Cardrona Hydrology

Low Flows and Reliability

Prepared for Otago Regional Council

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Prepared by:
Roddy Henderson
Dr Daniel Collins

For any information regarding this report please contact:

Roddy Henderson
Hydrologist
Hydrological Processes
+64-3-343 7873
roddy.henderson@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
PO Box 8602
Riccarton
Christchurch 8011

Phone +64 3 348 8987

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Contents

Tables

Figures

Executive summary

Naturalised flows for Cardrona at Mt Barker are derived using a mixed model that combines available water meter data over the last five years, a model of average water use derived from these water meter data, and a regression of simulated natural flows at Mt Barker against flows at Lindis Peak to infill a 12-year gap from 1988 to 2001.

The naturalised 7-day MALF for the Cardrona at Mt Barker using simulated natural flows from 1977 to 2019 is 1100 l/s ± 10%, or 1000 to 1200 L/s.

Water take reliabilities have been modelled at all summertime consumptive takes above Mt Barker. The results are very dependent on the water use scenario adopted.

For the theoretical scenario of summed consented maximum rates, full reliability is rarely achieved, as some locations in the catchment are modelled to have low reliability to satisfy the maximum take rate. For the reduced maximum scenarios (19% to 27% of the total consented rate), more in line with actual practice as recorded recently, reliabilities are higher, but still affected by supply issues around the catchment as modelled. Volumetric reliabilities are nearly all above 90% for these reduced take scenarios.

Analysis of flow and water temperature data in the lower reaches show that the river naturally loses surface connectivity below Mt Barker and sometimes as far as the state highway bridge, and that flows in the reach from there to the confluence with the Clutha River/Mata-Au are often made up of groundwater outflow. Disconnection in this lower reach occurs when flows at Mt Barker are at or below 1600 l/s when there is 400 L/s water abstraction downstream, or when flows are at or below 1,200 L/s with no abstraction downstream.

1 Introduction

An understanding of the Cardrona hydrology provides the basis for water management and allocation. The recorded in-river flow data are affected by consented water abstractions, and the abstraction data are only available for a limited recent period. To get robust estimates of low flows for planning purposes it is necessary to combine data recorded in the catchment with data recorded elsewhere, so that longer-term climate variability is accounted for.

Otago Regional Council (ORC) have asked for analyses of the following Cardrona surface water questions:

- A natural flow series at the Mt Barker flow recorder;
- An estimate of the natural 7-day mean annual low flow at the Mt Barker flow recorder;
- An analysis of the reliability of water supply above Mt Barker under several scenarios;
- An assessment of the reach of the river below Mt Barker, and flow disconnection there, using available flow and water temperature data and
- Characterisation of dry periods in the lower river.

A natural 7-day mean annual low flow value is needed at the flow recorder at Mt Barker, to be the basis of further decisions about water allocation and its effects.

Surface water flows downstream of Mt Barker can become disconnected, so that the river bed dries in some reaches between Mt Barker and the state highway. The dependence of this process on river flows at Mt Barker is investigated.

Reliability of water supply for out-of-stream users is an important aspect of the local and regional economy. Various scenarios of minimum flow setting, and water allocation are modelled to assess reliability.

2 Data

Water data in the Cardrona catchment are measured at flow recorders in the river and some of its tributaries, at water meters that are associated with the consented abstractions, and in ground water bores.

2.1 River flows and water temperatures

River flow data have been collected at Mt Barker and at other main stem and tributary locations since 1976 (Table 2-1). The data are sometimes patchy or discontinuous, and this limits their usefulness. For example, the Mt Barker flow record was discontinued between 1988 and 2001 and has a total of more than 13 years of gaps.

Table 2-1: Flow and temperature recorders in the Cardrona catchment. Where end dates are blank the recorder is open as of 2019.

Site Name	easting	northing	Variables collected	Start date	End date
Tributaries above Mt Barker					
Cardrona at Wrights Gully	2191185	5574388	Flow only	14-Jan-09	25-Jun-10
Cardrona at Callaghans Creek	1283624	5021137	Flow & temp	3-Dec-08	
Branch Burn at Cardrona Valley	1287829	5028361	Flow & temp	11-Aug-15	
Boundary Creek at Top Race u/s	1286448	5025428	Flow & temp	17-Sep-15	
Deep Creek at Cardrona Valley	1289937	5029087	Flow & temp	28-Jul-15	20-Apr-18
Spotts Creek at Race Intake u/s	1288173	5035862	Flow & temp	13-Nov-15	
Mt Barker					
Cardrona at Mt Barker	1292623	5037476	Flow	2-Dec-76	
"	"	"	Temperature	7-Oct-15	
Main stem downstream of Mt Barker					
Cardrona at Hillend 800m downstream	1294283	5038708	Flow & temp	20-Dec-16	
Cardrona at Ballantyne Road 150m u/s	1295728	5041111	Flow & temp	20-Dec-16	
Cardrona at Ballantyne Road	1295723	5041182	Flow	7-May-08	25-Jun-10
"	"	"	Temperature	8-Jul-08	
Cardrona at Black Peak Rd Power Lines	1296407	5042554	Temp only	20-Dec-16	
Cardrona at SH6	1297147	5043375	Temp only	7-Oct-15	
Cardrona at Clutha Confluence	1298391	5044857	Flow & temp	6-May-08	

2.2 Consents

Consents to use water have existed in the catchment since at least 1976, and have been renewed over time, some currently running until 2054. Table A-1 in Appendix A and Table B-1 in Appendix B list consents upstream and downstream of Mt Barker respectively as used in this report. They are current consents that are deemed consumptive in their use of water, and have a 'primary' designation rather than being considered a 'secondary' consent of lower priority..

2.3 Water meters and take data

Water take data are available from some water meters since 2007, but only since the 2014/15 season for most meters. Some meters measure water that is removed from the river upstream of the flow recorder, and others measure water removed from below the flow recorder or from nearby aquifers.

Meters corresponding to individual takes are listed in Table A-1 and Table B-1.

Some consents are measured through more than one meter, and some meters measure more than one consent.

The sum of the consented maximum rates of take in Table A-1 is 1305.484 L/s. The sum of the total consented flows through the meters is 1533.484 L/s, and the sum of the maximum consented rate through each meter is 1364.72 L/s. The largest of these numbers has been used in the naturalisation process described below.

3 Data analysis

3.1 Water take adjustments for missing data

Water take data have been quality checked, with removal of obvious spikes and data that exceeds twice the consented instantaneous MaxRate in Litres/second. Plots of the raw and QA'd data are shown in Appendix A for consents above Mt Barker and Appendix D for consents below Mt Barker.

Over time more meters have been installed, so that by the beginning of the 2014/15 water year (1 July 2014) 46% of the water used by volume was being measured. Figure 3-1 shows the total metered water take, simply as the sum of the meters, but also adjusted for missing meters in two different ways. Firstly, the share for each meter of the total consented MaxRate of the catchment upstream of Mt Barker is used to estimate the missing values, and secondly the share for each meter of the total measured maximum take rate for all meters is used to estimate the missing values.

The effect of these two methods can be seen in the differences on Figure 3-1, between the orange and red lines showing fraction measured, and the thin blue lines showing the estimated water take. The two methods are not significantly different, and the MaxRate ratio estimation method is used in the analysis that follows.

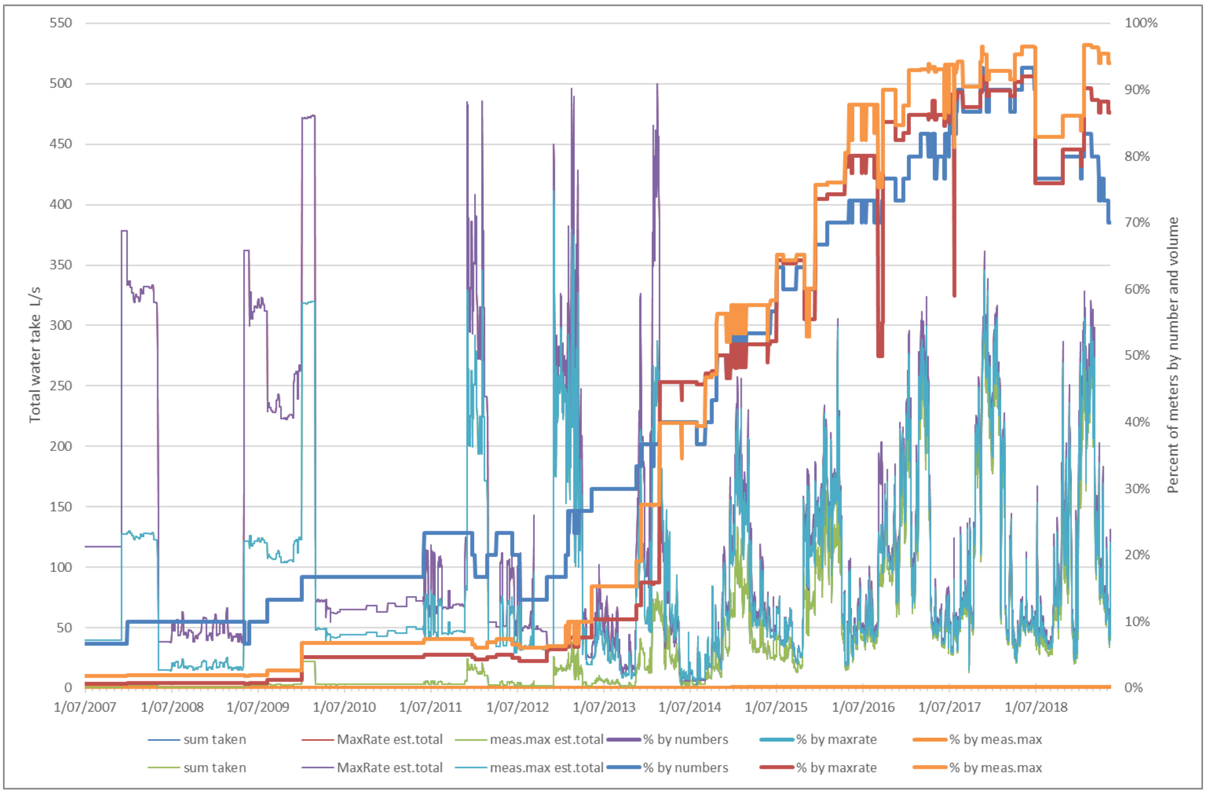


Figure 3-1: Water take data and fraction of meters represented. Thin green line is the sum of water measured (L/s, left axis). Thin blue lines are the estimated water use by two methods (L/s left axis). The thick blue line is the fraction of meters operating, and the orange and red lines are the fraction of water measured by volume, by two methods (%, right axis).

Figure 3-1 shows clearly that water use is low in winter and high across each irrigation season. The estimated flows from 1 July 2014 appear a reasonable approximation to what is likely to be happening; before that the adjustments between measured and estimated water use are too large and the data too coarse.

3.2 Water take patterns

Using the estimated data from the five recent irrigation seasons 2014/15 to 2018/19, the average behaviour of water users can be assessed. Figure 3-2 shows the estimated takes across five seasons, as a percentage of the total catchment MaxRate. The highest amount taken is 23% of the catchment MaxRate in November 2017. This is a consequence of many users taking water at a range of times and demand rates, and clear evidence that maximum use is not closely linked to consented maxima.

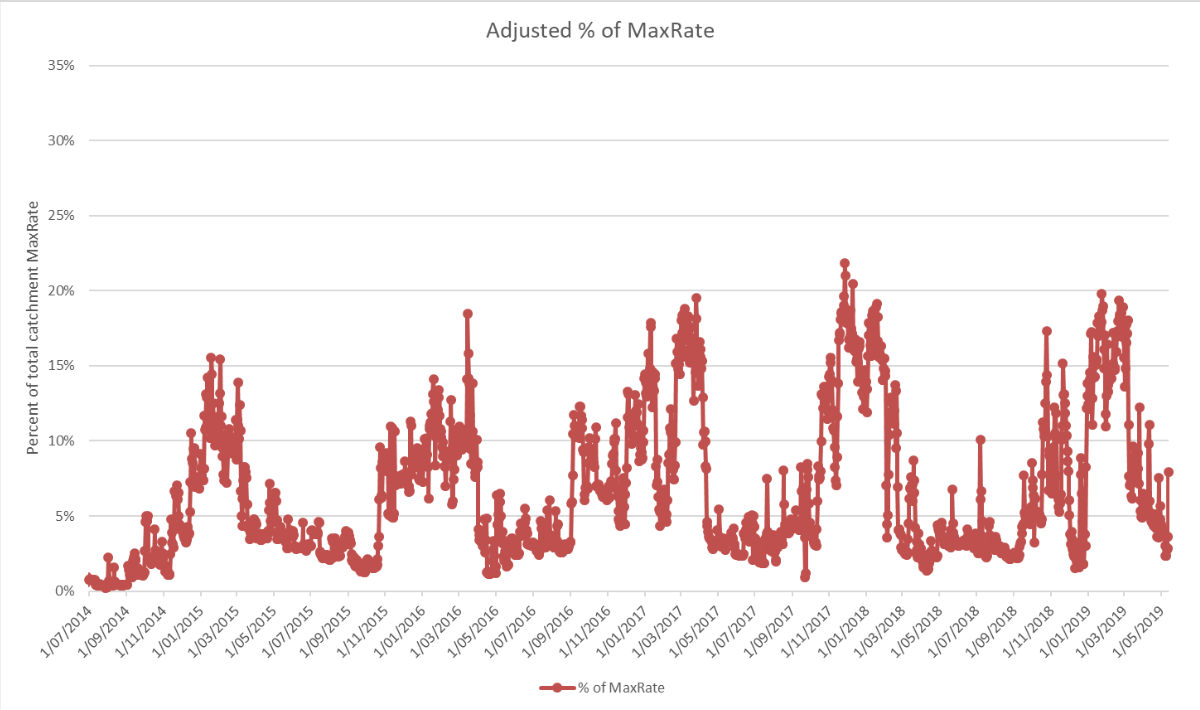


Figure 3-2: Estimated water use for the five recent seasons as a percentage of the catchment total MaxRate.

Figure 3-3 shows the average pattern across a water year derived from these five recent seasons. Water use in winter is nearly constant (54 L/s), and the use across the irrigation season can be approximated with a sine curve as shown. The RMSE (root mean squared error) of the fitted curve is 20 L/s overall, but 25 L/s in the irrigation season and 4 L/s in the off-season. The irrigation season RMSE is 21% of the average rate of take of 115 L/s. It will be the irrigation season part of the model that determines the low flows for each year when added to the recorded data.

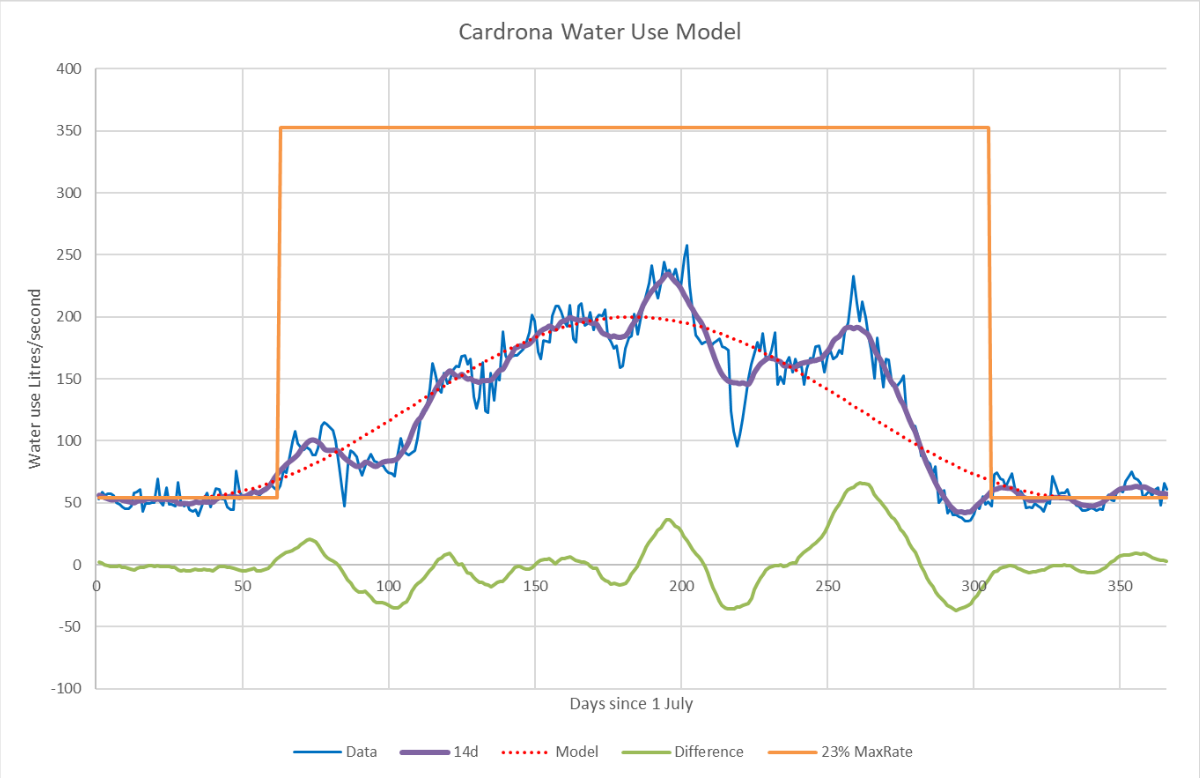


Figure 3-3: Average water use across the last five irrigation seasons. The average water use data are shown in blue, the thicker purple line is a 14-day moving mean, the red dashed line is the fitted model, and the green line the difference between the average data and the model. The square block orange line represents 23% of the total MaxRate for the catchment.

4 Naturalised flows for MALF estimation

The measured and estimated water meter data can be used with the measured flow data to provide several estimates of natural behaviour, or at least to provide some bounds for this, so that a naturalised MALF may be derived. Time series of naturalised daily flow data are prepared and the 7-day minimum extracted on an annual basis. The average of these provides the MALF, subject to issues related to the continuity of the various series that may be derived.

4.1 Models for MALF estimation

The following variations of measured and estimated river flows and water meter data are available to provide a range of potential values for the natural MALF and a natural flow time series of for the Cardrona at Mt Barker.

1. Observed flow at Mt Barker. The flows measured at Mt Barker provide a lower limit for the estimate, since it is known that water is abstracted upstream. Can be applied for 27 out of 43 years given the gaps in the Mt Barker record.

2. Observed flow at Mt Barker plus the sum of the consented MaxRates upstream of Mt Barker (1533.484 L/s). This series provides an upper bound, but a rather unrealistic one, since all consents have never been observed to be exercised at MaxRate at the same time. Can be applied for 27 out of 43 years.

3. Observed flow plus 23% of the sum of consented MaxRates (353 L/s). This series provides a more realistic upper bound, being the maximum observed usage over the last five years, when enough meter data exist to allow the calculation. Can be applied for 27 out of 43 years.

4. Observed flow plus the average water meter model. This series should be closer to the actual behaviour, as long as take rates from 1977 are similar to those in the last five seasons and allowing for the fact that the water meter record is too short to assess the relationship between take rates and climate variability. Can be applied for 27 out of 43 years.

5. Observed flow plus estimated water use. As discussed above, the adjustment by MaxRate proportion is used (5a), and results were similar for the alternative adjustment method using the maximum measured take rate (5b). Can be applied for only the last five out of 43 years.

6. Natural flow at Mt Barker derived from a regression against recorded flows at Lindis Peak. The regression was derived using the Mt Barker flow record plus estimated water meter data over the last five years. Two regressions were used; one below the lower quartile of flows and one above. This reflects the non-linear nature of the relationship between the two sites and helps to preserve the mean flow as well as representing low flows. These years included some of the driest periods in the vicinity, including the second and third lowest flows at Lindis Peak. Can be applied for the whole 43-year period and is reflective of climatic variability on the flow record, as long as the relationship between Lindis and Cardrona can be considered consistent over time.

7. An earlier model by Mohssen and Lu (2017) uses a winter regression of low flow periods to estimate summer low flow behaviour. These estimates are then corrected

to be within a band around the measured flow if the regression produces numbers seen to be too high or too low. The band is defined by averaged water take data as for model 4 above. The lower threshold is the measured flow plus a monthly varying fraction of deemed maximum actual take rates, and the upper band is the measured flow plus the total maximum take rate for the catchment. In practice, the band limitations are imposed 80-90% of the time, mainly to raise lower flows. This means that this model is very similar to model 4 above, being based on an assessment of available water meter data over a few years.

8. A hybrid model combines methods 5, 4 and 6 above, using the flow data plus estimated take rates for the most recent five years, the measured data plus the average water take model for all other years where the Cardrona flow record has data (22 of 43), and the regression model in the gaps to give a full record that uses measured data wherever possible. Can be applied for the whole 43-year period, is bound by the measured data plus modelled takes, and is reflective of climatic variability on the flow record, as long as water use in earlier years is like that in the last five, and the relationship between Lindis and Cardrona can be considered consistent over time.

4.2 Model assessment

The natural flow series to be derived will be used to address several questions about the water resource of the Cardrona River. These include derivation of the natural 7-day MALF and reliability modelling for out-of-river water use. The ability of the models to preserve relevant statistics is an important aspect of the decision of which to choose. Key evidence is contained in flow duration curves and time series plots of the cumulative departure from mean flow, and also in various flow statistics presented below.

4.2.1 Flow duration curves

A flow duration curve (FDC) encapsulates the complete hydrograph into a single curve, which represents the fraction of time that the flow has been exceeded (or not exceeded). Figure 4-1 shows the flow duration curves for all eight models over the period for which we have useable meter data. This is the period over which the water use model and the NIWA regression model have been calibrated.

The red line (model 1) shows the recorded flows at Mt Barker, and all other models are greater than this curve most of the time. The black line for model 2 shows clearly that estimating the natural flow by adding the total paper consented maximum rate is unrealistic. Model 3 (orange), using 22% of the paper take as determined from actual maximum use, seems to form a realistic upper bound. All the other models fit between model 1 and model 3, with some deviation of model 6 which is entirely based on Lindis Peak flows.

Closer examination of models 4 through 8 shows that for flows in the vicinity of the estimated MALF (1100 L/s) and below, there is little difference in the amount of time that flows are not exceeded (see Figure 4-2). Model 8, the mixed model is preferred because it uses the ‘best’ data for each time period; actual naturalised flows where these are available; measured flows plus an averaged take profile where measured flows are available; and a regression model only where no local data exist.

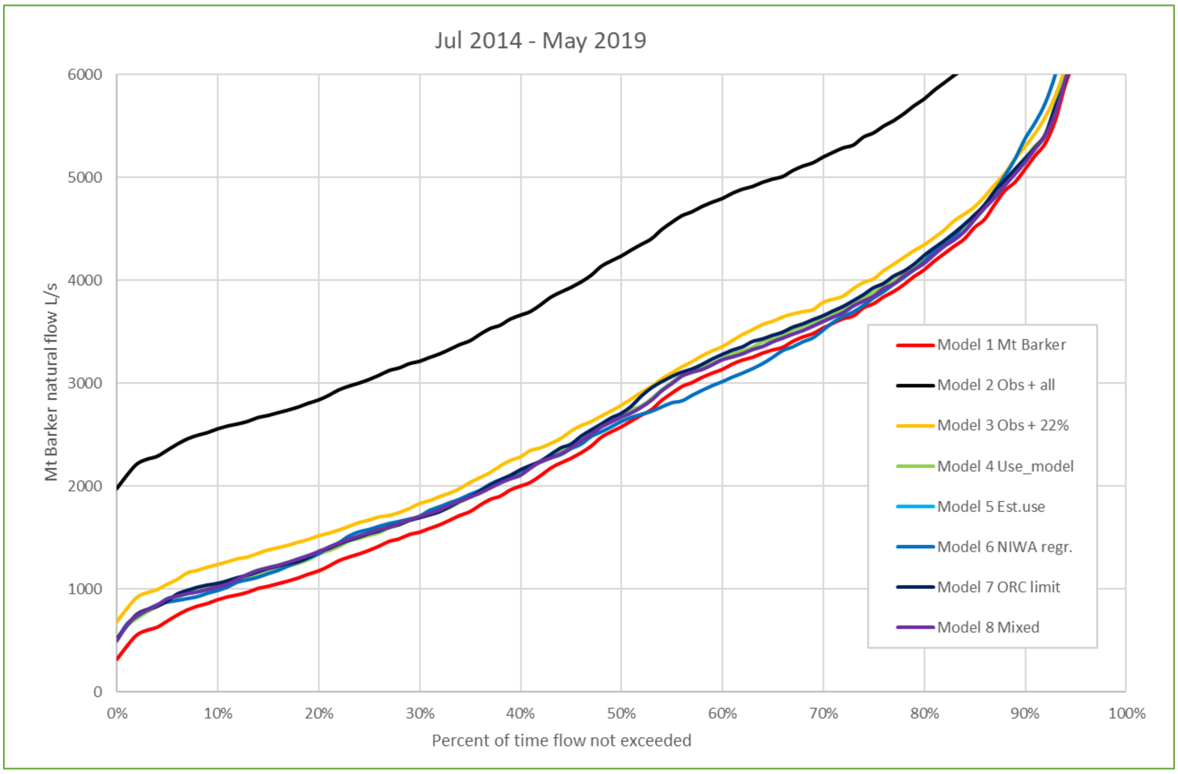


Figure 4-1: Flow duration curves for each model over the period Jul-2014 to Jun-2019.

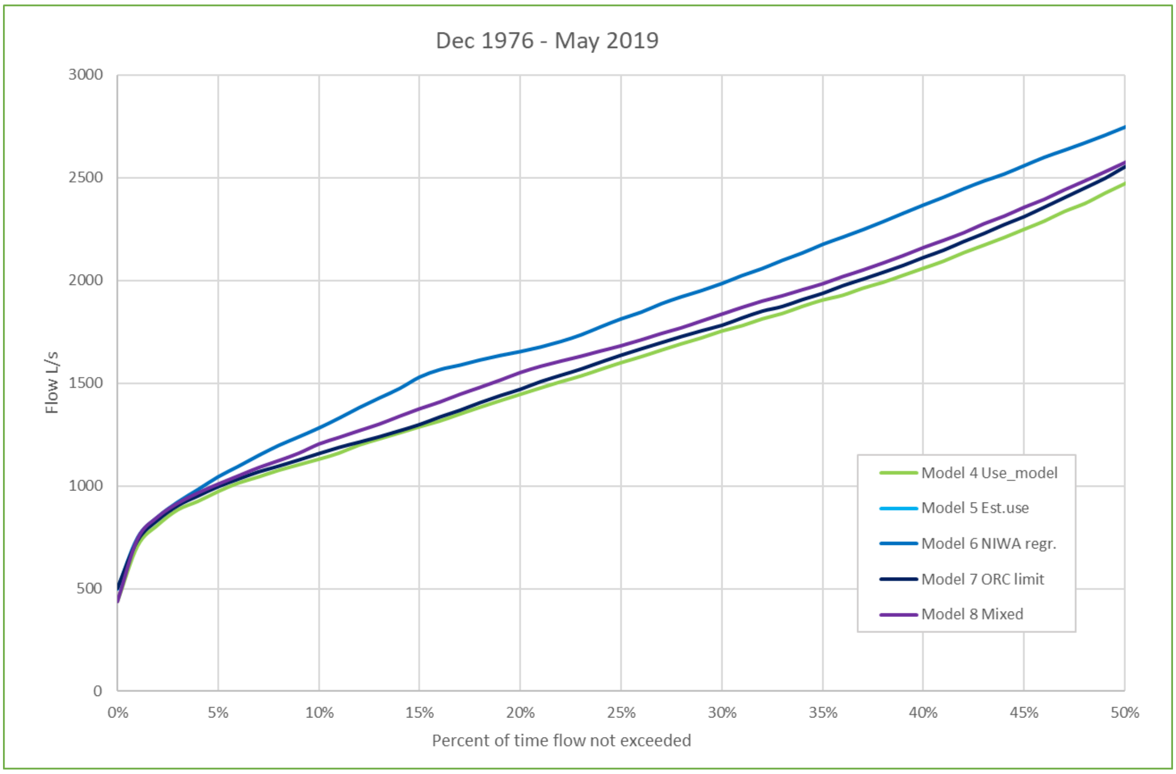


Figure 4-2: Flow duration curves for the best models and all data. The slightly higher mid-range flows for the mixed model are because it has flows for the 1990s and 2000 which contain a large flood event.

4.2.2 Cumulative departure curves

Another check on the overall modelling is to examine the behaviour of the time series for each model, by producing a normalised cumulative departure from the mean, according to:

$$Cusum_t = Cusum_{t-1} + \left(\frac{Q - Q_{mean}}{Q_{mean}}\right) \times dt$$

Where: Q is the flow at time t
Q_{mean} is the average flow over the full time period
dt is the time step in days (or other chosen unit)
thus cusum is the cumulative departure in days at mean flow.

When flows are above average this quantity rises, and where they are below average it falls. Consistency of cusums between models shows that similar climate drivers are operating and that the overall flow series are reasonable. Figure 4-3 shows cusums for Lindis Peak and five models including the measured flows at Mt Barker.

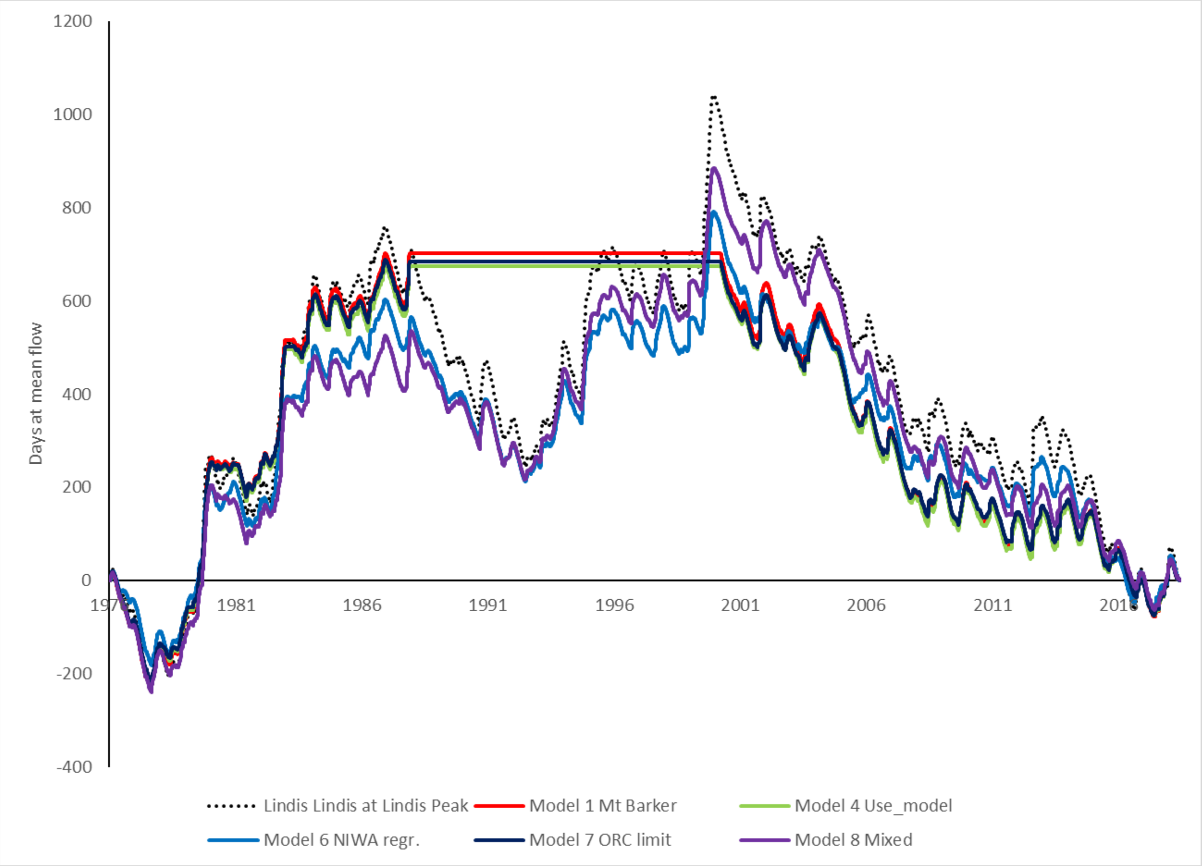


Figure 4-3: Cumulative departures from mean for five models and the Lindis flows. The accumulation of normalised departures from the mean flow has units of time, in this case days, at mean flow.

Similarities are obvious, and some major changes are also apparent. The flat line sections for models 1, 4 and 7 represents the period for which Mt Barker recorder was closed. This period ends just after a large flood event in 2000.

The overall wetness from 1979 to 2000 is related to circulation changes bringing more westerly winds, and from 2000 to 2019 the overall dryness corresponds to a circulation shift to reduced westerlies. The accumulated extra water over the earlier period of twenty years is equivalent to three to four years of mean flow, and the accumulated deficit in the following twenty years to two to three years of mean flow. The Lindis cusum follows a very similar pattern, with slightly more difference between the wetter and drier periods.

Overall the cusums give confidence in the use of the mixed model (model 8) to represent not only the low flows but also the mean flow at Mt Barker.

5 7-day MALF for Cardrona at Mt Barker

The preferred model is now used to calculate the low flow statistic 7-day MALF.

5.1 Variability over time

Climatic variability has an effect on water resources, because of variations in rainfall and temperature. Major drivers of this variability over time are the Inter-decadal Pacific Oscillation (IPO) and El Niño/Southern Oscillation (ENSO). While ENSO operates at sub-annual time scales, the IPO is a longer decadal or multi-decadal influence that is known to affect New Zealand climate and thus river flows, particularly in the north-east and south-west of the country.

Figure 5-1 shows the effect of IPO phase on the annual low flows of the Cardrona. In the IPO negative pre-2000s, MALF is 1300 L/s; post 2000s it is 975 L/s. Using the alternative approach of the modelled takes plus observed (method 4 above), gives very similar results (1300 and 960 L/s respectively).

The question of which estimate to use for future planning will be discussed later.

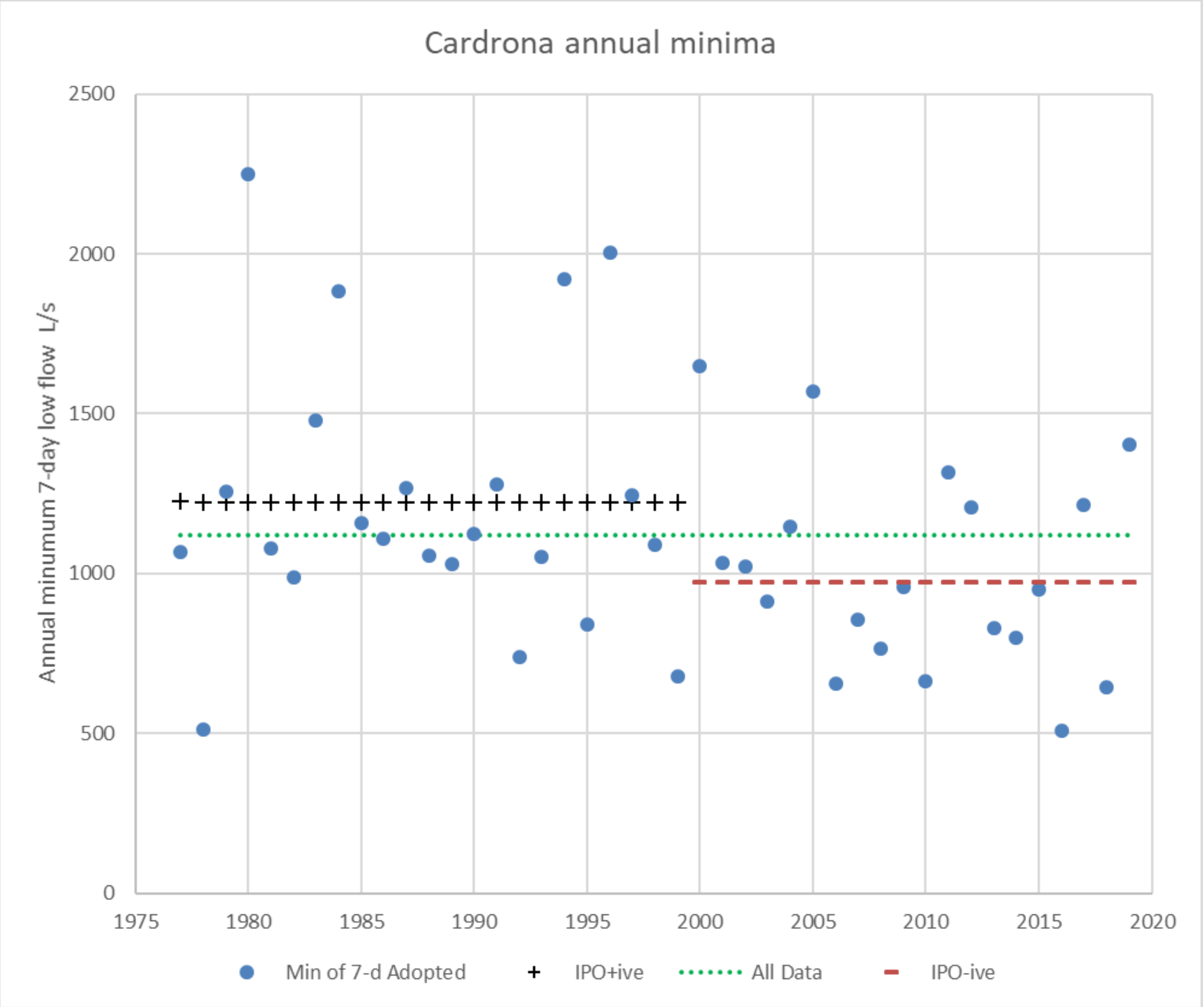


Figure 5-1: Annual minimum 7-day low flows for the Cardrona at Mt Barker, and their averages over the two phases of the IPO that prevailed during this time. The latest five years of this dataset are from the measured data plus estimated mater takes; the earlier values are from the regression model based on Lindis Peak flows.

5.2 MALF estimates at Mt Barker

Table 5-1 shows the result of calculating a 7-day MALF from seven different models, over six different time periods from 1977 to the present day. Depending on the model chosen, these estimates provide upper and lower bounds for the likely value of MALF, or close approximations to MALF.

Table 5-1: 7-day MALF estimates from six time periods and eight different models. Time periods are labelled by water year. Numbers bold and italic are scaled estimates.

	Model (bullet) no. from 4.1	IPO+ive 1977-1999	All data 1977-2019	"OK" years 1977-2019	IPO-ive 2001-2019	Meter data 2007-2019	Full meter data 2015-2019
Obs. flow	1			854	815	769	733
Obs + consented	2			2387	2349	2302	2266
Obs + 23% Consented	3			1171	1140	1109	1068
Obs + model	4		***1109***	993	956	910	887
Obs+MaxRate takes	5a					917	934
Obs + meas.max takes	5b					892	928
Lindis regression	6	1304	1167	1060	975	943	831
Mohssen and Lu 2017	7		***1125***	1031	991	944	908
Mixed model	8	1222	1121	1003	971	932	943
Lindis Peak measured flow		1668	1476	1311	1210	1168	1043

As the estimates for any given model include less of the pre-2000 data, they get smaller. This is the case for the Lindis, and for the regression model based on relations between Lindis and Cardrona natural flows (model 6). Estimates based on the average water use model (model 4) follow this trend, to the extent possible given their shorter duration and recent time period.

Estimates based on the shorter records from the period where some or reasonably complete meter data are available, are always less than those that include pre-2000 data.

The estimates for the “OK” years cover those years where the measured data at Cardrona are considered by inspection to have captured the low flow event of each year. Unfortunately, these years exclude many of the pre-2000 years, including all of the 1990s.

Both at Lindis Peak and for the Cardrona Lindis Regression model (model 6), the “OK” year estimates are biased low. An estimate of the result that might be obtained by use of the average water meter model, can be obtained by scaling the “OK” estimate by the ratio of the “OK” estimate to the all data estimate from the adopted mixed model. This value is indicated in Table 5-1 as bold italic, and the result is 1109 L/s.

An estimate of 7-day MALF has two uses: firstly, to provide a baseline flow against which environmental assessments are carried out; secondly, to provide a basis for the adoption of rules about water allocation under the water plan and to provide guidance for consenting into the future.

The future is uncertain, and specific predictions of future hydrology are even more so, based on work done using global climate models downscaled to New Zealand and run through rainfall-runoff models. Additionally, there are no useable predictions of future IPO states, and if there were, the uncertainty of their effect on river flows could not be assessed rigorously.

For these reasons, the recommended MALF estimate is that from the “all-data 1977-2019” period, of the adopted mixed model (model 8). This estimate is 1100 L/s ± 5-16%. 5% is the standard error of the estimated MALFs for the full record, without including the uncertainty on the individual annual low flow estimates. The standard error of the water use model is 21%. The standard error of the regression estimation of flows in the Cardrona from flows in the Lindis is ~16% at the daily time step. Averaging to obtain 7-day means, and further averaging to obtain a MALF should result in a reduction of this uncertainty. An overall standard error of 10% seems reasonable, giving a MALF range of 1000 to 1200 L/s.

The naturalised flow series produced by Mohssen and Lu (2017) has a MALF for the period 2015 to 2019 of 908 L/s, and for those “OK” years with good low flows measurements at Mt Barker, 1031 L/s. This translates to 1125 L/s when scaled by the ratios of the equivalent estimates for the adopted model, so is within the uncertainty band stated above.

6 Reliability of irrigation water above Mt Barker

Assessments of the reliability of irrigation water above Mt Barker are required as an input to economic analysis of the water allocation decisions. To do this the naturalised flow record at Mt Barker described above are used in a spreadsheet model.

There are 27 consents in the catchment upstream of Mt Barker that need to be considered. These are listed in Table A-1. This list includes all consents that are consumptive, but ignores snow making consents since these only apply in the winter away from the low flow season.

Assumptions made in the spreadsheet model are as follows:

A. Assume all takes apply at their nearest stream, subject to availability of flow there.

B. Total paper consented MaxRate of these consents in the catchment upstream is 1,291.364 L/s based on a list of water meters and their associated consents.

C. Model either:

   a. Constant take at a fraction of the total consented MaxRate for the whole catchment.

      i. Full consented take rate.

      ii. Three scenarios with different fractions of catchment total consented.

         1. 22% as measured maximum behaviour in last five years, equivalent to a maximum take of 289 L/s.

         2. 19%, equivalent to a maximum take of 250 L/s.

         3. 27%, equivalent to a maximum take of 350 L/s or

   b. Take at the rate of modelled seasonal behaviour from water use data as described in Figure 3-3. Maximum rate 200 L/s.

D. Only assess during irrigation season 1 October to 30 April.

E. Four scenarios with different minimum flows at Mt Barker (300, 600, 750, 900 L/s).

6.1 Estimation of flows at each take point

Given the lack of recorders on the true right tributaries all estimates within the catchment will be approximate. The method adopted here is to sample the estimated mean flow at each digital stream reach identified, from the mean flow estimates of Booker and Woods (2013). Each of these estimates is then scaled by the ratio of the Booker and Woods estimate at Mt Barker (2,889 L/s) to the estimated mean flow there from the naturalised flows reported above (3,299 L/s). The flow on each day at each take point is then estimated by applying this ratio to the Booker and Woods estimate and multiplying by the naturalised Mt Barker flow on that day.

6.2 Scenarios

Scenarios are defined by the minimum flow at Mt Barker (four different ones) and by the maximum take rate modelled:

- 1,305.484 L/s being the sum of consented maximum rates based on the list of consents in Table A-1.

- 300 L/s being 23% of that and reflective of actual water use as metered over the last five seasons.
- 250 L/s and 350 L/s being figures suggested by ORC.

Scenarios are modelled by abstracting the desired water at each take point, subject to availability from the modelled flow there, and subject to the residual flow there if one has been defined. Then the desired water takes from sites upstream are removed, so that there is an implied upstream to downstream precedence. When all take points have been assessed individually, the effect at Mt Barker is calculated. If the result is less than the minimum flow for the scenario, then all takes are reduced by the same proportion to achieve the minimum flow if possible, or reduced to zero if the flows in the catchment are so low that they are naturally below the minimum at Mt Barker.

For each maximum take scenario, a table of reliabilities is presented below, and flow duration curves, of river flows and takes, are presented in Appendix F..

Variables in the tables below are defined as follows:

- **Fraction**: the multiplier applied to maximum take rates.
- **Total takes**: the total of maximum takes rates above Mt Barker.
- **Max takes**: the scaled maximum take for the catchment for each scenario.
- **R**: reliability by volume, assessed as mean water taken divided by max water demanded.
- **R1**: percent of time that all water required can be taken.
- **R50**: percent of time that half the water required can be taken.
- **R2**: percent of time that some of water required can be taken.

Each table shows results for the four different minimum flows at Mt Barker as defined by ORC. All reliability figures are calculated over the irrigation season 1 October to 30 April.

6.2.1 100% constant take rate

This represents a theoretical but never occurring upper maximum to water demand.

Table 6-1: Statistics for 100% scenario.

Minimum Flow L/s	300	600	750	900
Fraction	100%	100%	100%	100%
Total takes	1305	1305	1305	1305
Max takes	1305	1305	1305	1305
R	82%	77%	73%	69%
R1	4%	4%	4%	4%
R50	93%	82%	77%	71%
R2	100%	99%	98%	95%

See Figure F-1 for flow duration curves.

The very low number for R1 under this scenario is because each individual take is affected differently by its residual flow, upstream takes and the minimum flow requirement at Mt Barker. A reliability of 4% reflects the reliability of the least reliable water source in the catchment (Clay Bank Creek as modelled). R1 reliabilities at take points range from 4% to 81%, average 66%.

6.2.2 23% constant take rate

This 23% of total catchment MaxRate consented reflects actual practice over the period of the water meter data (five seasons, July 2014 to June 2019).

Table 6-2: Statistics for 23% scenario.

Minimum Flow L/s	300	600	750	900
Fraction	23%	23%	23%	23%
Total takes	1305	1305	1305	1305
Max takes	300	300	300	300
R	99%	97%	94%	90%
R1	63%	63%	63%	63%
R50	99%	98%	95%	90%
R2	100%	99%	98%	95%

See Figure F-2 for flow duration curves.

Much higher reliabilities are achieved since the overall demand for water is significantly less than the summed maximum rates.

6.2.3 19% constant take rate

This 19% of total catchment MaxRate consented represents a maximum take rate of 250 L/s.

Table 6-3: Statistics for 19% (250 L/s) scenario.

Minimum Flow L/s	300	600	750	900
Fraction	19%	19%	19%	19%
Total takes	1305	1305	1305	1305
Max takes	248	248	248	248
R	99%	98%	95%	91%
R1	71%	71%	71%	71%
R50	100%	98%	96%	91%
R2	100%	99%	98%	95%

See Figure F-3 for flow duration curves. Reliabilities are slightly higher than for the 22% scenario as less water is required.

6.2.4 27% constant take rate

This 27% of total catchment MaxRate consented represents a maximum take rate of 350 L/s.

Table 6-4: Statistics for 27% (350 L/s) scenario.

Minimum Flow L/s	300	600	750	900
Fraction	27%	27%	27%	27%
Total takes	1305	1305	1305	1305
Max take	352	352	352	352
R	98%	97%	94%	89%
R1	53%	53%	53%	53%
R50	99%	97%	94%	89%
R2	100%	99%	98%	95%

See Figure F-4 for flow duration curves. Reliabilities are slightly lower than for the 22% scenario as more water is required.

6.2.5 Variable modelled take rate

This scenario uses seasonal behaviour modelled from water use data as described in Figure 3-3. Maximum rate 200 L/s. This scenario has only been applied to the simple case of all consents applying at Mt Barker. This is because the application of a catchment-wide model to individual consents is likely to introduce further uncertainty. Individual consent data have not been analysed to this level.

Table 6-5: Statistics for variable rate scenario. Some statistics cannot be calculated for this scenario (see text for explanation).

Minimum Flow L/s	300	600	750	900
Fraction				
Total takes	1277	1277	1277	1277
Max takes	200	200	200	200
R	100%	99%	97%	93%
R1	100%	98%	95%	90%
R50				
R2	100%	99%	98%	95%

See Figure F-5 for flow duration curves. Reliabilities for this scenario are significantly higher because all takes are assumed to be at Mt Barker and thus are not affected by reduced flows further up the catchment, as for the scenarios above. Also, the required water is less, since the maximum is lower and the demand is varied across the season.

6.3 Reliability summary

Water take reliabilities have been modelled at all summertime consumptive takes above Mt Barker. The results are very dependent on the water use scenario adopted, and also on the definition of reliabilities.

For the theoretical scenario of summed consented maximum rates, full reliability is rarely achieved, as some locations in the catchment are modelled to have low reliability to satisfy the maximum take rate. For the reduced maximum scenarios (19% to 27% of the total consented rate), more in line with actual practice as recorded recently, reliabilities are higher, but still affected by supply issues around the catchment as modelled. Volumetric reliabilities are nearly all above 90% for these reduced take scenarios.

7 Discontinuous surface water flows in the lower Cardrona River

Surface water flow in the lower Cardrona below Mt Barker has been observed to dry up and become discontinuous. This effect is known to occur in the reaches around Ballantyne Road and the Black Peak Road power line crossing. Two lines of evidence are used to determine whether, and under what conditions, the lower portion of the Cardrona River dries up: local flow data, and comparisons between upstream flow data and local water temperature fluctuations. Figure 7-1 shows the reach below Mt Barker flow recorder.

Figure 7-1: Map of the Cardrona River below Mt Barker flow recorder. Mt Barker flow recorder is at the bottom left, and the Confluence flow recorder at top right, marked with yellow stars.

7.1 Flow data analysis

Comparing flow data from the flow recorders at Mt Barker, Ballantyne Road, and Cardrona at Clutha Confluence from November 2008 to May 2009 (Figure 7-2), flow at Ballantyne drops to zero from 28 January to 20 February 2009. Ballantyne flow also drops to zero between 30 January and 3 April 2010 (Figure 7-3), with a short period of positive flows during freshes in late March and early April. When Ballantyne is dry, there is very little variation in flow at the confluence, and the flows at Mt Barker are low and do not include appreciable floods. These records show that the river can dry up and does so for significant periods of time when river flows at Mt Barker are low.

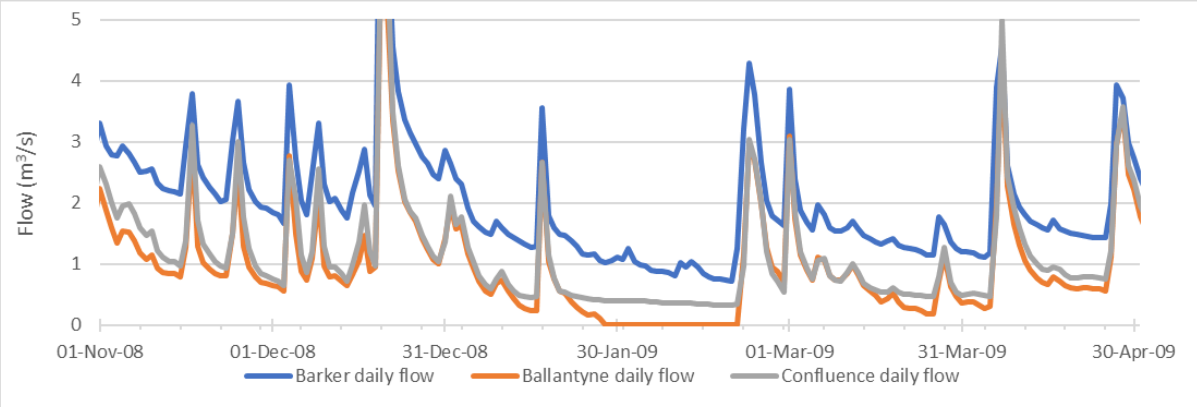


Figure 7-2: Lower Cardrona River flows 1 November 2008 to 1 May 2009. .

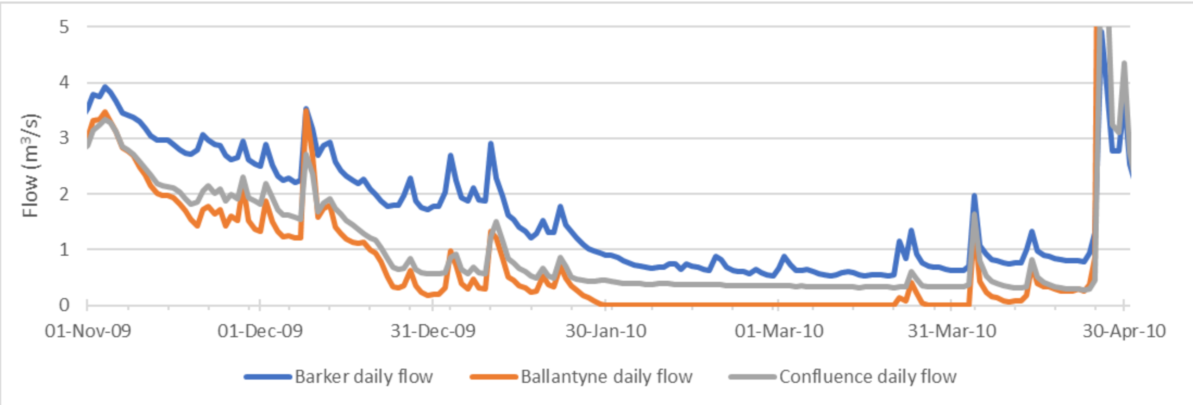


Figure 7-3: Lower Cardrona River flows from 1 November 2009 to 1 May 2010.

Water use data are very sparse over this period but become more available after 2013 (see Figure 3-1). Flow data have also been collected somewhat intermittently between Mt Barker and the Clutha / Mata Au Confluence, as have river temperature data. The different periods of data collection in the lower river are illustrated in Figure 7-4. The greatest data availability is from the 2015/16 summer.

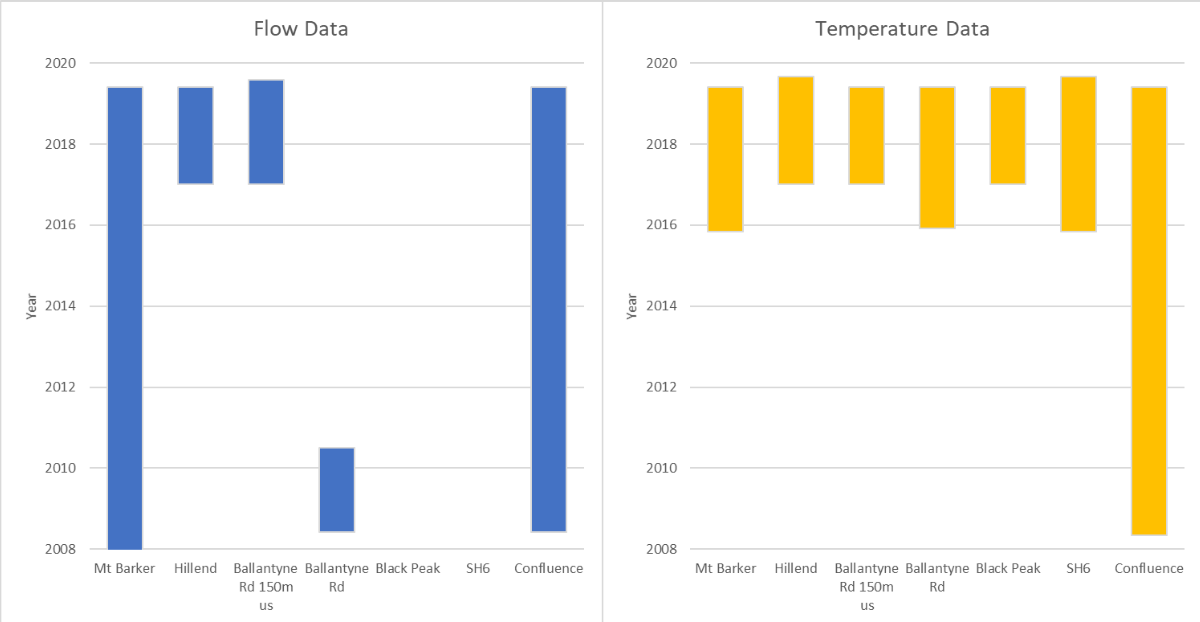


Figure 7-4: Time spans of flow (left) and temperature (right) data in the lower Cardrona.

7.2 Water temperature analysis

In the absence of flow data, water temperature data may be used to infer local drying of a river. When water is flowing continuously, daily water temperature fluctuations will be relatively small, but when flow ceases recorded temperatures can vary significantly. The difference in daily temperature ranges may thus be used to identify when river flow ceases. Furthermore, comparing daily temperature ranges with upstream flows can shed light on the levels of the threshold flows below which river connectivity ceases.

Figure 7-5 depicts flow and temperature range data for various sites from 15 November 2015 to 1 May 2016. At the start of the period the daily temperature range data match very closely, indicating hydraulic connectivity along the river. As river flows decline after about 5 December, the temperature ranges start to diverge. Mt Barker remains about the same, the Confluence drops, SH6 drops even further, and Ballantyne starts to rise. We infer several conclusions from this.

First, as flows drop low, Ballantyne temperature ranges increase and discontinuity occurs about 20 December. Water use in this period averages about 400 L/s. The flood on 18 February reconnects the river between Ballantynes and Mt Barker, resulting in the drop in temperature range at Ballantynes. The slight drop in temperature range at Ballantynes in late February may be due to local rainfall rather than flow from upstream.

Second, the drop in temperature ranges for SH6 and less so for the Confluence, imply they are groundwater-fed, or gaining reaches. This is to be expected lower down along the Cardrona River. Around 3 January 2016, however, the temperature range for SH6 abruptly increases. At the same time, water use increases to about 700-800 L/s for the rest of the month. It is likely that at this time the surface flow disconnects from the groundwater table, which had likely been lowering gradually over the summer. Around 3 March 2016, SH6 reconnects with the water table, due to the recharge associated with the 18 February flood, but not to the whole river as Ballantyne remains disconnected. Water use through the end of March is about 500 L/s.

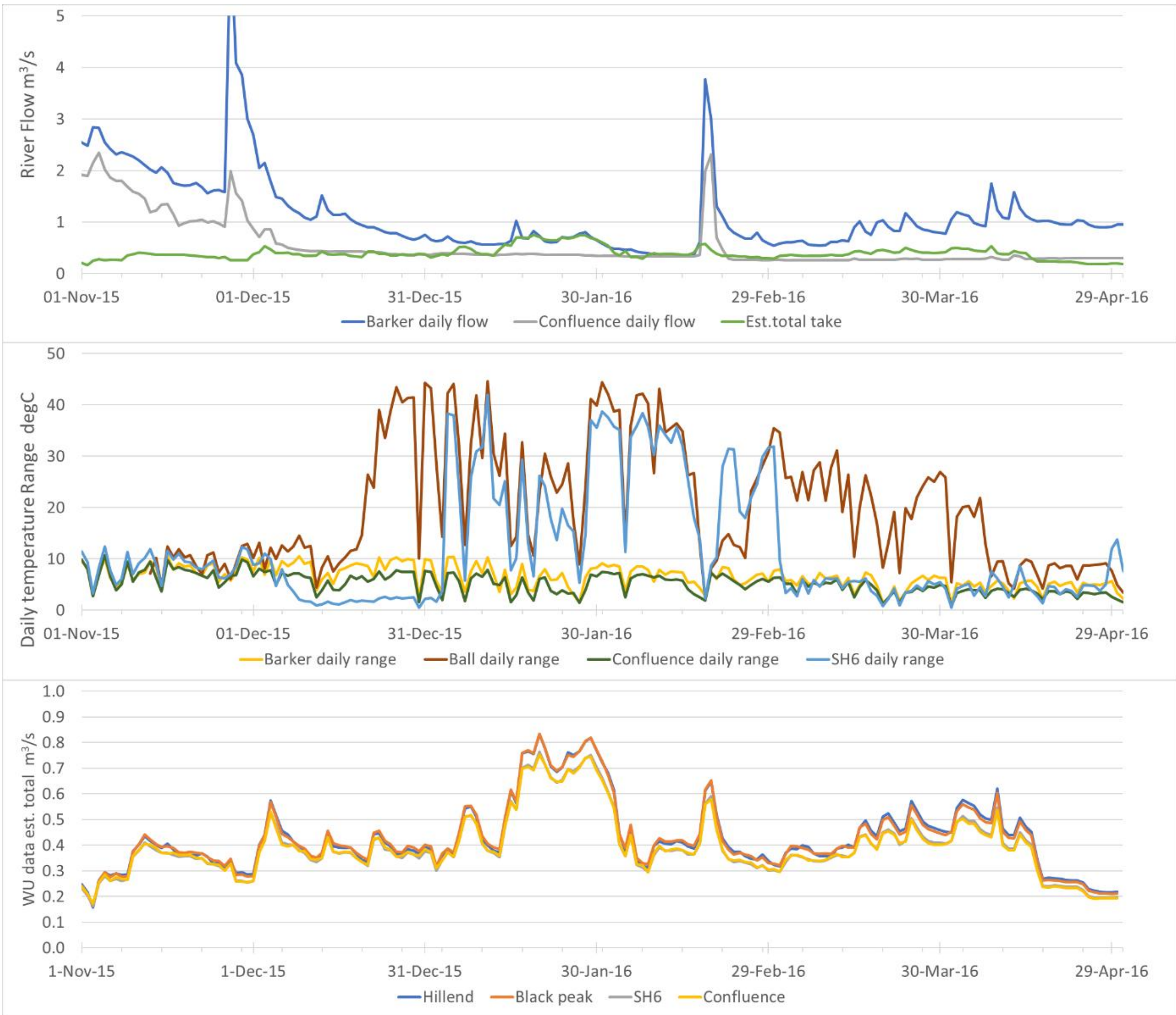


Figure 7-5: Flows, temperature ranges and estimated water use in the lower Cardrona River, 1 November 2015 to 1 May 2016. The top plot shows flow and water use in cumecs; the middle plot shows temperature range in degrees C, and the lower plot shows an expanded view of the estimated water use in cumecs.

Examining the data from 1 November 2018 to 1 May 2019 (Figure 7-6), which now includes Hillend flow and Black Peak temperature, the gradual rise in temperature ranges starting about 1 February implies disconnection of Black Peak from the monitored upstream reaches, but Hillend and Ballantyne remain connected; i.e., disconnection occurs downstream of Ballantyne and upstream of Black Peak. Temperature ranges for SH6 over this period again drop, again implying groundwater-influenced flows. Similar inferences may be drawn from 1 November 2016 to 1 May 2017, notwithstanding a suspected data anomaly in the Ballantynes temperature ranges late December.

Estimated water use starts after 1 January, and then increases from 150 L/s to 400-500 L/s in mid-January. It continues at about 400 L/s until the end of March.

Figure 7-6: Flows, temperature ranges and estimated water use in the lower Cardrona River, 1 November 2018 to 1 May 2019. The top plot shows flow and water use in cumecs; the middle plot shows temperature range in degrees C, and the lower plot shows an expanded view of the estimated water use in cumecs.

An even more nuanced picture emerges from data spanning 1 November 2017 to 1 May 2018 (Figure 7-7). SH6 temperature ranges start to decline around 25 November, implying a decline in surface water contribution to the flows, and proportionately more groundwater. Temperature ranges rise first for Black Peak around 3 December, followed by Ballantyne around 16 December, and later by Ballantyne Upstream around mid-January. Hillend flow reaches near zero at the end of January and its temperature range starts to follow the more downstream sites but does not become as extreme. This suggests an expansion of the dry reaches, first from Blacks Peak, then Ballantynes, then upstream of Ballantynes and possibly just to Hillend. By early May, SH6 starts to register temperature range increases, suggesting disconnection from the water table due to a long, dry summer, despite the two February floods. At this time, Ballantyne appears to have reconnected hydraulically with Mt Barker, but not Black Peak.

Water use estimated totals are sustained between 400 and 500 L/s throughout the season until the end of January.

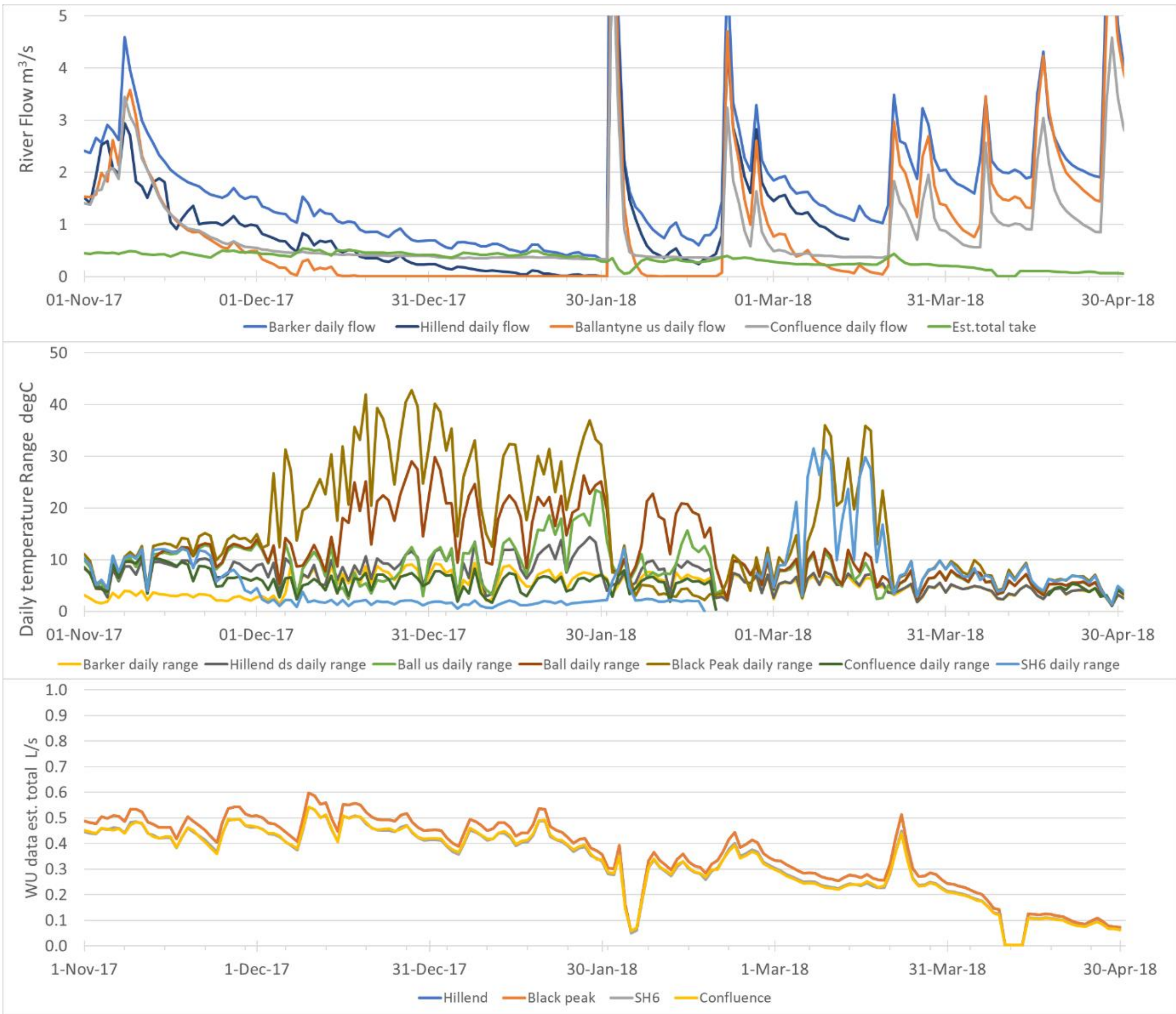


Figure 7-7: Flows and temperature ranges in the lower Cardrona River, 1 November 2017 to 1 May 2018. The top plot shows flow in cumecs, the bottom plot shows temperature range in degrees C.

Taking all of these results together we can build a conceptual picture of drying and wetting along the lower Cardrona River. When summer flows decline, at some point there is insufficient surface flows to maintain connected surface water flow between Mt Barker and Black Peak. Whether other reaches dry earlier the data cannot say since there are limited flow records in the reach below Black Peak. As the summer flows continue to decline, then the dry reach expands upstream to include Ballantynes, and then upstream of Ballantynes. Conversely, as surface flow increase, the length of the dry reach shrinks. At SH6, however, the river is variably gaining and losing, depending on the level of the water table. During most years, SH6 flows are due to groundwater gains, but after a particularly dry summer, flows here can also become disconnected from both surface and groundwater systems.

Determining at what conditions the flows at different locations become disconnected may be inferred by comparing the daily temperature ranges directly against the upstream flows, here chosen to be Mt Barker.

Temperature ranges plotted against daily flows at Mt Barker provide a baseline range of values to expect for conditions with surface water connectivity (Figure 7-8): between 0 and about 10 ^{o}C. The same is seen at the Confluence (Figure 7-14). Moving downstream from Mt Barker, the disconnection in flow at Hillend (Figure 7-9) shows some signs at around 0.45 to 0.5 m^3/s on only one occasion. At

Ballantyne (150m u/s) (Figure 7-10) appears to occur about 0.8 m^3/s, although the limited data make this hard to refine. Further downstream at Ballantyne Road (Figure 7-11), the divergence of data occurs when Mt Barker flows at below about 1 m^3/s. The Black Peak (Figure 7-12) and SH6 (Figure 7-13) separations both occur about 1.6 m^3/s, as measured at Mt Barker, however the cluster of lower temperature ranges for SH6 are distributed differently from Black Peak, reflecting the groundwater influence at this point along the river.

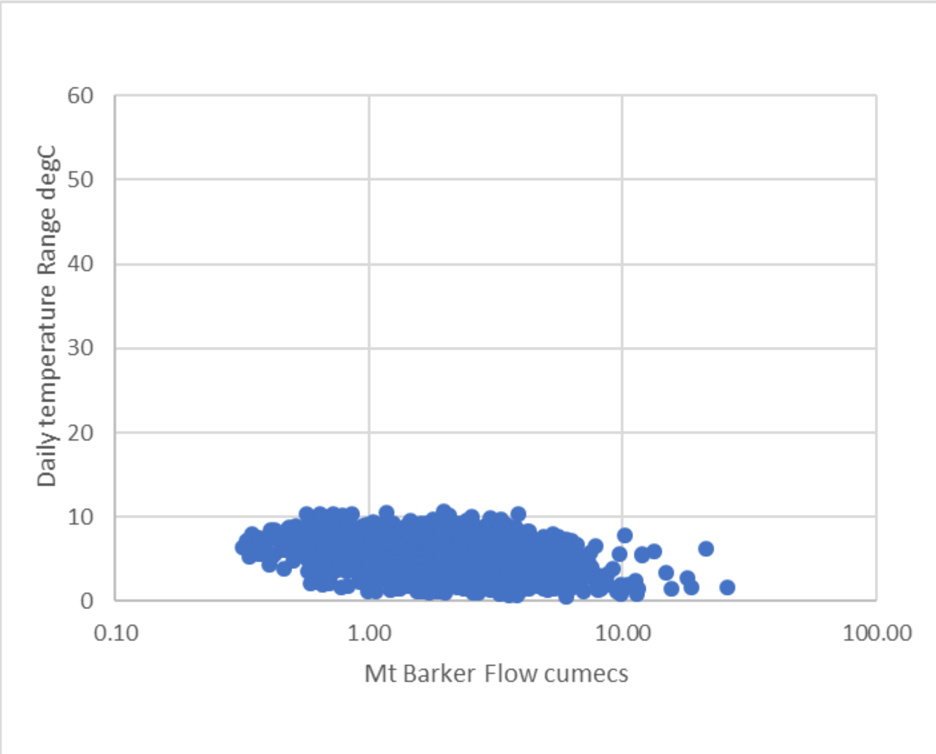


Figure 7-8: Mt Barker flow vs. Mt Barker daily temperature range. All available data October 2015 to May 2019.

Surface water disconnection requires Mt Barker flows below about 1.6 m^3/s when water use is of the order 0.4 m^3/s, from which it may be inferred that with no water use downstream, drying reaches would occur if the flow at Mt Barker dropped below 1.2 m^3/s. Fifteen of 43 years in the naturalised flow record, have a low flow for the year that is higher than 1.2 m^3/s. It is fairly certain then that surface water disconnection in the lower Cardrona is a natural phenomenon, the frequency of which is increased by water use.

Groundwater disconnection requires a different criterion altogether – one that cannot be measured without groundwater level data.

To assess the length of the drying reach and develop a model that predicted it will need further analysis: firstly, of the water use both from surface and groundwater sources over the periods described above, as this may influence the extent of drying; secondly, of groundwater levels which from the behaviour observed at SH6, clearly have an influence as well.

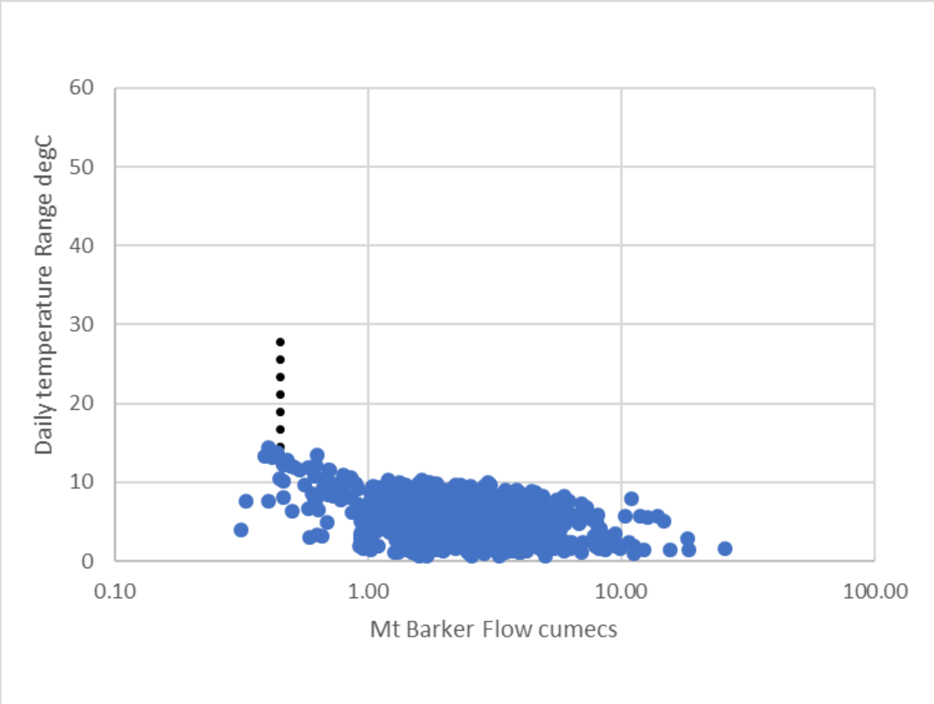


Figure 7-9: Mt Barker flow vs. Hillend daily temperature range. All available data October 2015 to May 2019. Dotted line indicates Mt Barker drying threshold for this location.

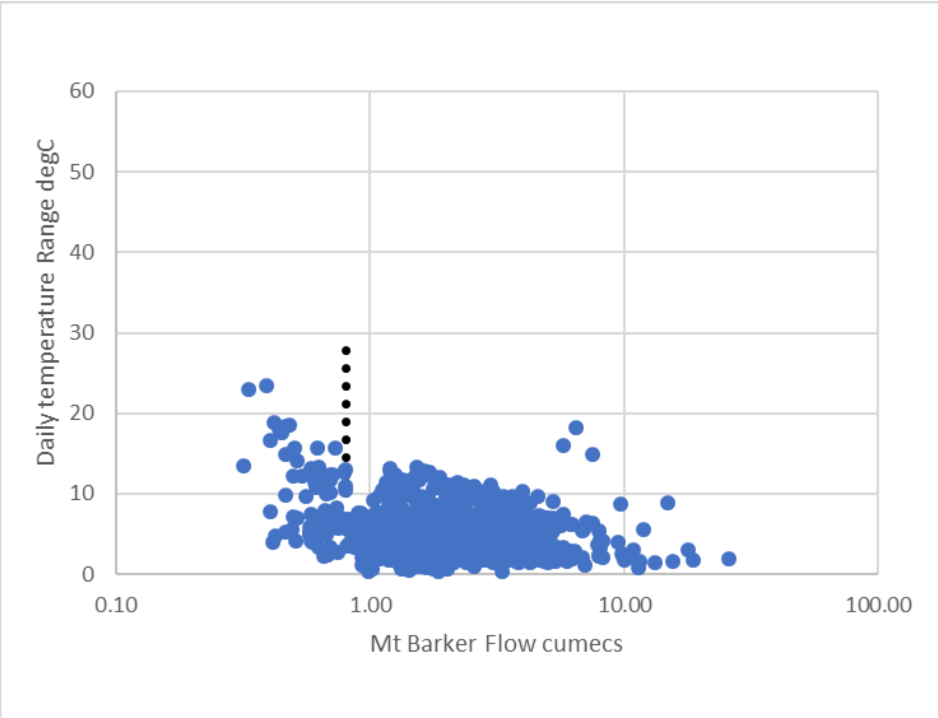


Figure 7-10: Mt Barker flow vs. Ballantynes 150m u/s daily temperature range. All available data from December 2016 to May 2019. Dotted line indicates Mt Barker drying threshold for this location.

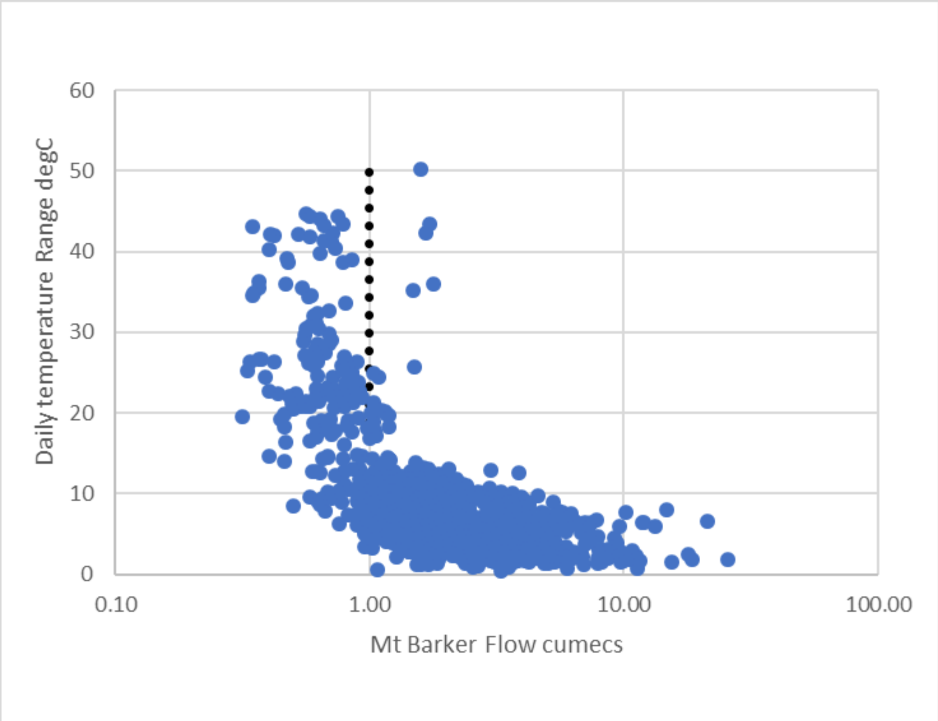


Figure 7-11: Mt Barker flow vs. Ballantyne Road daily temperature range. All available data from November 2015 to May 2019. Dotted line indicates Mt Barker drying threshold for this location.

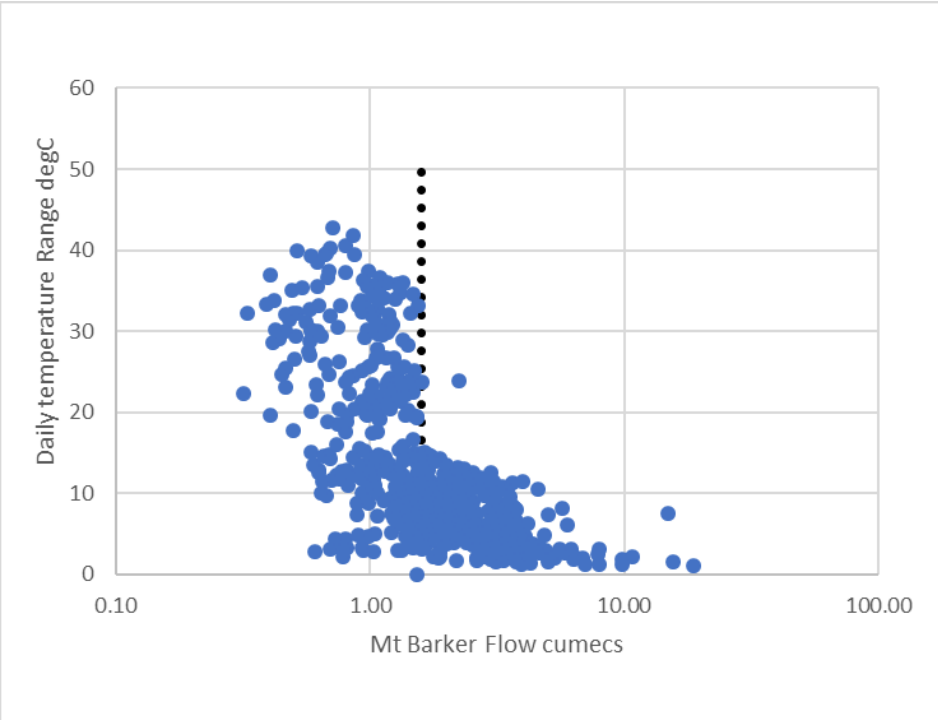


Figure 7-12: Mt Barker flow vs. Black Peak daily temperature range. All available data from December 2016 to May 2019. Dotted line indicates Mt Barker drying threshold for this location.

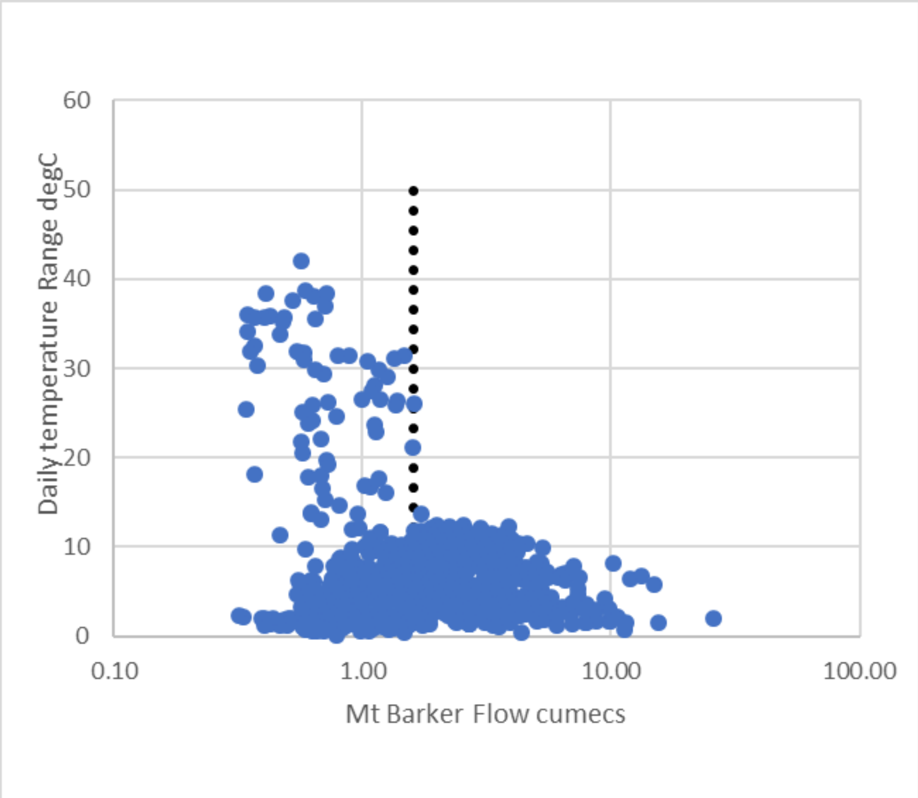


Figure 7-13: Mt Barker flow vs. SH6 daily temperature range. All available data from October 2015 to May 2019. Dotted line indicates Mt Barker drying threshold for this location.

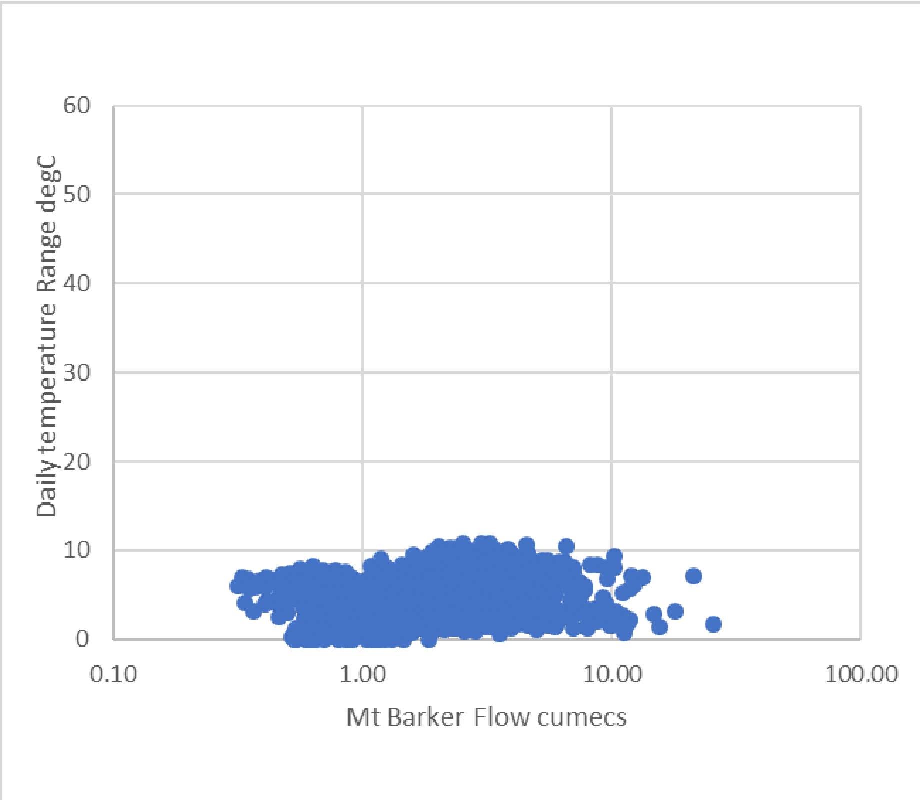


Figure 7-14: Mt Barker flow vs. Confluence daily temperature range. All available data from April 2008 to May 2019.

7.3 Dry period characteristics

Using the largest threshold from the section above (1,600 L/s at Mt Barker with 400 L/s of downstream takes operational, or 1,200 L/s at Mt Barker with no downstream takes operational) statistics of drying behaviour can be established, derived from both the Mt Barker recorded flows and the simulated natural flows. Simply counting the number of dry days in each time series and dividing by the number of days of data shows that the recorded flow series had dry days on 29% of days, and the natural series would have dry days on 22% of days, assuming 40 0L/s of takes downstream of Mt Barker. If we assume no takes downstream of Mt Barker, then we use a threshold of 1,200 L/s, and the figures are 16% with observed flows and 10% with simulated natural flows. These numbers are not completely comparable, as the recorded series has significant gaps, totalling more than 13 years of the 43 years of record. In the figures presented below, water years that are less than 95% complete (i.e., with less than 347 days of data) are ignored for both series, to calculate long term behaviour and allow comparison between recorded and natural flows. This leaves 22 water years of data from the long record that can be used.

7.3.1 Dry days per year

For the water years with sufficient data, dry days per year and other statistics are shown in Table 7-1.

Table 7-1: Dry day statistics from the recorded data and the simulated natural record. Values are derived from the 22 years with sufficient data to compare.

Statistic	Recorded flows		Simulated natural flows	
Threshold	1,600 L/s	1,200 L/s	1,600 L/s	1,200 L/s
Total Dry Days	2556	1432	2235	1095
Average dry days per year	116	65	102	50
Minimum dry days	17	0	7	0
Maximum dry days	221	147	207	133
% of time dry	32%	18%	28%	14%

Overall drying days are 14% more likely in the recorded data than in the simulated natural record in the scenario with abstraction downstream.

7.3.2 Dry events per year

For the water years with sufficient data, dry event number statistics are shown in Table 7-2. A dry event is any period of time when flows were below 1,600 L/s. One day of higher flow is sufficient to terminate the event.

Table 7-2: Dry event statistics from the recorded data and the simulated natural record. Values are derived from the 22 years with sufficient data to compare.

Statistic	Recorded flows		Simulated natural flows	
Threshold	1,600 L/s	1,200 L/s	1,600 L/s	1,200 L/s
Total dry events	214	148	196	116
Average dry events per year	9.7	6.7	8.9	5.3
Maximum no. of dry events	17	12	19	12

7.3.3 Dry event run lengths

For the water years with sufficient data, dry event run length statistics are shown in Table 7-3. A dry event is any period of time when flows were below 1,600 L/s. One day of higher flow is sufficient to terminate the event.

Table 7-3: Dry event run length statistics from the recorded data and the simulated natural record. Values are derived from the 22 years with sufficient data to compare.

Statistic	Recorded flows		Simulated natural flows	
Threshold	1,600 L/s	1,200 L/s	1,600 L/s	1,200 L/s
Average run length per year	12.8	9.1	12.5	7.1
Maximum run length in 1 year	47.7	27.2	41.5	20.7

8 Summary

Naturalised flows for Cardrona at Mt Barker are derived using a mixed model that combines available water meter data over the last five years, a model of average water use derived from these water meter data, and a regression of simulated natural flows at Mt Barker against flows at Lindis Peak to infill a 12-year gap from 1988 to 2001.

The naturalised 7-day MALF for the Cardrona at Mt Barker using simulated natural flows from 1977 to 2019 is 1100 l/s ± 10%, or 1000 to 1200 L/s.

Water take reliabilities have been modelled at all summertime consumptive takes above Mt Barker. The results are very dependent on the water use scenario adopted.

For the theoretical scenario of summed consented maximum rates, full reliability is rarely achieved, as some locations in the catchment are modelled to have low reliability to satisfy the maximum take rate. For the reduced maximum scenarios (19% to 27% of the total consented rate), more in line with actual practice as recorded recently, reliabilities are higher, but still affected by supply issues around the catchment as modelled. Volumetric reliabilities are nearly all above 90% for these reduced take scenarios.

Analysis of flow and water temperature data in the lower reaches show that the river naturally loses surface connectivity below Mt Barker and sometimes as far as the state highway bridge, and that flows in the reach from there to the confluence with the Clutha River/Mata-Au are often made up of groundwater outflow. Disconnection in this lower reach occurs when flows at Mt Barker are at or below 1600 l/s when there is 400 L/s water abstraction downstream, or when flows are at or below 1,200 L/s with no abstraction downstream.

9 Acknowledgements

Thanks to ORC staff for provision of river flow, water temperature and water meter data. Thanks also to Jason Augspurger and Dolina Lee for review of the draft reports.

10 Glossary of abbreviations and terms

7-day MALF or MALF	A common statistic of low flows is the 7-day mean annual low flow. This is the average of the lowest 7-day moving mean flow from each year of record.
Cusum	A time series of the accumulated departures from the mean flow over a given time period. Cusums increase when flows are above average, and decrease when the flow is below average.
Dry Event	A dry event is any period of time when flows were below 1,600 L/s. One day of higher flow is sufficient to terminate the event.
MaxRate	The consented maximum rate for a water consent, expressed as an instantaneous rate in L/s.
Water Year	To avoid biasing the value by splitting dry summer periods so that they appear in two different years, a water year is adopted that runs from 1 July to 30 June each year. Water years are labelled with the year value in the latter part of the water year, so that the water year that starts on 1 July 2018 and ends on 30 June 2019 is called the 2019 water year.

11 References

Booker, D.J., Woods, R.A. (2013) Comparing and combining physically-based and empirically-based approaches for estimating the hydrology of ungauged catchments. *Journal of Hydrology*, 508: 227-239.

Mohssen, M. and Lu, X. (2017) Naturalised daily flow time series for the Cardrona River at Mt Barker. ORC File Note A1025073, 3 August 2017.

Appendix A Consents upstream of Mt Barker for reliability

Table A-1: Consents upstream of Mt Barker. Sorted in downstream order of where the streams intersect the main stem, or where the main stem takes are located.

Consent number	River Name	MaxRate (L/s)	Residual flow (L/s)	Water meters
99151B.V2	Foxes Creek	5	3	WM0571
2005.493.v2	Little Meg	5.8	No	WM0827, WM1423
99151.V3	Little Meg	5	20	WM0570
2006.377.V1	Cardrona Alluvial Ribbon Aquifer	2.08	0	WM0865
RM17.307.01	Cardrona Alluvial Ribbon Aquifer	8.33	0	WM0325
2009.435.V1	Pringles Creek	30	25	WM0726
RM17.212.01	Pringles Creek	1	15	WM1339
RM12.255.01	German Gully	10	0	WM0630
2009.191.V2	Cardrona River	15	15	WM0726
RM12.254.01	Tuohys Gully	24	0	WM0629
RM18.297.01	Cardrona	1	0	No meter
RM14.155.01	Clay Bank Creek	26.77	0	WM0562
93390	Boundary Creek	41.66	0	WM1238
99357	Boundary Creek	83.33	0	WM1239, WM1492
99358	Boundary Creek	69.444	0	WM1239
95677.V1	Welshes Creek	27.77	0	WM1256
98058	Welshes Creek	13.88	0	WM1184
99129	Welshes Creek	55.55	0	WM1256
99356	Macdonald's Creek	55.55	0	WM0577, WM1102
RM12.259.01	Cardrona River	13.9	0	WM0555
RM12.438.01	unnamed TR trib. of Deep Creek	16.8	5	WM1316
RM12.473.01	Deep Creek	28	10	WM0638
RM12.258.01	Spotts Creek	146	50	WM1080
98494	Cardrona (Lower)	27.77	0	WM1233
99339.V1	Timber Creek	56	7	WM1002
97199.V1	Cardrona River	500	0	WM0553
RM12.512.02	Cardrona River	35.5	0	WM0639
SUM		**1305.484**		

Appendix B Consents downstream of Mt Barker

Table B-1: Consents downstream of Mt Barker. Sorted in downstream order of where the streams intersect the main stem, or where the main stem takes are located.

Consent number	River Name	Next downstream flow recorder	MaxRate (L/s)	Residual flow (L/s)	Water Meter
97199.V1	Cardrona	Hillend	500	No	WM0712
98370	Cardrona	Hillend	111.1	No	WM0712
96552	Shepherds Creek	Hillend	27.8	27.8	No meter
96553	Shepherds Creek	Hillend	27.8	27.8	No meter
97129	Cardrona	Hillend	138.9	No	No Meter
99478	Cardrona	Hillend	250	No	WM0583
RM14.345	Wanaka Basin Cardrona Gravels Aquifer	Hillend	38	GW	WM0987
2009.361	Wanaka Basin Cardrona Gravels Aquifer	Black Peak	24	GW	WM0927
2001.848.v2	Wanaka Basin Cardrona Gravels Aquifer	SH6	33.1	GW	WM0189, WM0190
99520	Upper Camerons Creek	SH6	5	No	No meter
2003.328.V1	Wanaka Basin Cardrona Gravels Aquifer	SH6	30	GW	WM0331, WM0332
95864.V1	Camerons Creek	Confluence	6.9	No	WM1508
RM13.495	Wanaka Basin Cardrona Gravels Aquifer	Confluence	22	GW	WM0734

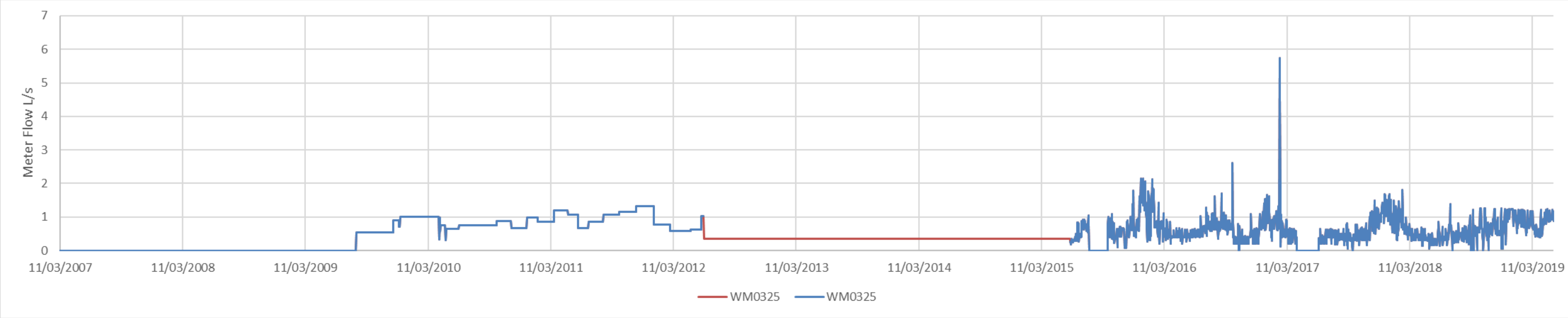
Appendix C Raw and QA'd water meter data above Mt Barker

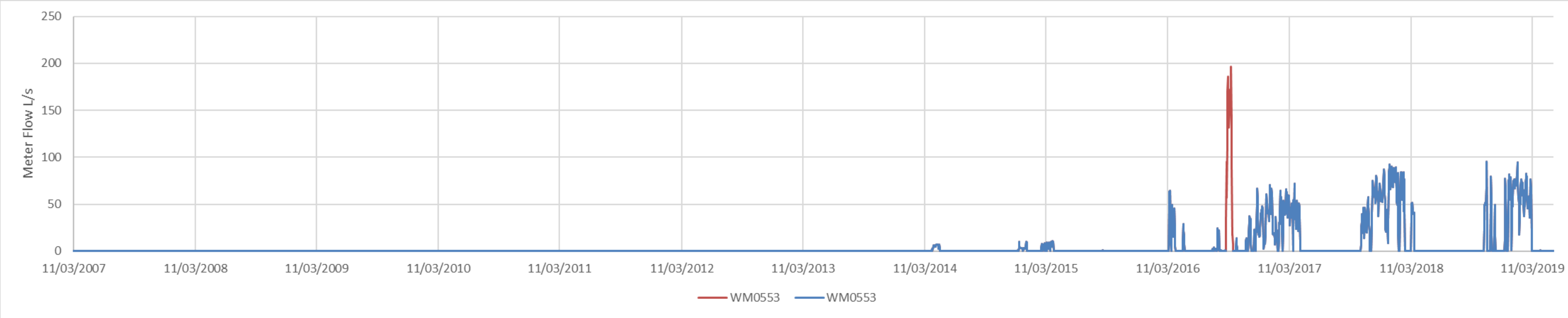
Commentary about each meter record is presented in Table C-1.

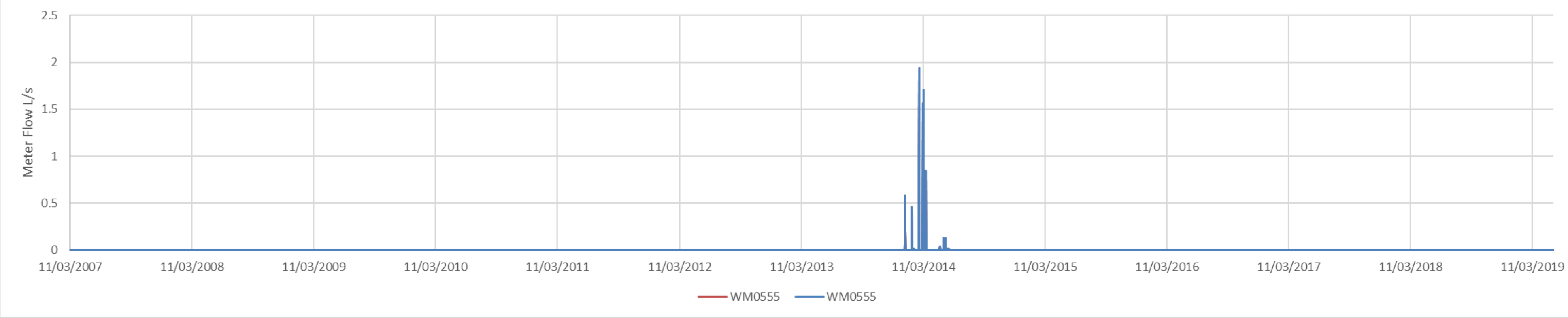
Table C-1: Water meter data quality commentary.

Meter Number	MaxRate (L/s)	Commentary
WM0325	8.33	Flat line in middle not valid so will be removed.
WM0553	500	Remove bulk spike in Sep 2016; Big impact on 'all data' analysis
WM0555	27.9	Odd behaviour but small impact
WM0562	27.77	These exceedances seem plausible so will be retained.
WM0570	5	These exceedances do not seem plausible so will be replaced with data gaps.
WM0571	5	These exceedances are plausible so will be retained.
WM0577	55.55	This exceedance is plausible so will be retained.
WM0629	24	Remove spikes in 2013
WM0630	10	These exceedances are plausible so will be retained.
WM0638	28	Remove all larger than 56 = 2x Maxrate
WM0639	35.5	Remove constant values from 2018 as not useful for river flow adjustment
WM0726	45	Large apparent spikes are less than MaxRate so leave for now
WM0827	5.8	Only 2018 onwards seems likely, but all within MaxRate so leave for now
WM0832	0.35	2019 is still within MaxRate so leave for now
WM0865	2.08	2014 exceedance isn't far above the limit, but is far above the background water take behaviour so it will be removed and replaced with data gaps.
WM1002	56	The first half of the data are very blocky and are thus doubtful, but still plausible so will be kept. 2015 values at exactly MaxRate seem unlikely so remove.
WM1080	146	OK
WM1102	55.55	OK
WM1184	97.2	OK
WM1233	27.77	Remove spikes in 2019. Generally poor quality data.
WM1238	41.66	very little data and no update to 2019
WM1239	152.774	Remove constant values from 2018/2019 as not useful for river flow adjustment.
WM1256	83.32	OK
WM1316	16.8	The exceedances are plausible and will be retained.
WM1339	1	OK
WM1416	14	Spike less than Max Rate so leave
WM1417	40	Only 11 days data, all well less than MaxRate
WM1423	11.6	OK
WM1492	83.33	OK
WM1493	40	remove one spike in 2019

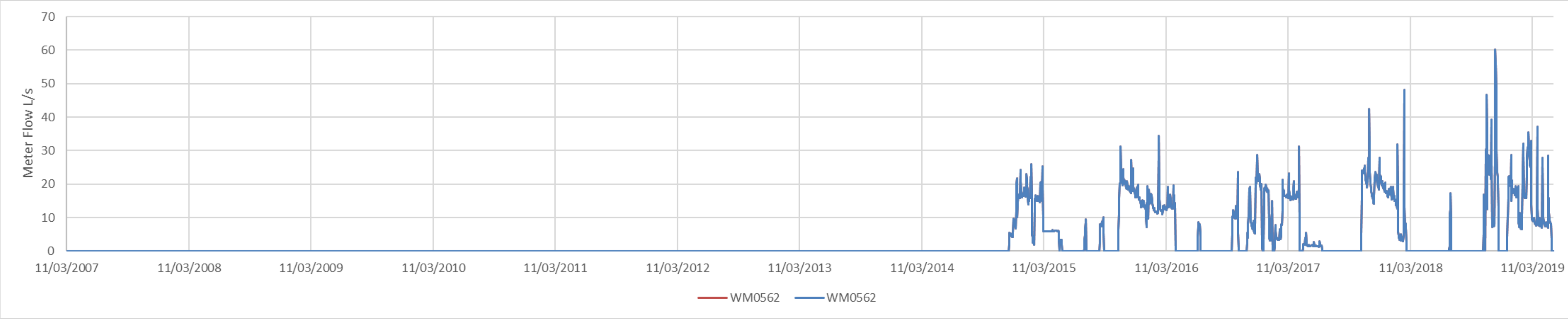
Figures below show the raw meter data for each meter from Table C-1 as a red line, with the QA'd meter data overplotted in blue. In general, where QA has led to removal of data, the raw data show up as a red line in the resulting gap. In some cases the scale change is so extreme that the QA'd data are plotted to a different scale, shown on the right hand side of the graph.



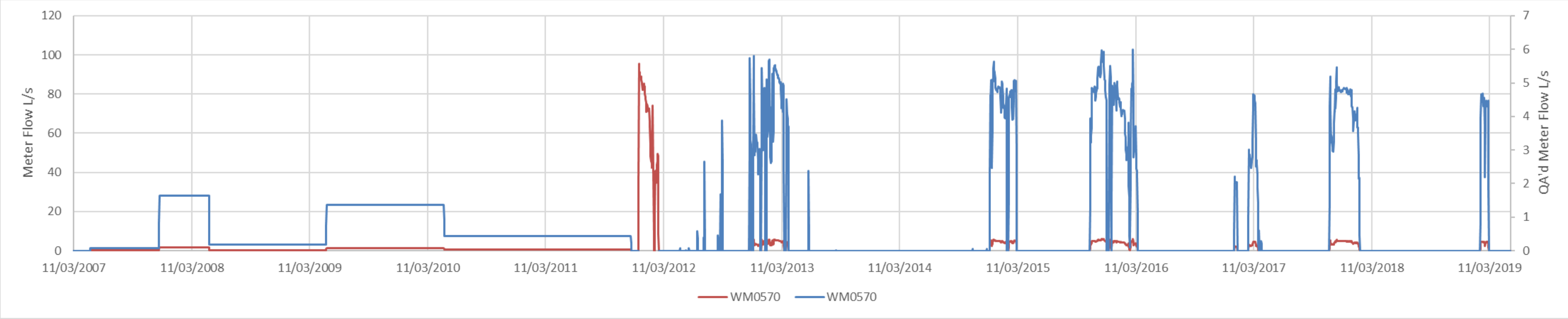




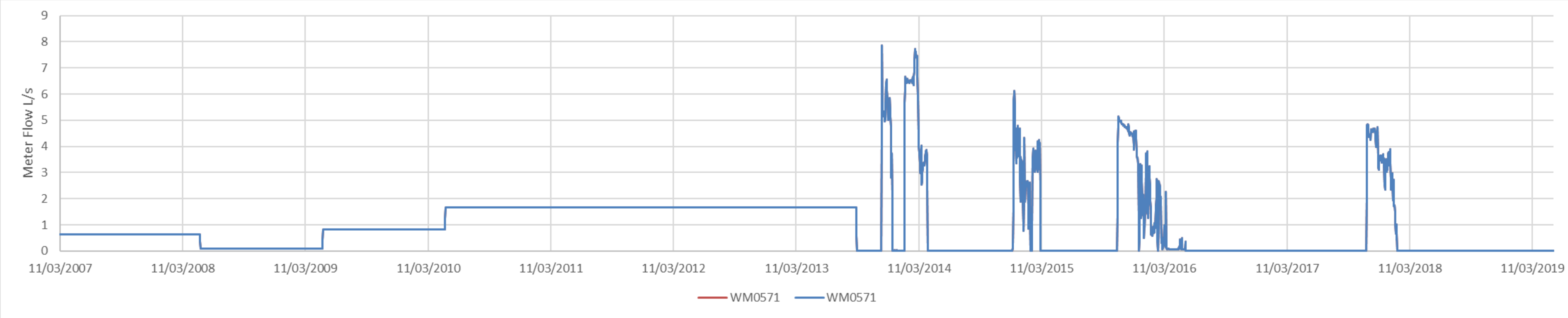
Meter Flow L/s
2.5
2
1.5
1
0.5
0
11/03/2007
11/03/2008
11/03/2009
11/03/2010
11/03/2011
11/03/2012
11/03/2013
11/03/2014
11/03/2015
11/03/2016
11/03/2017
11/03/2018
11/03/2019
WM0555
WM0555



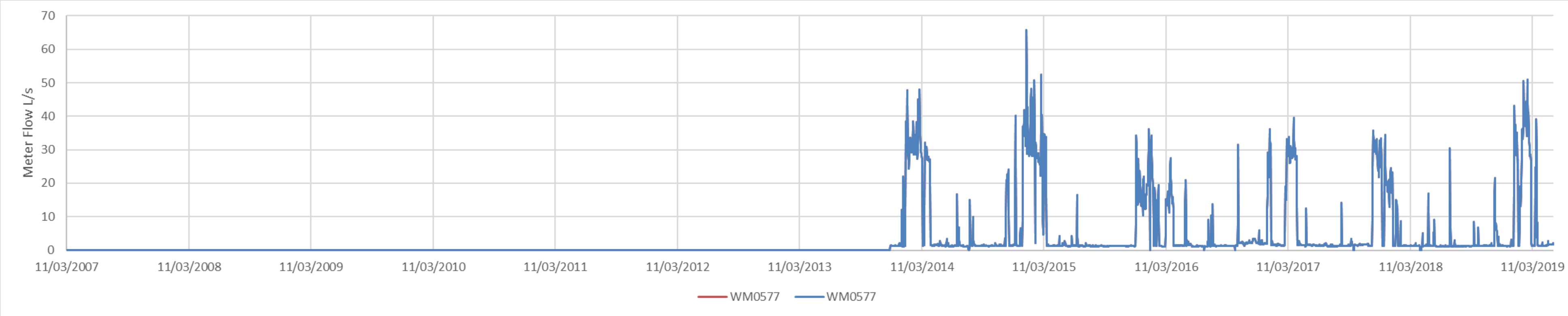
Meter Flow L/s
70
60
50
40
30
20
10
0
11/03/2007
11/03/2008
11/03/2009
11/03/2010
11/03/2011
11/03/2012
11/03/2013
11/03/2014
11/03/2015
11/03/2016
11/03/2017
11/03/2018
11/03/2019
WM0562
WM0562



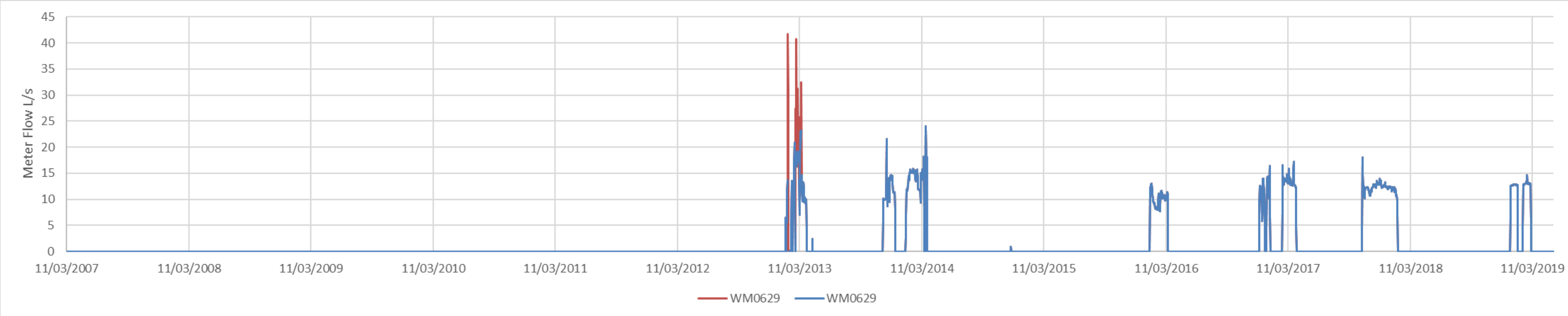
Meter Flow L/s
120
100
80
60
40
20
0
QA'd Meter Flow L/s
7
6
5
4
3
2
1
0
11/03/2007
11/03/2008
11/03/2009
11/03/2010
11/03/2011
11/03/2012
11/03/2013
11/03/2014
11/03/2015
11/03/2016
11/03/2017
11/03/2018
11/03/2019
WM0570
WM0570



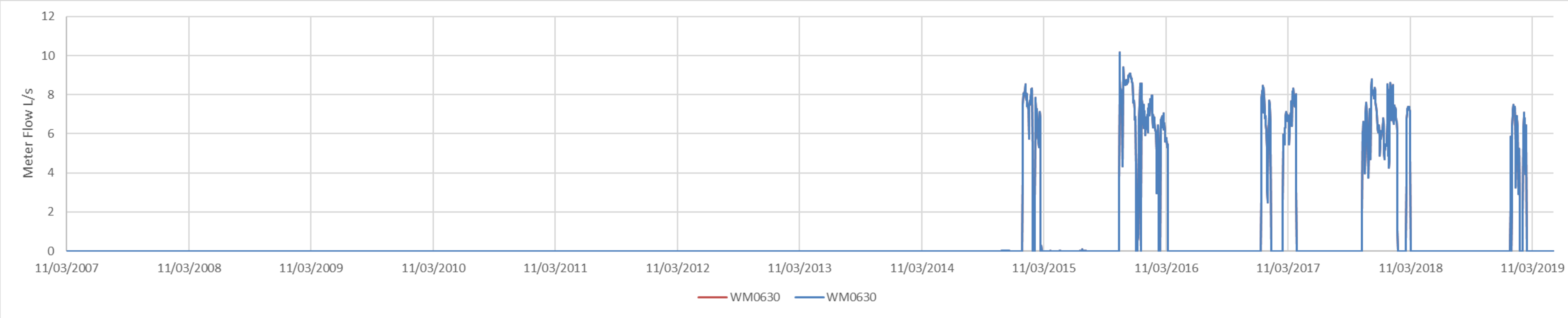
Meter Flow L/s
9
8
7
6
5
4
3
2
1
0
11/03/2007 11/03/2008 11/03/2009 11/03/2010 11/03/2011 11/03/2012 11/03/2013 11/03/2014 11/03/2015 11/03/2016 11/03/2017 11/03/2018 11/03/2019
WM0571
WM0571



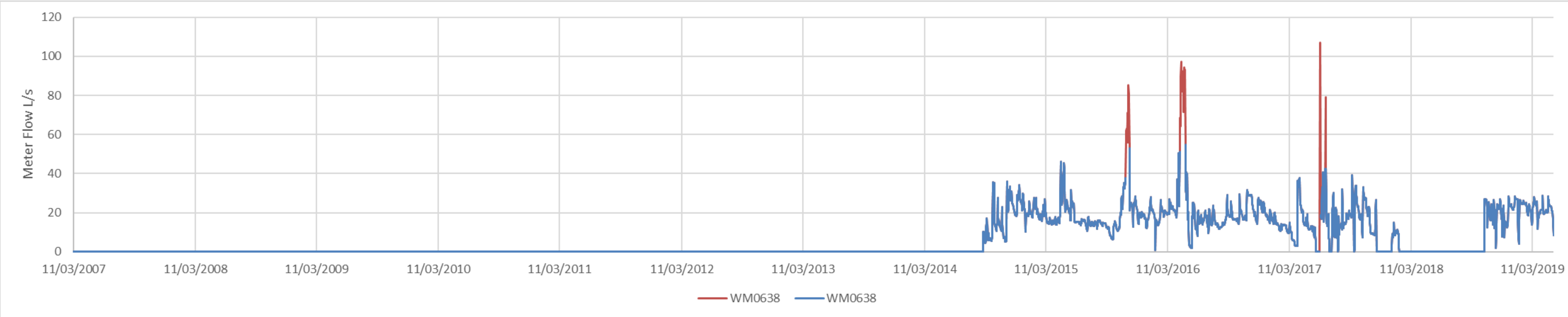
Meter Flow L/s
70
60
50
40
30
20
10
0
11/03/2007 11/03/2008 11/03/2009 11/03/2010 11/03/2011 11/03/2012 11/03/2013 11/03/2014 11/03/2015 11/03/2016 11/03/2017 11/03/2018 11/03/2019
WM0577
WM0577



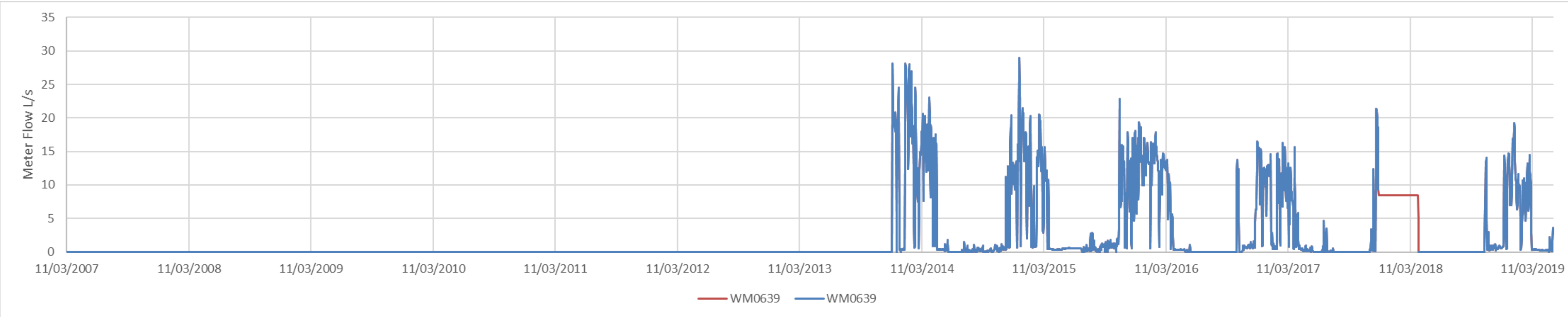
Meter Flow L/s
45
40
35
30
25
20
15
10
5
0
11/03/2007 11/03/2008 11/03/2009 11/03/2010 11/03/2011 11/03/2012 11/03/2013 11/03/2014 11/03/2015 11/03/2016 11/03/2017 11/03/2018 11/03/2019
WM0629
WM0629



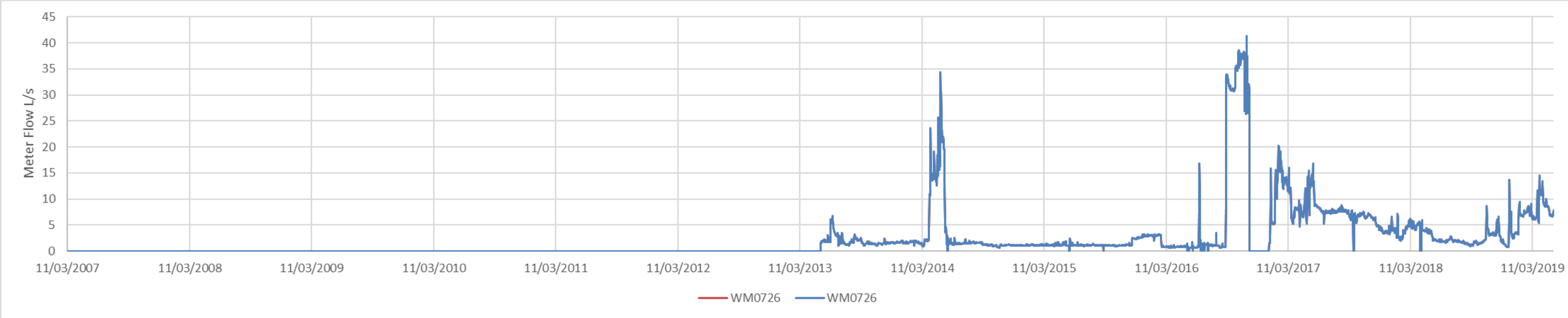
Meter Flow L/s
12
10
8
6
4
2
0
11/03/2007
11/03/2008
11/03/2009
11/03/2010
11/03/2011
11/03/2012
11/03/2013
11/03/2014
11/03/2015
11/03/2016
11/03/2017
11/03/2018
11/03/2019
WM0630
WM0630



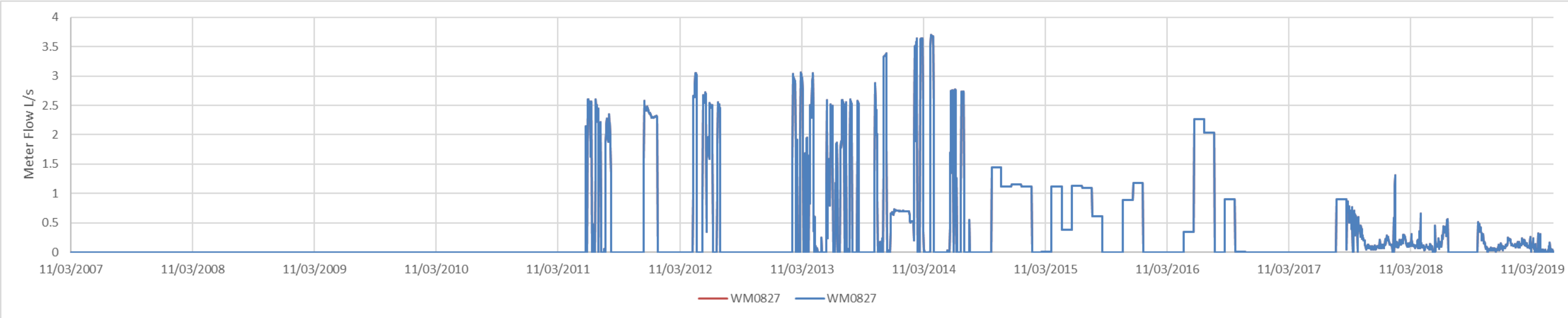
Meter Flow L/s
120
100
80
60
40
20
0
11/03/2007
11/03/2008
11/03/2009
11/03/2010
11/03/2011
11/03/2012
11/03/2013
11/03/2014
11/03/2015
11/03/2016
11/03/2017
11/03/2018
11/03/2019
WM0638
WM0638



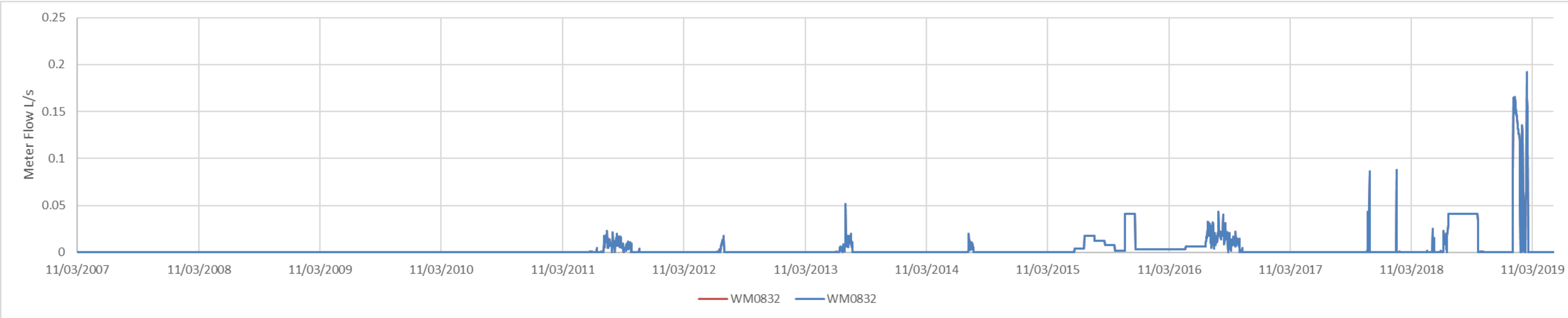
Meter Flow L/s
35
30
25
20
15
10
5
0
11/03/2007
11/03/2008
11/03/2009
11/03/2010
11/03/2011
11/03/2012
11/03/2013
11/03/2014
11/03/2015
11/03/2016
11/03/2017
11/03/2018
11/03/2019
WM0639
WM0639



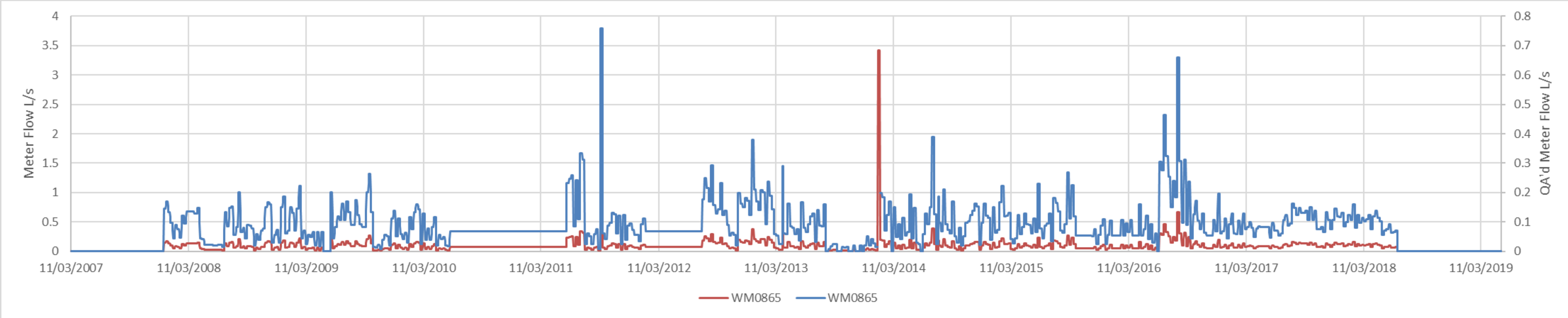
45
40
35
30
25
20
15
10
5
0
Meter Flow L/s
11/03/2007
11/03/2008
11/03/2009
11/03/2010
11/03/2011
11/03/2012
11/03/2013
11/03/2014
11/03/2015
11/03/2016
11/03/2017
11/03/2018
11/03/2019
WM0726
WM0726



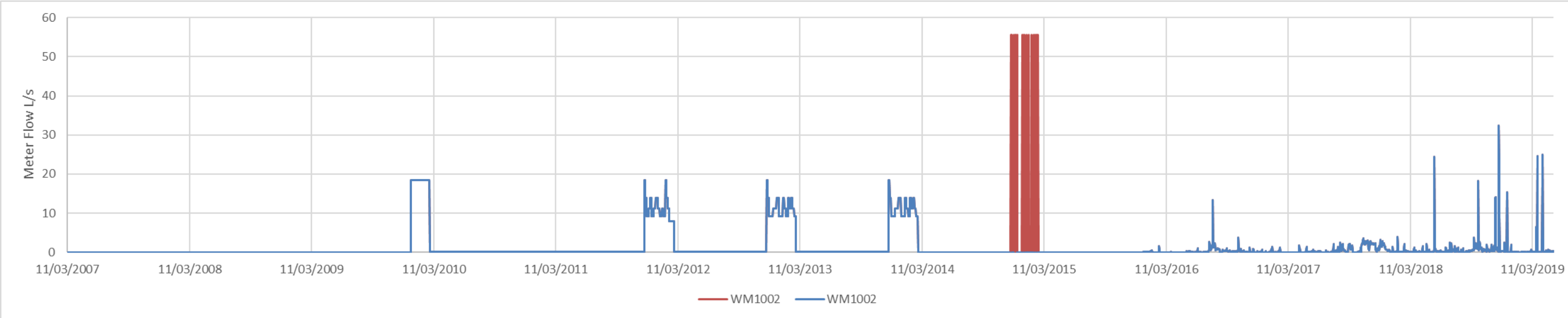
4
3.5
3
2.5
2
1.5
1
0.5
0
Meter Flow L/s
11/03/2007
11/03/2008
11/03/2009
11/03/2010
11/03/2011
11/03/2012
11/03/2013
11/03/2014
11/03/2015
11/03/2016
11/03/2017
11/03/2018
11/03/2019
WM0827
WM0827



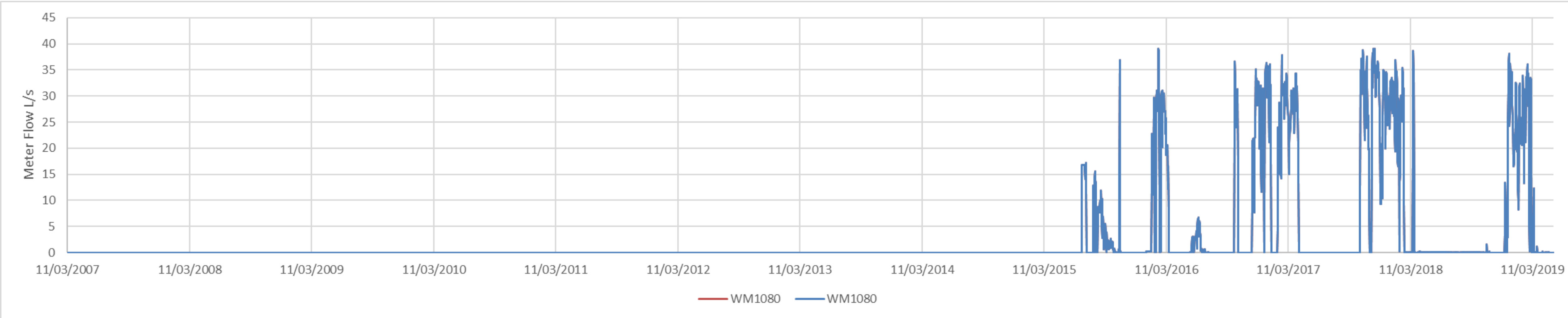
0.25
0.2
0.15
0.1
0.05
0
Meter Flow L/s
11/03/2007
11/03/2008
11/03/2009
11/03/2010
11/03/2011
11/03/2012
11/03/2013
11/03/2014
11/03/2015
11/03/2016
11/03/2017
11/03/2018
11/03/2019
WM0832
WM0832



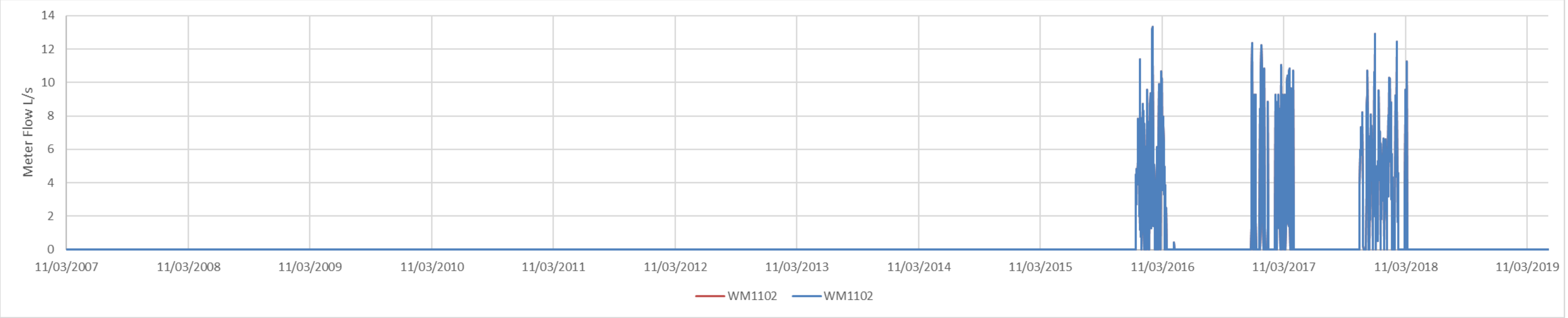
Meter Flow L/s
QA'd Meter Flow L/s
WM0865
WM0865

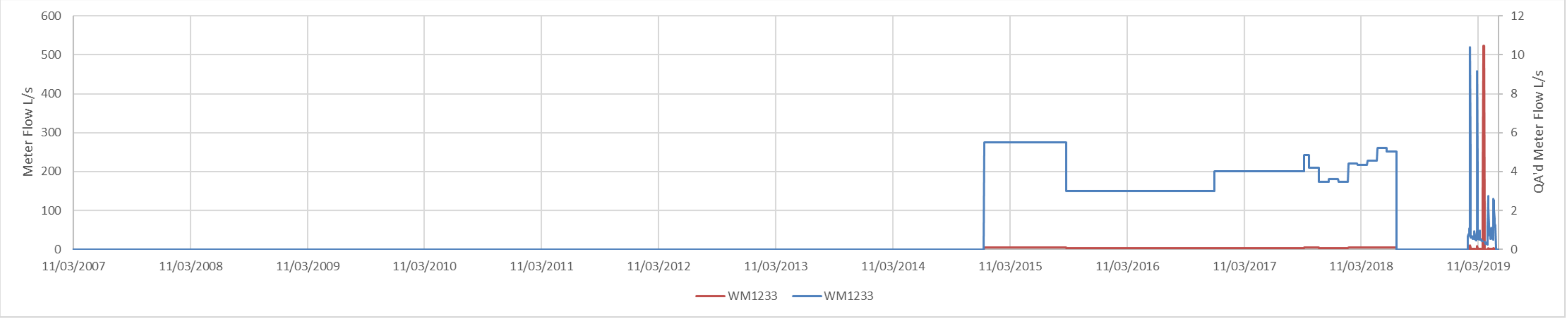


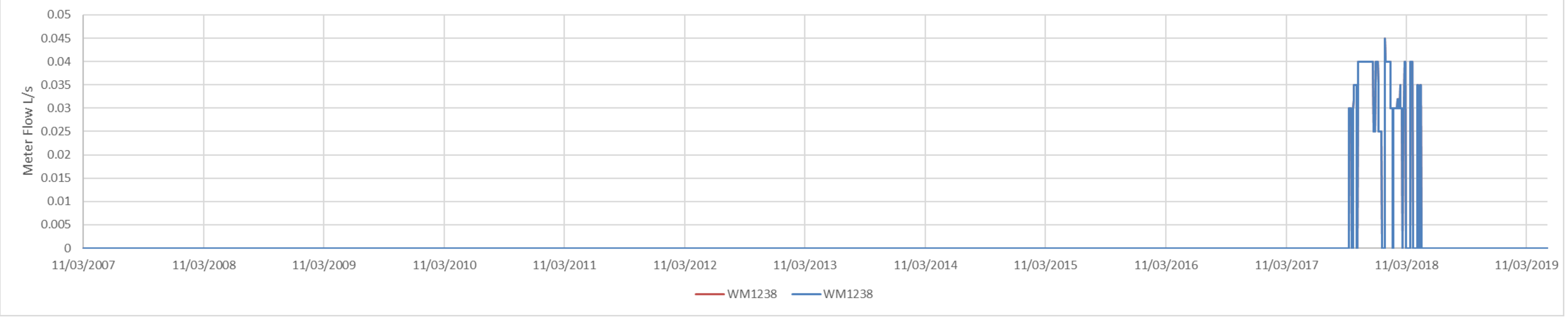
Meter Flow L/s
WM1002
WM1002

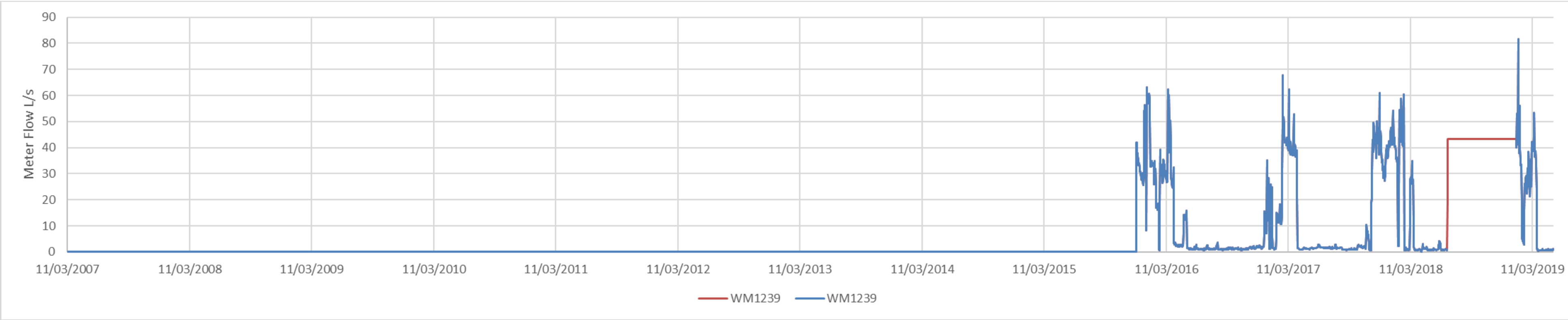


Meter Flow L/s
WM1080
WM1080

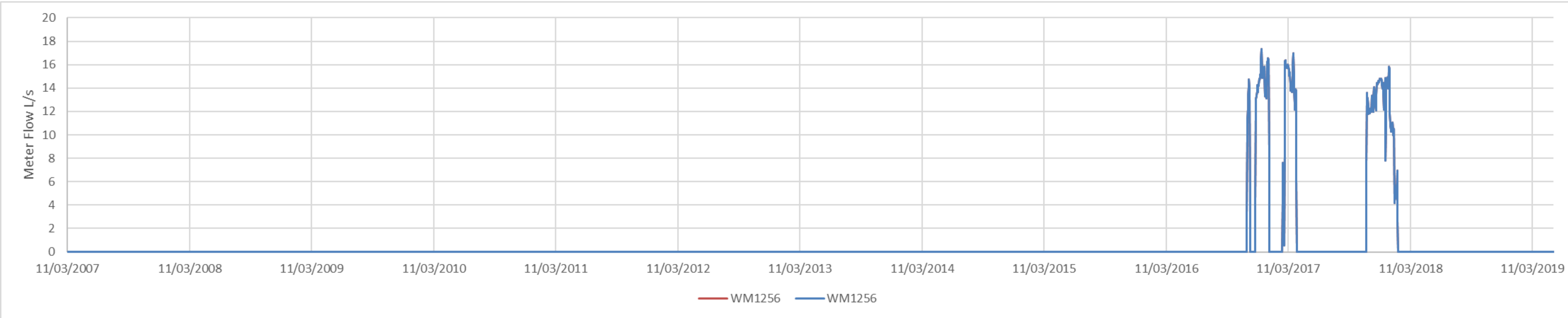

Meter Flow L/s
14
12
10
8
6
4
2
0
11/03/2007
11/03/2008
11/03/2009
11/03/2010
11/03/2011
11/03/2012
11/03/2013
11/03/2014
11/03/2015
11/03/2016
11/03/2017
11/03/2018
11/03/2019
WM1102
WM1102


Meter Flow L/s
600
500
400
300
200
100
0
QA'd Meter Flow L/s
12
10
8
6
4
2
0
11/03/2007
11/03/2008
11/03/2009
11/03/2010
11/03/2011
11/03/2012
11/03/2013
11/03/2014
11/03/2015
11/03/2016
11/03/2017
11/03/2018
11/03/2019
WM1233
WM1233

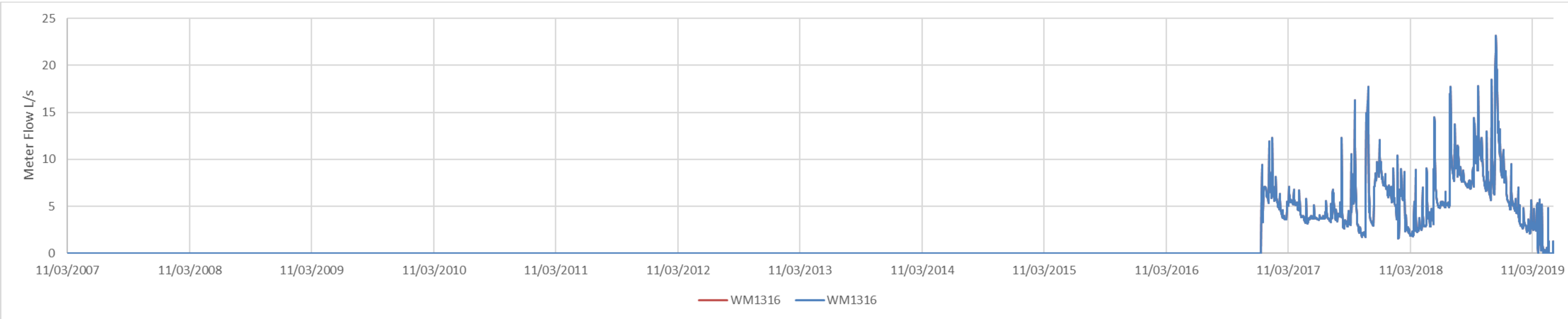

Meter Flow L/s
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
11/03/2007
11/03/2008
11/03/2009
11/03/2010
11/03/2011
11/03/2012
11/03/2013
11/03/2014
11/03/2015
11/03/2016
11/03/2017
11/03/2018
11/03/2019
WM1238
WM1238



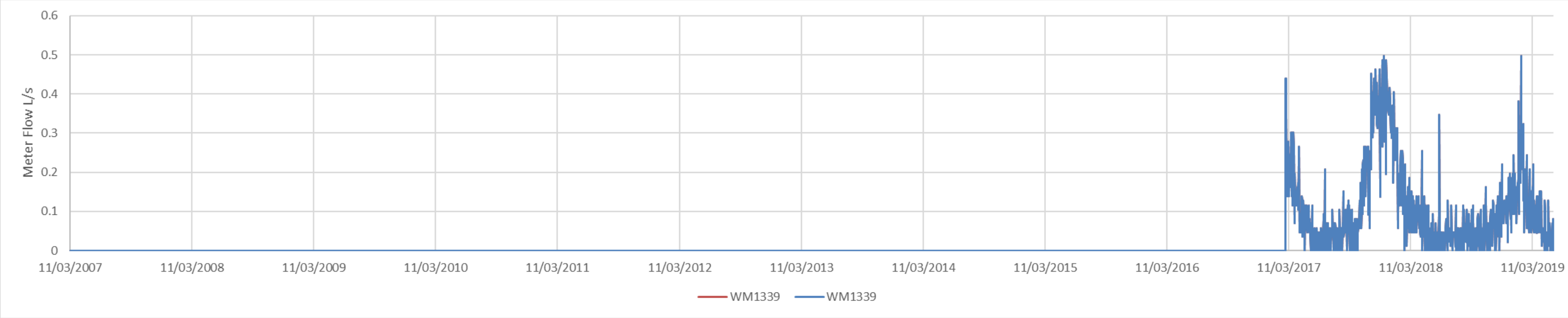
Meter Flow L/s
90
80
70
60
50
40
30
20
10
0
11/03/2007
11/03/2008
11/03/2009
11/03/2010
11/03/2011
11/03/2012
11/03/2013
11/03/2014
11/03/2015
11/03/2016
11/03/2017
11/03/2018
11/03/2019
WM1239
WM1239

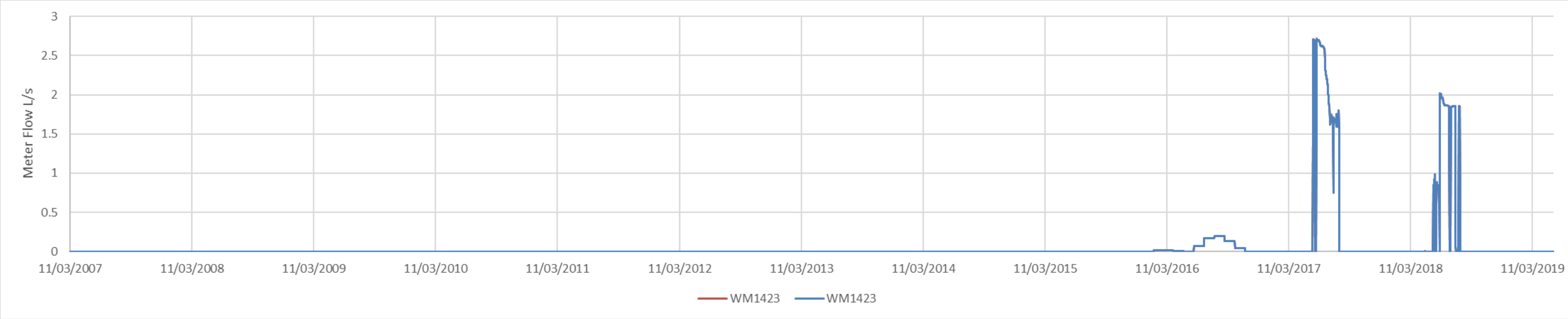


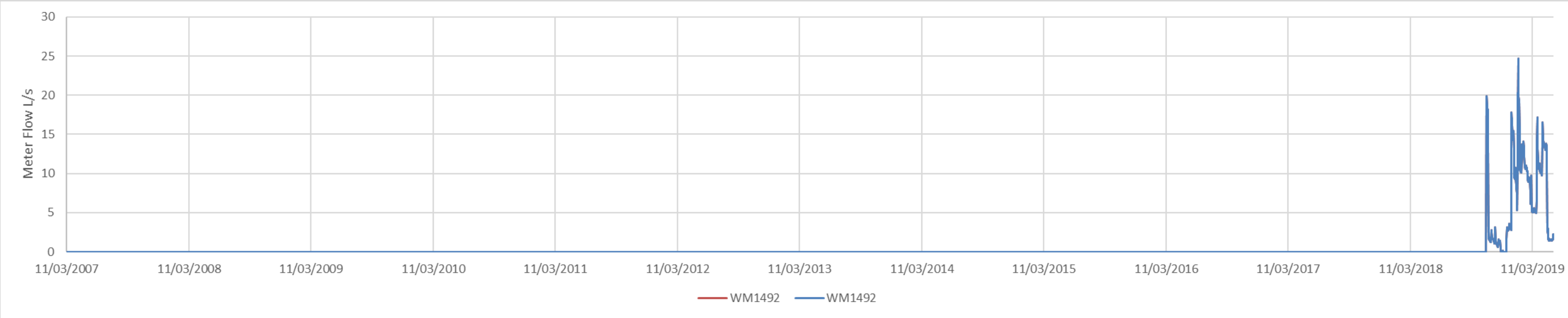
Meter Flow L/s
20
18
16
14
12
10
8
6
4
2
0
11/03/2007
11/03/2008
11/03/2009
11/03/2010
11/03/2011
11/03/2012
11/03/2013
11/03/2014
11/03/2015
11/03/2016
11/03/2017
11/03/2018
11/03/2019
WM1256
WM1256



Meter Flow L/s
25
20
15
10
5
0
11/03/2007
11/03/2008
11/03/2009
11/03/2010
11/03/2011
11/03/2012
11/03/2013
11/03/2014
11/03/2015
11/03/2016
11/03/2017
11/03/2018
11/03/2019
WM1316
WM1316


Meter Flow L/s
0.6
0.5
0.4
0.3
0.2
0.1
0
11/03/2007
11/03/2008
11/03/2009
11/03/2010
11/03/2011
11/03/2012
11/03/2013
11/03/2014
11/03/2015
11/03/2016
11/03/2017
11/03/2018
11/03/2019
WM1339
WM1339


Meter Flow L/s
3
2.5
2
1.5
1
0.5
0
11/03/2007
11/03/2008
11/03/2009
11/03/2010
11/03/2011
11/03/2012
11/03/2013
11/03/2014
11/03/2015
11/03/2016
11/03/2017
11/03/2018
11/03/2019
WM1423
WM1423


Meter Flow L/s
30
25
20
15
10
5
0
11/03/2007
11/03/2008
11/03/2009
11/03/2010
11/03/2011
11/03/2012
11/03/2013
11/03/2014
11/03/2015
11/03/2016
11/03/2017
11/03/2018
11/03/2019
WM1492
WM1492

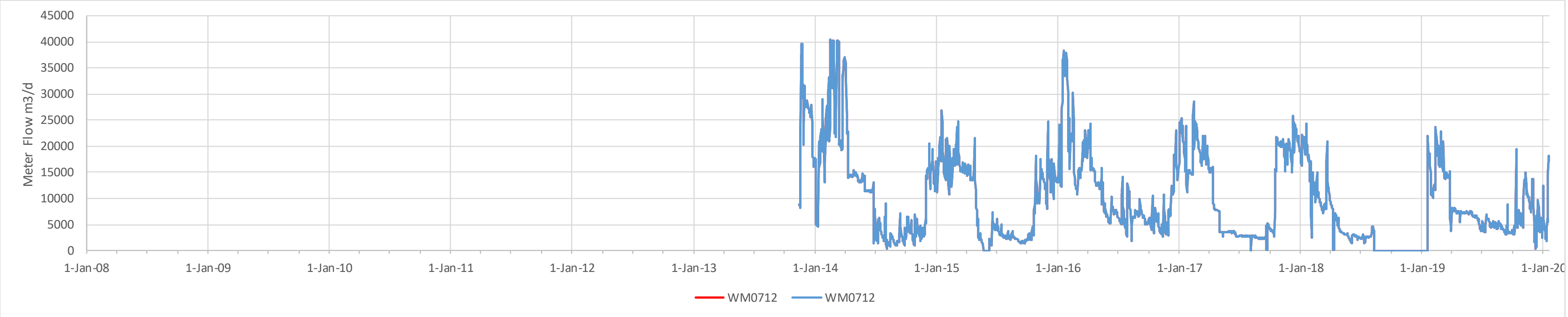
Appendix D Raw and QA'd water meter data below Mt Barker

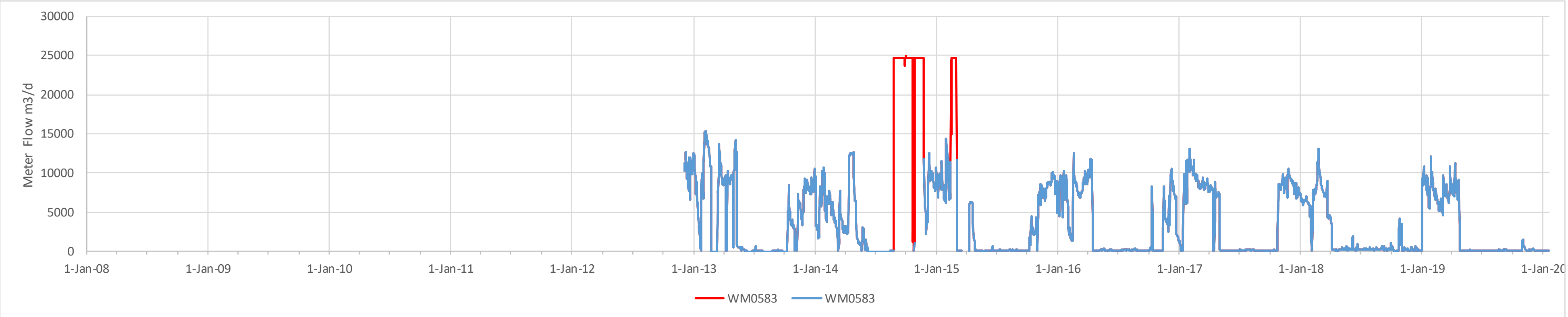
Commentary about each meter record is presented in Table D-1.

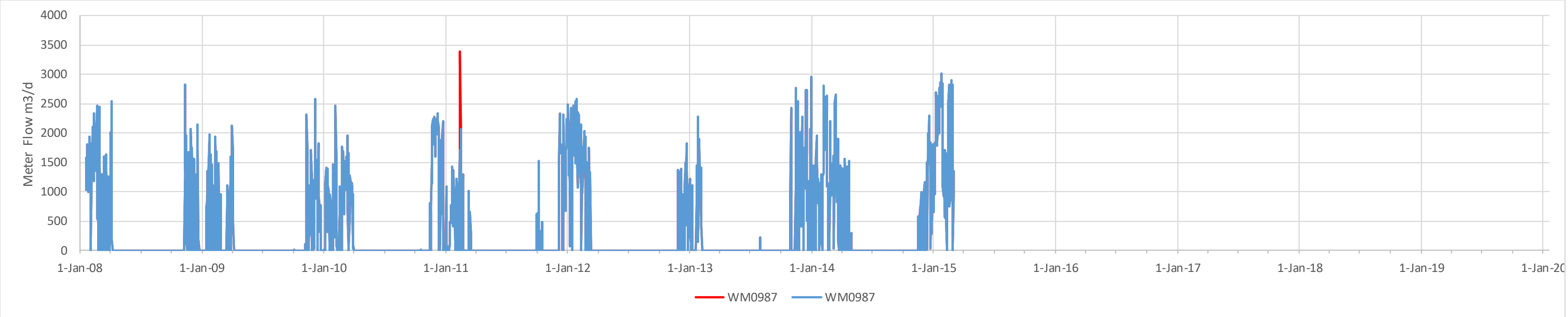
Table D-1: Water meter data quality commentary.

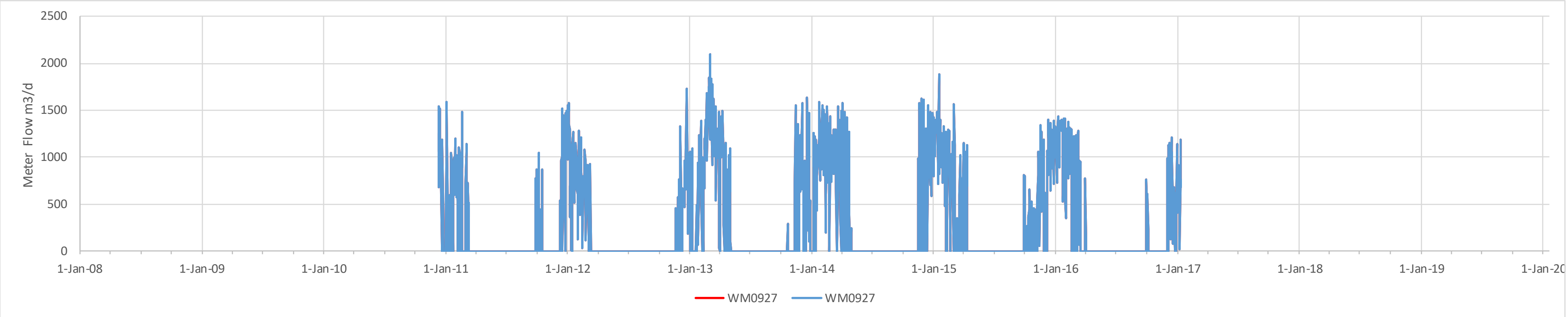
Meter Number	Upstream of flow recorder	MaxRate (L/s)	Commentary
WM0712	Hillend	500	This meter measures two consents, with a large combined MaxRate.
WM0583	Hillend	250	2014/15 looks unrealistic so remove.
WM0987	Hillend	38	One spike removed. Not up to date.
WM0927	Black Peak	24	No obvious problems. Not up to date.
WM0189	SH6	33.1	No obvious problems. Very coarse timesteps early and late.
WM0190	SH6	33.1	Some large spikes removed. 2016/17 season has much larger values, over 100% of MaxRate.
WM0331	SH6	30	Long gap removed. Large spikes removed. Block in 2012 removed. Gradual rise in late 2013 removed. Not up to date.
WM0332	SH6	30	Repetitive values in 4-day groups at end removed. 2017/18 constant removed. 2015 spike removed.
WM1508	Confluence	6.9	No obvious problems. Very short record.
WM0734	Confluence	22	No obvious problems. Possible missing data 2011, 2013, 2014 and 2015 summers.

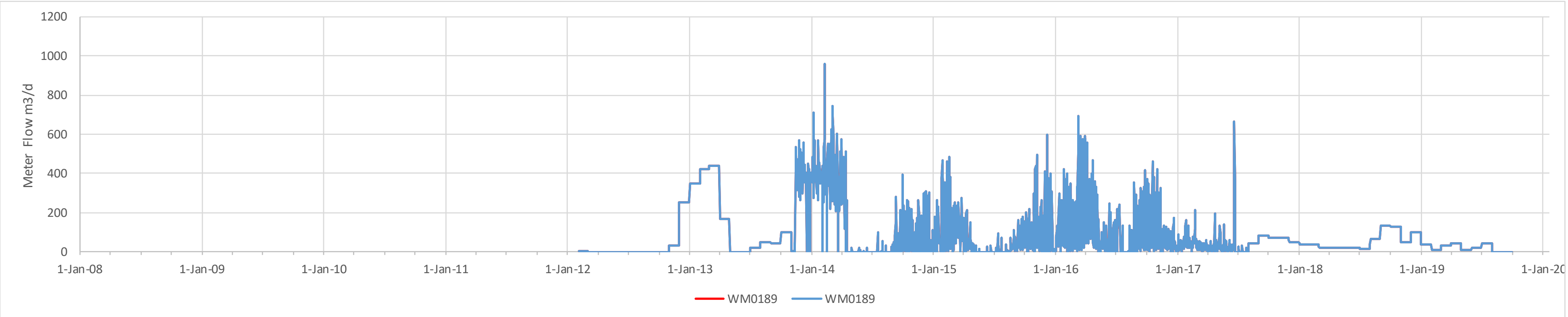
Figures below show the raw meter data for each meter in Table D-1 as a red line, with the QA'd meter data overplotted in blue. In general, where QA has led to removal of data, the raw data show up as a red line in the resulting gap. All flows are in m³/d.

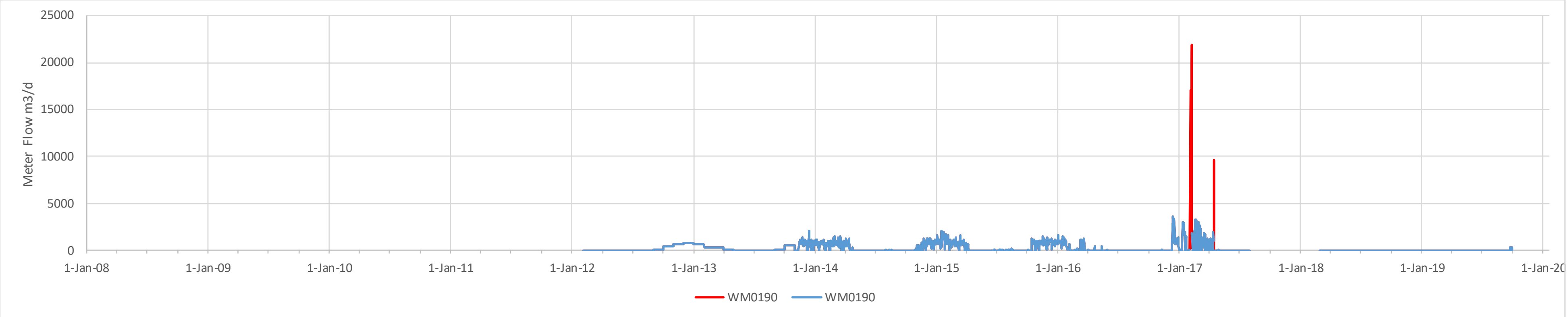




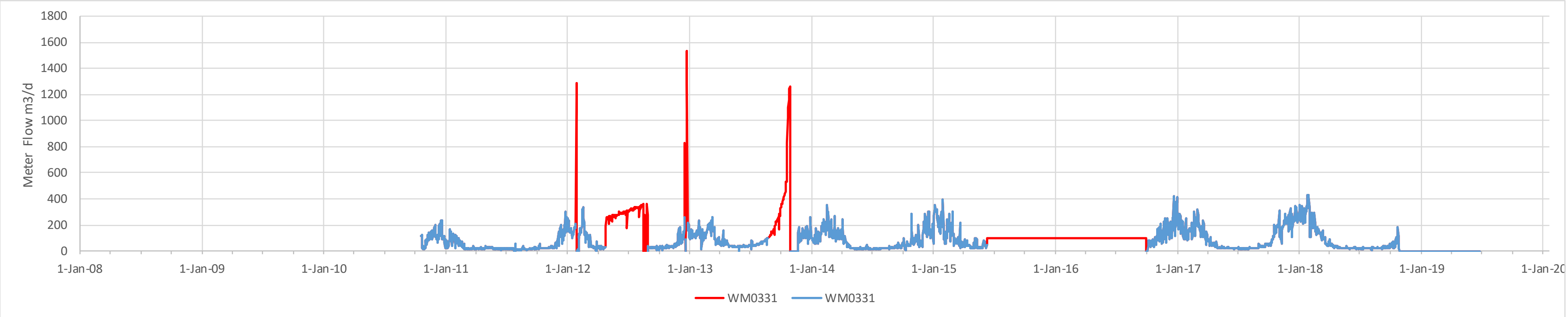

Meter Flow m3/d
4000
3500
3000
2500
2000
1500
1000
500
0
1-Jan-08
1-Jan-09
1-Jan-10
1-Jan-11
1-Jan-12
1-Jan-13
1-Jan-14
1-Jan-15
1-Jan-16
1-Jan-17
1-Jan-18
1-Jan-19
WM0987
WM0987


Meter Flow m3/d
2500
2000
1500
1000
500
0
1-Jan-08
1-Jan-09
1-Jan-10
1-Jan-11
1-Jan-12
1-Jan-13
1-Jan-14
1-Jan-15
1-Jan-16
1-Jan-17
1-Jan-18
1-Jan-19
WM0927
WM0927

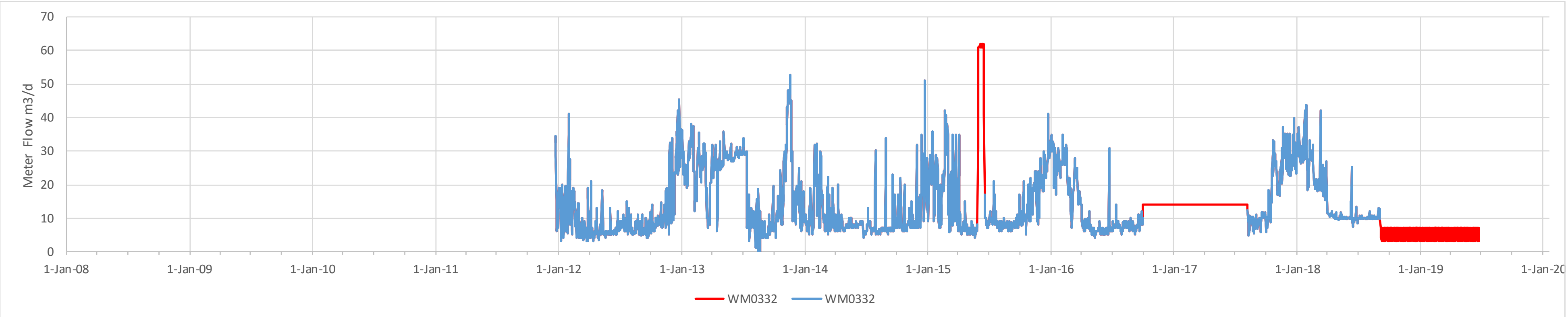

Meter Flow m3/d
1200
1000
800
600
400
200
0
1-Jan-08
1-Jan-09
1-Jan-10
1-Jan-11
1-Jan-12
1-Jan-13
1-Jan-14
1-Jan-15
1-Jan-16
1-Jan-17
1-Jan-18
1-Jan-19
WM0189
WM0189



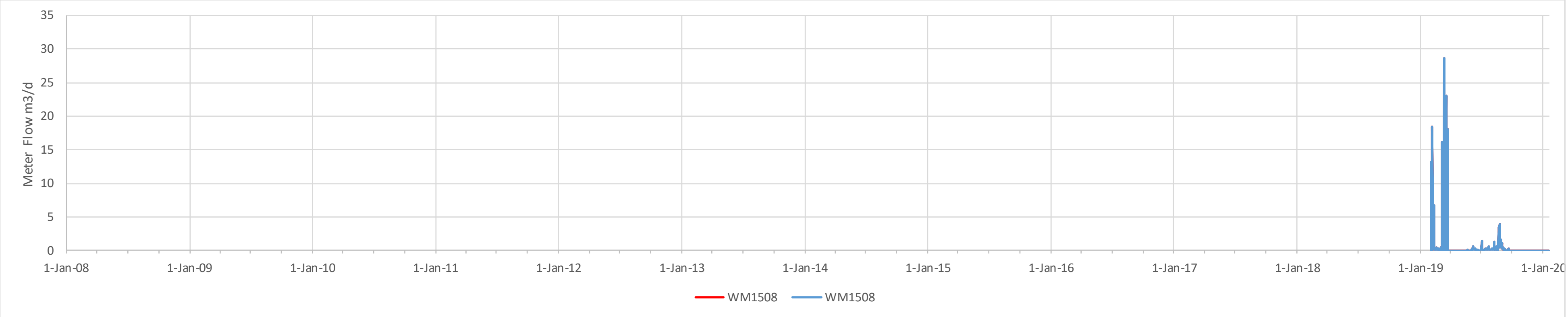
25000
20000
15000
10000
5000
0
Meter Flow m3/d
1-Jan-08
1-Jan-09
1-Jan-10
1-Jan-11
1-Jan-12
1-Jan-13
1-Jan-14
1-Jan-15
1-Jan-16
1-Jan-17
1-Jan-18
1-Jan-19
WM0190
WM0190

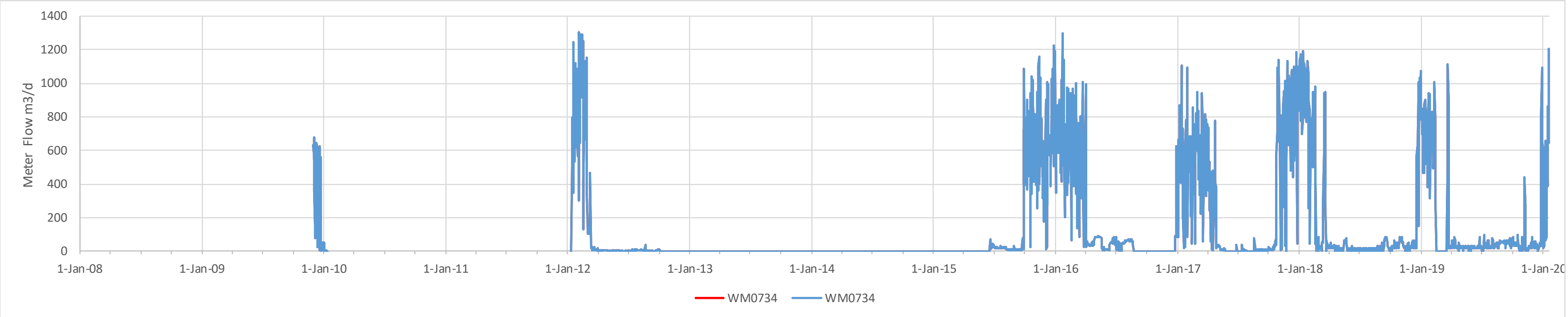


1800
1600
1400
1200
1000
800
600
400
200
0
Meter Flow m3/d
1-Jan-08
1-Jan-09
1-Jan-10
1-Jan-11
1-Jan-12
1-Jan-13
1-Jan-14
1-Jan-15
1-Jan-16
1-Jan-17
1-Jan-18
1-Jan-19
WM0331
WM0331



70
60
50
40
30
20
10
0
Meter Flow m3/d
1-Jan-08
1-Jan-09
1-Jan-10
1-Jan-11
1-Jan-12
1-Jan-13
1-Jan-14
1-Jan-15
1-Jan-16
1-Jan-17
1-Jan-18
1-Jan-19
WM0332
WM0332


35
30
25
20
15
10
5
0
Meter Flow m3/d
1-Jan-08
1-Jan-09
1-Jan-10
1-Jan-11
1-Jan-12
1-Jan-13
1-Jan-14
1-Jan-15
1-Jan-16
1-Jan-17
1-Jan-18
1-Jan-19
1-Jan-20
WM1508
WM1508


1400
1200
1000
800
600
400
200
0
Meter Flow m3/d
1-Jan-08
1-Jan-09
1-Jan-10
1-Jan-11
1-Jan-12
1-Jan-13
1-Jan-14
1-Jan-15
1-Jan-16
1-Jan-17
1-Jan-18
1-Jan-19
1-Jan-20
WM0734
WM0734

Appendix E Tables of annual drying statistics

Water years are from July to June, labelled as the end year.

Table E-1: Number of drying days per year. Left-most column shows which years have sufficient data (Use = 1). Threshold flows are 1,600 L/s and 1,200 L/s at Mt Barker.

Use	Water Year	Recorded flows		Simulated natural flows	
Year	Threshold	1600 L/s	1,200 L/s	1600 L/s	1,200 L/s
0	1977	92	45	84	32
1	1978	221	143	207	133
0	1979	53	15	63	5
0	1980	0	0	0	0
0	1981	20	16	39	14
0	1982	105	85	105	64
1	1983	18	1	7	0
0	1984	1	0	1	0
1	1985	65	23	61	9
0	1986	93	21	65	11
1	1987	67	24	50	0
1	1988	137	66	130	36
0	1989	3	0	44	10
0	1990	0	0	75	15
0	1991	0	0	38	0
0	1992	0	0	177	107
0	1993	0	0	78	23
0	1994	0	0	0	0
0	1995	0	0	50	32
0	1996	0	0	0	0
0	1997	0	0	36	2
0	1998	0	0	44	12
0	1999	0	0	93	62
0	2000	0	0	0	0
0	2001	102	76	117	67
1	2002	102	38	87	23
1	2003	135	74	119	59
1	2004	97	27	74	10
1	2005	17	0	8	0
1	2006	210	147	197	128
1	2007	160	108	139	91
1	2008	181	112	167	103
1	2009	86	32	66	15
1	2010	103	86	96	83
1	2011	77	6	35	0
1	2012	144	33	126	3
1	2013	135	85	123	63

Use	Water Year	Recorded flows		Simulated natural flows	
Year	Threshold	1600 L/s	1,200 L/s	1600 L/s	1,200 L/s
1	2014	99	72	96	66
1	2015	125	95	117	74
1	2016	157	144	152	130
1	2017	118	43	89	10
1	2018	102	73	87	59
0	2019	54	13	36	0

Table E-2: Number of drying events per year. Left-most column shows which years have sufficient data. Threshold flows are 1,600 L/s and 1,200 L/s at Mt Barker.

Use	Water Year	Recorded flows		Simulated natural flows	
Year	Threshold	1600 L/s	1,200 L/s	1600 L/s	1,200 L/s
0	1977	9	8	10	7
1	1978	13	12	17	11
0	1979	11	6	14	1
0	1980	0	0	0	0
0	1981	4	2	3	3
0	1982	6	8	11	7
1	1983	5	1	2	0
0	1984	1	0	1	0
1	1985	6	5	4	4
0	1986	11	3	10	3
1	1987	9	6	13	0
1	1988	10	10	10	8
0	1989	2	0	13	2
0	1990	0	0	8	5
0	1991	0	0	10	0
0	1992	0	0	13	17
0	1993	0	0	16	6
0	1994	0	0	0	0
0	1995	0	0	7	2
0	1996	0	0	0	0
0	1997	0	0	6	2
0	1998	0	0	11	3
0	1999	0	0	10	7
0	2000	0	0	0	0
0	2001	5	4	8	8
1	2002	11	6	5	2
1	2003	11	8	12	8
1	2004	13	5	10	3
1	2005	3	0	3	0
1	2006	13	12	17	9
1	2007	13	11	9	10
1	2008	17	11	19	12
1	2009	12	4	6	3
1	2010	5	4	4	5
1	2011	15	1	8	0
1	2012	14	10	15	1

Use	Water Year	Recorded flows		Simulated natural flows	
Year	Threshold	1600 L/s	1,200 L/s	1600 L/s	1,200 L/s
1	2013	9	10	8	7
1	2014	6	5	5	4
1	2015	5	11	8	9
1	2016	5	5	5	11
1	2017	12	5	13	4
1	2018	7	6	4	5
0	2019	8	5	7	0

Table E-3: Average run length per year (days). Left-most column shows which years have sufficient data. Nan indicates years with no data or no events. Threshold flows are 1,600 L/s and 1,200 L/s at Mt Barker.

Use	Water Year	Recorded flows		Simulated natural flows	
Year	Threshold	1600 L/s	1,200 L/s	1600 L/s	1,200 L/s
0	1977	10.2	5.6	8.4	4.6
1	1978	16.9	11.5	11.9	11.8
0	1979	5.9	4.4	5.3	10.0
0	1980	nan	nan	Na	nan
0	1981	5.0	8.0	13.0	4.7
0	1982	17.5	10.6	9.5	9.1
1	1983	3.6	1.0	3.5	nan
0	1984	1.0	nan	1.0	nan
1	1985	10.8	4.6	15.3	2.3
0	1986	8.5	7.0	6.5	3.7
1	1987	7.4	4.0	3.8	nan
1	1988	13.7	6.6	13.0	4.5
0	1989	1.5	nan	3.4	5.0
0	1990	nan	nan	9.4	3.0
0	1991	nan	nan	3.8	nan
0	1992	nan	nan	13.8	6.3
0	1993	nan	nan	5.3	4.1
0	1994	nan	nan	nan	nan
0	1995	nan	nan	7.1	16.0
0	1996	nan	nan	nan	nan
0	1997	nan	nan	6.0	1.0
0	1998	nan	nan	4.0	4.0
0	1999	nan	nan	9.3	8.9
0	2000	nan	nan	nan	nan
0	2001	20.4	19.0	14.6	8.4
1	2002	9.3	6.3	17.4	11.5
1	2003	12.3	9.3	9.9	7.4
1	2004	7.5	5.4	7.4	3.3
1	2005	5.7	nan	2.7	nan
1	2006	16.2	12.3	11.6	14.2
1	2007	12.3	9.8	15.4	9.1
1	2008	10.6	10.2	9.1	8.6
1	2009	7.5	8.0	9.9	5.0
1	2010	20.6	21.5	24.0	16.6
1	2011	5.1	6.0	4.4	nan

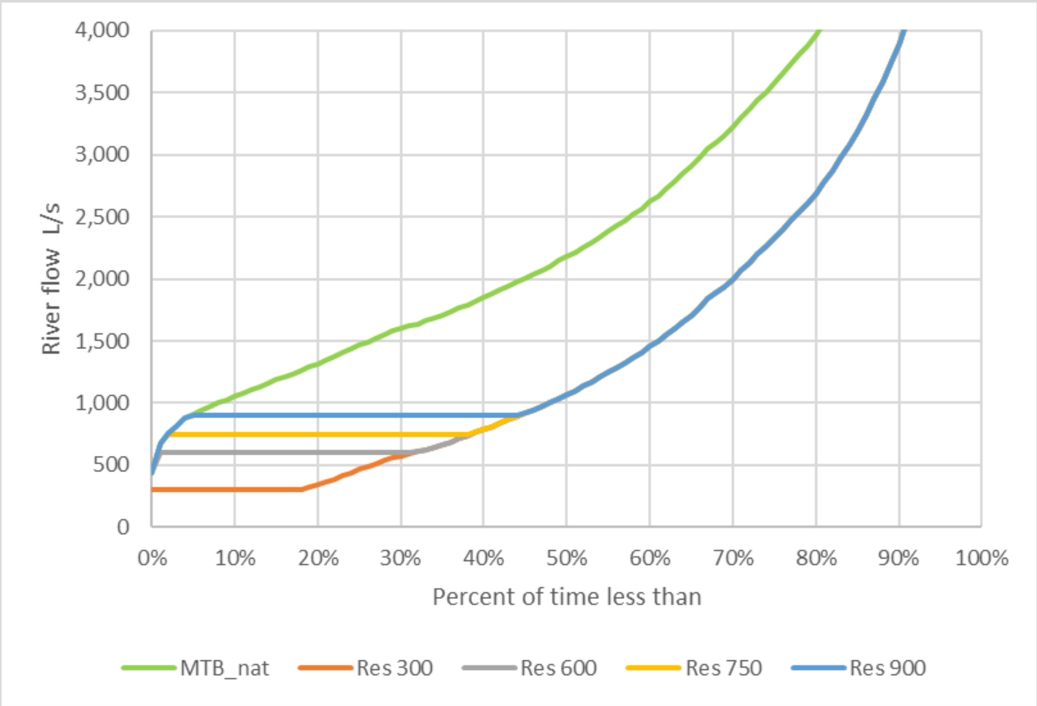
Use	Water Year	Recorded flows		Simulated natural flows	
Year	Threshold	1600 L/s	1,200 L/s	1600 L/s	1,200 L/s
1	2012	10.3	3.3	8.4	3.0
1	2013	16.0	8.5	16.7	9.0
1	2014	15.1	14.4	17.0	16.5
1	2015	25.0	8.6	14.6	8.2
1	2016	31.4	28.8	30.4	11.8
1	2017	9.8	8.6	6.8	2.5
1	2018	14.6	12.2	21.8	11.8
0	2019	6.8	2.6	5.1	nan

Table E-4: Maximum run length each year (days). Left-most column shows which years have sufficient data. Threshold flows are 1,600 L/s and 1,200 L/s at Mt Barker.

Use	Water Year	Recorded flows		Simulated natural flows	
Year	Threshold	1600 L/s	1,200 L/s	Year	Threshold
0	1977	24	16	24	14
1	1978	81	34	84	33
0	1979	21	19	20	18
0	1980	0	0	0	0
0	1981	9	8	26	11
0	1982	35	26	35	24
1	1983	8	1	6	0
0	1984	1	0	1	0
1	1985	36	17	35	5
0	1986	30	14	18	6
1	1987	23	12	12	0
1	1988	42	22	43	10
0	1989	2	0	15	8
0	1990	0	0	31	6
0	1991	0	0	23	0
0	1992	0	0	53	23
0	1993	0	0	24	9
0	1994	0	0	0	0
0	1995	0	0	38	25
0	1996	0	0	0	0
0	1997	0	0	12	1
0	1998	0	0	14	5
0	1999	0	0	35	23
0	2000	0	0	0	0
0	2001	79	38	44	16
1	2002	36	18	36	17
1	2003	73	27	61	24
1	2004	25	14	24	5
1	2005	8	0	5	0
1	2006	103	66	103	64
1	2007	56	25	41	24
1	2008	38	37	38	35
1	2009	33	18	30	7
1	2010	71	57	70	53
1	2011	17	6	14	0
1	2012	34	14	34	3

Use	Water Year	Recorded flows		Simulated natural flows	
Year	Threshold	1600 L/s	1,200 L/s	Year	Threshold
1	2013	47	32	47	27
1	2014	76	35	48	35
1	2015	49	35	49	34
1	2016	75	65	66	32
1	2017	53	15	16	4
1	2018	65	49	52	44
0	2019	23	5	7	0

Appendix F Flow duration curves for reliability scenarios



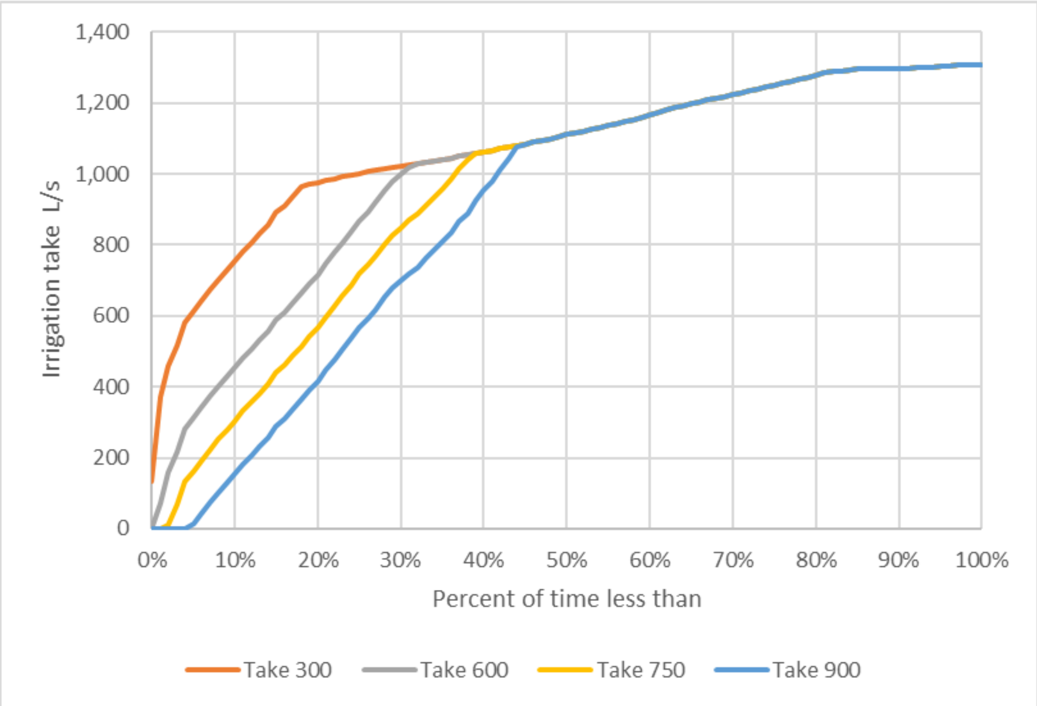
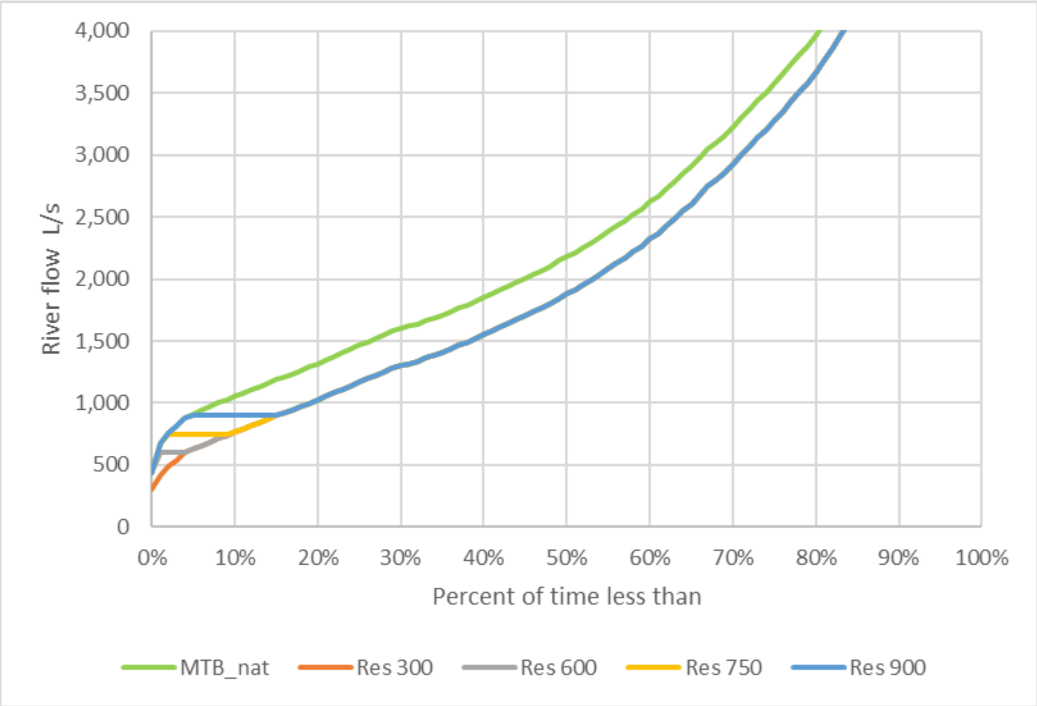


Figure F-1: 100% maximum take rate. Flow at Mt Barker (top graph), natural and four minimum flow scenarios; and irrigation takes (bottom graph), four minimum flow scenarios. All labelled by the minimum flow at Mt Barker.



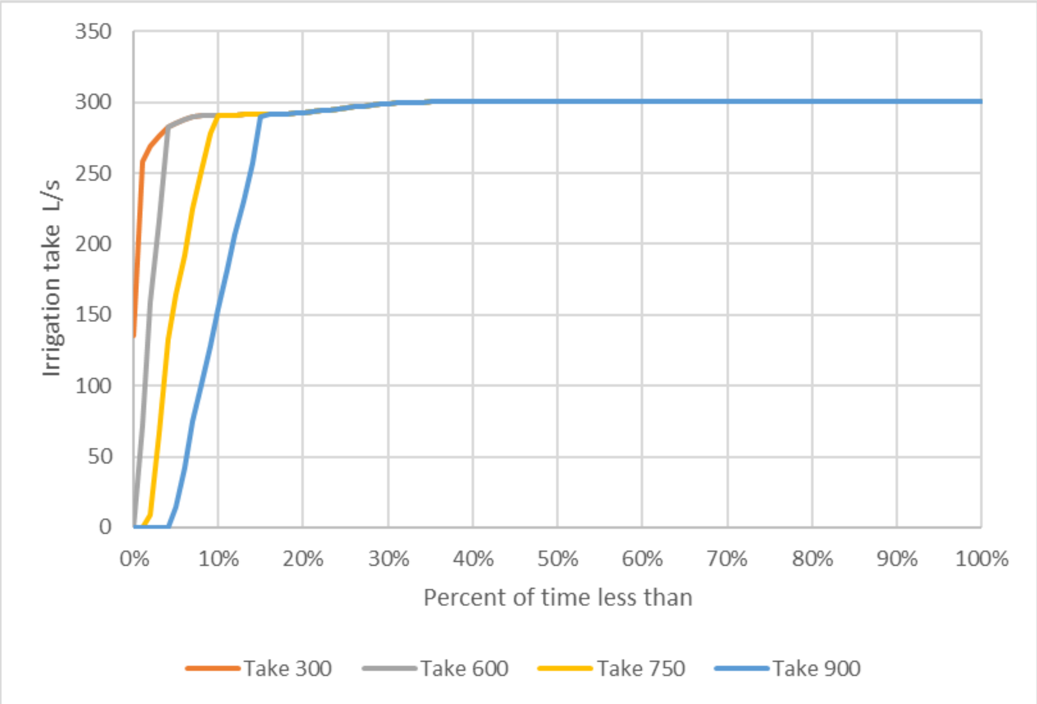
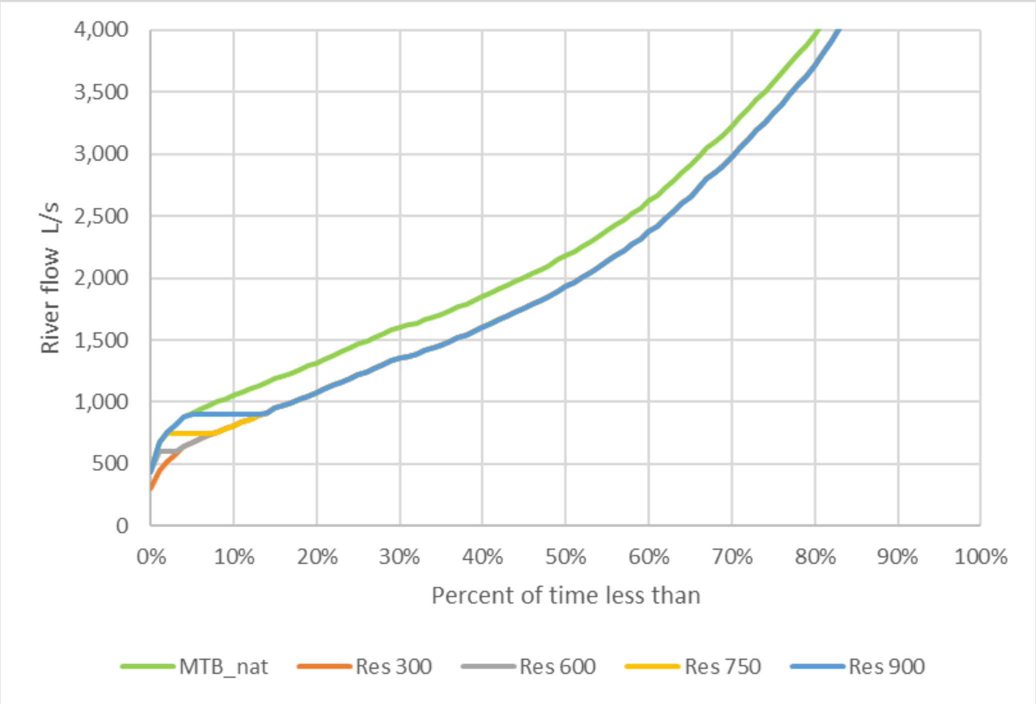


Figure F-2: 23% of maximum take rate (maximum take 300 L/s). Flow at Mt Barker (top graph), natural and four minimum flow scenarios; and irrigation takes (bottom graph), four minimum flow scenarios. All labelled by the minimum flow at Mt Barker.



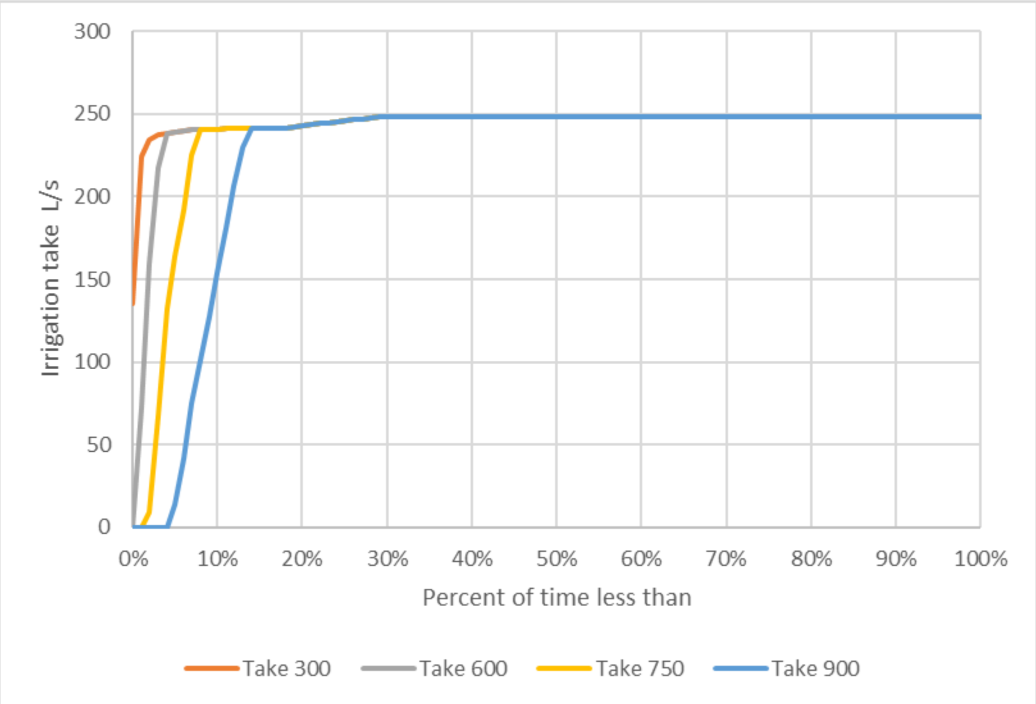
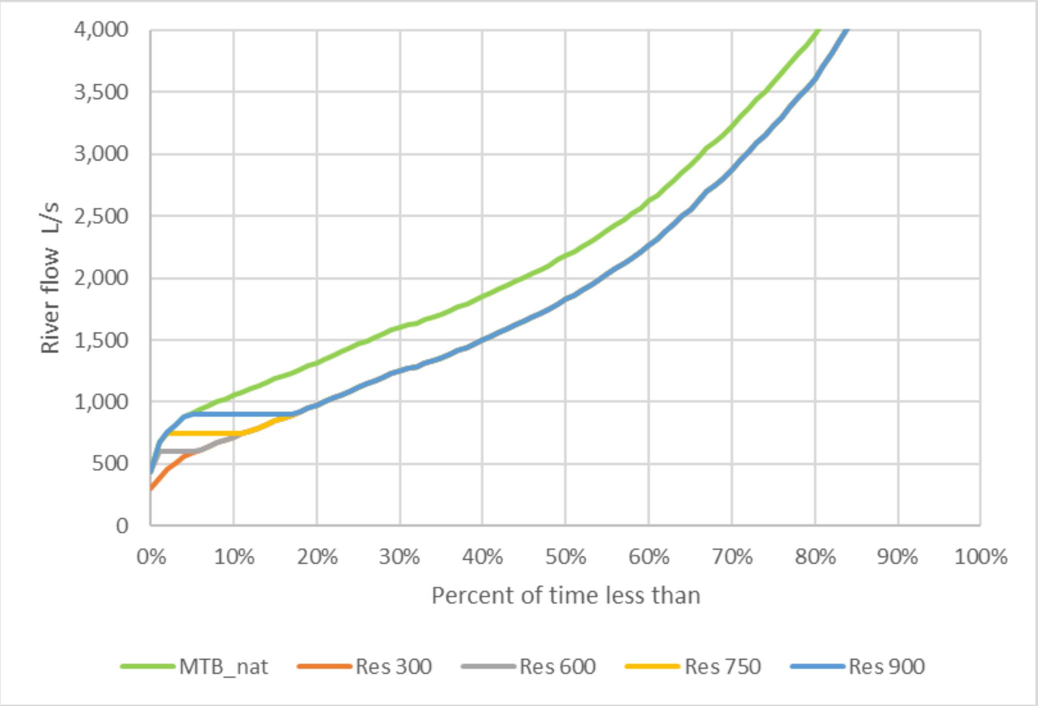


Figure F-3: 19% maximum take rate (maximum 250 L/s). Flow at Mt Barker (top graph), natural and four minimum flow scenarios; and irrigation takes (bottom graph), four minimum flow scenarios. All labelled by the minimum flow at Mt Barker.



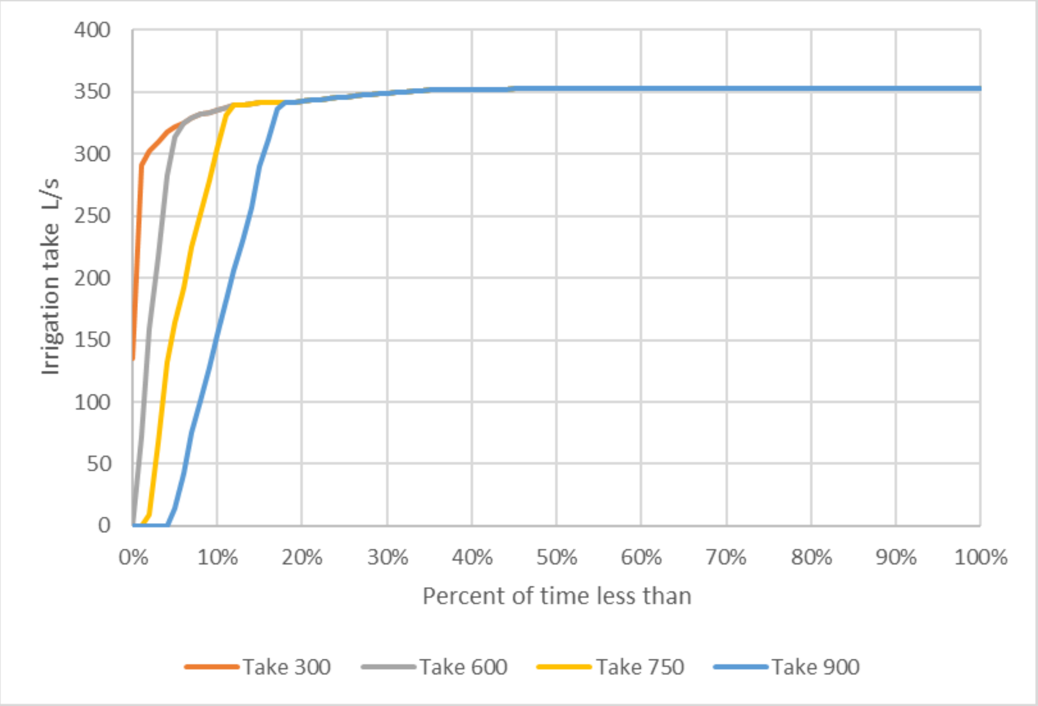


Figure F-4: 27% maximum take rate (maximum 350 L/s). Flow at Mt Barker (top graph), natural and four minimum flow scenarios; and irrigation takes (bottom graph), four minimum flow scenarios. All labelled by the minimum flow at Mt Barker.

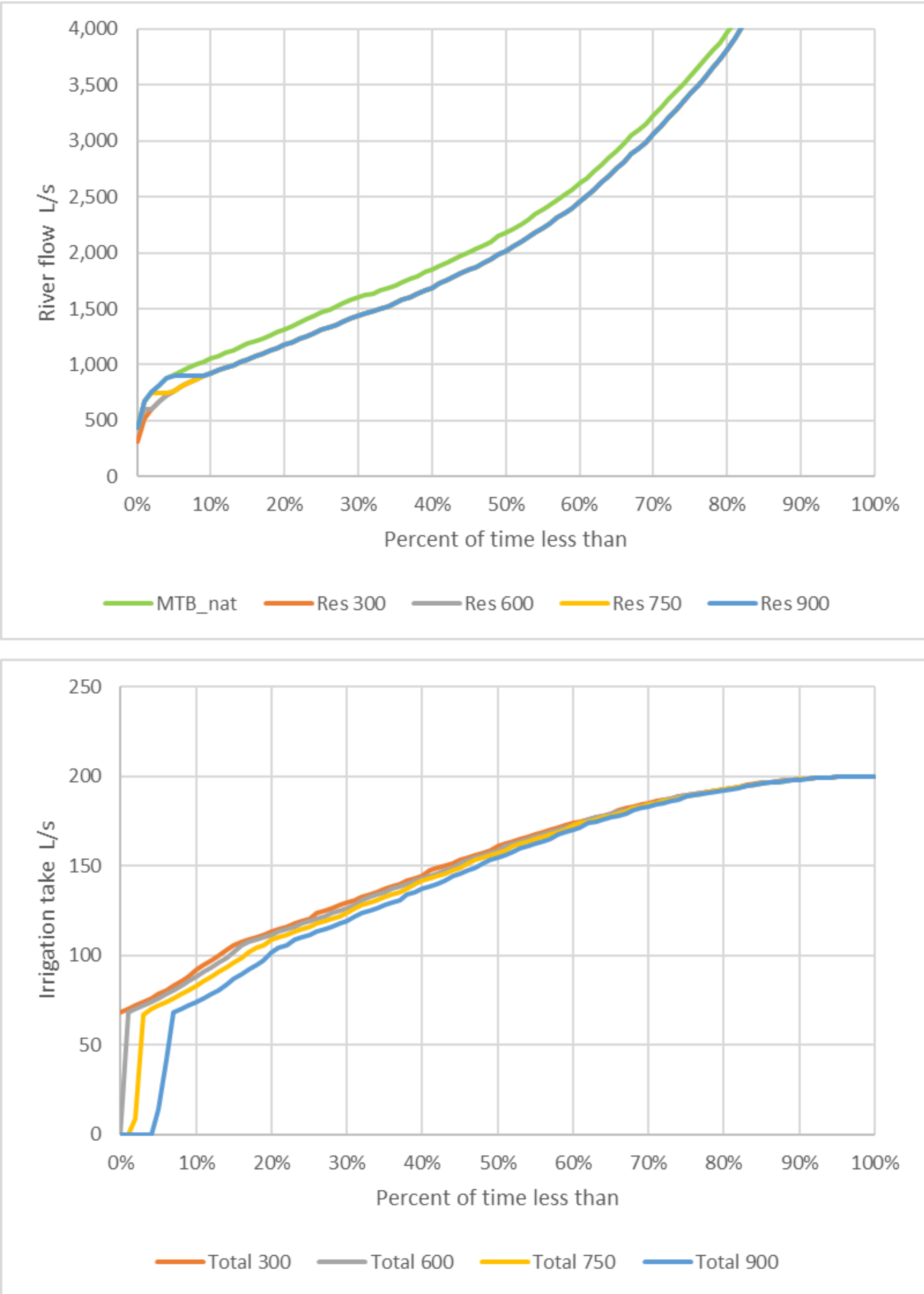


Figure F-5: Modelled variable take rate (maximum 200 L/s). Flow at Mt Barker (top graph) and irrigation take (bottom graph).