Simplified environmental flow metrics and environmental water requirements for Mediterranean seasonal rivers

Douglas Green[1] and Kumar Savadamuthu[1]

[1]South Australia Department for Environment and Water

June 9, 2023

Abstract

1. 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. 2. In order to effectively assess changes to 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. 3. 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 which may pose problems when considering how these metrics are assessed. The metrics are also often complicated which introduces issues for communication of results. We suggest that due to high internal correlation between metrics, significantly fewer metrics are required to describe the flow regime, and owing to the high correlation within same season flow metrics, simple metrics can be selected. 4. We report on a series of six flow metrics that cover the whole of the flow regime, that are reported annually and that are simple to assess and interpret. We then apply those six metrics to establish environmental water requirements for the North Para River in the Barossa Valley of South Australia. 5. Environmental water requirements are defined using upper and lower bounds of a moving average for each metric, rather than a defined threshold. We suggest this better reflects the highly variable nature of seasonal rivers, and the subsequent tolerances of the flora and fauna that inhabit them.

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). Previous efforts to define the flow regime has 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). The altering of the flow regime through water resource development (e.g. dams) has been linked to declines in riverine ecosystem condition, most commonly associated with reductions in flows (Poff et al., 2007, Poff et al., 2010, Poff and Zimmerman, 2010). It has been further identified that some aspects of the flow regime have a disproportionate impact on riverine ecosystems, in particular for intermittent rivers (Datry et al., 2014a, Datry et al., 2014b). It follows that the assessment of impacts of changes to the flow regime of intermittent rivers can be summarised using a suite of key, ecologically relevant flow metrics, and that these changes in flow metrics can be meaningfully translated into a level of potential ecological impact.

Seasonal rivers, as a class of intermittent rivers, are defined as rivers that have a predictable cease to flow period. The vast majority of these follow the typical Mediterranean flow regime of cease to flow periods over the hot and dry summer months and a predictable flowing period over the cooler, wetter winter months (Kennard et al., 2010). These seasonal rivers are the dominant type of river found in southern Australia and are often heavily developed for their water resources to provide water for agricultural activities (Malerba et al., 2021). The level of development in some of these regions has led to the need to regulate and manage the capture, extraction and use of water through legislation (e.g. Landscape South Australia Act, Government of South Australia, 2019).

The sustainable management of these water resources depends on archiving an equitable balance between users, while keeping the total requirements for water below a sustainable level. Generally these requirements are broken down into social, economic, cultural and environmental water requirements. For water planning in South Australia, there is a significant emphasis placed on environmental water requirements as a priority user for water resources. Generally, environmental water requirements (EWRs) are defined as the water regime needed to sustain the ecological values of aquatic ecosystems, including their process and biological diversity, at a low level of risk (VanLaarhoven and van der Wielen, 2009). Previous assessments of environmental water needs have used various different methods for describing the EWRs for seasonal rivers, ranging from qualitative descriptions (e.g. Barossa, Natural Resources AMLR, 2009) through to complex series of 50+ flow metrics (e.g. Western and Eastern Mt Lofty Ranges, Natural Resources AMLR, 2013, Natural Resources SAMDB, 2013).

The notion of establishing flow assessment methods is not novel, with hundreds of methods developed and reported (Tharme, 2003). The most recent attempt at quantifying EWRs for seasonal rivers in South Australia provides a pass/fail style threshold for 56 flow metrics. Subsequent assessment of these flow metrics identified significant correlation between some of the flow metrics, especially between flow 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. There are also a considerable number of metrics using non-zero daily flows which has been identified as an issue when comparing datasets. The changing proportion of data between different scenarios included in a non-zero flow assessment results in metrics that are not directly comparable.

The goal was to define a suite 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 vain to the functional flows approach used by Yarnell et al. (2020) with a focus both on function (e.g. intermittency, high flows) and season (e.g. low flow season, transition seasons). The number of metrics was determined by a combination of consideration of the aspects of the flow regime that were deemed to be important along with assessment of previous suites of metrics. A PCA of the metrics (normalised) from VanLaarhoven and van der Wielen (2009) suggested that the first six principal components contained ~91% of the variance of the overall dataset. While not directly relatable to individual metrics, six was chosen as the number of metrics to develop.

Previous assessments of flow data from seasonal rivers in South Australia has 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.

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., 2014a) Longer cease to flow periods leads to deteriorating water quality in refuge habitat (Chapin et al., 2014, Schmarr et al., 2014) Length of flow period dictates habitat availability and expected lifecycle completion (Bonada et al., 2007)

Flow regime area	Ecological functions
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 et al., 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 et al., 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)

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 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., 2014a).

The practical application of these flow metrics revolves around linking them to ecological responses. In order to demonstrate the practicality of these metrics, EWRs were developed for each for a seasonal river system. The notion of a pass/fail threshold for ecological systems is somewhat nonsensical as all ecological systems have a degree of resilience (Poff, 2018). This is especially true of seasonal riverine ecosystems the exist in a highly variable environment (Datry et al., 2014b). Rather than identify a single threshold based on a long-term average or individual year, a moving average approach was used to define boundaries within which the environmental water requirement was considered to be achieved.

In order to evaluate the metrics, 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 it 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 Savadamathu, 2014, Montazeri and Savadamathu, 2018). This represents approximately 52% of the resource capacity (total modelled runoff with the impacts of water extraction/capture and use removed (1997 - 2022) (Savadamathu et al., 2023). Overall about 10% of these dams are licensed under the existing WAP and account for approximately 60% of the dam capacity.

Ultimately, this report documents the six key ecologically relevant flow metrics used to quantify the flow regime and the upper and lower limits of the moving averages for each metrics used to describe the EWRs for the degraded but stable riverine ecosystems of the Barossa Valley seasonal rivers.

Methods

Data for this assessment as sourced from two key locations. Observed flow data was accessed for a series of flow monitoring stations across the PWRA. A total of six flow stations were used for the assessment with data accessed from Water Data SA (Department of Environment and Water, 2023). Only verified data was 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 Savadamathu (2014) and updated by Montazeri and Savadamathu (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 which 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 considered to be from December – November to capture the full flow seasons as the low flow season spans December - April.

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 x 10^{-5} ML/day (10 litres per day). Flows this low are nonsensical in reality, therefore a threshold is applied. Previous assessments in the Barossa have used the 0.05 ML/day threshold based on Green et al. (2014). Other environmental water planning assessments in the Mt. Lofty Ranges 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. Several thresholds were assessed including zero (no threshold), 0.015 ML/day, 0.03 ML/day, 0.04 ML/day, 0.05 ML/day 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.

Flow metric assessment

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

Low flows

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 five 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 et al., 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 for the Flaxman and Yaldara for the Barossa) (Hancock et al., 2014). The flow rate at the end of each of these areas was defined based on the flow rate required to turn over pools in the upstream area. Each of the individual management zones in each area were given a flow rate based on its proportion of the total catchment.

Break of Season

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). In order 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.

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.

Median and high flows

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

Establishment of environmental water requirements

The EWRs for the current ecosystems present in the PWRA was identified by examining the results of the flow metrics over the last approximately two decades. Concurrent work has identified 1997 – 2022 as a time window reflective of modern flow conditions that includes the Millennium Drought, several high rainfall years and the recent extreme variability (Savadamathu et al., 2023). The environment was considered stable up until the start of the extreme variability observed post 2017. Therefore, a baseline period of 1997-2016 was used to establish the expected and acceptable range of variability within each of the metrics, characterised as the upper and lower limits of a three-year moving average for each metric. Three years was identified as it is the general maximum life expectancy of Mountain Galaxias (McNeil and Hammer, 2007), a high priority ecological asset in the region. Post 2016, metrics were assessed as either meeting or failing the EWR by the three year moving average rather than the individual metric result for each year.

Results

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 this data due to the accuracies associated with Source Modelling and the issues with limiting the data at 365 days.

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

Flow metric assessment

Low flows

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

These values were also compared to the flow duration curves calculated from the observed flow data from the Penrice gauge (Flaxman Valley) and the Yaldara gauge (Barossa Valley). In both instances the flow values identified were close to the lower inflection point of the curves suggesting that the values were a good reflection of flows at the low end of the curve (Figure 1).

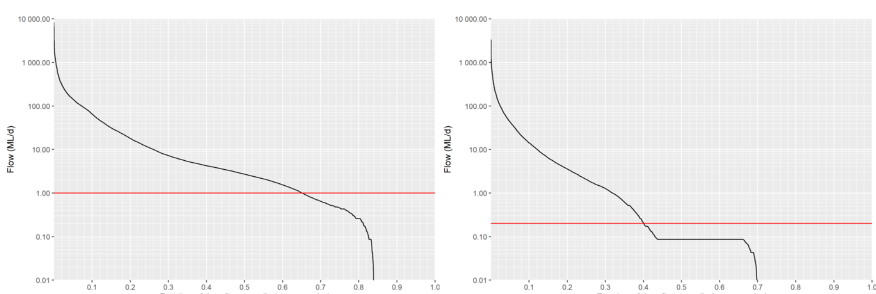

Figure 1: Flow duration curves for the Yaldara gauging station data (left) and the Penrice gauging station (right) showing the low flow thresholds identified for the two gauging stations (red lines).

The flow rate for Lyndoch Creek was set at 0.22 ML per day as it has similar area and rainfall as Jacob Creek. The flow rate for Duck Ponds was set at 0.1 ML per 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 per 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 3).

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 (Figure 2). There were two 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.

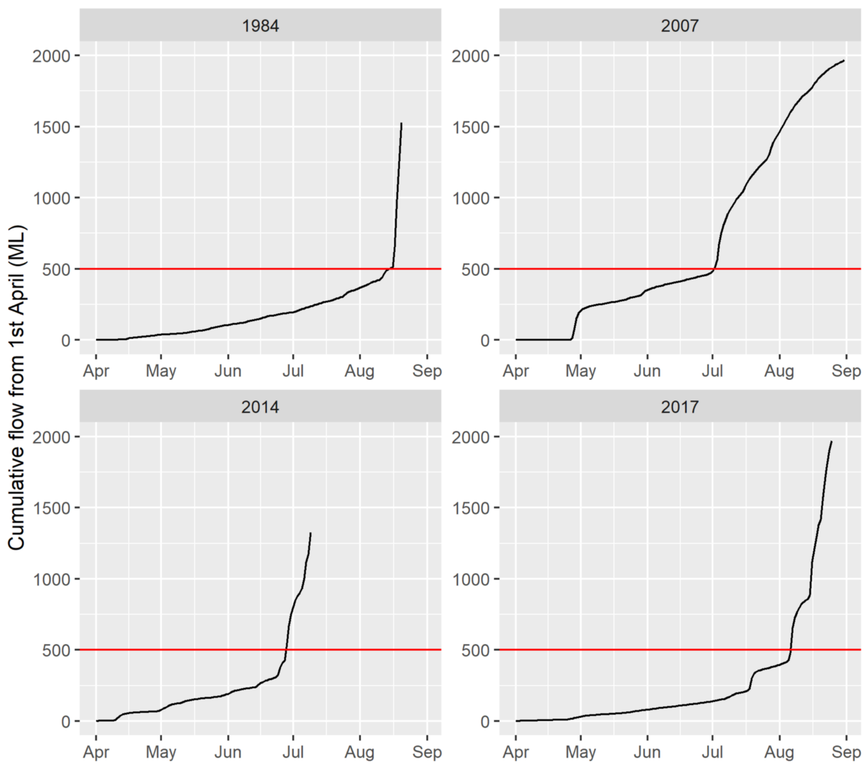

Figure : example years of cumulative flow from April 1st and the identified 500ML threshold identified for the Yaldara Gauging station (Barossa Valley Gorge).

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 the majority of 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 3). 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.

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 3).

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 non-zero 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.).

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/d)**	**Break of season cumulative**
Barossa Valley Gorge	Barossa	100%	1.000	500
Barossa Valley Floor	Barossa	88%	0.884	440
Lower Jacobs Creek	Barossa	22%	0.222	110
Upper Jacob Creek	Barossa	19%	0.189	95
Lower Tanunda Creek	Barossa	15%	0.146	75
Transition Zone	Barossa	14%	0.139	70
Upper Tanunda Creek	Barossa	10%	0.100	50
Lower Angaston Creek	Barossa	8%	0.082	40
Upper Angaston Creek	Barossa	6%	0.059	30
Duck Ponds Creek	Duck Ponds	100%	0.100	70
Lower Flaxman Valley	Flaxman	100%	0.200	250
Mid Flaxman Valley	Flaxman	68%	0.135	170
Upper Flaxman Valley	Flaxman	38%	0.076	95
Stone Chimney Creek	Flaxman	13%	0.050	32.5
Lyndoch Creek	Lyndoch	100%	0.220	95

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 3). In general this decline is more pronounced in the observed flow data rather than the modelled flow data, especially in the lower Flaxman Valley (Penrice gauge). It is generally considered that dam development does not have a significant impact on medium and high flows as these predominatly occur during the high flow season when dams are full and spilling (VanLaarhoven, 2012, VanLaarhoven and van der Wielen, 2012). The large differences noted in the Flaxman Valley, especially in the medium flows, likely reflects the very heavy dam development in this area.

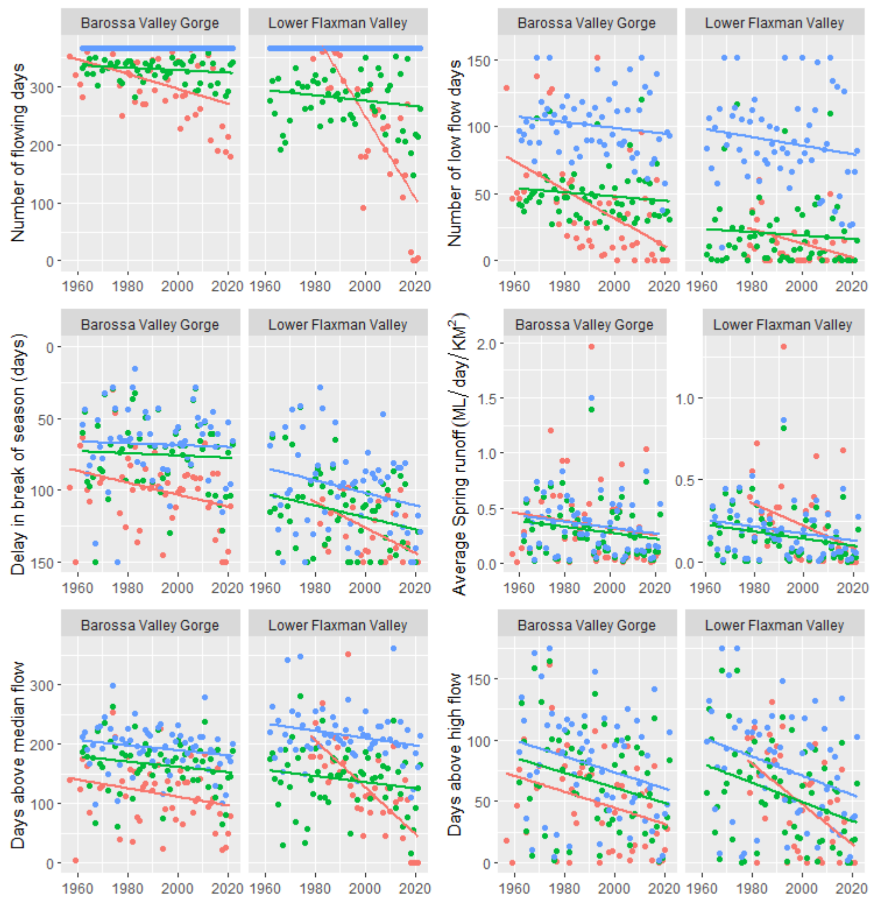

Figure 3: Example outputs of the metrics from the two key locations used in the development of the metrics. Barossa Valley gorge uses data from the Yaldara gauging station, Lower Flaxman Valley uses data from the Penrice gauging station. Red – observed data, blue – modelled no dams data, green – current modelled data.

Metric correlation

To ensure that there was no excessive correlation between metrics, a Pearson's correlation was undertaken between the six metrics. 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 that 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.

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	

	Flowing days	Low flow days	Break of season	Runoff	Medium flows	High flows
High flows	0.328	0.127	-0.510	0.537	0.704	1.000

Establishment of environmental water requirements

The moving average window of three years provided a good degree of variability while not being too responsive to individual year results (see Yaldara gauge example, Figure 4). There was a considerable amount of variability between zones, both in regards to the bounds and the range between the bounds, as expected given the variability in rainfall and dam development across the PWRA.

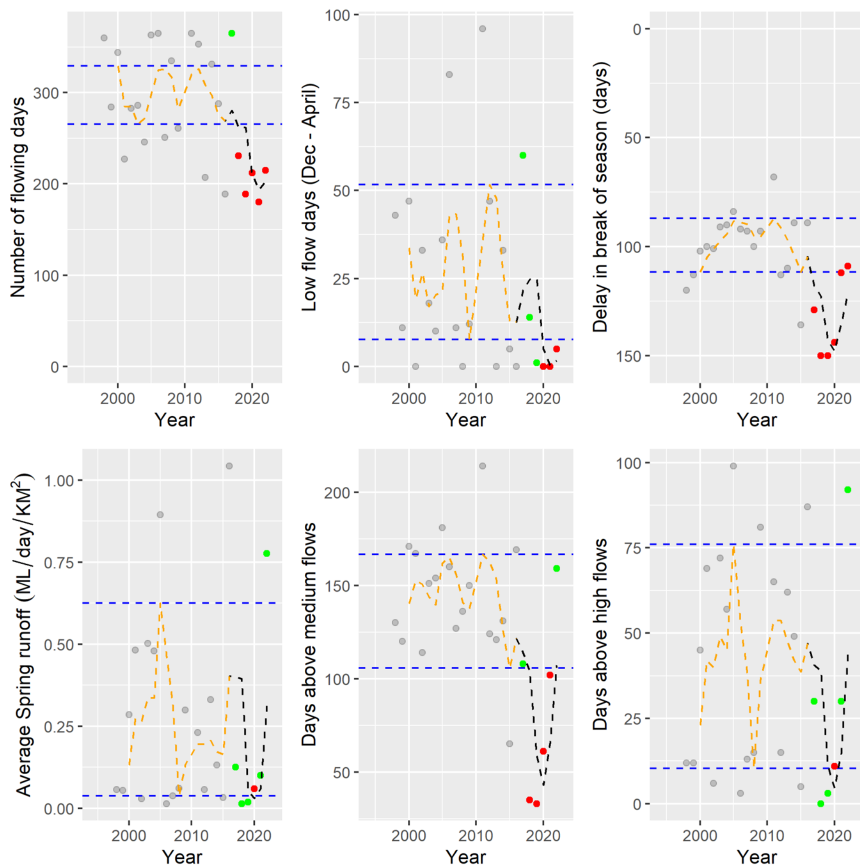

Figure 4: Combined plots of the six identified flow metrics assessed for the Barossa Valley Gorge (Yaldara gauging station) in the Barossa PWRA showing the environmental water requirement bounds (blue dashed lines) identified as the upper and lower limits of the three year moving average between 1997 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.

Across all 17 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 was 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 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, i.e. the season did not break. These bounds presents a problem when considering ongoing sustainability of the riverine ecosystems of the zone and will need to factored into assessment of environmental water requirement thresholds for water planning.

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 manner in which the flow regime of seasonal rivers are represented and assessed. This simplification is evident both in regards 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 regards 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 significant 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, variability within flow season etc.), 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 non-scientific 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. Time series metrics 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 XX. 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 April 1st and averaging the flow value over the time series.

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 levers 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.

References

BAUMGARTNER, L. J., CONALLIN, J., WOODEN, I., CAMPBELL, B., GEE, R., ROBINSON, W. A. & MALLEN-COOPER, M. 2014. Using flow guilds of freshwater fish in an adaptive management framework to simplify environmental flow delivery for semi-arid riverine systems. *Fish and Fisheries,* 15**,** 410-427.

BONADA, N., RIERADEVALL, M. & PRAT, N. 2007. Macroinvertebrate community structure and biological traits related to flow permanence in a Mediterranean river network.*Hydrobiologia,* 589**,** 91-106.

CARACO, N. & COLE, J. 2004. When terrestrial organic matter is sent down the river: the importance of allochthonous carbon inputs to the metabolism of lakes and rivers.*Food webs at the landscape level* **,** 301-316.

CHAPIN, T. P., TODD, A. S. & ZEIGLER, M. P. 2014. Robust, low-cost data loggers for stream temperature, flow intermittency, and relative conductivity monitoring. *Water Resources Research,* 50**,** 6542-6548.

DATRY, T., LARNED, S. T., FRITZ, K. M., BOGAN, M. T., WOOD, P. J., MEYER, E. I. & SANTOS, A. N. 2014a. Broad-scale patterns of invertebrate richness and community composition in temporary rivers: effects of flow intermittence. *Ecography,*37**,** 94-104.

DATRY, T., LARNED, S. T. & TOCKNER, K. 2014b. Intermittent Rivers: A Challenge for Freshwater Ecology.*Bioscience,* 64**,** 229-235.

DEPARTMENT OF ENVIRONMENT AND WATER 2023. Water Data SA, Department of Environment and Water, Government of South Australia [Online]. Available www.water.data.sa.gov.au Accessed: 07/03/2023.

DHUNGEL, S., TARBOTON, D. G., JIN, J. & HAWKINS, C. P. 2016. Potential Effects of Climate Change on Ecologically Relevant Streamflow Regimes. *River Research and Applications,* 32**,** 1827-1840.

EWATER. 2022. *eWater Source*[Online]. Australian Capital Territory: eWater. Available: https://ewater.org.au/products/ewater-source/ [Accessed 07/06/2022 2022].

FULLER, R. L., GRIEGO, C., MUEHLBAUER, J. D., DENNISON, J. & DOYLE, M. W. 2010. Response of stream macroinvertebrates in flow refugia and high-scour areas to a series of floods: a reciprocal replacement study. *Journal of the North American Benthological Society,* 29**,** 750-760.

GOVERNMENT OF SOUTH AUSTRALIA 2019. Landscape South Australia Act, version 21.11.2021, Government of South Australia, Adelaide.

GREEN, D. J., MAXWELL, S., VANLAARHOVEN, J. & DEANE, D. 2014. Barossa Valley Prescribed Water Resource Area Hydro-Ecological Risk Assessment, Department of Environment, Water and Natural Resources Technical Report 2014/08. Government of South Australia.

HANCOCK, M., GREEN, G. & STEWART, S. 2014. Interactions between groundwater and surface water systems, Barossa Valley. Department of Environment, Water and Natural Resources, Government of South Australia, Adelaide.

JONES-GILL, A. & SAVADAMATHU, K. 2014. Hydro-ecological investigations to inform the Barossa PWRA WAP review - Hydrology Report, Department of Environment, Water and Natural Resources, Adelaide, Australia.

KENNARD, M. J., PUSEY, B. J., OLDEN, J. D., MACKAY, S. J., STEIN, J. L. & MARSH, N. 2010. Classification of natural flow regimes in Australia to support environmental flow management. *Freshwater Biology,* 55**,** 171-193.

LOIRE, R., GROSPRÊTRE, L., MALAVOI, J.-R., ORTIZ, O. & PIÉGAY, H. 2019. What discharge is required to remove silt and sand downstream from a dam? An adaptive approach on the Selves River, France. *Water,* 11**,** 392.

LUCAS, M. & BARAS, E. 2008.*Migration of freshwater fishes* , John Wiley & Sons.

MACKAY, R. J. 1992. Colonization by lotic macroinvertebrates: a review of processes and patterns.*Canadian Journal of Fisheries and Aquatic Sciences,* 49**,**617-628.

MALERBA, M. E., WRIGHT, N. & MACREADIE, P. I. 2021. A Continental-Scale Assessment of Density, Size, Distribution and Historical Trends of Farm Dams Using Deep Learning Convolutional Neural Networks. *Remote Sensing,* 13**,** 319.

MAXWELL, S. E., GREEN, D. J., NICOL, J., SCHMARR, D., PEETERS, L., HOLLAND, K. & OVERTON, I. 2015. Water Allocation Planning: Environmental Water Requirements. GWAP Project: Task 4, Goyder Institute for Water Research Technical Report Series No. 15/53, Adelaide, South Australia. ISSN: 1839-2725 (PDF 2.4 MB).

MCNEIL, D. & HAMMER, M. 2007. Biological review of the freshwater fishes of the Mount Lofty Ranges, Report to the Adelaide and Mount Lofty Ranges NRM Board, SA Department of Water, Land and Biodiversity Conservation and SA Murray River NRM Board, SARDI Aquatic Sciences Publication No: F2006/000335.

MONTAZERI, M. & SAVADAMATHU, K. 2018. Hydrological investigations to inform Barossa PWRA WAP – Part 2. DEWNR Technical note 2018/42, Government of South Australia, Department of Environment, Water and Natural Resources, Adelaide.

MOORE, A., GIORGETTI, A., MACLEAN, C., GRACE, P., WADHWA, S. & COOKE, J. 2008. Review of the impacts of gambusia, redfin perch, tench, roach, yellowfin goby and streaked goby in Australia.

NAIMAN, R. J., LATTERELL, J. J., PETTIT, N. E. & OLDEN, J. D. 2008. Flow variability and the biophysical vitality of river systems. *Comptes Rendus Geoscience,*340**,** 629-643.

NATURAL RESOURCES AMLR 2009. Water Allocation Plan for the Barossa Prescribed Water Resource Area, Adelaide Mount Lofty Ranges Natural Resource Board, Adelaide.

NATURAL RESOURCES AMLR 2013. Water Allocation Plan for the Western Mount Lofty Ranges prescribed water resources area, Natural Resources Adelaide and Mt Lofty Ranges, Government of South Australia.

NATURAL RESOURCES SAMDB 2013. Water Allocation Plan for the Eastern Mount Lofty Ranges, South Australian Murray-Darling Basin Natural Resource Management Board, Murray Bridge, South Australia.

NICOL, J. 2013. Characterisation of the in stream and riparian plant communities in the Barossa Prescribed Water Resources Area. Data and Methods Report. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2013/000413-1. SARDI Research Report Series No. 745. 25pp.

PIRES, D. F., BEJA, P. & MAGALHAES, M. F. 2014. Out of pools: movement patterns of Mediterranean stream fish in relation to dry season refugia. *River Research and Applications,* 30**,** 1269-1280.

POFF, N. L. 2018. Beyond the natural flow regime? Broadening the hydro-ecological foundation to meet environmental flows challenges in a non-stationary world.*Freshwater Biology,* 63**,** 1011-1021.

POFF, N. L., ALLAN, J. D., BAIN, M. B., KARR, J. R., PRESTEGAARD, K. L., RICHTER, B. D., SPARKS, R. E. & STROMBERG, J. C. 1997. The natural flow regime: a paradigm for river conservation and restoration. *BioScience,* 47**,** 769-784.

POFF, N. L., OLDEN, J. D., MERRITT, D. M. & PEPIN, D. M. 2007. Homogenization of regional river dynamics by dams and global biodiversity implications. *Proceedings of the National Academy of Sciences of* *the United States of America,*104, 2732-2737.

POFF, N. L., RICHTER, B. D., ARTHINGTON, A. H., BUNN, S. E., NAIMAN, R. J., KENDY, E., ACREMAN, M., APSE, C., BLEDSOE, B. P., FREEMAN, M. C., HENRIKSEN, J., JACOBSON, R. B., KENNEN, J. G., MERRITT, D. M., O'KEEFFE, J. H., OLDEN, J. D., ROGERS, K., THARME, R. E. & WARNER, A. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology,* 55,147-170.

POFF, N. L. & ZIMMERMAN, J. K. H. 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows.*Freshwater Biology,* 55, 194-205.

SAVADAMATHU, K., MCCULLOUGH, D. & GREEN, D. 2023. Changing climate and the uncertainties in allocating water for consumptive and environmental needs in highly developed catchments. *25th International Congress on Modelling and Simulation, Conference Paper, Darwin, Australia* .

SCHMARR, D., MATHWIN, R. & CHESHIRE, D. 2014. Western Mount Lofty Ranges Fish Condition Report 2012-2013 incorporating the Barossa Valley Prescribed Water Resource Area fish community study, the verification of water allocation science project (VWASP) and the Western Mount Lofty Ranges fish community monitoring, SARDI Publication No. F2014/000113-1, South Australian Research and Development Institute Aquatic Sciences, Adelaide.

SEEBACHER, F. & KAZEROUNI-GHANIZADEH, E. 2021. Water flow and temperature interact to determine oxidative status, swimming performance, and dispersal of mosquitofish (Gambusia holbrooki). *Freshwater Biology,*66, 1366-1374.

STROMBERG, J. C., BEAUCHAMP, V., DIXON, M., LITE, S. & PARADZICK, C. 2007. Importance of low-flow and high-flow characteristics to restoration of riparian vegetation along rivers in arid south-western United States. *Freshwater Biology,*52, 651-679.

THARME, R. E. 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River research and applications,* 19, 397-441.

VANDER VORSTE, R., OBEDZINSKI, M., NOSSAMAN PIERCE, S., CARLSON, S. M. & GRANTHAM, T. E. 2020. Refuges and ecological traps: Extreme drought threatens persistence of an endangered fish in intermittent streams. *Global Change Biology,* 26,3834-3845.

VANLAARHOVEN, J. 2012. Assessment of the needs of water dependent ecosystems for the Western Mount Lofty Ranges Prescribed Water Resources Area, DFW Technical Report 2012/09, Government of South Australia, through Department for Water, Adelaide.

VANLAARHOVEN, J. & VAN DER WIELEN, M. 2009. Environmental water requirements for the Mount Lofty Ranges prescribed water resources areas, DWLBC Report 2009/29. Adelaide: Department of Water, Land and Biodiversity Conservation & South Australian Murray-Darling Basin NRM Board.

VANLAARHOVEN, J. & VAN DER WIELEN, M. 2012. Assessment of the needs of water dependent ecosystems for the Eastern Mount Lofty Ranges Prescribed Water Resources Area, Government of South Australia, through Department for Water, Adelaide.

YARNELL, S. M., STEIN, E. D., WEBB, J. A., GRANTHAM, T., LUSARDI, R. A., ZIMMERMAN, J., PEEK, R. A., LANE, B. A., HOWARD, J. & SANDOVAL-SOLIS, S. 2020. A functional flows approach to selecting ecologically relevant flow metrics for environmental flow applications. *River Research and Applications,*36, 318-324.