

RESEARCH ARTICLE

Simplified Environmental Flow Metrics and Environmental Water Requirements for Mediterranean Seasonal Rivers

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ABSTRACT

The flow regime of a river is well established as being one of the key drivers of riverine ecosystem type, diversity and condition. This is especially true of seasonal rivers that experience a cease to flow period over the dry months of the year. To effectively assess changes in the components of the flow regime, it is required that flow data be quantified into metrics for ease of assessment and to effectively relate changes to environmental outcomes. Previous methods have used large numbers of, often complex, flow metrics to assess the flow regime. These metrics are often highly internally correlated with each other, and their complicated nature makes communication difficult. We suggest that the high correlation and the targeted nature of ecological flow regime assessment means a smaller number of well selected metrics can be used more effectively than large suites of generic metrics. We report on a series of six flow metrics that cover the whole of the flow regime, are reported annually and are simple to assess and interpret. We further expand on the practical use of these metrics as environmental indicators in their application to the highly variable seasonal rivers of southern Australia by using a moving average approach rather than single years. This approach accounts for, and allows for, the interannual variability expected in these systems. Environmental water requirements are defined using upper and lower bounds of a moving average for each metric over an environmentally stable period. We argue that this approach represents a more representative and robust approach to the assessment of environmental water requirements that is simpler and easier to interpret and communicate than existing flow regime assessment methods.

1 | Introduction

The flow regime of a river, defined as the magnitude, timing, duration and frequency of flow events, has long been established as one of the key driving influences on riverine ecosystems (Naiman et al. 2008; Poff et al. 1997). To understand, define and quantify the flow regime, flow metrics are generally used to summarise flow and investigate individual components of the flow regime (Kennard et al. 2010). These flow metrics can be used to relate the flow regime to the aquatic ecosystems of the rivers, either in investigating current conditions (e.g., Maxwell et al. 2015) or modelling ecological

responses to changes in the flow regime (e.g., Vanlaarhoven and van der Wielen 2012).

Previous efforts to define the flow regime have provided a multitude of flow metrics that can be used to quantify nearly any aspect of the flow regime (Kennard et al. 2010; Vanlaarhoven and van der Wielen 2009). Previous efforts have focused on quantifying all aspects of the flow regime, leading to large suites of metrics (e.g., 120 metrics in Kennard et al. 2010 or 56 metrics in VanLaarhoven and van der Wielen 2009). These large suites of metrics are well suited for whole of flow regime assessment, specifically comparing whole flow regimes either spatially or

temporally using ordination or similar approaches that consider internal correlation within the metrics.

To assess environmental water requirements (EWRs), these large suites of metrics are problematic for several reasons. Assessment of the metrics within these suites identified significant correlation between some of the metrics, especially between metrics within the same flow season (Maxwell et al. 2015). This correlation was indicative of potential bias within the metrics, especially when using percentage passing/failing as the overall indicator, as metrics would fail in batches rather than independently.

The other notable issue with assessing flow metrics for seasonal rivers is the large degree of interannual variability (Kennard et al. 2010). The link between the flow regime and the ecosystems of seasonal rivers is well established, as is the notion that changes to the flow regime will result in stress to the current ecosystem (Poff 2018; Poff et al. 1997). Individual wet or dry years are less important than series of wet or dry years for seasonal systems which is not adequately captured in existing methods either because the assessment period is a single year (too short) or decades (too long).

Therefore, the notion of using a single year or a multidecade pass/fail threshold as a representation of EWRs being met or not is somewhat nonsensical as all ecological systems have a degree of resilience (Poff 2018). This is especially true of seasonal riverine ecosystems that exist in a highly variable environment (Datry, Larned, and Tockner 2014).

There are also issues when assessing between different modelled scenarios with metrics that use 'nonzero flows'. Different proportions of nonzero flows between scenarios means that the results are not directly comparable, that is, a modelled 'no development' scenario may show an average cease to flow period of 1 month, while a 'developed' scenario may show an average cease to flow period of 4 months. By comparing the nonzero flows of these two scenarios, there will be significant differences introduced by the different proportion of flow, independent of the values of the flowing days.

Finally, there is a significant communication issue with these larger suites of flow metrics. The large numbers of metrics and the often-complicated method of calculation make communicating the results of these assessments to stakeholders difficult. Often, results are simply presented as numbers of metrics passing or failing with little to no background on what those metrics are or how they have been applied.

Ultimately, it was considered that a simplified series of metrics that seeks to overcome the above identified issues would greatly benefit the development of water plans and improve the transparency of these for stakeholders in seasonal river systems. The goal of this work was to define a suite of flow metrics that were representative of all aspects of the flow regime that were ecologically relevant and not correlated with each other. This is in a similar vein to the functional flows approach used by Yarnell et al. (2020) with a focus both on function (e.g., intermittency and high flows) and season (e.g., low flow season and transition seasons). Once the metrics were identified, the goal was to

establish a method of quantifying and assessing EWRs that was reflective of the variable nature of seasonal rivers.

2 | Methods

To develop the metrics and EWRs, the Barossa Valley Prescribed Water Resource Area (the PWRA) was used as a case study. The Barossa Valley is an internationally renowned wine region in South Australia that derives its water resources from the North Para River and groundwater resources of the PWRA. The PWRA's mild, wet winters and hot, dry summers are typical of a Mediterranean climate. Annual rainfall varies from more than 850 mm at high points in the Flaxman Range to about 300 mm north of Angaston. The surface water resources of the area are heavily developed with an estimated 1790 dams with an estimated total capacity of 8.1 GL (Jones-Gill and Savadamuthu 2014; Montazeri and Savadamuthu 2018). This represents approximately 52% of the resource capacity (total modelled runoff with the impacts of water extraction/capture and use removed [1997–2022]) (Savadamuthu, McCullough, and Green 2023).

Data for this assessment were sourced from two key locations. Observed flow data were accessed for a series of flow monitoring stations across the PWRA. A total of four flow stations were used for the assessment with data accessed from Water Data SA (Department of Environment and Water 2023). Only verified data were used for the assessment with no interpolated data included. Modelled flow data was sourced from a surface water model run using eWater Source (eWater 2022) developed for the Barossa by Jones-Gill and Savadamuthu (2014) and updated by Montazeri and Savadamuthu (2018) run for the period 1969–early 2023. Two modelled scenarios used in this assessment: the modelled current scenario that represents the current hydrological situation in the PWRA and the no-dams/extraction scenario that reflects a scenario with water capture and extraction removed, referred to as the 'no-dams' scenario.

All metrics calculated are based on years with a minimum of 95% of data present to avoid missing data being interpreted as days below relevant thresholds. The flow year is defined as December–November. This is to capture the full flow seasons, as to the 'low flow season' is defined as December–April.

Previous assessments of flow data from seasonal rivers in South Australia have shown that there is significant correlation between flow metrics per season (Maxwell et al. 2015) so single metrics per season were identified to avoid this correlation. Based on assessment of previous suites of flow metrics used (e.g., Kennard et al. 2010; Poff and Zimmerman 2010; Vanlaarhoven and van der Wielen 2009; Yarnell et al. 2020), the six key areas of interest were identified as (1) intermittency, (2) low flows, (3) break of season, (4) spring flows, (5) medium flows and (6) high flows. The links between these flow metrics and riverine ecosystem function is summarised in Table 1.

Flow metrics for each flow regime area were identified by examining existing flow metrics for each key part of the flow regime. Learning from the issues identified in previous flow metric assessments and considering the communicability of

TABLE 1 | Summary of ecological functions identified for each of the flow regime areas summarised from conceptual understanding of seasonal rivers and literature review.

Flow regime area	Ecological functions
Intermittency	• Considered the master variable for intermittent rivers (Datry et al. 2014) • Longer cease to flow periods leads to deteriorating water quality in refuge habitat (Chapin, Todd, and Zeigler 2014; Schmarr, Mathwin, and Cheshire 2014) • Length of flow period dictates habitat availability and expected lifecycle completion (Bonada, Rieradevall, and Prat 2007)
Low flows over the low flow season (Dec–April)	• Flushing of permanent pools • Maintenance of habitat (Vander Vorste et al. 2020) • Watering of in channel riparian vegetation over low flow season (Nicol 2013) • Opportunities for dispersal (Baumgartner et al. 2014)
Break of season	• Cues for migration and breeding (Lucas and Baras 2008; Mackay 1992; Pires, Beja, and Magalhaes 2014) • Increased stress on refuge habitats (Vander Vorste et al. 2020) • Likelihood of lifecycle completion (Mackay 1992)
Spring flows	• Promotes resilience leading into the low flow/cease to flow period (eWater 2022) • Promotes fish recruitment success (Green et al. 2014) • Migration of obligate aquatic fauna (Lucas and Baras 2008) • Discourages exotic fish species (Seebacher and Kazerouni-Ghanizadeh 2021)
Medium flows	• Promotes large-scale fish migration (Lucas and Baras 2008) • Discourages exotic fish species (Moore et al. 2008) • Expand riffle habitat for macroinvertebrate species (Bonada, Rieradevall, and Prat 2007) • Inundate vegetation on benches and lower banks (Maxwell et al. 2015) • Control terrestrial vegetation in channel (Maxwell et al. 2015)
High flows	• Inundate vegetation higher on banks (Maxwell et al. 2015) • Habitat maintenance including silt removal and algae scouring (Fuller et al. 2010; Loire et al. 2019) • Entrain organic material from banks (Caraco and Cole 2004) • Plant propagule transport (Stromberg et al. 2007) • Management of reed beds (Stromberg et al. 2007)

the resulting metrics, simple metrics were preferred, generally revolving around a number of days. Further to this, metrics that encompass longer time periods (i.e., annual metrics) were identified as being preferred as they combined many of the more specific and ultimately correlated metrics (Datry et al. 2014).

2.1 | Zero Flow Threshold

Part of using modelled data is the need to manage the issues of the zero flow threshold. The zero flow threshold is the cut-off used to describe a flow being zero in the modelled data. The modelling software will attenuate daily flows down to 1×10^{-5} ML/day (10 L per day). Flows this low are an artefact of the modelling process, rather than reflective of such small flows on the ground, and therefore, a threshold is applied. Previous assessments in the Barossa have used a 0.05 ML/day threshold (Green et al. 2014) while other environmental water planning assessments have used no threshold (e.g., Vanlaarhoven 2012; Vanlaarhoven and van der Wielen 2009). The zero flow threshold used for this assessment was established by comparing the number of flowing days in the observed flow data and the modelled current data from the eWater Source model at the four flow gauge locations used for this assessment. Several thresholds

were assessed including 0 (no threshold), 0.015, 0.03, 0.04, 0.05 and 0.1 ML/day. The threshold used was selected based on the highest correlation (Pearson correlation coefficient) and the degree of overlap with the observed data.

2.2 | Flow Metric Assessment

The development of the flow metrics applied the zero flow threshold developed for modelled data. Observed data were used with no modification. Where suitable observed data were available, this was used in preference to the modelled current data.

2.2.1 | Intermittency

Intermittency is well established as one of the key environmentally relevant flow metrics, characterised as the ‘master variable’ (Datry et al. 2014). The duration of the flowing period is linked to macroinvertebrate diversity (Datry et al. 2014), fish recruitment success (Whiterod, Hammer, and Vilizzi 2017) and the maintenance of aquatic and riparian vegetation (Maxwell et al. 2015).

Intermittency was measured as the number of flowing days over the whole flow year.

2.2.2 | Low Flows

Low flows over the low flow season are important for seasonal river systems as they provide respite from the cease to flow conditions. This includes freshening and topping up water in permanent pools, improving water quality and expanding available habitat (Vander Vorste et al. 2020), wetting in channel vegetation (Nicol 2013) and providing opportunities for dispersal to escape crowding or predation pressure (Baumgartner et al. 2014).

The low flow rate was identified by assessing the flow of water required to turn over the entire volume of water in an average permanent pool in 5 days. Five days was selected as this was a reasonable approximation of the flow duration of a pulse flow in response to a large summer storm based on the observed data. Pool volumes were estimated using a simple ellipsoid formula with length and width estimated from aerial imagery and depth based on data collected during previous surveys (unpub. data, Schmarr, Mathwin, and Cheshire 2014). The PWRA was divided into four areas based on understanding of the runoff generation and watercourse characteristics across the landscape as well as the location of key monitoring stations (Penrice [A5050517] for the Flaxman Valley and Yaldara [A5050502] for the Barossa Valley) (Hancock, Green, and Stewart 2014). In total, 24 pools were assessed (11 in the Flaxman Valley and 13 in the Barossa Valley). Each of the individual management zones in each area were given a flow rate based on its proportion of the total catchment.

2.2.3 | Break of Season

The timing of the break of season is critical for seasonal systems as the greater the delay in the onset of flows, the more inhospitable the environment becomes (Vander Vorste et al. 2020). It also provides cues for migration and breeding (Lucas and Baras 2008; Mackay 1992; Pires, Beja, and Magalhaes 2014) and increases the likelihood of lifecycle completion (Mackay 1992).

The break of season represents the period of change from the low flow season to the medium/high flow season, generally considered to be between the start of May and the end of June (commonly referred to as the Transition 1 season). To identify the point at which the season breaks, a threshold value was identified by looking at the average inflection point of the cumulative flow plots for the two key flow monitoring stations. The cumulative flow calculation excluded flow from January through March to exclude the impacts of large summer storms.

As with the low flow calculation, the threshold value for the individual zones was apportioned by the total catchment area. The break of season value was reported as the number of days after the first of April that the cumulative flow (from the start of April) reached the break of season threshold for each zone.

2.2.4 | Spring Flows

Spring flows were calculated based on the Mountain Galaxias response model reported in Green et al. (2014). The model used mean daily flow between August and November (inclusive)

calculated as the average daily flow in ML divided by the catchment area in square kilometres.

2.2.5 | Median and High Flows

Median and high flows support several key ecological and geomorphological processes including dispersal flows (Lucas and Baras 2008), inundating higher parts of the bank providing water requirements for riparian vegetation (Maxwell et al. 2015), removing silt and detritus (Fuller et al. 2010; Loire et al. 2019) and expanding wetted habitat for fish and macroinvertebrates (Bonada, Rieradevall, and Prat 2007; Lucas and Baras 2008).

Flow metrics representing the medium and high flows were developed based on values reported in Jones-Gill and Savadamuthu (2014). The threshold for medium flows was defined as the median (50th percentile exceedance) of nonzero daily flows for the modelled current scenario. Likewise, the threshold for high flows was defined as the 20th percentile exceedance of nonzero daily flows for the modelled current scenario. These thresholds were applied across all scenarios, that is, the threshold was not recalculated for different scenarios. Using the same threshold regardless of scenario removes the issue with using nonzero flow metrics relating the changing portions of zero flow (changing baselines).

2.3 | Establishment of EWRs

The setting of EWRs requires a baseline period or target level against which assessments will be made. Concurrent work has identified 1997–2022 as a time window reflective of modern flow conditions in the Barossa Valley that includes the Millennium Drought, several high rainfall years and the recent extreme variability (Savadamuthu, McCullough, and Green 2023). The recent extreme variability from 2017 to 2022 has resulted in notable shifts and declines in fish populations across the region (DEW, unpub. data), and for the purposes of establishing an ecologically stable baseline, these years were excluded, leaving a baseline period of 1997–2016.

Across the Barossa PWRA there are 15 management zones that were used for this assessment. The daily timeseries of outflow from each of these zones were used for the assessment of the metrics and the development of the EWRs. The six metrics were calculated for each flow year within this baseline period. The metrics were calculated based on the actual observed data where available (four zones) or the modelled current water use and development scenario (11 zones). Metrics were also calculated for the modelled no-dams/development scenario at all locations for comparison though were not used in the development of the EWRs.

To provide a measure that is inclusive and reflective of the variability inherent in seasonal river systems, a 3-year moving average was used rather than individual years. The 3-year moving average was selected as the lifecycle of the Mountain Galaxias (*Galaxias olidus*), the key native fish species in the Barossa PWRA, is generally 3 years (Mcneil and Hammer 2007). It is considered that significant changes

(mainly focusing on decreases) in the 3-year moving average are likely to result in significant stress to the Galaxias population as an entire cohort will have experienced conditions below optimal.

The EWRs were defined as the upper and lower bound of the 3-year moving average over the 1997–2016 baseline period under the general assumption that the environment present has been relatively stable over this period with minimal changes to ecological condition, primarily represented by the population of Mountain Galaxias (DEW, unpub. data).

3 | Results

3.1 | Zero Flow Threshold

The assessment supported the use of a threshold of 0.04 ML/day as the zero flow threshold with a Pearson correlation coefficient of 0.64 (Table 2). Thresholds of 0.03, 0.04, and 0.05 ML/day all showed good overlap with observed flow data, so the higher correlation score was used to identify the best value. A higher correlation was not expected from these data due to the accuracies associated with Source Modelling and the issues with limiting the data at 365 days.

3.2 | Flow Metric Assessment

3.2.1 | Low Flows

Twenty-four pools were assessed in the Flaxman Valley and Barossa Valley area for estimated volume. Pools in the Flaxman Valley ranged from approximately 0.7–3.2 ML with a mean value of 1.2 ML. Pools in the Barossa Valley ranged from approximately 1.1–7.8 ML with a mean value of 4.8 ML. The larger pools were towards the end of the valley in both cases as expected. Based on these volumes, flow rates of 0.2 and 1 ML/day were established for the end of the Flaxman Valley and Barossa Valley, respectively. These values represented the approximate complete turnover of an average pool near the end of the valley in approximately 5 days. Flow rates for the remaining management areas are described in Table 3.

TABLE 2 | Pearson correlation coefficient results for the different flow thresholds used when compared back to the observed flow data for the number of flowing days.

Threshold (ML/day)	Pearson correlation coefficient
No threshold	−0.0804
0.015	0.5614
0.03	0.6345
0.04	0.6390
0.05	0.6127
0.1	0.5692

The flow rate for Lyndoch Creek was set at 0.22 ML/day as it has similar area and rainfall as Jacob Creek. The flow rate for Duck Ponds was set at 0.1 ML/day in line with Upper Flaxman Valley which is of comparable size. The flow rate for Stone Chimney Creek was set at 0.05 ML/day as the flow rate established by portioning was below the zero flow threshold established.

In general, there was a good distribution of the number of days per low flow season that the flow exceeded the threshold with a clear distinction between the modelled no-dams scenario and the modelled current scenario (Figure 1).

3.2.2 | Break of Season

Assessment of the cumulative flow from the first of April for the Yaldara gauge suggested that the inflection point occurred at approximately 500 ML of cumulative flow in most years. There were 2 years where the 500-ML threshold was not reached by the end of September (2018 and 2019). Assessment from the Penrice gauge suggested that the inflection point occurred at approximately 250 ML of cumulative flow. There were 11 years that did not reach this threshold by the end of September including a series of dry years from 2018 to 2021. The apportioned flow thresholds are reported in Table 3.

As for the low flow threshold assessment, the value of Lyndoch Creek was based on Jacob Creek and set to 95 ML. Duckponds Creek was initially set to 95 ML in line with upper Flaxman Valley; however, this value was deemed to be too high with most years not ‘breaking’. A lower value of 70 ML produced more sensible results. Based on the thresholds reported in Table 3, the date of the break of season was identified for each year and the number of days between the break of season and the first of April calculated for each of the zones (Figure 1). While the data showed great variability in the delay in the break of season, there is a clear trend of increasing delay, especially since the end of the Millennium Drought.

3.2.3 | Spring Flows

Spring flows calculated according to the Mountain Galaxias runoff response model from Green et al. (2014) showed a good level of variability and the same declining trend as observed for the rest of the metrics (Figure 1).

3.2.4 | Medium and High Flows

The thresholds developed for the medium and high flows are reported in Table 3. The requirement to base these thresholds on nonzero flow was due to the proportion of zero flows being greater than 50% of the flow in some zones (Duck Ponds Creek and Stone Chimney Creek under the modelled current scenario) and close to the low flow threshold identified in other zones (Lower Flaxman, Angaston Creek etc.). While this was noted as a weakness of previous methods, the practicalities of working in seasonal systems requires consideration of flows outside the cease to flow period. The issues are mitigated by establishing the flow threshold and then using that threshold consistently

TABLE 3 | Threshold values used for the calculation of the flow metrics for the Barossa Valley PWRA.

Zone	Area	Percentage of area	Low flow rate (ML/day)	Break of season cumulative flow threshold (ML)	Medium flow rate (ML/day)	High flow rate (ML/day)
Barossa Valley Gorge	Barossa	100%	1.000	500	6.4	37.92
Barossa Valley Floor	Barossa	88%	0.884	440	5.84	29.59
Lower Jacobs Creek	Barossa	22%	0.222	110	3.68	15.14
Upper Jacob Creek	Barossa	19%	0.189	95	0.87	8.25
Lower Tanunda Creek	Barossa	15%	0.146	75	1.94	8.15
Transition Zone	Barossa	14%	0.139	70	3.11	17.16
Upper Tanunda Creek	Barossa	10%	0.100	50	1.48	7.08
Lower Angaston Creek	Barossa	8%	0.082	40	1.04	4.08
Upper Angaston Creek	Barossa	6%	0.059	30	0.46	2.62
Duck Ponds Creek	Duck Ponds	100%	0.100	70	0.33	2.04
Lower Flaxman Valley	Flaxman	100%	0.200	250	0.53	7.92
Mid Flaxman Valley	Flaxman	68%	0.135	170	3.76	16.45
Upper Flaxman Valley	Flaxman	38%	0.076	95	0.59	5.52
Stone Chimney Creek	Flaxman	13%	0.050	32.5	0.29	1.47
Lyndoch Creek	Lyndoch	100%	0.220	95	3.16	14.98

Note: Shading added to rows to identify area used for flow metric proportioning.

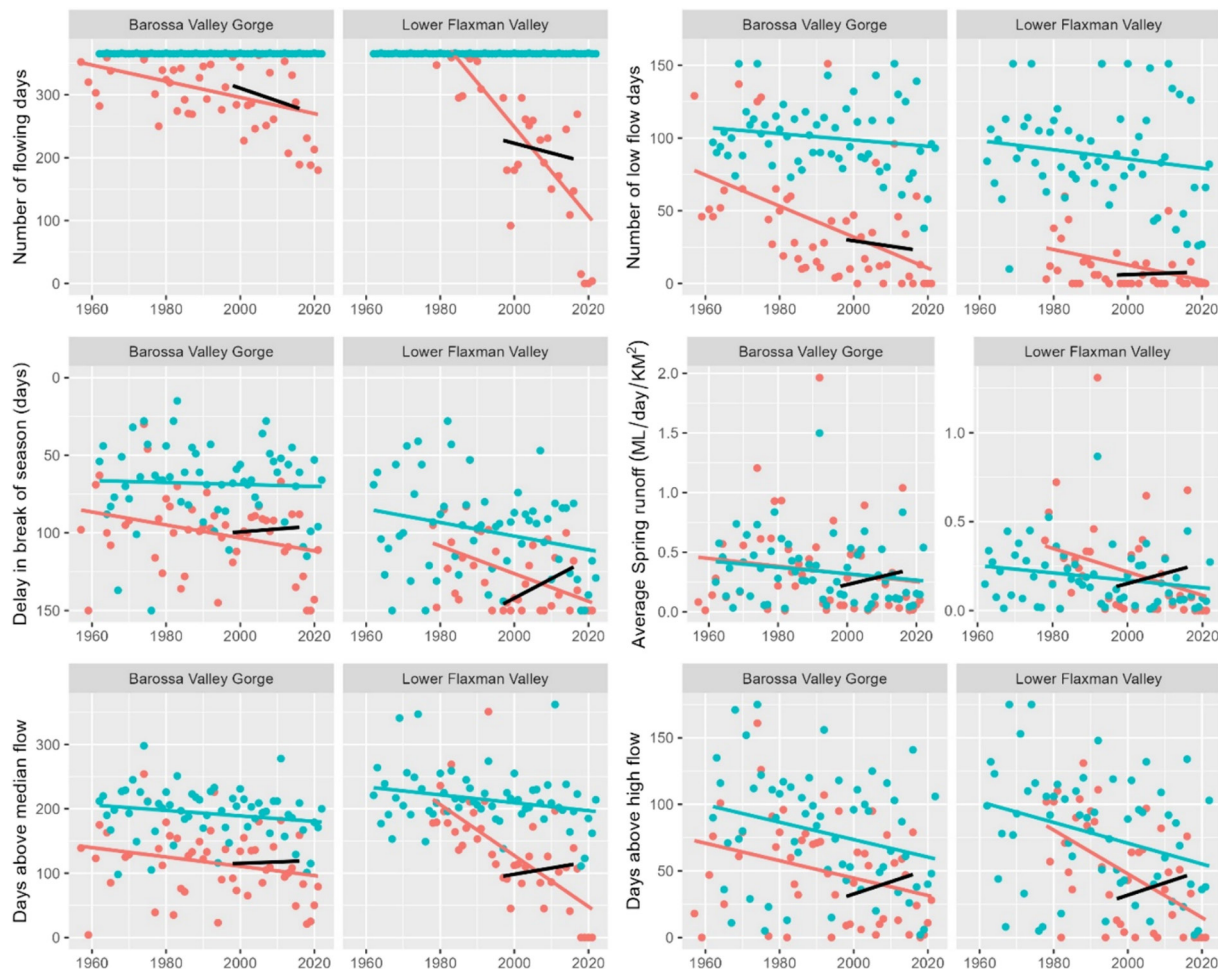


FIGURE 1 | Example outputs of the metrics from the two key locations used in the development process. Barossa Valley gorge uses data from the Yaldara gauging station (A5050502), and Lower Flaxman Valley uses data from the Penrice gauging station (A5050517). Red—observed data, green—modelled no-dams data and black line—linear regression over the observed data for the baseline assessment period (1997–2016).

rather than regenerating the threshold for each comparative assessment, that is, the flow threshold identified in Table 3 is used across all assessments undertaken, regardless of what scenario or input flow data is being assessed, providing a consistent benchmark.

Inspection of the number of days of medium and high flows showed that the same declining trend observed in other metrics is observed in these metrics (Figure 1). In general, this decline is more pronounced in the observed flow data rather than the modelled flow data. It is generally considered that dam development does not have a significant impact on medium and high flows as these predominantly occur during the high flow season when dams are full and spilling (Vanlaarhoven 2012; Vanlaarhoven and van der Wielen 2012).

3.3 | Metric Correlation

To ensure that there was no excessive correlation between metrics, a Pearson correlation was undertaken between the six metrics across all sites assessed. While a degree of correlation between the metrics was expected driven by climatic drivers (e.g., wet/dry years), the objective was to produce metrics that

were no more than 75% correlated. The results of the correlation assessment (Table 4) showed that the highest correlation was 70.4% between medium and high flow days. This was followed by flowing days and low flow days over the low flow season with a correlation of 67.9%. The remaining metrics were well below the level of concern.

3.4 | Establishment of EWRs

The moving average window of 3 years provided a good degree of variability while not being too responsive to individual year results (see Yaldara gauge example, Figure 2). There was a considerable amount of variability between zones, both regarding the value of the bounds and the range between the bounds, as expected given the variability in rainfall and dam development across the PWRA.

Across all 15 zones assessed, there were two instances where the lower bound was zero (low flow days over the low flow season for Lower and Mid Flaxman Valley). The metrics for these zones were checked against the no-dams modelled data to ensure that the thresholds developed were suitable and, in both instances, the thresholds were deemed appropriate. The lower bound of

TABLE 4 | Correlation assessment between the six identified metrics using Pearson correlation.

	Flowing days	Low flow days	Break of season	Runoff	Medium flows	High flows
Flowing days	1.000					
Low flow days	0.679	1.000				
Break of season	−0.454	−0.414	1.000			
Runoff	0.266	0.195	−0.376	1.000		
Medium flows	0.542	0.419	−0.511	0.314	1.000	
High flows	0.328	0.127	−0.510	0.537	0.704	1.000

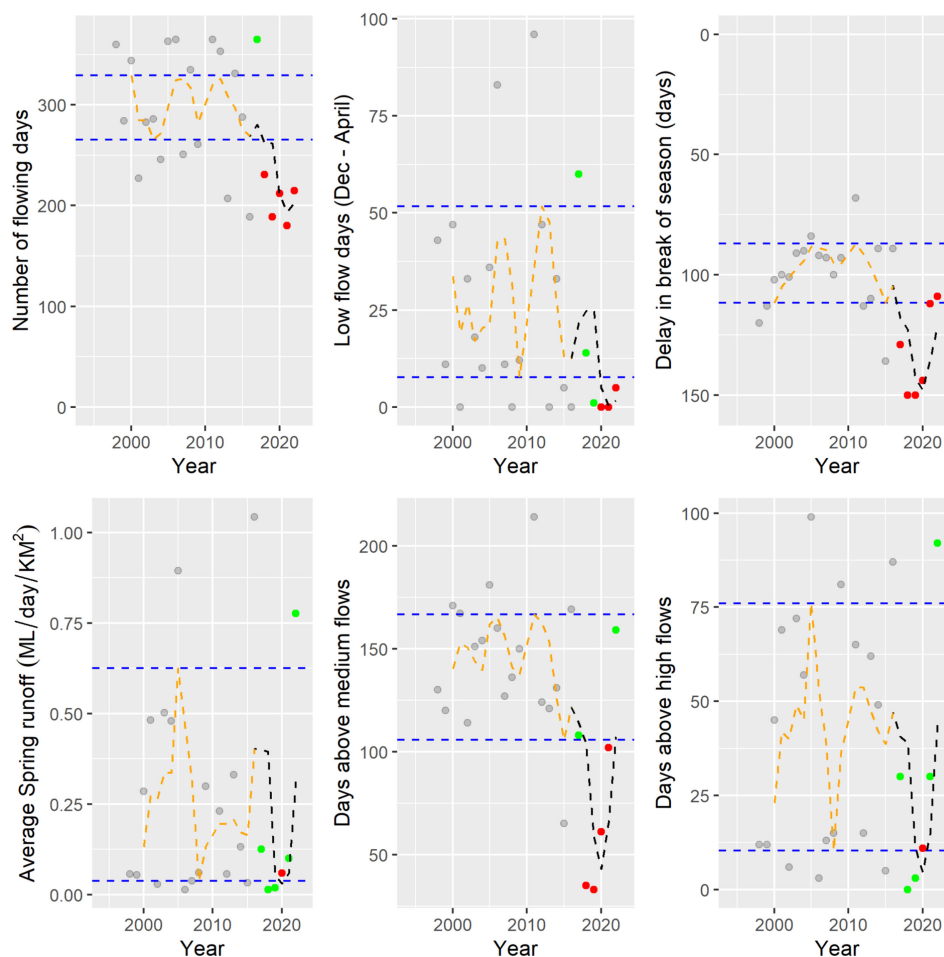


FIGURE 2 | Combined plots of the six identified flow metrics assessed for the Barossa Valley Gorge (Yaldara gauging station, A5050502) in the Barossa PWRA showing the environmental water requirement bounds (blue dashed lines) identified as the upper and lower limits of the 3-year moving average between 1997 and 2016 (orange dashed line). Grey points are metric results for the baseline period. The moving average post 2016 (black dashed line) showing current variability in the flow regime. For years where the moving average is outside the expected bounds, the data point is red; if it is inside the bounds, the data point is green, regardless of the actual position of the data point relative to the bounds.

zero suggests that the level and layout of dam development in these zones is having such an effect that there are periods of three or more years where there are no low flows over the low flow season. Similarly, there were two zones, Duck Ponds Creek and Upper Flaxman Valley, where the upper limit of the delay of break of season was the maximum 150 days, that is, the season did not break. These bounds present a problem when considering ongoing sustainability of the riverine ecosystems of the zone

and will need to factor into assessment of EWR thresholds for water planning.

4 | Discussion

The ability to represent the entire flow regime in a simple yet scientifically robust series of six environmentally relevant

flow metrics represents a significant simplification in from the superfluous way the flow regime of seasonal rivers are represented and assessed. This simplification is evident both in regard to the number of flow metrics used (e.g., compared to 56 in VanLaarhoven and van der Wielen (2009) or 120 in Kennard et al. (2010)) and in regard to the complexity of the metrics themselves. The results of the correlation assessment show that there is enough differentiation between the metrics that they all individually add information to the overall narrative. While it is clear that the additional functions of the flow regime (e.g., Yarnell et al. 2020) could have been identified (e.g., overbank flows and variability within flow season), it was determined that these would have added excess complication to the process without adding sufficient additional information to the assessment. This was considered especially important as a significant role of these metrics will be to communicate flow regime changes to community groups and other nonscientific stakeholders.

The metrics that been identified are all simple metrics reported as annual values. This provides benefits over previous complex metrics or metrics that are calculated over the entire time series. Indeed, the current investigations presenting trend through time is not possible using the previous EWR metrics for the Mt Lofty Ranges (Vanlaarhoven and van der Wielen 2009). The overall improvement in interrogation ability resulting from the ability to see annual results, rather than single values representing decade-long windows, allow for more detailed investigations into changes through time, especially relevant when considering the implications of a changing climate. The impacts of climate change on flow regime are likely to be a significant focus both for these metrics and in the broader seasonal rivers field akin to Dhungel et al. (2016).

The use of set threshold values identified from outside the flow data itself was possible for the Barossa as there was only two locations where this was required to inform the process, with the remaining values portioned by catchment area. This provided a tangible link to the physical environment and a clear line between observed information, the metrics and associated EWRs. This may prove difficult for larger areas where information may not be available (e.g., permanent pool depth for pool volumes) or where the number of locations to be assessed is prohibitively large to do individual threshold assessments.

For the development of low flow thresholds, it was noted that the threshold values were close to the lower inflection point of the flow duration curve for the site. This could provide a method for identifying the low flow threshold from within the flow data. This will remove the direct link to a tangible on ground measure but should retain the overall functions defined for the low flow metric described in Table 1. With the high correlation observed in other flow metric sets within the same flow season, it is highly likely that any flow threshold used close to the lower inflection point of the flow duration curve will be highly correlated with a value identified from the physical assessment used here. Therefore, they would be likely to convey the same information for flow regime assessment. The same argument could be made with the commence-to-flow threshold used for the assessment of the break of season. The identification of the threshold could be achieved by identifying the inflection point

of the cumulative flow post 1 April and averaging the flow value over the time series.

The method presented here is readily translatable to other seasonal systems with a few small modifications. Except for the low flow seasons flow threshold and the cumulative flow threshold, all of the values are derived from within the data. The process for the Barossa PWRA benefited from a significant amount of local data that allowed for these more specific thresholds to be developed. In areas with less local information, or for assessments covering larger regions, thresholds for the low flow season flow rate and the cumulative flow for break of season could be developed from within the data as well. The second limitation of translating this assessment to other regions is the establishment of a baseline period and which dataset the baseline should be established on. Ultimately this will relate more to the local targets and objectives (e.g., maintain current, restore to some previous reference condition or an alternate reference condition). The decision over what baseline to use will also drive how comparisons can be made.

Ultimately, the six flow metrics were able to provide a basis for the establishment of EWRs for the region based on the premise that the ecology of the region was stable between 1997 and 2016. This ability to not only characterise the flow regime, but the relationship of the environment to it, and quantify thresholds that can be used as management triggers or targets provides a powerful tool for managers and researchers alike but is simple enough to be interpreted by the broader public. By quantifying these thresholds based on a moving average rather than an individual year, it provides a more meaningful representation of the impacts on the riverine ecosystems in an inherently highly variable system.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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