is that hydrologic uncertainties will overwhelm the design estimates.

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Appendix A – M. Leonard Curriculum Vitae

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TEACHING

The following is a list of subjects I have lectured

- Engineering Modelling & Analysis I (2007-2009)
- Water Engineering IIIB (2004, 2008)
- Advanced Water Resources Management IV (2003)
- Introduction to Geostatistics (Masters of Geostatistics) (2010, 2011)
- Computing for Geostatistics (Masters of Geostatistics) (2010, 2011)

REVIEWER FOR JOURNALS (in past 2 years)

Journal of Applied Mathematics and Decision Sciences (Hindawi) , *Journal of Hydraulic Engineering* (ASCE), *Hydrology and Earth System Sciences* (EGU), *Atmospheric Research* (Elseveir), *Water Resources Research* (AGU), *Journal of Hydrology* (Elseveir), *Environmental Modelling & Software* (Elseveir), *Hydrological Sciences* (Taylor & Franics), *Advances in Water Resources* (Elsevier), *Australian Journal of Water Resources* (IEAust)

REVIEWER FOR CONFERENCES

MODSIM 2005 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2005

Hydrology and Water Resources Symposium, 2006 – 2011, Institute of Engineers Australia

AWARDS

Best presentation by a student or recent graduate, Engineering Mathematics & Applications, 2009

Best presentation by a student or recent graduate, Water Down Under 2008

Postgraduate Research Award, AWA, 2006

CAMWE prize for best honours Civil & Environmental project thesis, Optimisation of water distribution systems including the effects of uncertainty (Industry partner: United Water International, 2002) (joint authorship - Zecchin, A., Berrisford, M., Leonard, M., Roberts. A.).

PROFESSIONAL ACTIVITIES

2008: Technical editor for Water Down Under 2008 Hydrology & Water Resources Symposium peer review process, Institute of Engineers, Australia

2007-2008: Delivered seminars to female secondary school students as part of 'Women in Technology' conference

2005-2008: Secretary for Engineering and Computer Science Faculty, Computer Aided Teaching Suite Steering Committee

2004-2009: Assistance in preparation of ARC research proposals

2003-ongoing: Member of the Hydrological Society of South Australia

2003: SAPAC Workshop High Performance Computing / Parallel Programming

Appendix B - Joint Analysis Method Detail

The aim of this section is twofold:

(i) Review the implementation and assumptions of the joint probability analysis by WMA
(ii) Formulate and document a methodology suitable for uncertainty analysis

The material in this Appendix is intended for technical readers, whereas the main document summarises the outcomes and discusses assumptions. Appendix C summarises data used in this study. Unfortunately the outcome of the study is limited by the use of an approximation surface to the hydraulic response (i.e. Figure B6, WMA, 2011).

The overall goal of the joint probability analysis is to construct a probability distribution of only those flows ($Q_{Amb,}$ Q_{Sav}) that will yield the maximum water height at Ipswich (H_{Ips}).

Figure B.1 summarises the joint distribution of **all** pairwise flows at Savages Crossing and Amberley from which the subset of pairs are required that yield annual maximums H_{Ips}. The Q_{sav}=100 threshold identifies occasions when Savages Crossing has high flow and the Q_{Amb}=100 threshold shows occasions when Amberley has high flows. The top right most corner is when both flows are high, but it is possible that annual maximums are contributed by two additional scenarios (i) Q_{sav} is high and Q_{Amb} takes on any coinciding value (right hand region) and (i) Q_{Amb} is high and Q_{Sav} takes on any coinciding value (top most region). The WMA analysis pursues the first case assuming that the Brisbane River is the dominant flood generating mechanism. In other words, the assumption is that the top-left corner of the plot does not contribute annual maximum water heights in Ipswich (or has sufficiently low occurrence rate to be ignored).

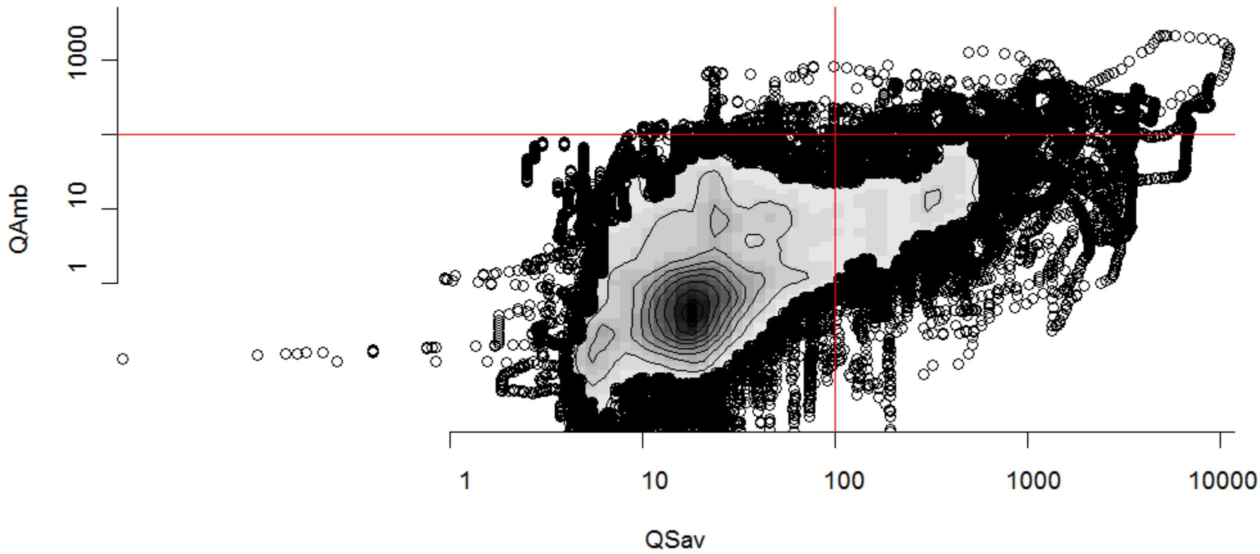

Figure B.01 Comparison of scatter produced by all pairs of Q_{Sav} and Q_{Amb} flows (not just selected independent or extreme values). Contours show density of inner data points whereas outer values are represented by points.

A basic check was conducted to see whether there were any years when the annual maximum flows at Amberley caused higher values of H_{Ips}, than choosing annual maximum flows at Savages Crossing. If this proves to be true, then the WMA analysis is biased by having ignored these cases. Table B.1 summarises the findings. It shows that there are 5 years out of 47 where using Q_{Amb} to identify annual maximums results in higher water levels than if Q_{Sav} had been used. Of these 3 of the cases appear to be a matter of timing, that with more attention the correct flow pair for that event (the one producing the maximum height) would be selected. Only 2 of the cases were from independent events. The ratio 2/47 is about 4% which suggests that the assumption used by WMA is reasonable. To otherwise accommodate this 4% would require double the number of parameters of that used by WMA and would cause significant uncertainty in the methodology. The reviewer also expects that the 4% of cases are not as significant for the upper tail of the distribution of water levels in Ipswich than those contained within the 96%.

Table B.1 A Comparison of flow pairs based. Case 1: based upon annual maximums at Savages Crossing and with coincident Amberley flows obtained via 12 hour timing rule. Case 2: : based upon annual maximums at Amberley and with coincident Savages Crossing flows obtained via 12 hour timing rule. Height at Ipswich obtained from gauge 40101. The classification "Timing" indicates flows are from the same event and "Different" implies two different events.

Case 1: Annual Max based on Q_{Sav}				Case 2: Annual Max based on Q_{Amb}				
Date	**Q_{Sav}**	**Q_{Amb}±12hr**	**H_{Ips}***	**Date**	**Q_{Amb}**	**Q_{Sav}±12hr**	**H_{Ips}***	**Classified**
20/02/1971	3123.2	130.9	7.7	4/02/1971	880.85	1473.87	11.71	Different
28/01/1974	11136.9	1359.5	20.7	27/01/1974	2107.53	9276.46	20.7#	Timing
22/01/1976	1844.3	95.4	5.3	11/02/1976	1288.92	973.41	13.65	Different
6/04/1988	1897.9	184.2	3.7	4/04/1988	542.13	1506.29	11.2	Timing
9/02/1991	374.5	372.1	7.2	8/02/1991	678.76	368.90	7.2#	Timing

* Nearest value read from gauge 40101. Does not necessarily correspond to exact flow from hydraulic model
# Where H_{Ips} appears the same, hydraulic model will show height difference (based on inspection of WMA Figure B6)

Proceeding with the joint analysis, it is reasonable to consider the case of annual maximum flows Q_{Sav} and the coincident flows Q_{Amb}. A fit of the annual maximum flows is shown in Figure B.2 using the lognormal distribution. The reviewer considers the skewness to be sufficiently negligible that a 2-parameter distribution is suitable. The alternatives presented by WMA using the GEV and LP3 offer similar quality of fit. The reviewer's preference is for the lognormal because of convenience in its implementation.

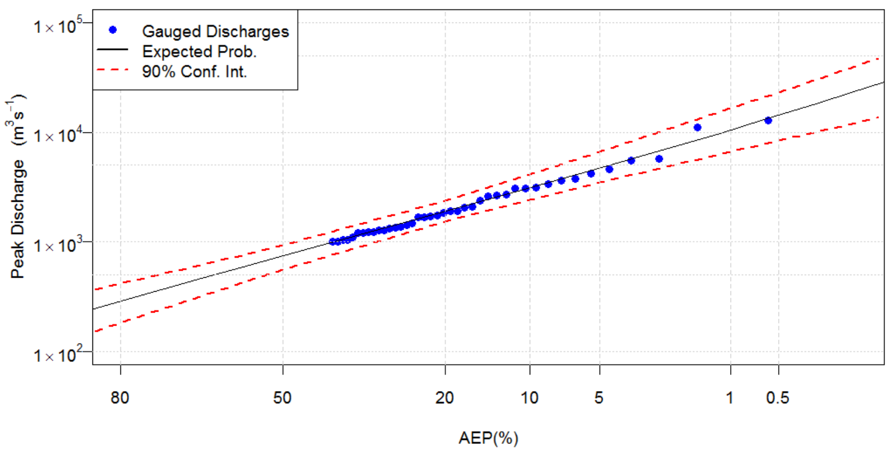

Figure B.02 Lognormal distribution fitted to Q_{Sav} using Flike

The next step is to model the Q_{Amb} flows that come from the same event corresponding to the Q_{Sav} annual maximum. In doing so a joint (bivariate) probability distribution is specified which can handle the case of correlated data. There are many alternate ways to model the joint distribution and the assumptions can be critical, especially when interest is in the region of the upper tail. WMA have opted to use a peak-over-threshold method (POT) which allows for more pairs of points to be collected than taking just one pair each year. Figure B.3 shows a comparison of the POT analysis[2] by the reviewer criteria (crosses) which obtained many additional pairs as compared to the points identified by WMA (circles). While there are many coinciding pairs, the reason for this difference is not clear and is likely to come down to a stricter independence criteria by WMA. Either way, this difference is unlikely to affect the WMA result as both datasets share the same overall scatter. The main challenge is to estimate the association between the pairs for increasing flows (i.e. if the Q_{Sav} flow is higher does this imply that the Q_{Amb} flows are similarly high, and how strong is the relationship?). Using a POT analysis bears the assumption that the association would be the same if only the Q_{Sav} annual maximums were used (triangles in Figure B.3). Although there are less of these points and they can occur at lower flows, it appears they have a similar association.

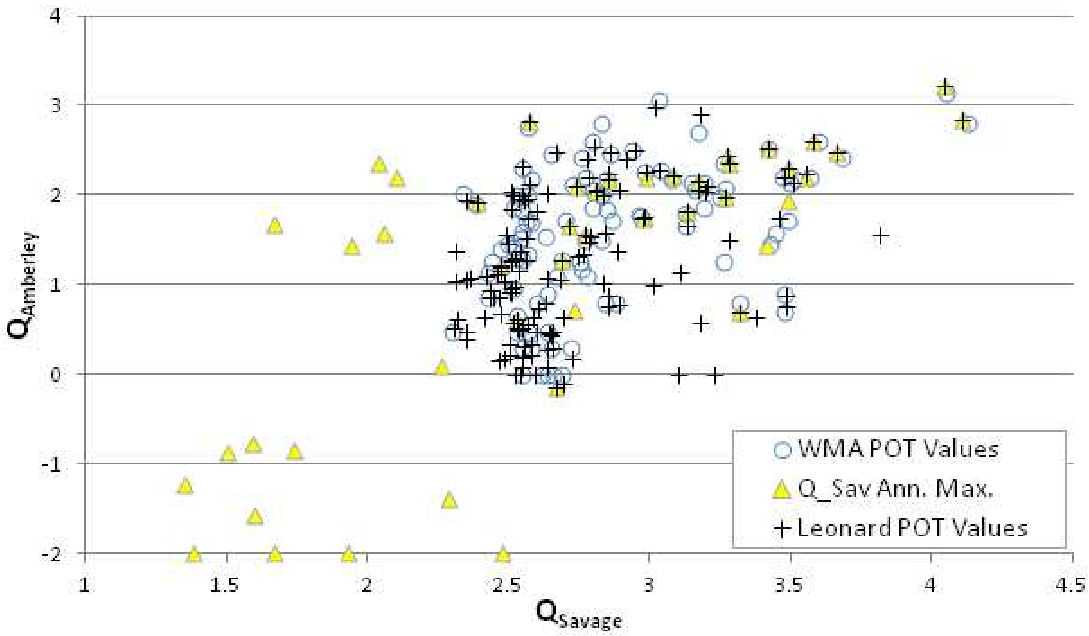

Figure B.3 Comparison of scatter produced by Q_{Sav} and Q_{Amb} flows. WMA POT values (Figure B2 Ipswich Report) are compared directly to Leonard POT values. Q_{Sav} annual maximums and coincident Q_{Amb} flows demonstrate similar correlation as POT values.

WMA have modelled the probability density of Q_{Amb} flows conditioned on a given flow of Q_{Sav}, denoted $f(Q_{Amb}|Q_{Sav})$. If the proability density of the Q_{Sav} annual maximums is specified $f(Q_{Sav})$ (i.e. the distribution in Figure B.2), then the joint distribution is obtained by the product of these two distributions.

$$f(Q_{Sav},Q_{Amb}) = f(Q_{Amb}|Q_{Sav})\, f(Q_{Sav}) \quad \text{(B1)}$$

The distribution of Q_{Amb} flows (those that coincide on the day of annual maximum Q_{Sav}) is then obtained by integrating the joint distribution

$$f(Q_{Amb}) = \int f(Q_{Sav}, Q_{Amb})\mathrm{d}Q_{Sav} \quad \text{(B2)}$$

The purported benefit of this procedure is that it uses the longer Q_{Sav} record and exploits additional information from the POT analysis, but one could have alternatively fitted the relevant pairs directly (the triangles in Figure B.3). It serves as a useful check to compute B2 to see how well the Amberley flows are

[2] 5-day independence criteria was used. Identified values shown in Appendix C. Also note, the threshold is not actually 100 m^3s^{-1} since it was applied to flows before the dam conversion and is closer to 300 m^3s^{-1} pre-Wivenhoe and 200 m^3s^{-1} post-Wivenhoe. The difference will have trivial impact on results.

modelled, even though the Amberley record is short. This will be done after giving further discussion to the joint relationship.

WMA have opted for a regression of the conditional mean and standard deviation of Q_{Amb} flows for given values of Q_{Sav}. This is a reasonably flexible approach but not the only one. Two more direct alternatives that use the Q_{Sav} annual maximums come to mind

(i) fit a joint log-normal distribution to the annual maximum pairs
(ii) fit the marginals using the best identified distribution (not necessarily lognormal) and then test a variety of copula functions to handle the dependence structure

Both of these approaches can be fitted using maximum likelihood methods which is convenient for an uncertainty analysis. A third option is to fit the POT distributions and then construct the annual maximums from the exceedances, but this would be much more complicated. Given a longer time frame the reviewer would be more confident with the results if a variety of cases were implemented to test the correlation structure between the two variables as the overall result is likely to be sensitive to this assumption.

As a verification of the WMA procedure, the regression approach has been re-implemented here. However a difference has been made to allow the standard deviation parameter to be formally regressed, rather than using a more ad-hoc estimation technique. The chief advantage is that this approach allows the uncertainty in the parameters to be assessed. The regression model is specified as

$$Q_{Amb} = m(Q_{Sav}) + s(Q_{Sav}) * \text{error} \tag{B3}$$

where $m(Q_{Sav})$ is the function of the mean which changes for a given value of Q_{Sav}

$s(Q_{Sav})$ is the function of the standard deviation which changes for a given value of Q_{Sav}

error explains the residual variance which is assumed to be normally distributed ~ N(0,1)

Linear regressions are assumed for the mean and standard and the model has 4 parameters

$$\frac{Q_{Amb} - (\mathrm{m}_0 + \mathrm{m}_1 Q_{Sav})}{\mathrm{s}_0 + \mathrm{s}_1 Q_{Sav}} = \text{error} \tag{B4}$$

where m_0 and m_1 are respectively the intercept and slope of the conditional mean

s_0 and s_1 are respectively the intercept and slope of the conditional standard deviation

This model was fitted using maximum likelihood techniques and results in the following parameters

Table B.2 Fitted regression parameters including covariance matrix of parameter variability

Param	Expected Value	Covariance	m_0	m_1	s_0	s_1
m_0	-0.94453		0.2246	0.0738	0.0200	0.0068
m_1	0.882515		0.0738	0.0248	0.0068	0.0023
s_0	1.249539		0.0200	0.00686	0.13928	0.0461
s_1	0.19652		0.0068	0.00235	0.04617	0.0155

The expected values of the parameters agree closely to those obtained by WMA. The residuals are comparable (Figure B.4) to those from WMA but the standard deviation obtained here is higher at high values of Q_{Sav} (Figure B.5). The WMA estimate has differing amounts of data in each sub-range they used to estimate the standard deviation. In the highest sub-range there were few data points and the WMA estimate of the slope in that region is less reliable. Figure B.6 shows the resulting conditional distribution, which is similar to WMA (cf. WMA Figure B2), but has noticeably higher variability in the region Q_{Sav}>5000.

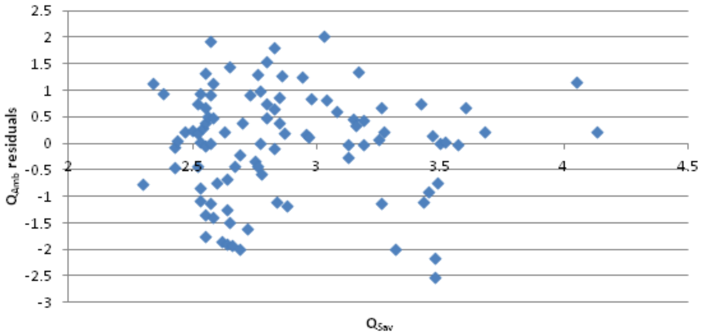

Figure B.4 Residuals of Q_{Amb} flows regressed against Q_{Sav} flows.

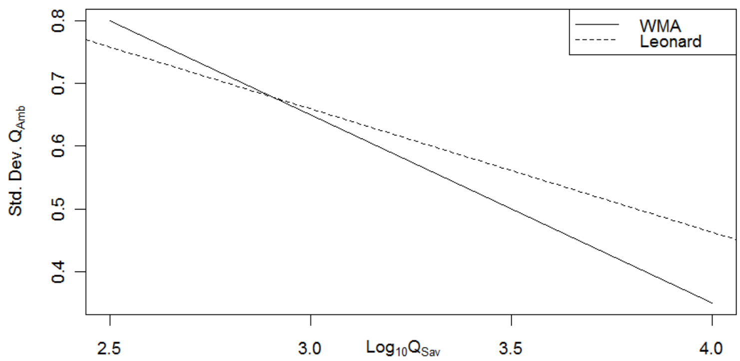

Figure B.05 Difference in regression of standard deviation of Q_{Amb} conditioned on Q_{Sav}

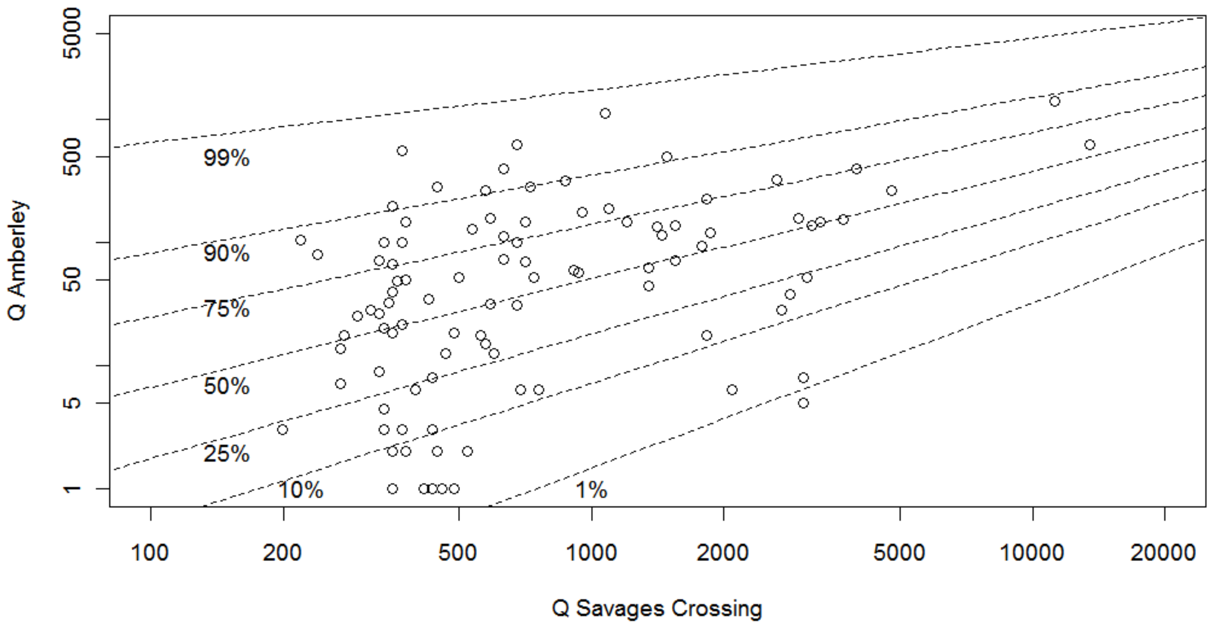

Figure B.6 Conditional distribution of Q_{Amb} given Q_{Sav} (Cf. WMA Fig B5)

The parameters in Table B.2 can be used to specify a multivariate normal distribution. Sampling this distribution allows random sets of parameters to be obtained which are then used in the uncertainty analysis.[3] A plot of the parameters in Figure B.7 shows the strong relationship between them. Fitting this regression line for a random sample of 1000 parameter sets shows any of the potential regression lines that could be followed (Figure B.8). For each of these regression lines Equation (B2) can be numerically integrated to obtain the distribution of Q_{Amb} flows. This check, as mentioned earlier is shown in Figure B.9

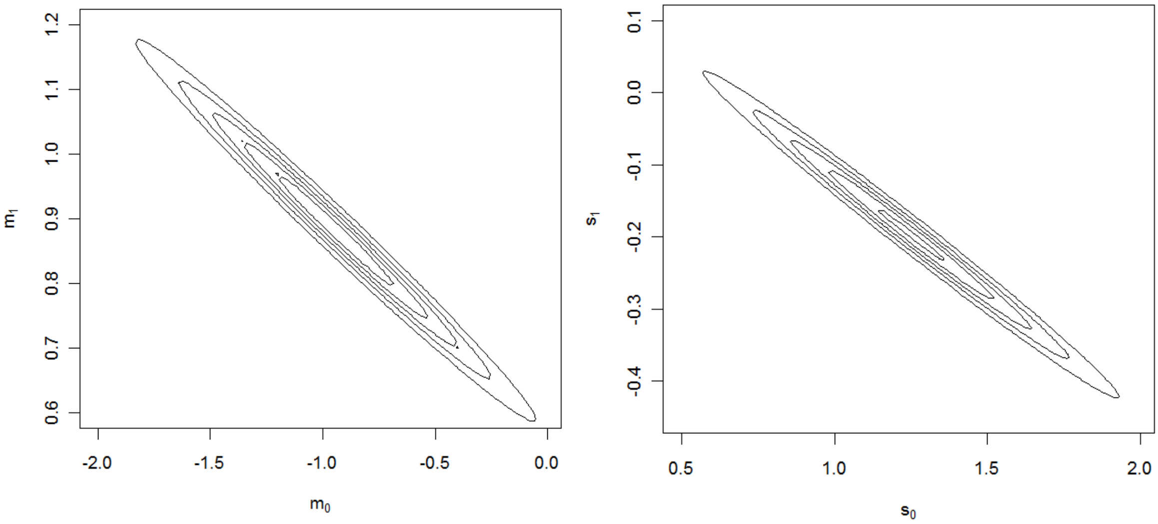

Figure B.7 Conditional distribution of Q_{Amb} given Q_{Sav} (Cf. WMA Fig B5)

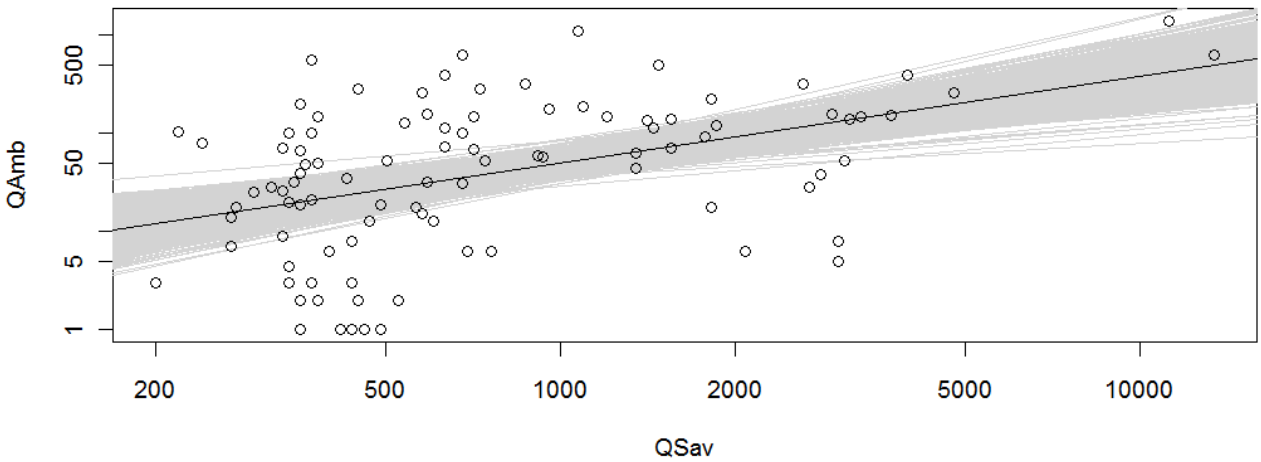

Figure B.08 Conditional distribution of Q_{Amb} given Q_{Sav} (cf. WMA Fig B5) Simulated values in grey. Expected value line in black.

Figure B.9 shows that the model adopted by WMA slightly underestimates the variability in the lower tail than if a more direct approach was adopted (leading to the lognormal or copula method mentioned earlier). This will have some impact on the final results, but it is likely to cause a slight underestimation in the variability at lower water levels of H_{Ips}. WMA Figure 5 currently have an overestimation in the lower tail

[3] Kuczera (1999) and FLIKE help files specify how covariance matrix is obtained from likelihood function. FLIKE uses the multivariate normal approximation to sample the true posterior distribution via importance sampling. Here, the multivariate normal is directly sampled (i.e. importance sampling not conducted). This is a reasonable first order approximation.

of H_{Ips}, which is likely due to compensating factors in the hydraulic model having masked out the effect being noted here (or that the observed values in this region are suspect).

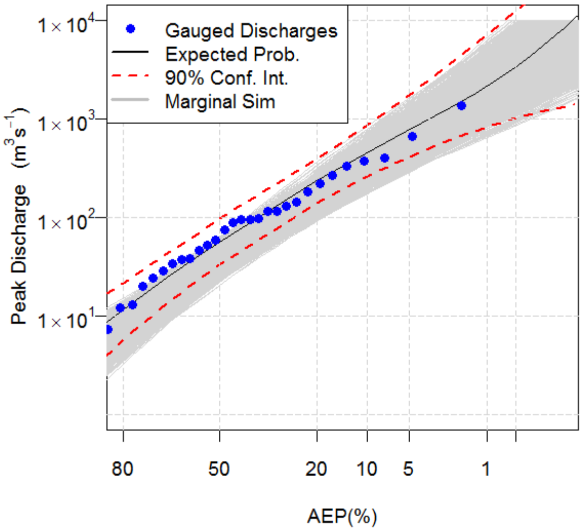

Figure B.09 Marginal distribution of Q_{Amb}. Simulated values in grey. 90% confidence limits obtained by directly fitting the Q_{Amb} distribution using FLIKE software (Kuczera, 1999)

Now that a probability model of the flows is constructed, it can be used with a transformation function to determine the probability of heights H_{Ips}. The reviewer did not have access to the hydraulic model results and manually constructed an approximation based on WMA Figure B6 (shown in Appendix C). Figure B.10 shows the comparison of the contours used here which are notably less detailed in the region of lower flows than WMA Figure B6. This has led to a significant restriction on the analysis presented in this review which was not otherwise expected when the approximation was constructed. Applying this methodology with actual contours developed from the hydraulic model should remedy the issue.

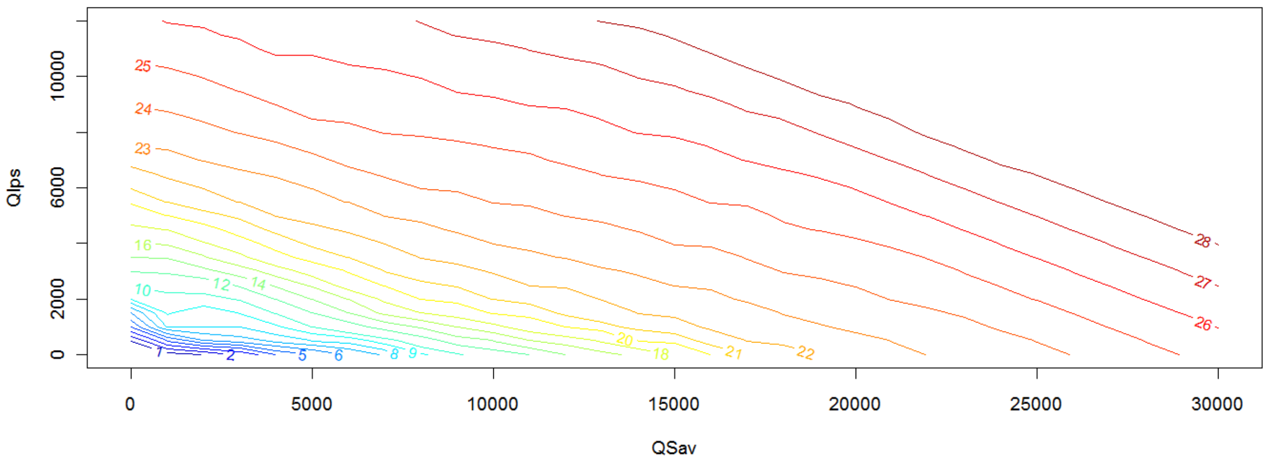

Figure B.010 Interpolated approximation of Figure B6 from WMA Ipswich Report. Converts flow inputs Q_{Ips} and Q_{Sav} to height of the Bremer River. The function is a summary and approximation of the hydraulic model.

Figure B.11 is identical to Figure B.10 except is uses the 0.6 conversion factor of flows between Q_{Ips} and Q_{Amb} (i.e. the y-axis labels have changed). Section 2.1 (para. 9) cites Warrill Creek as two thirds of the Bremer's total catchment area yet a conversion of 0.6 is used. More detail explaining this factor would be appreciated, e.g. is it a ratio of catchment rainfalls or is it based on the partial area to the location of the Q_{Amb} gauge?

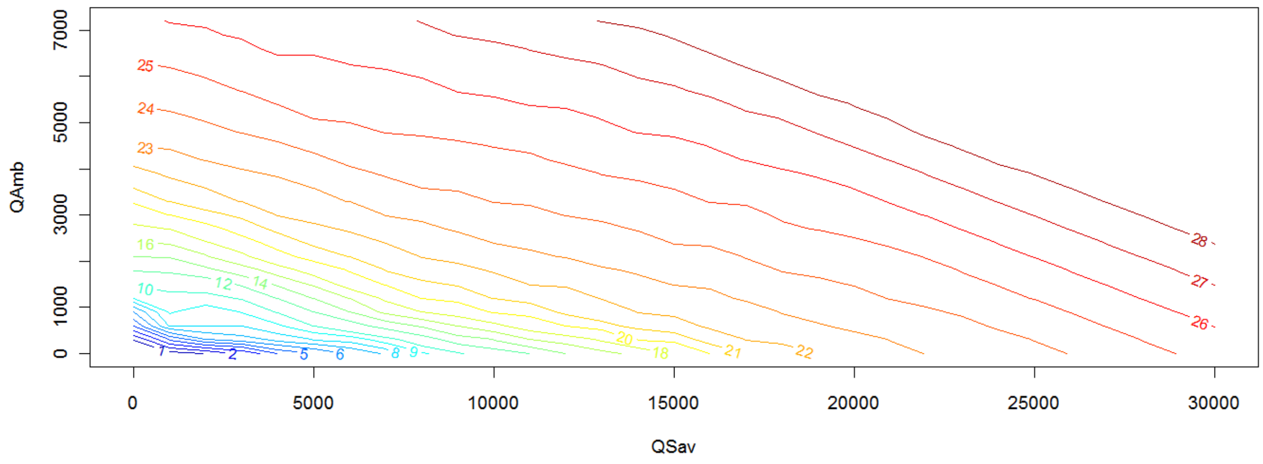

Figure B.11 Interpolated approximation of Figure B6 from WMA Ipswich Report. Converts flow inputs Q_{Amb} and Q_{Sav} to height of the Bremer River. The function is a summary and approximation of the hydraulic model.

The heights H_{Ips} are obtained by considering every possible pair of flows and weighting them by the probability that that pair of flows occurs and by the probability they exceed the specified height of interest. The notation presented here is different to the WMA Ipswich report but the procedure is fundamentally the same. A point of note is that the summation technique used here is computationally demanding and requires a small increments to achieve the desired precision whereas WMA required only 66 ordinates (WMA para. B14). The total probability theorem can be used to estimate the probability a height is exceeded,

$$Prob(H > h) = \iint Prob(H(Q_{Sav}, Q_{Amb}) > h) f(Q_{Sav}, Q_{Amb}) dQ_{Sav}\, dQ_{Amb} \qquad \text{(B5)}$$

where

- *h* is a threshold of interest

- *Prob*(*H>h*) is the probability the river exceeds a certain specified height. As an example *Prob*(*H>20 m*) is the probability that the height exceeds 20 m. If this is evaluated to, for example, 2%, it means that 20m is a 2% AEP.

- *H*(Q_{Sav},Q_{Amb}) is the function converting input flows to heights (Figure B.11)

- *Prob(H*(Q_{Sav},Q_{Amb})>h) is the chance a specific height exceeds the threshold, either 0 if it doesn't or 1 if it does.

- *f*(Q_{Sav},Q_{Amb}) is the joint density function of the input flows. (Figure B.12)

- ∫∫ dQ_{Sav} dQ_{Amb} means the values are to be summed over the entire range of flows

The procedure to implement this is quite straightforward to understand graphically. Figure B.12 shows the joint probability density function with height contours overloaded. An exceedance probability is by definition the probability of exceeding a certain height, so the procedure is simply to identify a height contour of interest and then summate the probabilities of the underlying distribution above the contour. The resulting estimate can be spurious if either the contours are incorrect (the hydraulic model) or the probability function is not representative. The issue of association between high flows is critical because, with reference to Figure B.12, more of the top-right portion of the shaded grey region can easily be pushed above contours of interest for a change in correlation parameter.

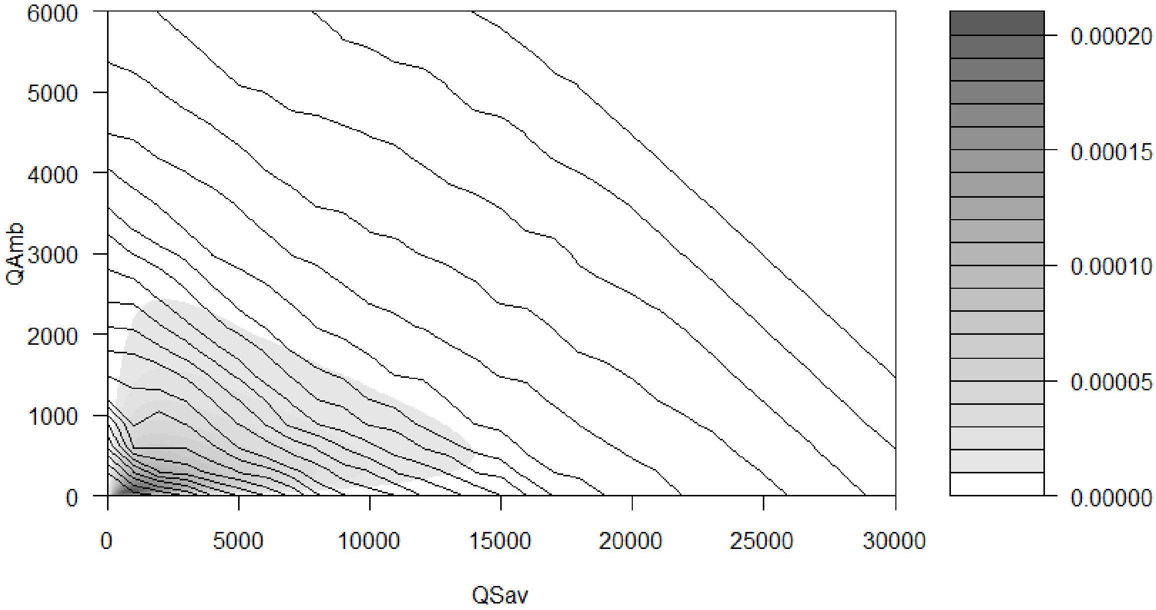

Figure B.12 Joint probability density function $f(Q_{Amb}, Q_{Sav})$ shown in shaded levels. H_{Ips} height contours are overlaid. The procedure for getting an exceedance probability is to locate a H_{Ips} contour of interest and then summate all the values of the probability function that lie above this line.

An uncertainty analysis proceeds by sampling different sets of parameters controlling the joint probability distribution. A given sample represents one possible characterisation for which the integration in Equation (B5) is performed at all water level heights of interest. This procedure is repeated for many replicates from which confidence limits can be constructed. The parameters of the Amberley flows have already been provided in Table B.2, but it is also necessary to allow the Savages Crosssing parameters to vary. These are provided in Table B.3. The procedure used here assumes that the Q_{Sav} marginal distribution parameters (Table B.3) are independent of the parameters used to specify the conditional distribution (Table B.2).

Table B.3 Savages Crossing marginal distribution fitted lognormal parameters

Scenario	Param	Expected Value	Covariance	Log_e mean	Log_e sdev
Without dams	**Log_e mean**	6.63131		0.0228	0.0109
	Log_e sdev	0.07775		0.0109	0.0158
With dams	**Log_e mean**	7.50498		0.0121	0.0000
	Log_e sdev	-0.54096		0.0000	0.0121

The parameters of the "With dams" scenario are presented in Table B.3 although final results are not able to be presented from this scenario. The reason is that the approximation used in Figure B.11 is unreliable at lower flows and the effect of the different parameters for the dams scenario is to lower the Q_{Sav} flows into this region so that results at the 1% AEP cannot be relied upon. The final result is shown in the body of the report in Figure 3.1.

Appendix C – Data Summary

This review was done in a short time frame so please do not rely on figures in this Appendix without checking them. They are presented here for reproducibility of results. The reviewer has performed only limited checks.

Table C.1 Savages pre-dam to post-dam flow conversion used by WMA Ipswich Report, 1943-1985 (Somerset only). Units m^3s^{-1}.

Pre	Post	Ratio
0	0	-
288	100	0.347
5692	5363	0.942
9807	7393	0.754
13922	11508	0.827
18037	15623	0.866
22152	19738	0.891
26267	23853	0.908
30382	27968	0.921

Table C.2 Savages pre-dam to post-dam flow conversion used by WMA Ipswich Report (Figure 2) for period 1986-present (Wivenhoe & Somerset). Units m^3s^{-1}.

Pre	Post	Ratio	Pre	Post	Ratio	Pre	Post	Ratio	Pre	Post	Ratio
0	0	1.00	10700	6917	0.67	13100	9400	0.71	15500	11882	0.77
1	1	1.00	10800	7020	0.67	13200	9503	0.71	15600	11986	0.77
2000	1000	0.50	10900	7124	0.67	13300	9606	0.71	15700	12089	0.77
8600	3657	0.42	11000	7227	0.67	13400	9710	0.71	15800	12192	0.77
8700	4486	0.53	11100	7331	0.67	13500	9813	0.71	15900	12296	0.77
8800	4952	0.56	11200	7434	0.67	13600	9917	0.71	16000	12399	0.77
8900	5055	0.56	11300	7538	0.67	13700	10020	0.71	16100	12503	0.77
9000	5159	0.59	11400	7641	0.67	13800	10124	0.71	16200	12606	0.77
9100	5262	0.59	11500	7745	0.67	13900	10227	0.71	16300	12710	0.77
9200	5365	0.59	11600	7848	0.67	14000	10331	0.71	16400	12813	0.77
9300	5469	0.59	11700	7951	0.67	14100	10434	0.71	16500	12916	0.77
9400	5572	0.59	11800	8055	0.67	14200	10537	0.77	16600	13020	0.77
9500	5676	0.59	11900	8158	0.67	14300	10641	0.77	16700	13123	0.77
9600	5779	0.59	12000	8262	0.67	14400	10744	0.77	16800	13227	0.77
9700	5883	0.63	12100	8365	0.71	14500	10848	0.77	16900	13330	0.77
9800	5986	0.63	12200	8469	0.71	14600	10951	0.77	17000	13434	0.77
9900	6090	0.63	12300	8572	0.71	14700	11055	0.77	24000	18400	0.77
10000	6193	0.63	12400	8675	0.71	14800	11158	0.77	31000	23366	0.77
10100	6296	0.63	12500	8779	0.71	14900	11261	0.77	38000	28332	0.77
10200	6400	0.63	12600	8882	0.71	15000	11365	0.77			
10300	6503	0.63	12700	8986	0.71	15100	11468	0.77			
10400	6607	0.63	12800	9089	0.71	15200	11572	0.77			
10500	6710	0.63	12900	9193	0.71	15300	11675	0.77			
10600	6814	0.63	13000	9296	0.71	15400	11779	0.77			

Table C.3 Annual maximums obtained from Amberley site. Water years begin in July, e.g. year=1961 implies 01/07/1961 to 31/06/1962. Units are m^3s^{-1}.

Date	Q_{Amb}	Date	Q_{Amb}	Date	Q_{Amb}	Date	Q_{Amb}	Date	Q_{Amb}
21/11/1961	271.948	29/10/1972	402.947	2/12/1983	187.811	18/02/1995	23.061	17/02/2006	30.662
8/05/1963	382.574	27/01/1974	2107.531	28/07/1984	156.37	3/05/1996	448.543	22/07/2006	0.461
23/04/1964	216.079	26/02/1975	286.573	13/02/1986	23.741	15/02/1997	29.956	6/02/2008	232.16
3/07/1964	64.113	11/02/1976	1288.919	29/01/1987	23.621	25/12/1997	35.513	21/05/2009	304.004
8/12/1965	133.568	11/03/1977	223.694	4/04/1988	542.134	9/02/1999	194.594	16/02/2010	127.34
12/06/1967	329.847	3/04/1978	127.122	6/07/1988	315.936	28/12/1999	81.38	12/01/2011	705.826
13/01/1968	402.947	21/06/1979	97.525	5/04/1990	345.566	3/02/2001	95.649		
15/05/1969	81.026	9/05/1980	158.4	8/02/1991	678.76	2/02/2002	2.084		
20/11/1969	36.814	7/02/1981	284.814	12/12/1991	807.292	4/06/2003	5.951		
4/02/1971	880.853	4/11/1981	236.462	19/07/1992	65.356	4/02/2004	146.157		
3/04/1972	101.996	22/06/1983	437.418	11/03/1994	79.147	11/12/2004	29.131		

Table C.4 Annual maximums obtained from Savages site for the period 1961-2011. Peak flows obtained from Amberley site where timing of ± 12 hours is allowed (note: the Amberly flows are not necessarily the annual maximum). Water years begin in July. Units are m^3s^{-1}. Savages flows converted to pre-dam.

Date	Q_{Sav}	Q_{Amb}	Date	Q_{Sav}	Q_{Amb}	Date	Q_{Sav}	Q_{Amb}
10/01/1962 06:00	595.14	28.74	22/01/1982 08:00	1217.81	145.005	18/12/2001 12:00	39.18	0.157
19/03/1963 06:00	1364.37	2.881	24/06/1983 00:00	1896.98	116.477	23/01/2003 12:00	46.56	0
01/04/1964 12:00	464.54	0.715	02/07/1983 13:00	545.20	5.122	06/03/2004 04:00	514.62	0.188
04/07/1964 12:00	113.51	19.976	14/11/1984 15:00	296.60	7.245	07/11/2004 18:00	85.59	0
21/07/1965 10:00	1689.64	0	09/07/1985 04:00	181.92	1.03	14/10/2005 12:00	24.00	0
12/06/1967 05:00	2644.09	329.847	01/10/1986 00:00	32.00	0.094	12/01/2007 10:00	301.15	0
13/01/1968 23:00	3792.18	402.947	06/04/1988 10:00	1897.95	184.179	05/02/2008 13:00	108.66	220.304
03/01/1969 04:00	339.06	2.829	05/04/1989 07:00	3103.45	33.798	21/11/2008 07:00	715.29	96.434
29/08/1969 07:00	348.47	0	29/05/1990 10:00	1482.29	87.69	03/03/2010 11:00	244.05	75.222
20/02/1971 03:00	3123.18	130.93	09/02/1991 10:00	374.52	372.104	12/01/2011 01:00	12926.21	667.386
14/02/1972 15:00	2092.72	3.04	17/03/1992 15:00	2587.87	11.937			
19/02/1973 15:00	957.56	38.321	20/08/1992 00:00	54.94	0.143			
28/01/1974 01:00	11136.89	1359.496	01/03/1994 07:00	46.78	0.6			
15/01/1975 05:00	393.65	0	01/02/1995 00:00	39.81	0.019			
22/01/1976 09:00	1844.33	95.398	05/05/1996 21:00	4590.43	264.558			
02/11/1976 06:00	641.78	37.178	17/02/1997 12:00	87.20	24.282			
03/04/1978 11:00	545.81	115.561	18/09/1997 12:00	22.55	0.043			
24/01/1979 12:00	491.63	13.018	10/02/1999 11:00	3596.54	94.494			
09/05/1980 12:00	126.41	52.226	05/08/1999 06:00	194.53	0.011			
09/02/1981 13:00	971.03	58.583	04/02/2001 16:00	951.34	46.376			

Table C.5 Annual maximums obtained from pre-dam Savages Composite site. Water years begin in July. Units are m^3s^{-1}.

Date	Q_{Sav}	Date	Q_{Sav}	Date	Q_{Sav}	Date	Q_{Sav}
28/12/1909 12:00	813.52	03/03/1940 15:00	697.33	29/08/1969 07:00	348.47	05/08/1999 06:00	194.5328
13/01/1911 13:00	1316.89	25/01/1941 23:00	425.27	20/02/1971 03:00	3123.18	04/02/2001 16:00	951.3354
04/03/1912 23:00	460.75	10/02/1942 18:00	1360.14	14/02/1972 15:00	2092.72	18/12/2001 12:00	39.1831
23/06/1913 08:00	416.42	31/12/1942 07:00	833.44	19/02/1973 15:00	957.56	23/01/2003 12:00	46.56479
27/02/1914 12:00	234.46	31/12/1943 16:00	1425.54	28/01/1974 01:00	11136.89	06/03/2004 04:00	514.6169
11/02/1915 06:00	1035.35	13/06/1945 08:00	328.65	15/01/1975 05:00	393.65	07/11/2004 18:00	85.59432
12/04/1916 04:00	159.20	26/03/1946 19:00	1265.58	22/01/1976 09:00	1844.33	14/10/2005 12:00	24.00151
29/01/1917 18:00	475.23	02/03/1947 23:00	1010.19	02/11/1976 06:00	641.78	12/01/2007 10:00	301.1502
13/12/1917 16:00	522.28	11/12/1947 09:00	1002.23	03/04/1978 11:00	545.81	05/02/2008 13:00	108.6639
08/05/1919 16:00	90.61	04/03/1949 16:00	1225.24	24/01/1979 12:00	491.63	21/11/2008 07:00	715.2873
22/01/1920 08:00	402.41	01/03/1950 07:00	3048.37	09/05/1980 12:00	126.41	03/03/2010 11:00	244.0536
11/06/1921 15:00	1237.26	01/02/1951 12:00	3394.09	09/02/1981 13:00	971.03	12/01/2011 01:00	12926.21
30/12/1921 23:00	1280.09	18/06/1952 12:00	50.90	22/01/1982 08:00	1217.81		
16/10/1922 01:00	46.34	24/03/1953 12:00	1214.10	24/06/1983 00:00	1896.98		
12/02/1924 14:00	173.20	13/02/1954 12:00	971.40	02/07/1983 13:00	545.20		
21/06/1925 09:00	778.43	30/03/1955 04:00	5692.98	14/11/1984 15:00	296.60		
06/01/1926 12:00	126.45	12/03/1956 20:00	2384.10	09/07/1985 04:00	181.92		
27/01/1927 15:00	2715.26	23/12/1956 12:00	405.08	01/10/1986 00:00	32.00		
20/04/1928 12:00	4225.43	11/06/1958 20:00	1746.15	06/04/1988 10:00	1897.95		
21/01/1929 13:00	2064.30	19/02/1959 10:00	1720.58	05/04/1989 07:00	3103.45		
30/06/1930 11:00	749.23	14/11/1959 14:00	1674.36	29/05/1990 10:00	1482.29		
06/02/1931 14:00	5574.73	27/02/1961 12:00	206.40	09/02/1991 10:00	374.52		
10/12/1931 18:00	327.63	10/01/1962 06:00	595.14	17/03/1992 15:00	2587.87		
20/01/1933 21:00	311.94	19/03/1963 06:00	1364.37	20/08/1992 00:00	54.94		
23/02/1934 16:00	614.28	01/04/1964 12:00	464.54	01/03/1994 07:00	46.78		
26/02/1935 16:00	119.91	04/07/1964 12:00	113.51	01/02/1995 00:00	39.81		
24/03/1936 09:00	138.63	21/07/1965 10:00	1689.64	05/05/1996 21:00	4590.43		
17/03/1937 17:00	1102.97	12/06/1967 05:00	2644.09	17/02/1997 12:00	87.20		
28/05/1938 23:00	1052.08	13/01/1968 23:00	3792.18	18/09/1997 12:00	22.55		
17/03/1939 09:00	459.89	03/01/1969 04:00	339.06	10/02/1999 11:00	3596.54		

Table C.6 Peaks over 100m^{3}s^{-1} threshold at savages and separated by a minimum of 5 days. Peak flows obtained from Amberley site where timing of ± 12 hours is allowed. Water years begin in July. Units are m^{3}s^{-1}. Savages flows converted to pre-dam.

Date	Q_{Sav}	Q_{Amb}	Date	Q_{Sav}	Q_{Amb}	Date	Q_{Sav}	Q_{Amb}
19/11/1961 04:00	316.46	28.247	13/03/1974 06:00	1082.9	194.45	06/07/1988 20:00	888.44	315.936
21/12/1961 06:00	341.39	90.672	20/03/1974 00:00	437.0	1.935	23/12/1988 11:00	494.23	0.775
10/01/1962 06:00	595.14	36.442	15/01/1975 05:00	393.6	NA	12/04/1989 20:00	225.89	11.291
16/01/1962 12:00	291.38	7.205	27/02/1975 18:00	362.6	32.454	27/04/1989 06:00	2992.31	158.197
14/04/1962 09:00	353.62	1.612	03/09/1975 16:00	333.5	NA	02/05/1989 07:00	2366.44	4.316
02/01/1963 18:00	349.65	24.463	20/10/1975 17:00	308.7	36.442	09/05/1989 07:00	223.28	3.051
19/03/1963 06:00	1364.37	64.709	25/12/1975 02:00	718.9	174.515	17/05/1989 22:00	1608.77	124.063
31/03/1963 09:00	352.08	100.312	22/01/1976 09:00	1844.3	95.398	22/05/1989 23:00	273.38	8.891
08/05/1963 18:00	640.39	348.89	27/01/1976 12:00	322.5	19.114	28/05/1989 16:00	271.18	7.371
22/05/1963 12:00	324.03	8.954	12/02/1976 17:00	1045.7	946.404	03/06/1989 10:00	225.51	2.524
01/04/1964 12:00	464.54	0.715	01/03/1976 01:00	1272.1	NA	03/02/1990 02:00	264.63	12.324
24/04/1964 08:00	370.43	93.017	09/03/1976 07:00	697.1	38.314	31/03/1990 04:00	305.14	11.1
21/07/1965 10:00	1689.64	NA	15/03/1976 18:00	716.0	5.756	08/04/1990 12:00	1365.02	44.927
01/02/1967 02:00	448.20	2.726	31/03/1976 18:00	380.7	1.69	22/04/1990 15:00	376.91	131.201
26/02/1967 01:00	379.40	2.194	27/05/1976 18:00	434.4	1.225	27/04/1990 16:00	334.18	9.608
10/03/1967 20:00	324.53	17.968	02/11/1976 06:00	641.8	109.827	29/05/1990 10:00	1482.29	141.425
19/03/1967 23:00	1490.34	117.191	15/11/1976 19:00	322.9	108.058	03/06/1990 13:00	323.09	8.175
08/05/1967 15:00	405.73	5.5	12/03/1977 21:00	361.3	86.854	08/06/1990 14:00	260.92	4.289
12/06/1967 05:00	2644.09	329.847	03/04/1978 10:00	545.8	127.122	09/02/1991 10:00	374.52	657.611
27/06/1967 11:00	1579.91	107.176	08/09/1978 22:00	288.2	12.991	22/11/1995 00:00	436.05	104.93
02/07/1967 17:00	339.06	3.371	31/12/1978 19:00	345.6	14.385	11/01/1996 09:00	395.13	66.971
13/01/1968 23:00	3792.18	402.947	24/01/1979 12:00	491.6	18.758	05/05/1996 21:00	4590.43	297.607
19/02/1968 12:00	306.66	1.493	09/02/1981 12:00	971.0	178.552	10/05/1996 22:00	206.34	10.869
21/03/1968 17:00	333.49	20.39	17/02/1981 03:00	483.1	11.614	10/02/1999 08:00	3596.54	173.554
03/01/1969 04:00	339.06	4.211	22/02/1981 22:00	365.6	19.064	15/02/1999 09:00	1504.90	3.742
29/08/1969 07:00	348.47	NA	05/11/1981 00:00	352.6	207.425	09/03/1999 10:00	331.13	3.71
11/12/1970 08:00	782.82	113.47	05/12/1981 10:00	584.2	22.276	14/03/1999 12:00	318.32	1.652
01/01/1971 12:00	679.88	100.312	25/12/1981 16:00	329.7	99.7	04/02/2001 16:00	951.34	54.805
05/02/1971 05:00	1512.45	795.928	22/01/1982 08:00	1217.8	164.742	09/02/2001 17:00	320.23	2.197
11/02/1971 10:00	833.37	249.448	27/01/1982 09:00	296.6	15.863	06/03/2004 04:00	514.62	46.5
20/02/1971 03:00	3123.18	201.478	04/02/1982 08:00	353.4	1.214	21/11/2008 07:00	715.29	152.242
25/02/1971 04:00	764.74	23.708	28/02/1982 04:00	432.4	12.175	14/04/2009 04:00	231.55	12.061
02/03/1971 23:00	296.59	14.152	12/03/1982 07:00	618.2	35.262	20/05/2009 16:00	468.89	304.004
29/12/1971 13:00	778.29	5.942	17/03/1982 15:00	452.0	2.977	03/03/2010 11:00	244.05	81.834
14/02/1972 15:00	2092.72	5.074	04/05/1983 13:00	607.8	157.546	08/03/2010 12:00	206.31	23.704
20/02/1972 18:00	718.89	7.71	09/05/1983 17:00	341.1	3.192	14/10/2010 12:00	3059.85	7.717
05/04/1972 04:00	1903.17	32.302	14/05/1983 20:00	292.2	1.444	19/10/2010 13:00	208.44	4.232
13/11/1972 02:00	612.81	29.568	29/05/1983 08:00	724.2	303.763	06/12/2010 18:00	223.40	86.465
19/02/1973 15:00	957.56	56.75	03/06/1983 10:00	317.2	8.272	22/12/2010 04:00	2867.58	53.84
01/03/1973 23:00	388.23	4.403	24/06/1983 00:00	1897.0	272.066	30/12/2010 12:00	3249.00	139.643
09/07/1973 10:00	3045.21	5.867	29/06/1983 02:00	681.8	10.326	12/01/2011 01:00	12926.21	705.826
30/07/1973 11:00	369.68	3.602	04/07/1983 05:00	499.2	4.363	17/01/2011 03:00	6566.55	37.058
13/10/1973 00:00	452.59	1.972	09/07/1983 07:00	426.5	6.365	22/01/2011 04:00	368.89	55.381
08/11/1973 19:00	353.05	3.315	14/07/1983 11:00	395.5	2.978	27/01/2011 05:00	279.56	7.14
11/01/1974 15:00	645.98	117.191	19/07/1983 13:00	360.0	2.123	11/02/2011 03:00	202.00	3.365
17/01/1974 02:00	557.90	20.669	09/04/1984 04:00	323.0	69.836	01/03/2011 20:00	532.88	1.537
28/01/1974 01:00	11136.89	1664.289	14/11/1984 15:00	296.6	16.262			
06/02/1974 22:00	1037.15	10.192	06/04/1988 10:00	1897.9	225.258			
12/02/1974 02:00	295.28	4.868	12/04/1988 12:00	1283.0	13.638			
20/02/1974 03:00	442.48	2.881	05/06/1988 05:00	603.3	254.025			

Table C.7 Estimate of peak over threshold flow data underlying Figure B2 of WMA Ipswich Report (manually read from graph). Flows are Log_{10} m^3s^{-1}. There will be minor loss of precision compared to actual data due to ability to resolve symbol placement.

Q_{Sav}	Q_{Amb}	Q_{Sav}	Q_{Amb}	Q_{Sav}	Q_{Amb}	Q_{Sav}	Q_{Amb}
2.55	0	2.43	1.14	2.97	1.76	3.57	2.19
2.62	0	2.76	1.18	2.96	1.78	2.77	2.2
2.64	0	2.44	1.25	3.13	1.8	3.47	2.2
2.66	0	2.75	1.25	2.55	1.82	2.98	2.25
2.69	0	3.26	1.25	2.85	1.84	3.04	2.28
2.55	0.3	2.55	1.27	2.52	1.85	2.55	2.3
2.58	0.3	2.69	1.27	3.19	1.85	3.26	2.35
2.65	0.3	2.53	1.3	2.8	1.86	2.76	2.42
2.72	0.3	2.57	1.33	2.38	1.9	3.68	2.42
2.3	0.48	2.47	1.4	3.25	1.97	2.65	2.45
2.53	0.48	2.52	1.42	2.53	2	2.86	2.45
2.57	0.48	2.5	1.45	2.57	2	2.94	2.5
2.64	0.48	3.43	1.45	2.83	2	3.42	2.51
2.53	0.65	2.83	1.49	2.34	2.02	2.8	2.6
3.48	0.7	2.77	1.5	2.8	2.05	3.6	2.6
2.6	0.8	2.54	1.51	3.16	2.06	3.17	2.7
2.84	0.8	2.63	1.54	3.27	2.08	2.57	2.75
2.88	0.8	3.45	1.58	2.73	2.11	2.83	2.8
3.32	0.8	2.55	1.6	3.15	2.13	4.13	2.8
2.43	0.85	3.13	1.65	3.19	2.14	3.03	3.05
2.64	0.9	2.56	1.69	3.5	2.14	4.05	3.15
3.48	0.9	2.58	1.7	2.58	2.17		
2.52	0.95	2.7	1.72	2.85	2.17		
2.67	1.1	2.87	1.72	3.08	2.17		
2.78	1.1	3.49	1.72	3.52	2.17		

Table C.8 Approximation of Figure B6 in WMA Ipswich Report, Bremer River heights given Amberley and Savages flows. Units are m. Data manually determined by reading graph. Data captures the underlying relationship but loses significant precision for lower flows. Data is interpolated at a higher resolution to retrieve some precision.

Q_{amb} \ Q_{Savage}	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000	12000	13000	14000	15000
12000	25.75	26	26.1	26.3	26.5	26.6	26.7	26.8	27	27.2	27.4	27.6	27.8	28	28.25	28.5
11500	25.5	25.75	25.9	26.1	26.3	26.4	26.6	26.7	26.8	27	27.2	27.3	27.5	27.66	27.75	28.1
11000	25.25	25.5	25.6	25.8	26.2	26.2	26.3	26.4	26.7	25.7	26.8	27	27.2	27.33	27.5	27.8
10500	25	25.1	25.2	25.5	25.8	25.8	26	26.1	26.2	25.4	26.6	26.7	26.9	27	27.25	27.5
10000	24.6	24.8	25	25.2	25.4	25.6	25.8	25.9	26	25.2	26.4	26.5	26.5	26.8	27	27.2
9500	24.33	24.5	24.7	25	25.2	25.4	25.5	25.7	25.8	26	26.1	26.3	26.4	26.6	26.75	26.9
9000	24	24.2	24.4	24.5	25	25.2	25.3	25.4	25.7	25.8	25.9	26	26.1	26.3	26.5	26.7
8500	23.66	23.3	24.1	24.25	24.5	25	25.1	25.2	25.3	25.4	25.6	25.7	25.8	26	26.2	26.4
8000	23.3	23.5	23.75	24	24.25	24.5	24.8	25	25.1	25.2	25.3	25.4	25.5	25.8	26	26.1
7500	23	23.1	23.3	23.6	23.9	24.2	24.6	24.7	24.75	24.9	25	25.1	25.4	25.5	25.7	25.8
7000	22.33	22.75	23	23.2	23.5	23.8	24.2	24.4	24.5	24.7	24.8	24.9	25.1	25.3	25.4	25.5
6500	21.66	22.2	22.5	22.9	23.1	23.4	23.8	24.1	24.25	24.3	24.6	24.6	24.8	25	25.1	25.2
6000	21	21.5	22	22.33	22.7	23	23.33	23.66	24	24.1	24.2	24.3	24.5	24.8	24.9	25
5500	20.2	21	21.5	22	22.33	22.7	23	23.3	23.5	23.75	24	24.1	24.2	24.4	24.7	24.75
5000	19	20	20.7	21.2	22	22.35	22.5	23	23.2	23.5	23.75	23.8	24	24.1	24.3	24.5
4500	17.5	18	19.5	20.5	21.2	21.8	22.1	22.5	22.8	23.1	23.25	23.4	23.5	23.9	24	24.25
4000	16	16.2	17.8	19.5	20.5	21.2	21.6	22	22.33	22.66	23	23.1	23.3	23.5	23.8	24
3500	14	14.2	15.8	17.5	19.5	20.5	21	21.5	22	22.3	22.6	22.9	23	23.3	23.4	23.66
3000	12	12.3	13.5	15	17	19	20.1	21	21.5	21.7	22.1	22.3	22.5	22.9	23.1	23.33
2500	10	10.4	10.7	12.5	14.3	16.4	19	20.1	20.8	21.1	21.5	22	22.1	22.5	22.8	23
2000	9	9.7	9.5	10.1	12	14	16	18.4	20	20.5	21	21.33	21.66	22	22.25	22.5
1500	6	9.1	8.5	9	10.1	12	14	16.5	18	19	20.2	20.5	21.2	21.5	22	22.25
1000	4	8	8	8	8.8	10	11	12.8	14.2	16	17.5	19	20	20.75	21.25	21.5
500	1	4	6	6.5	7.3	8	8.5	9.5	11	13	14	16	17	18.3	20	20.5
0	0	0.5	1	2	4	5	5	7.2	8.8	9.8	11.1	12	14	15.3	16.6	18

Q_{amb} \ Q_{Savage}	16000	17000	18000	19000	20000	21000	22000	23000	24000	25000	26000	27000	28000	29000	30000
12000	28.75	29	29.33	29.66	30	30.25	30.5	30.75	31	31.5	31.7	32	32.2	32.4	32.6
11500	28.5	28.75	29.1	29.4	29.7	30	30.25	30.5	30.75	31.1	31.5	31.75	32	32.2	32.4
11000	28.1	28.5	28.75	29.1	29.4	29.7	30	30.25	30.5	30.8	31.25	31.5	31.75	32	32.2
10500	27.8	28.1	28.5	28.75	29.1	29.4	29.7	30	30.25	30.5	30.9	31.25	31.5	31.75	32
10000	27.5	27.8	28.1	28.5	28.7	29.1	29.4	29.7	30	30.5	30.6	31	31.25	31.5	31.75
9500	27.2	27.5	27.8	28.1	28.4	28.7	29.1	29.5	29.66	30	30.3	30.6	31	31.25	31.5
9000	26.8	27.2	27.5	27.8	28	28.4	28.7	29.1	29.33	29.65	30	30.3	30.6	31	31.25
8500	26.6	25.8	27	27.5	27.8	28	28.4	28.7	29	29.33	29.66	30	30.3	30.6	31
8000	26.4	25.6	26.8	27	27.4	27.8	28.1	28.4	28.8	29	29.33	29.66	30	30.3	30.66
7500	25	25.2	26.5	26.8	27	27.4	27.8	28.1	28.4	28.65	29	29.33	29.66	30	30.33
7000	25.8	26	26.2	26.5	26.66	27	27.4	27.8	28.1	28.33	28.66	29	29.33	29.66	30
6500	25.4	25.7	25.9	26.1	26.33	26.56	27	27.4	27.8	28	28.33	28.66	29	29.33	29.66
6000	25.2	25.4	25.6	25.8	26	26.33	26.66	27	27.4	27.65	28	28.33	28.66	29	29.33
5500	25	25.1	25.4	25.6	25.8	26	26.33	26.66	27	27.33	27.66	28	28.33	28.66	29
5000	24.66	24.8	25.1	25.3	25.5	25.8	26	26.33	26.66	27	27.33	27.66	28	28.33	28.66
4500	24.33	24.5	24.9	25	25.2	25.4	25.66	26	26.33	26.65	27	27.33	27.66	28	28.33
4000	24.1	24.3	24.5	24.7	24.9	25.1	25.33	25.66	26	26.33	26.66	27	27.33	27.66	28
3500	23.7	24	24.2	24.4	24.6	24.8	25	25.33	25.66	26	26.33	26.66	27	27.33	27.66
3000	23.5	23.8	24	24.1	24.3	24.6	24.8	25	25.33	25.65	26	26.33	26.66	27	27.33
2500	23.1	23.4	23.7	23.9	24	24.2	24.6	24.8	25	25.33	25.66	26	26.33	25.66	27
2000	22.8	23.1	23.3	23.5	23.75	24	24.2	24.5	24.8	25	25.33	25.66	26	25.33	26.66
1500	22.5	22.7	23	23.4	23.5	23.56	23.9	24.1	24.4	24.65	25	25.33	25.66	26	26.33
1000	22.2	22.33	22.7	22.9	23.25	23.33	23.5	23.8	24.1	24.33	24.66	25	25.33	25.66	26
500	21.4	22	22.2	22.4	22.66	23	23.25	23.5	23.75	24	24.33	24.66	25	25.33	25.66
0	20	21	21.5	22	22.33	22.56	23	23.25	23.5	23.75	24	24.33	24.66	25	25.33