Functional flow Australia (FFAus): User Manual

Commonwealth Environmental Water Holder (CEWH): Flow Monitoring, Evaluation and Research Program

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FLOW Monitoring Evaluation Research

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This report was prepared in 2020 as a CSIRO Data61 internal document. The 2024 version (Second edition) retains the technical content and includes information on the Flow-MER project that co-funded the work with CSIRO.

Acknowledgements

The project team and the Commonwealth Environmental Water Holder (CEWH) respectfully acknowledge the Traditional Owners of the land on which this work was conducted, their Elders past and present, their Nations of the Murray–Darling Basin, and their cultural, social, environmental, spiritual and economic connection to their lands and waters. In particular, we are grateful to those who joined us in the field, sharing their strength, insights, experience and knowledge. Waterbirds, rivers and wetlands are known by many names, and while European names will be used here, the authors recognise the important associations and history of Indigenous names in the Murray–Darling Basin and Australia.

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Cover photograph

Confluence of the Murray River and Broken Creek at Barmah Forest, Victoria. Photo credit: Flow-MER Program.

Important disclaimer

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1 INTRODUCTION

1.1 The Flow-MER program

The Commonwealth Environmental Water Holder (CEWH) is responsible under the *Water Act 2007* for managing Commonwealth environmental water holdings. The CEWH's Science Program invests in monitoring, evaluation and research (Flow-MER) building on the Long-Term Intervention Monitoring (LTIM) and Environmental Water Knowledge and Research (EWKR) Projects (2014–20). Flow-MER monitors and evaluates the contribution of Commonwealth environmental water to environmental outcomes in the Murray–Darling Basin (the Basin) for 6 Basin Matter Themes described in the Environmental Water Outcomes Framework. The framework provides the scientific rationale for Theme indicators that address the environmental objectives contained within Chapter 8 of the Basin Plan and the Basin-wide Environmental Watering Strategy. Each Theme has a set of evaluation questions outlined in Foundation Reports.

The Program is the primary means by which the CEWH invests in research to deliver improved methods and a richer evaluation of environmental outcomes from Commonwealth environmental water. The Flow-MER Basin-scale Project commenced in July 2019 and runs to June 2025 and is led by CSIRO in partnership with the University of Canberra, collaborating with Alluvium, Charles Sturt University, Deakin University, South Australian Research and Development Institute, Arthur Rylah Institute, NSW Department of Primary Industry, University of New England, Australian River Restoration Centre and Brooks Ecology & Technology.

1.2 Research portfolio

The Flow-MER Basin-scale research portfolio was developed through a prioritisation and planning process undertaken in 2019. The portfolio aimed to enhance evaluation by improving approaches and methods, including scaling outcomes across the Basin, and improving understanding of the outcomes of Commonwealth environmental watering. Research was funded that would:

- continue and leverage research already being undertaken in the Basin
- inform the evaluation of outcomes of Commonwealth water for the environment
- build on and complement science networks across Selected Areas
- integrate across physical scales as well as across Basin Themes.

The research portfolio supported 13 projects.

1.3 This User Manual

The flow metrics coding described in this report was prepared within the *Developing flow-ecology relationships to predict response to environmental water* (BW2) project, led by Danial Stratford, CSIRO. The project ran from 2019 to 2020 and the research published in a research report (Lloyd-Jones et al. 2023); and this User Manual (Lloyd-Jones et al. 2024). The FFAus R code (which has extensive inline documentation) is available from https://bitbucket.csiro.au/users/llo080/repos/functional-flows-australia/browse.

2 APPROACH

To summarise flow we customised the functional flows (FF) approach of Yarnell et al. (2015) to the Australian context. FF focuses on retaining specific process-based components of the flow hydrograph, or functional flows, rather than attempting to mimic the full natural flow regime. Key functional components include magnitude, timing and duration of the wet-season initiation flows, wet-season baseflows, peak magnitude flows, recession flows, dry-season low flows, and inter-annual variability.

We converted the functional flows Python code (available at https://github.com/leogoesger/func-flow) to the R programming language to integrate with other components of the MER modelling workflow. This required conversion of the primary functions that compute the within-year functional flows metrics from the data. The FF code was initially translated to mimic and recreate the output from the University of California, Davis team's test data and then modified heavily to account for the variability in gauge profiles across the Murray–Darling Basin (MDB).

This document details the calculations in the Functional Flow Australia (FFAus) R programming implementation.

> **NOTE: A large proportion of the concepts embedded in the code is attributed to the University of California, Davis team and intellectual credit should be paid to them.**
>
> The code has been implemented in an R package titled `ffaus`.

Globally the code is designed to take in daily streamflow (e.g. megalitres per day (ML/day)) information in a 2 column format (Date, Flow). The code uses original helper functions to first format daily stream flow information into a by-water-year format (water year is defined by the user). The default water year start date is July 1, which coincides with hydrology reporting within the MDB. These formatted data are passed to a master function with key input parameters and then FF hydrometrics are reported back to the user. The hydrometrics are reported for each year by column and a final column reports the average values over the watering years. It is best to input complete year data so imputing any missing data with the previous or following days flow is recommended if missingness is low or else the code will remove these non-complete years. A global table of the metrics computed using the `ffaus` package is presented in Table 1.

3 DETAILED FFAUS METRIC DESCRIPTIONS

The code is integrated with a set of exceedance metrics, which are a priority output for components of the modelling work for Flow-MER projects undertaken within the MDB.

3.1 Simple annual metrics

These metrics are computed using the `calcAllYear` function in the `all_year.R` R programming source file.

- **Avg_Ann** – Average annual flow. For each water year the arithmetic mean over the flow values is computed. For the final column `All_Years_Avg` column in the metrics output file the arithmetic mean is taken over the full flow vector spanning the years analysed rather than the mean over the yearly means.
- **SD_Ann** – Standard deviation of annual flow. For each water year the standard deviation over the flow values is computed. Similar to the above annual average the `All_Years_Avg` column for the standard deviation uses all values.
- **CV_Ann** – Coefficient of variation of annual flow. For each water year the annual water year flow standard deviation is divided by the annual water year flow average. For the `All_Years_Avg` column the values for the SD and average are taken from the `All_Years_Avg` column.

Troubleshooting

These metrics should be very robust with no instances of NA expected.

3.2 Annual percentile exceedance metrics

We report for each watering year summaries of magnitude, timing, frequency, and duration that coincide with exceedances of the (10, 25, 50, 75, 90) percentiles. These metrics are computed using the `calcAllYear` function in the `all_year.R` R programming source file.

To initiate the computation of these metrics we compute the (10, 25, 50, 75, 90) **percentiles over flow vector for all years passed** to the function. The magnitudes corresponding to these percentiles are then used as the within year thresholding values except for the within year magnitude percentiles, which are calculated again within water year.

Within year the number of flow events that exceed the all-years percentiles are computed and the timing, duration and frequency are summarised. The use of * in the following definitions is used as a placeholder for the elements of the (10, 25, 50, 75, 90) percentile vector.

- **Q*_Mag** – percentile magnitude. For each water year the (10, 25, 50, 75, 90) percentiles are computed using sample quantiles. For the `All_Years_Avg` column the percentiles over all years are reported.
- **Q*_Tim** – percentile timing. For all flow events that exceed the * magnitude percentile the weighted average of the start date of each of these events is reported. The weights used are the durations of each of the exceedance events. The computation is

$$T_{Q*} = \frac{\sum_{e=1}^{E} S_e \times D_e}{\sum_{e=1}^{E} D_e}$$

where T_{Q*} is the timing for quantile $*$ (e.g. Q50), e indexes over the total number of within year events E, S_e is the water year start date index for event e and D_e is the duration in days of event *e,* i.e. the number of days that flow exceeded the all-year percentile value. The weighted average is used to preference the timing of the largest duration event.

- **Q*_Fre** – percentile frequency. The number of unique events where flow exceeded the all-years * magnitude percentile. Gaps between events must be greater than 3 days to be a unique event and the minimum duration is 1 day.
- **Q*_Dur** – percentile duration. The number of total water-year days that flow exceeded the all-years * magnitude percentile.

To distinguish the longest duration exceedance event in water year days we summarise for each percentile the magnitude, timing, season, and duration of this flow event. The magnitude thresholds used to define the events are again the (10, 25, 50, 75, 90) percentiles computed over all years of data.

- **Q*_Mag_Lng_Evt** – peak magnitude of flow for the days of longest Q* flow event
- **Q*_Strt_Tim_Lng_Evt** – the initiation day of the water year for the longest Q* flow event
- **Q*_Strt_Sea_Lng_Evt** – the season in which the longest Q* event initiated. Reported as **summer** `sum`, **autumn** `aut` , **winter** `win`, or **spring** `spr`.
- **Q*_Dur_Lng_Evt** – the number of total water-year days of the longest Q* event.

Troubleshooting

These metrics are subject to instances of `NA`. When might these arise and for what reasons?

- There may be instances, particularly for Q75 and Q90 metrics, where within a watering year the flow exceeds the all-years percentile magnitudes. In essence there are no exceedances for that year. In these cases NAs are reported.
- For instances where all flow values exceed the Q* threshold then a summary of the whole year's flow is reported e.g., duration would be 365/366 and frequency 1.

3.3 Flow initiation

This component represents the first major storm event following the dry season and signals the transition from dry to wet season. This serves important functions, such as moving nutrients downstream, improving stream flow water quality, and signalling species to migrate or spawn. The flow initiation typically is distinct from the wet-season start but may not be distinguishable in some years depending on climate conditions. The metrics calculated for flow initiation include the timing, magnitude, and duration of the initiation flow event and typically occur in winter or spring across the MDB. The core function that implements the algorithms (below) in the FFAus R package is `flow_initiation.R`.

3.3.1 Detailed algorithmic steps

1. Separate out flow data for each watering year
2. For each watering year compute the dry-season start date – see description below for details.

3. Append data from prior year's dry season. This assists with smoothing algorithm, where problems usually arise at edges of the smoothed hydrograph. If no dry-season available then just current years data is used and edge problems accepted.

4. Compute 3 layers of smoothed data using `sm.regression` function. This is a Gaussian Kernel smoothing approach and σ determines how close a fit to the observed data is expected. Low values of σ give close fit with higher values a smoother fit.

    - Wet season filter data. Default smooth of $\sigma = 4$, which is a mid-range smooth.
    - Slope detection data. Default $\sigma = 2$, which leads to a smooth close to the observed data.
    - Broad filter data filter. Default $\sigma = 15$, which is a heavy smooth, i.e. summarises major peaks of the flow hydrograph.

5. Calculate the return to wet date, which signals the start of the wet season. To calculate this we perform the following steps

    a. Compute the peaks of the wet-season filter data. Note the largest peak magnitude Q_{max}. Compute the Q_{min} as the minimum value of flow from the first day of the water year up to the date of Q_{max}.

    b. Use the `splinefun` function to perform cubic (or Hermite) spline interpolation on the slope detection data.

    c. Calculate the first derivative of the spline function, which is easily performed once we have a spline function of Hermite type.

    d. Cycle over the peaks p from start of flow hydrograph to Q_{max} and calculate

    $$(Q_p - Q_{\text{min}})/(Q_{\text{max}} - Q_{\text{min}}))$$

    If this ratio is greater than 0.3 then set this to be the maximum search index. Looking to find the first peak that is 30% of the maximum peak height from the minimum flow.

    e. From this 30% peak cycle in reverse over the daily flow data and compute

    - The daily *d* value ratio of the maximum

      $$R_1 = (Q_d - Q_{\text{min}})/(Q_{\text{max}} - Q_{\text{min}}))$$

    - $R_2 = Q_{max}$/slope_sensitivity. Default slope_sensitivity = 300. Cap on the rate of change, which is dependent on maximum flow.

    f. When $R_{1d} < 0.2$ & $R_2 < f'(d)$ then set *d* to be the start date of the water year. $f'(d)$ is the first derivative of the spline function above evaluate for index *d*. Looks for value that is 20% of the maximum and slope is changing such you would reach maximum in 300 days.

    g. Report wet-season start date as the day index corrected for number of dry-season days appended from previous year.

6. Compute filter data `sm.regression` function. Default $\sigma = 2$.

7. Use the `splinefun` function to get spline interpolation of filter data.

8. Compute the peaks and troughs of the spline fit to the filter data.

9. Note the date and value of the largest peak magnitude Q_{max} of the filter data. Compute the Q_{min} as the minimum value of flow from the first day of the water year up to the date of Q_{max}.

10. Use data from previous water year's, which is really part of the same dry-season but may span the water year boundary, and current dry-season baseflow and compute the $Q_{50\text{-}baseflow}$ over these flow values.

11. Define the minimum initiation flow $Q_{min\ init\ mag}$ magnitude as 2 × dry-season baseflow median.

12. Cycle over the peaks $p \in (1, \ldots, P)$ of the spline fit to the filter data and test the following 4 cases:

    - **Case 1** Initiation flow date is before half-duration

$$
\begin{aligned}
&(I_p < D_{1/2}) \wedge \\
&(I_p \neq 1) \wedge \\
&[Q_p > Q_{\texttt{broad filter}}(I_p)] \wedge \\
&(Q_p > Q_{\texttt{min init mag}}) \wedge \\
&(I_p <= I_{\texttt{max init day}})
\end{aligned}
$$

      where I_p is the water year day (index) at peak $_p$, $D_{1/2}$ = 20 the default half-duration, Q_p is the flow value at p, $Q_{\text{broad filter}}(I_p)$ is the flow value of the smoothed broad filtered data at I_p, $I_{max\ init\ day}$ = 175 is a user-defined last water-year date for initiation flow.

    - **Case 2** If peak and valley is separated by half duration, or half duration to the left is less than 30% of its value.

$$
\begin{aligned}
&\left[\left(\frac{Q_p - f(I_p - D_{1/2})}{Q_p} > \tau_{\text{init}}\right) \vee (I_m - I_p < D_{1/2})\right] \wedge \\
&[Q_p > Q_{\texttt{broad filter}}(I_p)] \wedge \\
&(Q_p > Q_{\texttt{min init mag}}) \wedge \\
&(I_p <= I_{\texttt{max init day}})
\end{aligned}
$$

      where τ_{init} = 0.3 is default initiation threshold percent, I_m is the water year day (index) at minimum $m \in (1, \ldots, M)$.

    - **Case 3** Valley and peak are distanced by less than half duration from either side

$$
\begin{aligned}
&[(I_m - I_p < D_{1/2}) \vee (I_p - I_{m-1} < D_{1/2})] \wedge \\
&[Q_p > Q_{\texttt{broad filter}}(I_p)] \wedge \\
&(Q_p > Q_{\texttt{min init mag}}) \wedge \\
&(I_p <= I_{\texttt{max init day}})
\end{aligned}
$$

    - **Case 4** Both sides of flow value at the peak plus half duration index fall below initiation threshold percentage.

$$
\begin{aligned}
&\frac{f(I_p - D_{1/2}) - Q_{\text{min}}}{Q_p - Q_{\text{min}}} < \tau_{\text{init}} \wedge \\
&\frac{f(I_p + D_{1/2}) - Q_{\text{min}}}{Q_p - Q_{\text{min}}} < \tau_{\text{init}} \wedge \\
&[Q_p > Q_{\texttt{broad filter}}(I_p)] \wedge \\
&(Q_p > Q_{\texttt{min init mag}}) \wedge \\
&(I_p <= I_{\texttt{max init day}})
\end{aligned}
$$

13. **If any of these cases are satisfied then I_p is set at the initiation flow water-year timing and Q_p the initiation flow magnitude**.

14. The duration is calculated by setting slope and magnitude thresholds on either side of the initiation flow event peak (rising limb (left) and falling limb (right)). The derivative threshold ($\tau_{f'i}$ = 0.5) is higher for the left side (steeper rising limb) and lower ($\tau_{f'i}$ = 0.3) for the right side (less steep falling limb). The magnitude threshold are percentile requirements for the left or right side of the initiation flow peak. For the rising limb, the bottom of the rising limb must be below a relative magnitude threshold (τ_{Ql} = 0.5 = 0.80 (80th percentile)) based on all flow values on the left side of the peak. The same requirement is used for the right side (τ_{Qr} = 0.5 = 0.80 (80th percentile)) of the peak. Given these input values we then

    - Determine the peaks and minimums of the smoothed filtered data.

- If a Q_m is within 10 days of the initiation flow peak on either side, set that minimum date as the start (left) or end (right) of the initiation flow.
- If not, fit a smoothing spline to data from left side minimum to peak and peak to right side minimum separately.
- Compute the first derivative of these two sets of smooths.
- If rising limb side of initiation flow is not within 10 days of the peak, then from the peak find the first filter data value such that

$$f'(d)_l < \tau_{f'_l} \wedge$$
$$Q_{dl} < \tau_{Q_l}$$

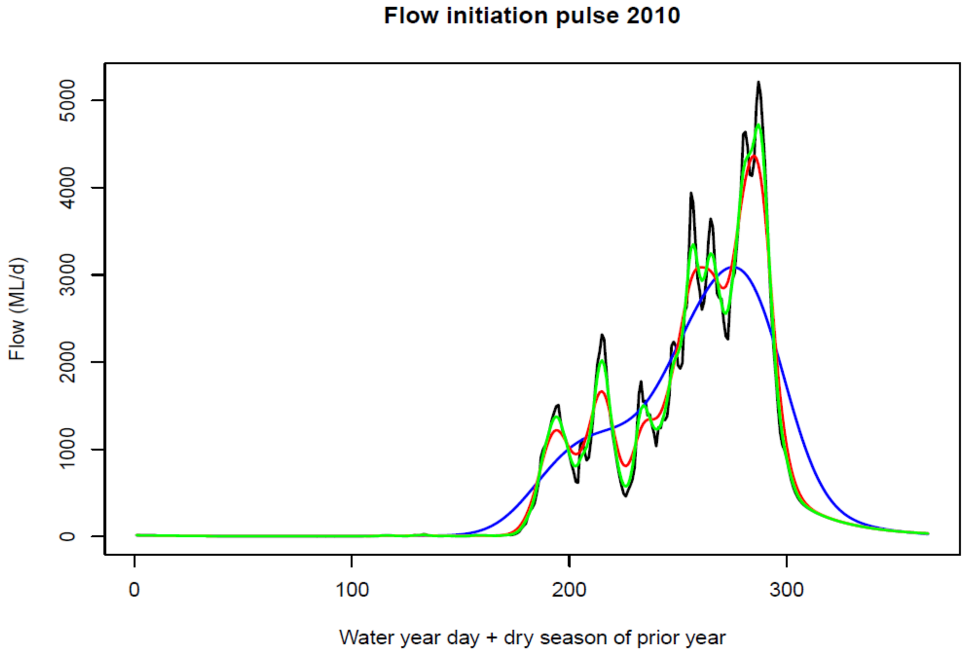
where d iterates over the days to the left of the initiation peak and e.g. Q_{dl} is the magnitude at day d from the left side l.

- A similar process is performed for the right hand side except spline and derivatives are computed for the falling limb.
- Once the left and right ends of the initiation flow have been detected then

  – set the duration as the number of days between the left side of the fall pulse flow peak and the initiation flow peak.

  – If there is no left side identified, set the duration as the number of days between the initiation flow peak and the right value of the falling limb.

Figure 1 Example of the 3 layers of smoothing for flow initiation detection



- **Init_Mag** – peak magnitude of initiation flow detected by above algorithm.
- **Init_Tim** – the water year day of peak initiation flow detected using above algorithm.
- **Init_Dur** – the number of days from peak to rising or falling limb such that the flow is less than 80% off the peak and the slope of the hydrograph is 30% (left) or 50% (right) of the observed slope values computed from the spline of the observed flow values to the left or right of the peak.

Troubleshooting

These metrics are subject to rare instances of NA. When might these arise and for what reasons?

- In rare instances the broad filter smoothing parameter can lead to a failing of the code to detect an initiation flow. This parameter can be adjusted by changing the `init_broad_sigma` parameter in the `getFFMetrics` R function.

3.4 Dry season start and baseflows

The dry season period represents the low magnitude, low variability portion of the water year, which typically spans the winter periods. For FFAus the dry season functional flow component is summarised using the following metrics:

- **Dry_Tim** – the water year day where the wet-season has receded sufficiently and dry-season deemed to have started.
- **Dry_Dur** – the number of water year days from dry-season start to wet-season start.
- **Dry_NoFL_Days** – the number of water year days within the dry-season duration in which no flow was recorded.
- **Dry_Mag_*** – the 10th, 50th, and 90th percentile magnitude of the dry-season flow data.

3.4.1 Detailed algorithmic steps

The key computational components required for the dry-season summary is the dry-season timing and the wet-season initiation timing. The wet-season timing calculation is detailed below. To compute the dry-season timing we perform the following computational steps:

1. For each water year we append 30 days of the following water year conditional this year not being the final year or there is a gap in water years. If it is the final year or a gap, the final 30 days of that year are repeated. The rationale for this is to assist with smoothing at the end of the water year boundary, which typically, and by construction, divides the dry-season.
2. Fit an intermediate smoothing spline default σ = 5 to the water year flow data.
3. Fit a spline function ($f(.)$) to the smoothed data and then compute the derivation ($f'(.)$).
4. Determine the peaks and minimums of the smoothed data.
5. Find the first peak in flow after the maximum peak flow date (IMPD), which defaults to water-year day 250 from a 01/07 water year start (early March).
6. Determine a minimum threshold $\tau_{ds\text{-}min}$ set to be the 12.5 percentile of the flow data from maximum peak flow date to end of the extended flow year's data.
7. Iterate of each water year day d and determine the first water year day such that

$$
\begin{aligned}
&|f'(d)| < Q_{\mathsf{max}}/\gamma \wedge \\
&I_d > I_{\mathsf{MPD}} \wedge \\
&Q_{\mathsf{d}} <= \tau_{\mathsf{ds\text{-}min}}
\end{aligned}
$$

   where γ is referred to as the sensitivity in the code.
8. **The date in which this criteria is satisfied is set as the dry-timing**.

The above logic summarises that flow must drop below the 12.5 percentile and have an absolute rate of change that is slow and determined by the maximum flow and sensitivity.

Given the dry-season start date and wet-season start-date we compute

- Duration is just the number of days between dry-season start date and wet-season start date.
- $Q10_{DS}$, $Q50_{DS}$, $Q90_{DS}$ is computed from the percentiles of the flow data for the duration of the dry-season.
- No flow days is just the sum over the days of no flow.

Troubleshooting

These metrics are subject to rare instances of NA. When might these arise and for what reasons?

- In rare instances the last peak may be great than the default I_{MPD} = 250. This can be set using the `max_peak_flow_date` parameter in the `getFFMetrics` R function.

3.5 Wet season

The wet season describes the period of the annual hydrograph with elevated flows. We summarise this portion of the annual hydrograph using peak magnitude flows and a description of the baseflow including magnitude ($Q10$, $Q50$), timing and duration. The peak flows are summarised using the whole annual flow hydrograph.

The pivotal computations for describing the wet season are the **wet season initiation dates** and the **recession dates** as these define the portion of the hydrograph that is summarised for baseflow calculation.

3.5.1 Detailed algorithmic steps

The peak flows are summarised using the whole year's hydrograph and thus don't rest on the wet-season start and end date computations. The flow recession start date is detailed below. The wet season start dates were computed as part of the initiation flows computation and the reader is referred to Step 5 of the algorithm in that section.

- **Wet_BFL_Mag_*** – we compute the 10th and 50th percentiles of the flow data for the period between the wet-season start and recession start
- **Wet_Tim** –defined explicitly in Step 5 of the initiation flows descriptions. However, the wet season baseflow start date is defined as the date that sufficient baseflow has accrued based on a magnitude and rate of change threshold
- **Wet_BFL_Dur** – the number of days between the wet-season start and recession start
- **Peak_Mag_Ann** – the peak magnitude for that water year
- **Peak_Mag_Tim** – the water year day of peak magnitude.

For the following metrics we compute the 80th, 90th, and 95th percentiles of the flow data for the whole period of flow. These are then used as exceedance values for the computation of the following metrics. For each magnitude threshold the flow events above these thresholds are summarised in the following way.

- **Peak_Mag_*** – For all events that exceed the $Q*$ threshold take the median over the maximum values for each event. For example, if there are 3 events that exceed a Q80 threshold of 390 with peak magnitudes for each event being 400, 500, and 450 then the metric reported would be 450.
- **Peak_Dur_*** – Sum over the days in which flow exceeds the $Q*$ threshold.

- **Peak_Fre_*** – the number of events that exceed the $Q*$ threshold. **An event has to be at least one day and a gap of 3 days to be a unique event**.
- **Peak_Tim_*** – the median over the exceedance event start dates.

We further summarise peak flow shape and peak frequency hydrometrics functions from Allison Whipple's `hydrospatial` R package. The code rests on passing a user defined percentile value in which to summarise the peaks of each year's hydrograph using the `Whipple_exceed_thresh` parameter, with the default being 0.95. The threshold is then used to calculate a magnitude value corresponding to that percentile over all years of flow data. Data are then prepared into format `hydrospatial` and then flood events determined using the `hydrospatial` R function `utils_floodid`. For each water year the following hydrometrics are summarised given the magnitude threshold:

- **No_Events** – number of events that exceed the threshold defined by:
- **No_Peaks_Avg** – the average number of peaks within exceedance events. For example, if we have 4 exceedance events and the first event has 2 peaks and the rest one peak, then the metric reported is 1.25.
- **No_Peaks_Max** – the maximum number of inter-event peaks. For example, for the above scenario of 4 events the value reported would be 2.
- **Frac_V_Cent_Avg** – over all events the mean value of the number of days to > 0.5 of total flood event volume divided by the total number of event days.
- **Frac_V_Cent_Max** – for the event that contains the maximum flow for the water year, the value of the number of days to > 0.5 of total flood event volume divided by the total number of event days.

Troubleshooting

These metrics are subject to instances of `NA`. When might these arise and for what reasons?

- If the wet season start date or recession start date are absent then summaries of the intermediate wet season baseflows may not be present. Refer to these sections separately if these are absent.
- For particular watering years, it is possible and likely for Q95 thresholds that there are no flow events that exceed the $Q*$ threshold. In these instance the metrics that depend on these thresholds will report `NA`, which typically includes the Whipple metrics. The threshold percentile for the Whipple metrics can be altered using the `Whipple_exceed_thresh` parameter.

3.6 Recession flows

The recession marks the shift from high magnitude flows to the dry season baseflow. A continuous decline in flows is expected during this period until the beginning of the summer baseflow is reached. The metrics used to characterise the flow recession are magnitude and timing on the first day of the recession, duration of the spring recession period, and rate of change of flow across the period of decline.

3.6.1 Detailed algorithmic steps

The principal calculation is the detection of the start of the recession which is calculated as follows:

1. Smooth the within year flow data using Gaussian smoothing spline with default filter σ = 10 to create the 'filter data'.
2. Compute the peaks and minimums of the filter data.

3. Starting with the first peak before the dry season iterate in reverse over peaks p and set final wet season peak as

$$
\begin{aligned}
&I_p < I_{\text{MPD}} \wedge \\
&I_p \geq I_{\text{MMFD}} \wedge \\
&\frac{Q_p - Q_{\text{min}}}{Q_{\text{max}} - Q_{\text{min}}} > \tau_{PF} \wedge \\
&I_p < I_{\text{DSS}}
\end{aligned}
$$

   where I_{MPD} is maximum peak flow date (default = 300), I_{MMFD} is the minimum max flow day (default = 80), τ_{PF} is the peak percentage filter (default = 0.5), and I_{DSS} is the dry season start date.

4. Given the date for this maximum we define a window around this date of 20 days to the left and 50 days to the right.

5. For these windowed data we fit a smoothing spline that closely matches the data. We then fit a spline to these data and compute the derivative of this spline.

6. Find all peaks and minimums of this smoothed interval.

7. Iterate over the peaks and minimums and **set the recession start date as the peak that satisfies**

$$
\begin{aligned}
f(p) - f(p-1) &> (\tau_{max-f'} \times 1)/\gamma \wedge \\
f(p-1) - f(p-2) &> (\tau_{max-f'} \times 2)/\gamma \wedge \\
f(p-2) - f(p-3) &> (\tau_{max-f'} \times 3)/\gamma \wedge \\
f(p-3) - f(p-4) &> (\tau_{max-f'} \times 4)/\gamma \wedge \\
\frac{f(p) - Q_{\text{min-win}}}{Q_{\text{max-win}} - Q_{\text{min-win}}} &> \tau_{PFMF}
\end{aligned}
$$

   where $\tau_{max-f'}$ is the maximum slope value over all $f'(p_{win})$ in the windowed interval, γ (default = 1000) is the sensitivity parameter that limits the rate of change prior to the maximum, $Q_{min\text{-}win}$ is the minimum flow in the window and similarly for the maximum and τ_{PFMF} is the percentage of maximum flow threshold (default = 0.5).

8. Search over the observed (unsmoothed data) for highest flow value and s**et this recession start date as the peak**.

9. Set the **recession magnitude** as the flow value at this date.

Given these above calculations we can define the metrics reported by the FF code.

- **Rec_Mag** – the magnitude at the water year recession start date defined as above.
- **Rec_Tim** – the water year recession start date defined as above. Essentially the date of the last peak before recession to start of dry season.
- **Rec_Dur** – the number of days between the recession start date and the dry season start date.
- **Rec_ROC** – the median of the first derivative values divided by the flow of that day over the recession duration period. Therefore, the ROC represents a percentage rate of change.

Table 1 Summary of functional flow hydrometrics suite generated by the ffaus R package

The units for magnitude are megalitres per day (ML/day) because the Flow-MER reporting and data generation use this metric – however it can be any flow unit. Water year day refers to the days from July 1 of each year, which is considered the default water year start. Q* refers to the (10, 25, 50, 75, 90) percentiles with ∗ representing a place holder for abbreviation i.e., for Q* metrics these are calculated and reported for all these percentiles. Bolded metric name identifies the metrics that were included in the understorey vegetation PFG percent cover analyses (Lloyd-Jones et al. 2023).

Metric name	Flow component	Units	Metric ode
Average annual flow	Magnitude	ML/day	Avg_Ann
Standard deviation of annual flow	Variation	ML/day	SD_Ann
Coefficient of variation	Relative variation	Unitless	CV_Ann

Metric name	Flow component	Units	Metric ode
Initiation flow magnitude	Magnitude	ML/day	Init_Mag
Initiation flow timing	Timing	Water year day	Init_Tim
Initiation flow duration	Duration	Day	Init_Dur
Wet-season median baseflow	Magnitude	ML/day	Wet_BFL_Mag_50
Wet-season low baseflow	Magnitude	ML/day	Wet_BFL-Mag_10
Wet-season timing	Timing	Water year day	Wet_Tim
Wet-season duration	Duration	Days	Wet_BFL_Dur
Peak magnitude year	Magnitude	ML/day	Peak_Mag_Ann
Peak magnitude timing	Timing	Water year day	Peak_Mag_Tim
Magnitude over quantiles events	Magnitude	ML/day	Peak_Mag_*
Duration over quantiles events	Duration	Days	Peak_Dur_*
Frequency of quantiles events	Frequency	Integer >= 0	Peak_Fre_*
Timing of quantiles events	Timing	Median start WY day	Peak_Tim_*
Recession magnitude	Magnitude	ML/day	Rec_Mag
Recession timing	Timing	Water year day	Rec_Tim
Recession duration	Duration	Days	Rec_Dur
Recession rate of change	Rate of change	Days	Rec_ROC
Dry-season high baseflow	Magnitude	Integer >=0	Dry_Mag_90
Dry-season median baseflow	Magnitude	Integer >=0	Dry_Mag_50
Dry-season low baseflow	Magnitude	Real number > 0	Dry_Mag_10
Dry-season timing	Timing	Real number >	Dry_Tim
Dry-season duration	Duration	ML/day	Dry_Dur
Dry-season no flow days	Duration	Average start day WY	Dry_NoFL_Days
Number peaks over Q95 events	Frequency	Integer >= 0	No_Keaks_Avg
Number peaks for max Q95 event	Frequency	Days	No_Pes_Max
Average peak shape over Q95 events	Peak shape	ML/day	Frac_V_Cent_Max
Shape of peak for max Q95 event	Peak shape	Start day WY	Frac_V-Ent_Avg
Percentile (Q*) magnitudes	Magnitude	Season as character	Q*_Mag
Percentile (Q*) timing	Timing	Days	Q*_Tim
Percentile (Q*) frequency	Frequency		Q*_Fre
Percentile (Q*) duration	Duration		Q*_Dur
Percentile (QU) magnitude longest event	Magnitude		QU_Mag_Lng_Ext
Percentile (QU) start timing longest event	Timing		Q*_Strt_Tim_Long_Evt
Percentile (QU) start season longest event	Timing		QU_Strt_Sea_Lng_Ect
Percentile (QU) duration longest event	Duration		Q*_Dur_Lng_Evt

Appendix A Output examples

Table 2 Metrics for some years between 1980 to 2008 for Lachlan@Jemalong Weir

Metric	1980	1981	...	2000	2001	2002	2003	2004	2005	2006	2007	2008	All_Years_Avg
Avg_Ann	490.45	2279.13		2600.757	1133.101	186.29	619.107	440.482	1640.254	176.556	752.461	389.908	2764.505
SD_Ann	850.918	4500.108		3966.014	2420.235	322.114	1278.528	809.915	3068.295	552.019	1916.796	683.416	6027.056
CV_Ann	1.735	1.974		1.525	2.136	1.729	2.065	1.839	1.871	3.127	2.547	1.753	2.18
Q10_Mag	4.84	6.64		77.64	8.08	2.64	3.9	3.78	8	1.9	3.25	4.58	9.6
Q25_Mag	8.5	13.8		156.8	48.2	4.6	7.025	6.7	12.4	2.7	7.1	9	114.5
Q50_Mag	78.3	208.9		802.5	379	32	174.15	59.6	266.9	16.8	121.45	96.4	584.5
Q75_Mag	529.1	1903.7		2706.9	900	284	777.725	539.3	1831.9	126.7	585.9	467.5	2326
Q90_Mag	1890.4	8766.48		8452.2	2551.08	484.62	1432	1239.36	4497.64	338.72	1618.85	1233.06	8520.96
Q10_Tim	112	75		1	102	130	63	4	15	162	22	33	39
Q25_Tim	129	56		85	109	103	55	63	30	181	82	87	74
Q50_Tim	146	15		40	69	75	60	106	54	290	69	110	93
Q75_Tim	157	13		65	91	12	78	117	88	358	40	109	108
Q90_Tim	NA	30		70	84	NA	60	NA	118	NA	5	NA	112
Q10_Fre	7	5		1	3	4	5	2	2	5	3	3	2
Q25_Fre	7	7		6	4	7	6	5	3	8	4	5	3
Q50_Fre	6	3		4	4	5	5	6	3	3	5	6	5
Q75_Fre	5	3		6	4	1	4	4	7	1	2	3	5
Q90_Fre	NA	3		6	3	NA	1	NA	4	NA	2	NA	4
Q10_Dur	268	294		365	322	216	251	256	297	214	264	263	329
Q25_Dur	159	208		292	255	143	192	164	210	109	184	181	274
Q50_Dur	89	166		196	144	22	129	89	172	23	94	75	184

Metric	1980	1981	...	2000	2001	2002	2003	2004	2005	2006	2007	2008	All_Years_Avg
Q75_Dur	26	84		121	40	1	17	16	76	8	23	7	95
Q90_Dur	NA	40		41	11	NA	2	NA	19	NA	8	NA	44
Q10_Mag_Lng_Evt	5192.9	25232.3		17716.7	15518.3	2377.2	11514.5	5342.9	17319.8	542.1	14260.8	5881.2	32731
Q25_Mag_Lng_Evt	5192.9	25232.3		17716.7	15518.3	2377.2	11514.5	4990	17319.8	434.5	14260.8	5881.2	30710
Q50_Mag_Lng_Evt	3064.3	25232.3		17716.7	15518.3	2377.2	11514.5	4990	17319.8	5107.3	14260.8	2528.1	30381
Q75_Mag_Lng_Evt	3708.6	25232.3		15351.3	15518.3	2377.2	11514.5	4990	17319.8	5107.3	14260.8	5881.2	29789
Q90_Mag_Lng_Evt	NA	25232.3		15351.3	15518.3	NA	11514.5	NA	17319.8	NA	14260.8	NA	32739
Q10_Strt_Tim_Lng_Evt	1	1		1	1	1	1	1	1	5	1	1	1
Q25_Strt_Tim_Lng_Evt	1	1		1	1	1	1	28	1	22	1	17	17
Q50_Strt_Tim_Lng_Evt	341	1		1	29	10	47	66	72	356	1	70	50
Q75_Strt_Tim_Lng_Evt	232	1		43	61	12	58	74	76	358	1	111	90
Q90_Strt_Tim_Lng_Evt	NA	25		59	62	NA	60	NA	94	NA	1	NA	98
Q10_Strt_Sea_Lng_Evt	win	win		win	win	win	win	win	win	win	win	win	win
Q25_Strt_Sea_Lng_Evt	win	win		win	win	win	win	win	win	win	win	win	win
Q50_Strt_Sea_Lng_Evt	win	win		win	win	win	win	spr	spr	win	win	spr	win
Q75_Strt_Sea_Lng_Evt	sum	win		win	win	win	win	spr	spr	win	win	spr	win
Q90_Strt_Sea_Lng_Evt	NA	win		win	win	NA	win	NA	spr	NA	win	NA	spr
Q10_Dur_Lng_Evt	147	219		365	177	112	193	254	285	84	247	237	285
Q25_Dur_Lng_Evt	75	163		203	157	93	140	124	181	26	91	110	204
Q50_Dur_Lng_Evt	25	155		171	115	11	46	23	96	10	49	24	121
Q75_Dur_Lng_Evt	9	74		45	26	1	8	6	32	8	18	4	54
Q90_Dur_Lng_Evt	NA	28		21	6	NA	2	NA	7	NA	5	NA	21
Init_Mag	524.652	235.595		1311.227	654.537	3935.253	527.675	121.296	2295.91	367.484	568.426	66.558	4480.265
Init_Tim	-24	-167		-79	-132	-124	-104	-121	6	27	-116	-2	-90.735
Init_Dur	12	15		32	15	11	23	7	17	12	8	16	15.286
Wet_BFL_Mag_10	96.5	1914.84		1460.9	969.42	25.84	516.25	165.75	599.76	NA	41.22	34.26	1081.464

Metric	1980	1981	...	2000	2001	2002	2003	2004	2005	2006	2007	2008	All_Years_Avg
Wet_BFL_Mag_50	813.8	4172.3		2920.05	5992.7	231.5	1157.85	601.95	1834.4	NA	546.55	747	3954.791
Wet_Tim	-4	-3		-8	55	-146	43	36	-2	NA	-19	64	-21.533
Wet_BFL_Dur	39	39		156	25	159	58	132	138	NA	200	110	135.311
Peak_Mag_Ann	5192.9	25232.3		17716.7	15518.3	2377.2	11514.5	5342.9	17319.8	5107.3	14260.8	5881.2	33643.122
Peak_Mag_Tim	34	35		147	65	12	60	167	97	361	3	112	138.408
Peak_Mag_95	NA	25232.3		15351.3	15518.3	NA	NA	NA	17319.8	NA	NA	NA	21930.279
Peak_Mag_90	NA	13706.2		11363.65	14116.4	NA	11514.5	NA	13895.15	NA	11960.1	NA	19185.344
Peak_Mag_80	4450.75	8824.55		10299.7	9672.8	NA	8491.95	5166.45	13604.2	5107.3	9790	5881.2	12874.501
Peak_Dur_95	NA	14		12	2	NA	NA	NA	3	NA	NA	NA	24.368
Peak_Dur_90	NA	40		41	11	NA	2	NA	19	NA	8	NA	44.571
Peak_Dur_80	4	63		80	30	NA	10	6	52	5	21	3	78.362
Peak_Fre_95	NA	1		3	1	NA	NA	NA	1	NA	NA	NA	3.211
Peak_Fre_90	NA	3		6	3	NA	1	NA	4	NA	2	NA	4.81
Peak_Fre_80	2	4		6	3	NA	2	2	7	1	2	1	5.021
Peak_Tim_95	NA	25		77	64	NA	NA	NA	96	NA	NA	NA	120.592
Peak_Tim_90	NA	25		54.5	78	NA	60	NA	113.5	NA	6	NA	105.488
Peak_Tim_80	135.5	16		37	111	NA	79	121	93	361	90	112	132.5
Rec_Mag	5192.9	25232.3		17716.7	14116.4	2377.2	5469.4	5342.9	14095	542.1	5319.2	1563.3	23434.084
Rec_Tim	34	35		147	79	12	100	167	135	77	180	173	109.224
Rec_Dur	148	187		60	102	142	138	149	160	32	81	115	109.143
Rec_ROC	0.118	0.153		0.133	0.093	0.111	0.132	0.053	0.075	0.102	0.149	0.068	0.109
Dry_Mag_90	1974.5	NA		994.07	9.76	780	182.12	6.21	NA	244.09	371.13	122.19	1280.963
Dry_Mag_50	16.3	NA		276.85	5.5	25.9	7.7	3.1	NA	6.95	8	4.75	203.819
Dry_Mag_10	3.1	NA		55.82	4.1	2.5	2.5	2.7	NA	1.7	2.5	2.87	66.558
Dry_Tim	182	222		207	181	154	238	316	295	109	261	288	218.367
Dry_Dur	181	NA		214	39	255	165	48	NA	238	170	78	128.644

Metric	1980	1981	...	2000	2001	2002	2003	2004	2005	2006	2007	2008	All_Years_Avg
Dry_NoFL_Days	0	NA		0	0	0	0	0	NA	0	0	0	0
No_Peaks_Avg	NA	2		1.333	1	NA	NA	NA	1	NA	NA	NA	1.317
No_Peaks_Max	NA	3		1	1	NA	NA	NA	1	NA	NA	NA	1.605
Frac_V_Cent_Avg	NA	0.792		0.774	1	NA	NA	NA	0.667	NA	NA	NA	0.672
Frac_V_Cent_Max	NA	0.583		0.75	1	NA	NA	NA	0.667	NA	NA	NA	0.559

Figure 2 Dry season start dates Lachlan@Jemalong Weir (412036) 1985–2008

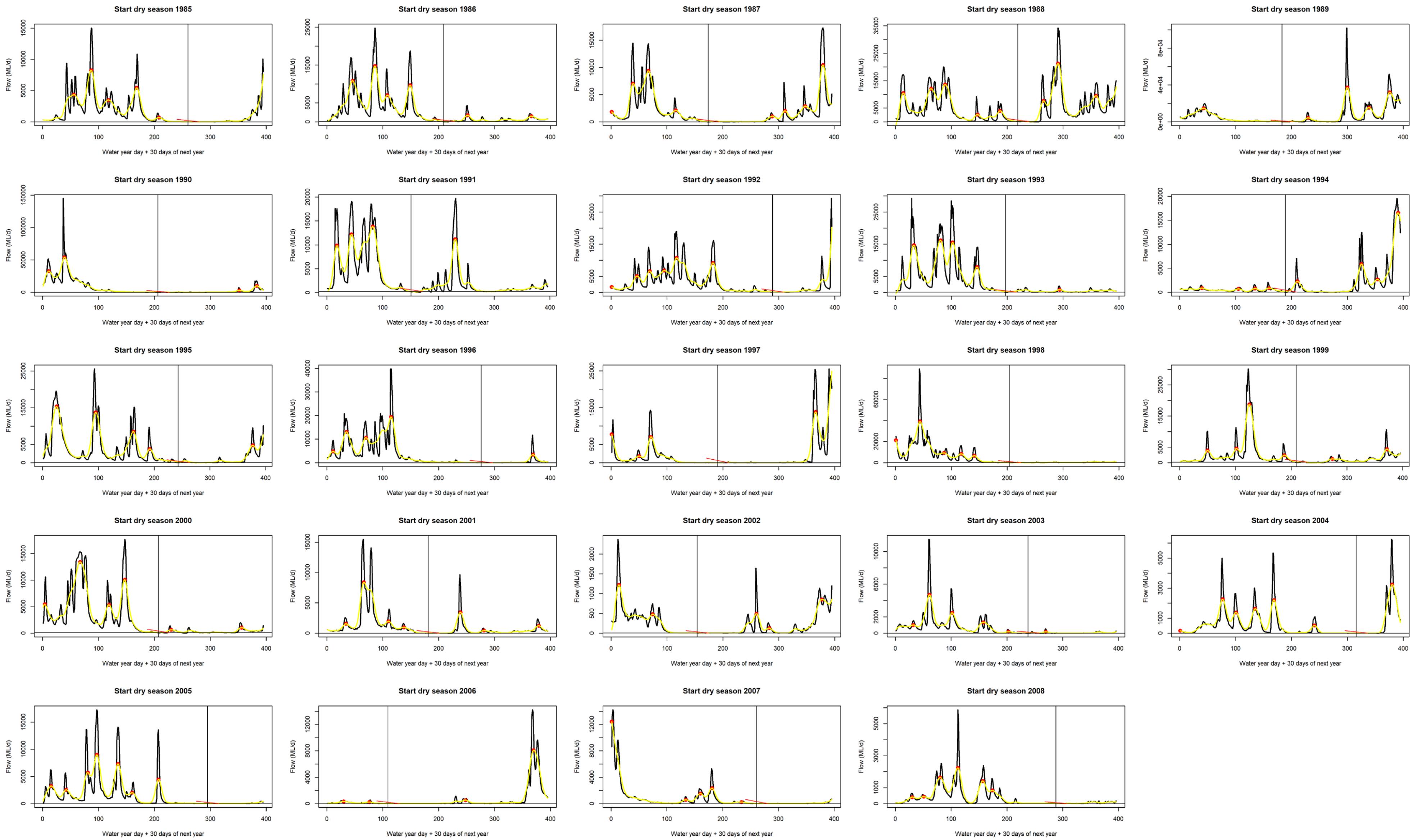


Figure 3 Wet season baseflows Lachlan@Jemalong Weir (412036) 1985–2008

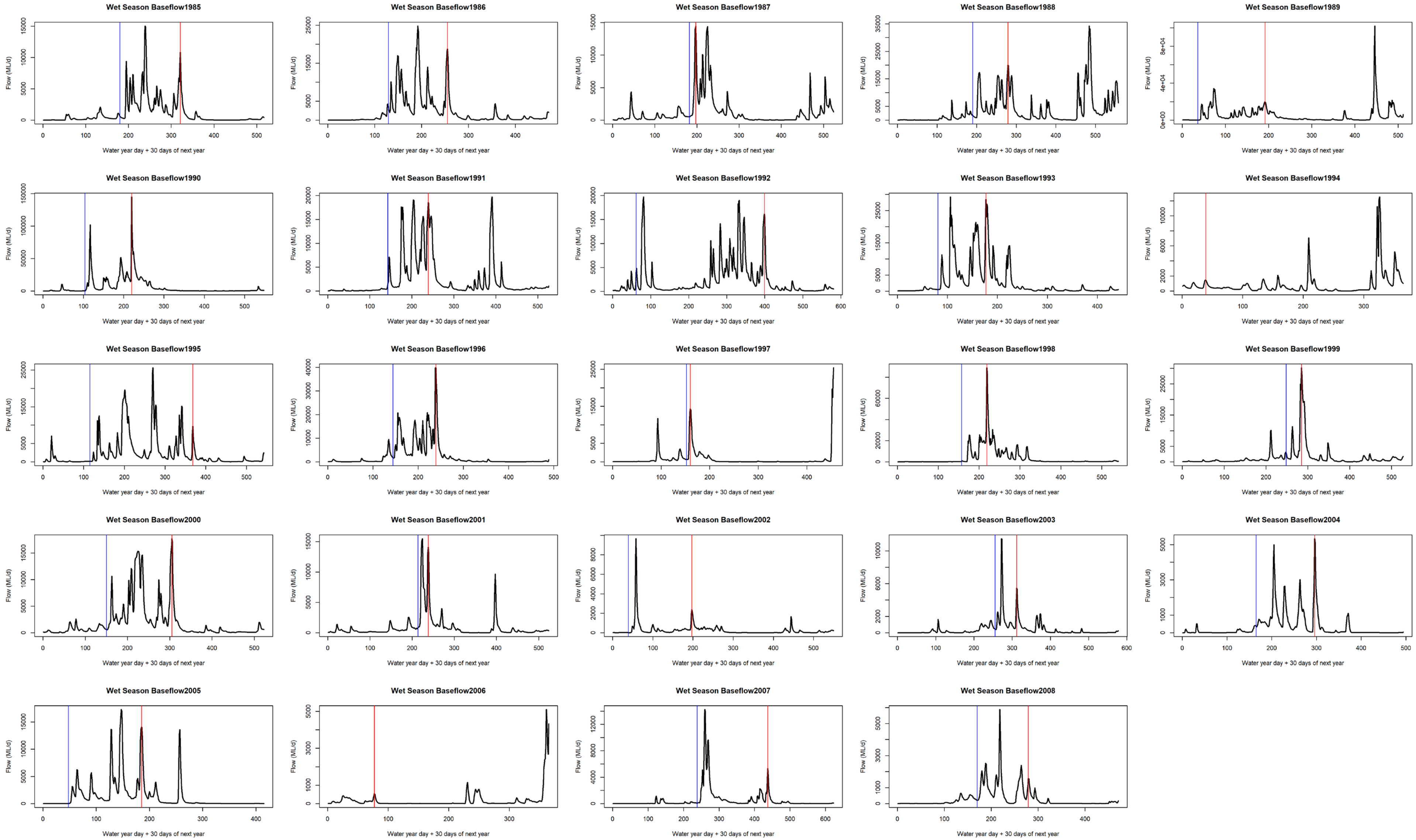


Figure 4 Annual percentiles Lachlan@Jemalong Weir (412036) 1985–2008

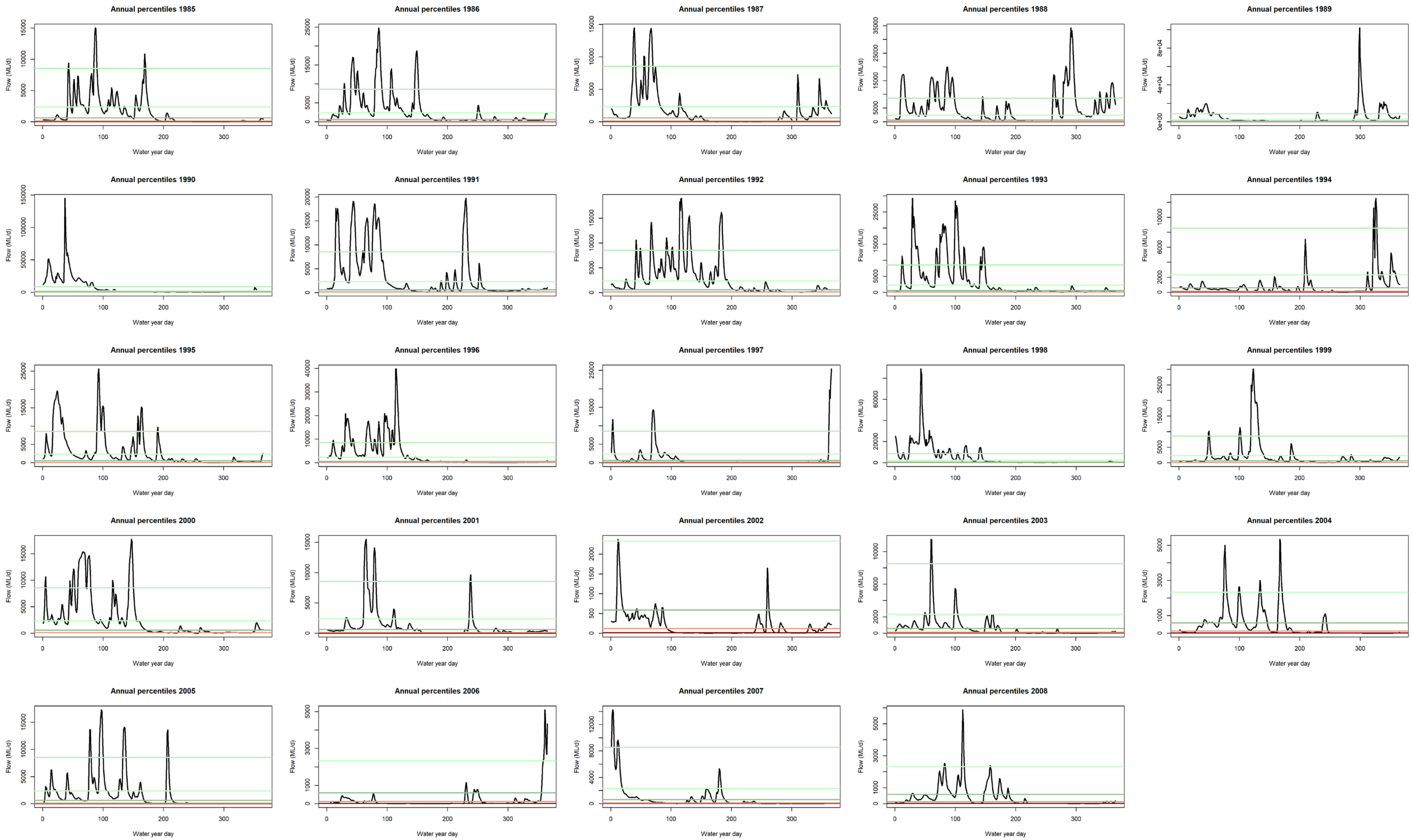


Figure 5 Initiation flows Lachlan@Jemalong Weir (412036) 1985–2008

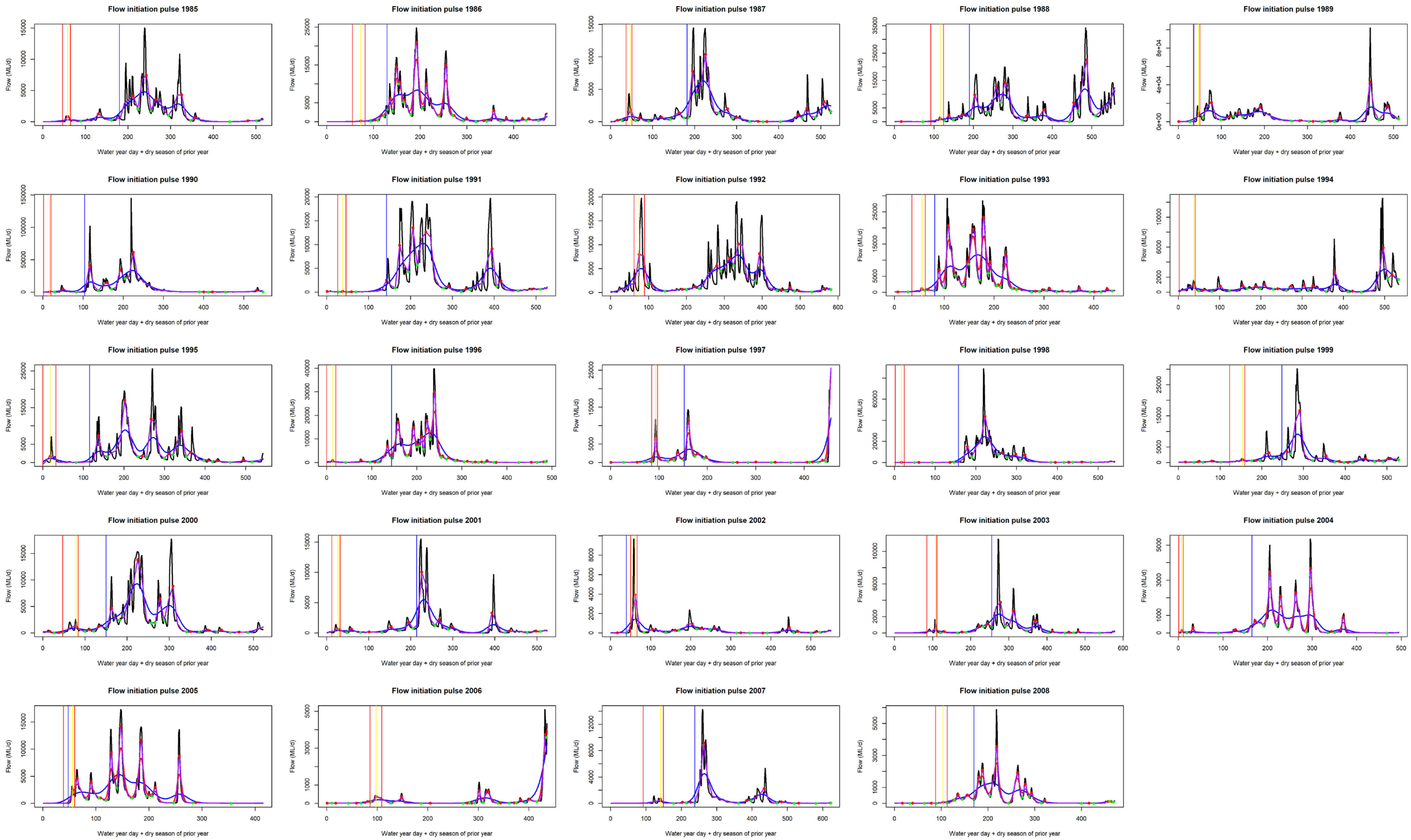
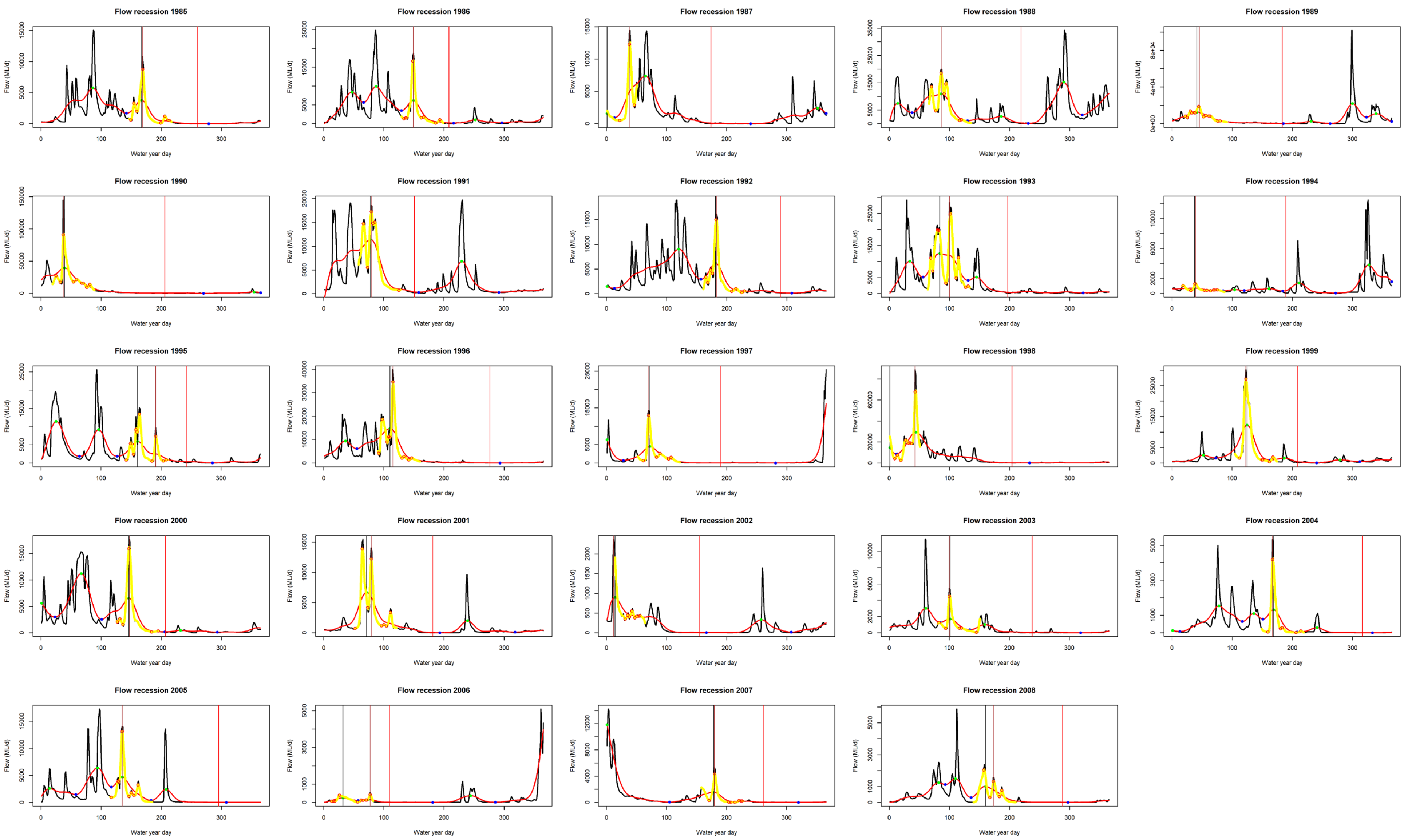


Figure 6 Flow recession timing duration Lachlan@Jemalong Weir (412036) 1985–2008



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