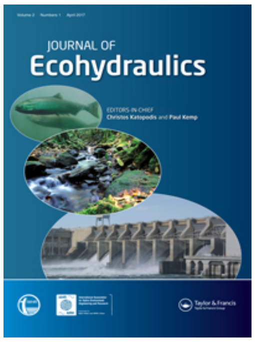

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Challenges for determining frequency of high flow spells for varying thresholds in environmental flows programmes

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ABSTRACT
High flow spells (or "pulses") are important flow components providing ecological triggers and connectivity in rivers. While the ecological importance of flow spells is well-recognized, the link between ecosystem processes and statistical methods used to define flow spells occurrence has received little attention. Commonly, a spell is defined as an event that exceeds a threshold for a minimum number of consecutive days; however, such arbitrary metrics may be ecologically irrelevant. For example, the ecological value of a sustained high flow spell may be unaffected by a brief period in which flows fall just below the nominated threshold. The inclusion of an independence criterion has the potential to better characterize the ecological relevance of spell metrics, but it introduces the additional problem of how best to define "independence". Existing techniques present inconsistencies in the number of spells identified as the thresholds vary, and this becomes more apparent when characterizing streamflow behaviour over shorter planning periods. This paper presents a new spell metric that resolves the identified inconsistencies and ensures that the number of high flow spells of varying duration varies in a monotonic manner with the threshold. We retain the usual conceptual basis of high flow spells, but adopt an independence criterion that facilitates their characterization for operational purposes, which is more relevant to ecological functions. The simplicity of the approach allows easy incorporation in decision support tools where identifying high flow spells plays a critical role in making important decisions.

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Environmental flow; fresh; pulse; flow threshold; spells analysis

1. Introduction

Environmental flows are now embedded in water policy and laws across many countries to combat declining river health due to human demands for water (O'Donnell 2013). Environmental flows describe "the quality, quantity, and timing of water flows required to maintain the components, functions, processes, and resilience of aquatic ecosystems that provide goods and services to people" (Hirji and Davis 2009). This recognizes that the population dynamics of the aquatic biota of a river – including most organisms, fishes and plants – depends on the magnitude and temporal variability of flows (Richter et al. 1996; Poff et al. 1997; Puckridge et al. 1998). Environmental flows are often aimed at maintaining or mimicking the key components of the natural flow regime (Arthington et al. 2006) required to maintain river ecosystem condition.

In an unregulated river, streamflow can be considered as a combination of baseflows released from natural subsurface stores, and flow spells produced by storm-events within the catchment (Hornberger et al. 2014). Flow spells, also referred to as pulses (Poff et al. 2010; Arthington and Balcombe 2011), freshes (Shenton et al. 2011) or events (Stewardson and Gippel 2003), can vary from small increases in water level above baseflows, to extreme flood events. Seasonal variations in baseflows contribute to variability in the flow regimes but it is flow spells that dominate the temporal variability of flow behaviour.

Flow spells support critical ecological functions including: short-term relief from low-flow conditions and poor water quality such as high temperatures and low dissolved oxygen availability (Tockner et al. 2000); delivery of organic matter (Tockner et al. 2000); prevention of vegetation encroachment into the river channel (Mathews and Richter 2007; Gippel et al. 2009; Poff and Zimmerman 2010; Webb et al. 2015); provision of cues for fish migration and spawning (Lake 1967; Reynolds 1976, 1983; Reinfelds et al. 2013; Webb et al. in press); connection of floodplains and wetlands (Poff et al. 1997) and maintenance of channels through the scour of sediments and gravel from the river bed (Kondolf and Wilcock 1996; Pitlick and Van Steeter 1998). Flow spells provide a pulse disturbance, which is important for maintaining the structure and function of river ecosystems (Downes et al.

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2002). Flow spells are often prescribed as components of an environmental flow regime (Poff et al. 1997; Richter and Thomas 2007) and can represent the bulk of total environmental water volume recommended for a river. For example, in the Goulburn River, south-eastern Australia, over the four years 2012–2015, 76% of the almost 1000 GL of environmental water released was to create or augment high-flow events[1].

A method of characterizing flow spells is required to specify environmental flow requirements and to evaluate change in spell occurrence under alternate flow management regimes. Flow spells analysis is a technique to assess the frequency and duration of flow spells over a defined flow threshold (Yevjevich 1972; Gordon et al. 2004) – particularly spells of intermediate magnitude (Richter et al. 1996; Clausen and Biggs 1997; Olden and Poff 2003) – and is commonly used to help specify environmental water requirements for rivers (Richter et al. 1996; Donald et al. 1999; Stewardson and Gippel 2003). However, many studies do not clearly detail the analytical procedure (analysis approach and parameters) used to define the spells (Richter et al. 1996; Harman and Stewardson 2005; Pollino et al. 2011). This causes confusion when water authorities attempt to design operating rules to deliver the required flow spells and report compliance against the flow target.

In its simplest form, flow spells analysis provides the frequency of spells above (or below) a given threshold discharge. Within an environmental flow assessment, recommendations for flow spells usually specify a minimum (or potentially the maximum) frequency for these spells. One challenge with this approach is that flow spell frequency does not decrease monotonically with increasing discharge threshold. This is because two flow spells defined as discrete events at a high flow threshold may be considered a single flow spell at a lower threshold. A small change in the threshold considered can produce changes in the frequency and duration of the event that are counter intuitive (Section 2). The key contribution of this paper is the development of a straightforward procedure for obtaining the number of independent high flow spells of varying duration that vary in a monotonic fashion with flow threshold (Section 3). The presented approach retains the usual conceptual basis of flow spells, but adopts an independence criterion that facilitates their characterization for simulation and operational purposes in a manner considered to be more relevant to ecological function. The approach is simple numerically and can be easily incorporated in decision support tools, where the identification of high flow spells plays a critical role in making important decisions. The approach is demonstrated for a regulated river system in Section 4, and is validated against the identification of independent spells by experts in Section 5. The conclusion and further research are discussed in Section 6.

2. Importance of independence criteria in spells analysis

2.1. Spells analysis methodology

A spell is usually taken to be a number of consecutive days in a flow series with flow above or below a given threshold (Gippel 2001), referred to herein as "threshold-based" spells analysis. For the discussion below, we refer only to flows above threshold, but the concepts apply equally to spells below threshold values. The conventional analysis of flow spells typically involves converting a long-term flow series to a binary series indicating whether flow is above or below the selected threshold (T). A number of criteria are required to then convert this binary series into a summary of the duration and frequency of individual spells. The first requirement is the minimum duration ($D_{\min}$) above a threshold that constitutes an event. It may be, for example, that a minimum duration is required to ensure adequate travel time for fish to migrate upstream. Second, is the criterion to determine when an event is independent of a subsequent event, typically based on a minimum number of days required between events ($I_{\min}$) (see Figure 1). To our knowledge there is no established approach to selecting the criterion for independence; or for those adopted an ecohydrological rationale is rarely provided. It is

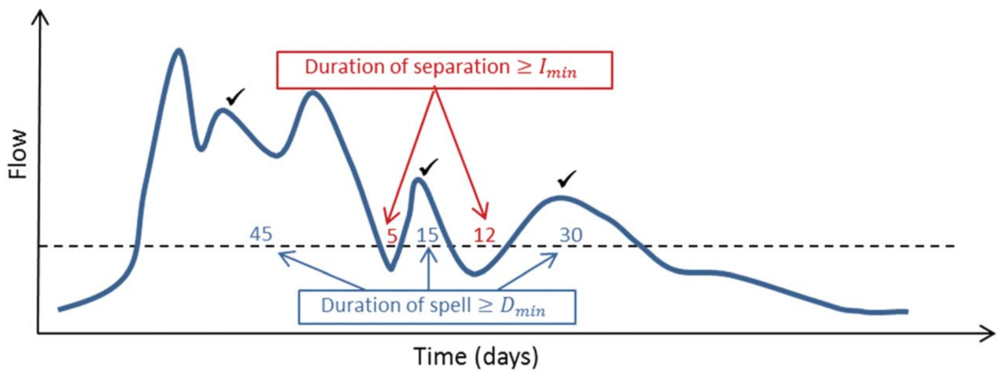

Figure 1. Example to show three independent flow spells identified over a threshold (given by the black dashed line) when the minimum duration for a spell ($D_{\min}$) is 10 days and the minimum days of separation between independent spells ($I_{\min}$) is 5 days.

Table 1. Characteristics and criteria of three approaches in literature to identify independent spell events.

	Threshold-based spells analysis	Peaks-over-threshold method	Baseflow separation
Start of a spell event	First day flow goes above the threshold	First day flow goes above the threshold	Event has a low baseflow index
End of spell event	First day flow goes below the threshold	First day flow goes below the threshold	N/A
Duration criteria	Included	Included	N/A
Independence criteria	Flow falls below the threshold for a minimum number of days	Flow fall by some fraction of the peak flows of two independent spells; spells must be separated by a minimum number of days	An event with low baseflow index is followed by an event with high baseflow index
Traditional use	Determining flow spells in long term flow series	Evaluating the risk of flooding by calculating exceedance probability of occurrence of floods	Obtaining the baseflow hydrograph in a flow series.

possible that the independence criterion might vary with the ecological function of concern. For example, fish might be sensitive to a particular sequence of low flow intervals associated with oxygen depletion, but this may not be relevant to the prevention of vegetation encroachment.

There are alternative hydrological methods for characterizing the behaviour of high flow events. Below we review two such methods, noting that while there are insights from these methods, they have not traditionally been used for environmental flow assessment. The two methods are the peaks-over-threshold method and the baseflow separation method (Table 1).

The peaks-over-threshold (or "partial duration series") method is used for predicting the frequency of floods, and requires selection of a reasonable threshold level and a criterion to establish independence of flood events from each other (Lang et al. 1999). The start and end of a spell is defined by the first day the flow goes above and below the threshold, respectively. The method specifies that the independence of two flood events is defined by a minimum number of days separating the peaks, also requiring that flows between independent events must fall by some fraction of the peak flows (USWRC 1976; Cunnane 1979). The complexities in the choice of threshold and the independence criteria have limited the uptake of the peaks-over-threshold approach (Lang et al. 1999).

Baseflow separation is another method used to distinguish between baseflow and discrete flow spells within a hydrograph (Hall 1971; Nathan and McMahon 1990; Smakhtin 2001). In this method, the baseflow index (BFI) of a spell, defined as the ratio of the total flow in the baseflow component of the event to the total flow of the event, is used to separate high flow spells from baseflow events (Gippel et al. 2009). Events with low BFI are identified as flow spells and a threshold value (in BFI rather than in discharge) is required to define this separation. This method focuses more on obtaining the baseflow hydrograph than identifying the frequency of spells.

While both the peaks-over-threshold, and the baseflow separation methods can be used to identify spells, these were developed to evaluate the exceedance probability of flooding and obtaining the baseflow hydrograph in a flow series, respectively. The nature and the key aim of these methods differ significantly to the aim of identifying flow spells that have significant impact on ecological outcomes in a river. For this reason, we compare the approach proposed in this paper only with the threshold-based spells analysis approach. However, it will be seen through our proposed approach that we have adopted concepts from these methods.

2.2. Why independence criteria matter

The selection of the independence criterion ($I_{\min}$) can significantly impact spell analysis results. If the independence criterion is specified as the number of days below the threshold, it is dependent on the threshold value chosen, and hence the number of independent spells will change as the threshold changes. This dependence can yield inconsistent outcomes. For example, when looking at mid-range events, it would be expected that the number of spells would increase as the threshold decreases, as a spell event identified at a higher threshold will also be identified at a lower threshold. However as shown in Figure 2, this may not be the case if the independence criterion is defined in terms of the threshold value. This figure shows the number of independent events identified at different thresholds (shown as dashed lines) when $I_{\min}$ is taken to be 2 and 7 days. It can be noted that for both values of $I_{\min}$ the number of spells varies in an inconsistent and non-monotonic manner with changes in threshold.

Environmental water management is becoming increasingly adaptive, requiring ongoing assessment of compliance against flow recommendations and seasonal watering decisions (Horne et al. in press). This review and adaptation might typically occur annually. It may be that the inconsistencies in spells analysis with different thresholds may be averaged or masked when investigating long-term average reoccurrence of spells. However, when looking at a single planning year in terms of watering decisions or compliance, these inconsistencies can have management implications. For instance, consider a situation where a water resource manager can make decisions on the threshold for the spell event to release in a given year (Horne et al. 2017), or where compliance must be assessed for a specified release volume. In both instances, the outcomes depend on the occurrence of independent flow spells in the river at various thresholds. Referring back to Figure 2, if the threshold was set at level A and two

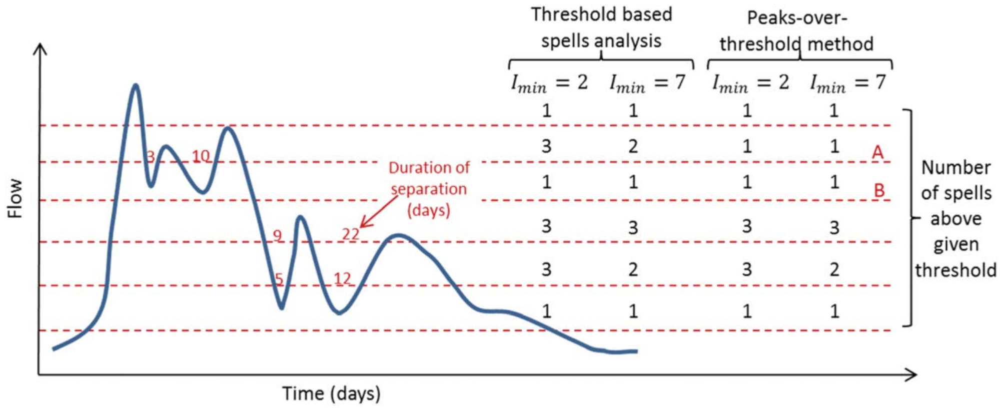

Figure 2. Example to demonstrate the effect of independence criteria on the frequency of independent spells with the threshold based spells analysis approach and the peaks-over-threshold method. Dashed lines are the different thresholds chosen, with the superimposed numbers being the number of flow spells identified over those thresholds for two different values of the independence criterion ($I_{\min} = 2$ and $I_{\min} = 7$). It can be noted that for both values of $I_{\min}$, the number of spells varies in an inconsistent and non-monotonic manner with changes in threshold.

events were required, compliance would show that the spell target was achieved. However, if the threshold target was level B (a lower magnitude) and two events were required, compliance would show that the spell target was not achieved as the spells method only registers a single event.

Multiple approaches are possible for flow spells analysis, but the challenge for ecological studies is to develop a method for identifying discrete flow spells that provide distinct pulse disturbances for different groups of the biota (Gordon et al. 2004). The habitat requirements of different organisms depend on flow in the river over time, and hence it is important that any attempt to assess the frequency of occurrence of spells varies in a manner that is physically consistent with changes in flow conveyance. Thus, it is desirable that a method used to identify independent spells yields results that vary in a predictable and monotonic manner with flow threshold.

3. A new approach to defining spells independence criteria

We propose a new approach to defining flow spells that builds on the principles in the threshold-based spells analysis method and the peaks-over-threshold method. Importantly, the method ensures that the independence criterion is not affected by the threshold chosen; instead, we propose using total volume of water between two spells to define independence. Below, we first give the precise definition of a flow spell and then provide the details of the proposed criterion to define independence of the spell events.

We retain the traditional definition for a spell as an event with a minimum duration ($D_{\min}$) above a threshold (T). For two events to be independent, we require that

- they must be separated by a minimum number of days ($I_{\min}$), and
- the total volume of flow between spells must be less than some fraction of the total flow over the first $D_{\min}$ days within the spell.

More precisely, we deem the flow spells starting at day d and d’ to be independent if there exists a day d^* between d and d' such that $d + D_{\min} \le d^* < d^* + I_{\min} \le d'$ with

$$\frac{W(d^*)}{I_{\min}} \le \frac{K}{D_{\min}} \min\left(V(d), V(d')\right). \quad (1)$$

Equation 1: Proposed criterion for determining independent spells where,

$W(d^*) = \sum_{t=d^*}^{d^* + I_{\min}-1} q(t)$,

$V(d) = \sum_{t=d}^{d + D_{\min}-1} q(t)$,

$V(d') = \sum_{t=d'}^{d' + D_{\min}-1} q(t)$,

q(t) is the total water volume on day t (see Figure 3), and K is an input parameter between zero and one that controls the ratio between the average flows in two independent flow spells and the average flows over the period separating them, thereby controlling the size of the flow spells over the baseflows.

The proposed criterion is similar to the independence criteria used in the peaks-over-threshold method, but it considers the reduction in flow volume over the interval between spells rather than the reduction in flow rate, which is generally adopted in the peak-over-flows method. Furthermore, in the peaks-over-threshold method, an event is assumed to end on the first day the flow falls below the threshold, but in the proposed method the end is identified by the time when the flow volume has substantially reduced relative to the total flow volume during the spell

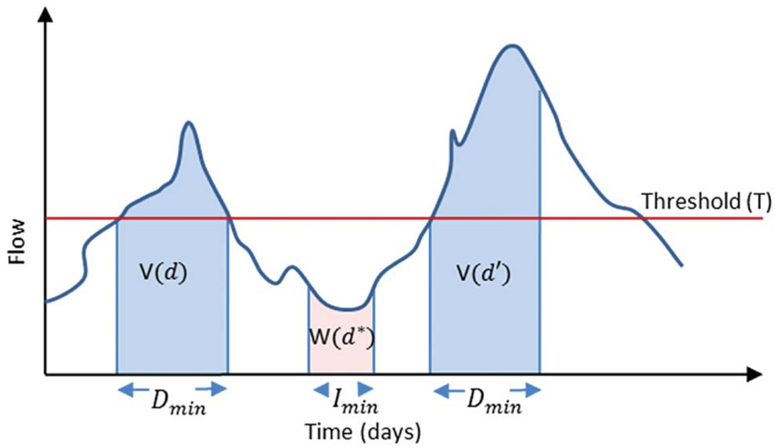

Figure 3. Flow volumes used in the proposed independence criterion.

(represented by the criterion in Equation (1)). This identifies the end of the spell regardless of whether the threshold is crossed in the downward direction or not.

Since we are using total volumes in the above definition (given by variables V and W), for fixed values of the input parameters, i.e. $D_{\min}$, $I_{\min}$ and K, any two valid flow spells identified as independent at a higher threshold will also remain so at lower thresholds. To prove this, consider two thresholds T_1 and T_2 with $T_1 \geq T_2$. Suppose two flow spells over threshold T_1 starting at day d and d', respectively, are deemed independent using the proposed independence criterion. This implies there exists a day d^* with $d + D_{\min} \leq d^* < d^* + I_{\min} \leq d'$ such that inequality (1) is satisfied. Since $T_1 \geq T_2$, by definition flow spells over threshold T_1 are also flow spells over threshold T_2. Now since $W(d^*), V(d)$ and $V(d')$ in Equation (1) are defined by the total volume of water over $I_{\min}$ or $D_{\min}$ days (and hence independent of the thresholds magnitude), inequality (1) remains satisfied for the flow spells starting at d and d' over threshold T_2 as well, implying independence of the two events over threshold T_2. Note while this proves that spell independence does not change even when very low flow thresholds are considered, in practice one would be interested in thresholds that are well above the general base flow contribution.

Lastly, it is worth noting that the input parameters ($T, D_{\min}$, $I_{\min}$ and K) need to be selected to suit the hydrological or ecological processes being targeted by the high flow events. The need to select input parameters is consistent with the existing flow spells methods. To facilitate adoption and implementation of the proposed approach in existing river analysis tools, a pseudocode for the same is provided in the Supplementary material.

4. Analysis

We demonstrate the proposed method by applying it to the Yarra River at Warrandyte (which is downstream of a major dam), Victoria, Australia. Modelled streamflow data for the year 1995 was used (obtained using a water resource model of the Yarra River taking into account inflows to the reservoirs and lag times for flow along the river).

4.1. Varying threshold (T)

A spells analysis was conducted for a range of flow thresholds (T). Five thresholds were considered based on proportions of the mean daily flow (T_{avg}) in a given year: T_{avg}, $T_{avg} \pm 25\%$, $T_{avg} \pm 50\%$. Note that the thresholds levels were varied around T_{avg}, purely to provide values to demonstrate the proposed method. When applied in practice, T (and similarly other parameters such as $D_{\min}$, $I_{\min}$ and K) would be chosen based on the flow requirements of the ecological endpoints being targeted. The spells analysis was undertaken using two definitions of independence: (1) the number of days below the threshold and (2) the proposed criterion based on the number of days between peaks and a minimum volume. The required duration ($D_{\min}$) was set to vary between 1 day and 30 days, separated by at least 3 days (i.e. $I_{\min}$ set at 3 days). For this example, K was fixed to 0.75, and the sensitivity of the results to this parameter is discussed in the following section. Figure 4 shows that when the independence criterion is based simply on the number of days below the threshold (as in Figure 4(a)), the curves for different thresholds cross on a number of occasions (threshold of T_{avg} and 0.75^*T_{avg} in Figure 4(a)). This means for spells of certain durations (at $D_{\min} =$ 6 and 8 days in Figure 4(a)), fewer independent spells are identified at lower thresholds than at the higher thresholds. However, with the proposed independence criterion, the curves at different threshold vary in a consistent manner with no crossing over (Figure 4(b)).

This difference is demonstrated further in Figure 5, which shows the spells of duration with minimum duration of 6 days. When the spells analysis is conducted using a threshold-based independence

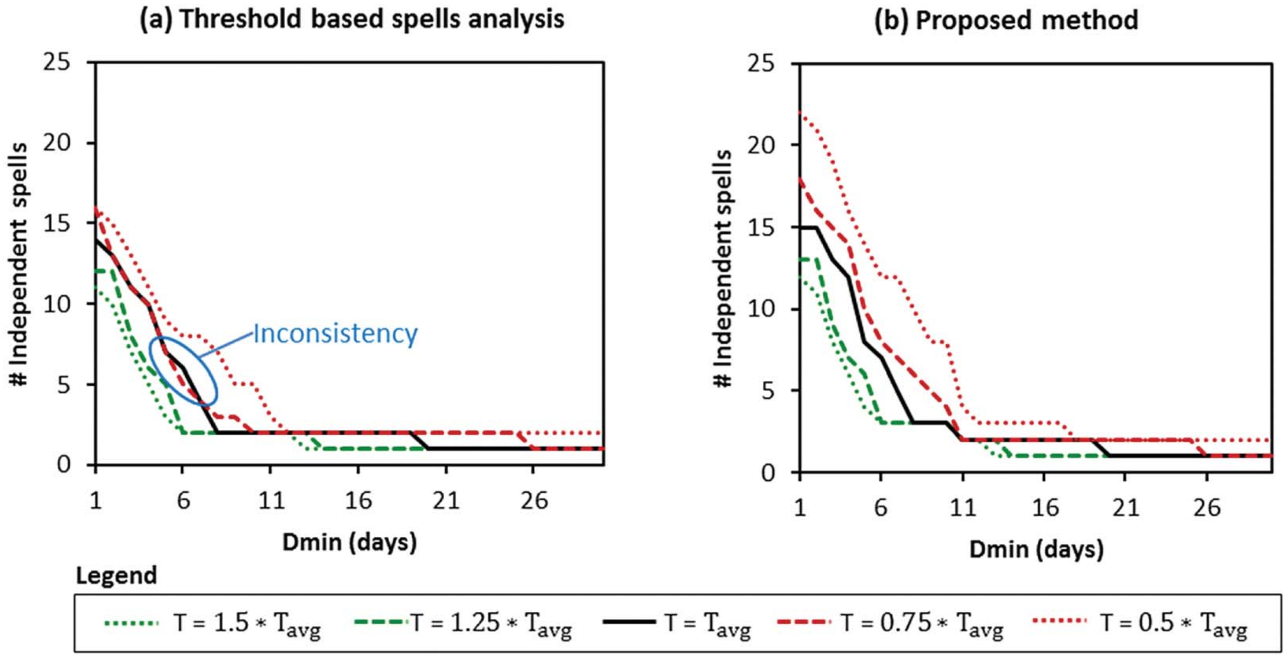

Figure 4. (Color online). Number of independent spells separated by at least 3 days ($I_{min} = 3$) identified at different thresholds for regulated flows using (a) the independence criterion based on the number of days below the threshold and (b) the proposed independence criterion. When the independence criterion is based on the number of days below the threshold, the curves for different thresholds cross on a number of occasions (threshold of T_{avg} and $0.75^{*}T_{avg}$ in (a)). This means for spells of certain durations (at $D_{min} = 6$ and 8 days in (a)), fewer independent spells are identified at lower thresholds than at the higher thresholds. However, with the proposed independence criterion, the curves at different threshold vary in a consistent manner with no crossing over (b).

criterion, it is seen (Figure 5(a)) that while two independent spells are identified over the threshold T_{avg} in the first quarter of the year, only one spell is suggested at the threshold of $0.75^{*}T_{avg}$ as flow does not fall below the threshold of $0.75^{*}T_{avg}$ between the two spells. Conversely, using the proposed independence criterion (Figure 5(b)), more spells are identified at the lower threshold than the higher threshold, with all spells identified at the higher threshold being maintained at the lower threshold.

4.2. Sensitivity analysis of parameter K

The input parameter K controls the ratio between the average flows in two independent flow spells and the average flows over the period separating them, and can be varied to align with the types of events that are being identified for an ecological endpoint under consideration. To assess the sensitivity of the chosen value of K, a spells analysis was conducted for representative wet, dry and average years with varying thresholds and varying values of K (with fixed values of D_{min} and I_{min}). Figure 6 shows that as K increases, the total number of independent high flow spells identified also increases. Furthermore, the choice of K is less sensitive to identification of spells at higher thresholds as compared to spells at lower thresholds (as seen by the smaller gradient of the slope at higher thresholds). This can be attributed to the fact that the spells at higher thresholds will have higher total volumes, making the right hand side of Equation (1) less sensitive to the choice of K.

5. Evaluation

The previous sections have demonstrated the statistical basis for the proposed approach to defining flow spells. However, the objective of a spells analysis is to use a statistical metric to represent an ecological cue or process. To assess the ecological relevance of the adopted approach, two ecologists were shown a number of flow series and asked to identify the independent flow spells that were relevant to a particular species or an ecosystem process.

The first expert used the selection of flow spells for Australian grayling (*Prototroctes maraena*) spawning, which occurs primarily in April and May (O'Connor and Mahoney 2004), limiting the assessment to these months. The identified spells are shown with purple ticks in Figure 7 for two demonstration years. Using the threshold-based spells analysis, it is impossible to define a single threshold that allows two spell events to be identified in both flow series shown in Figure 7(a) and 7(b). Ensuring the two events are selected in Figure 7(a) requires a threshold of no greater than 1.5 GL, and at this flow threshold, the identified spells in Figure 7(b) would not be considered independent. However, using the proposed spells analysis method, these four events are successfully identified (with K fixed to 0.7).

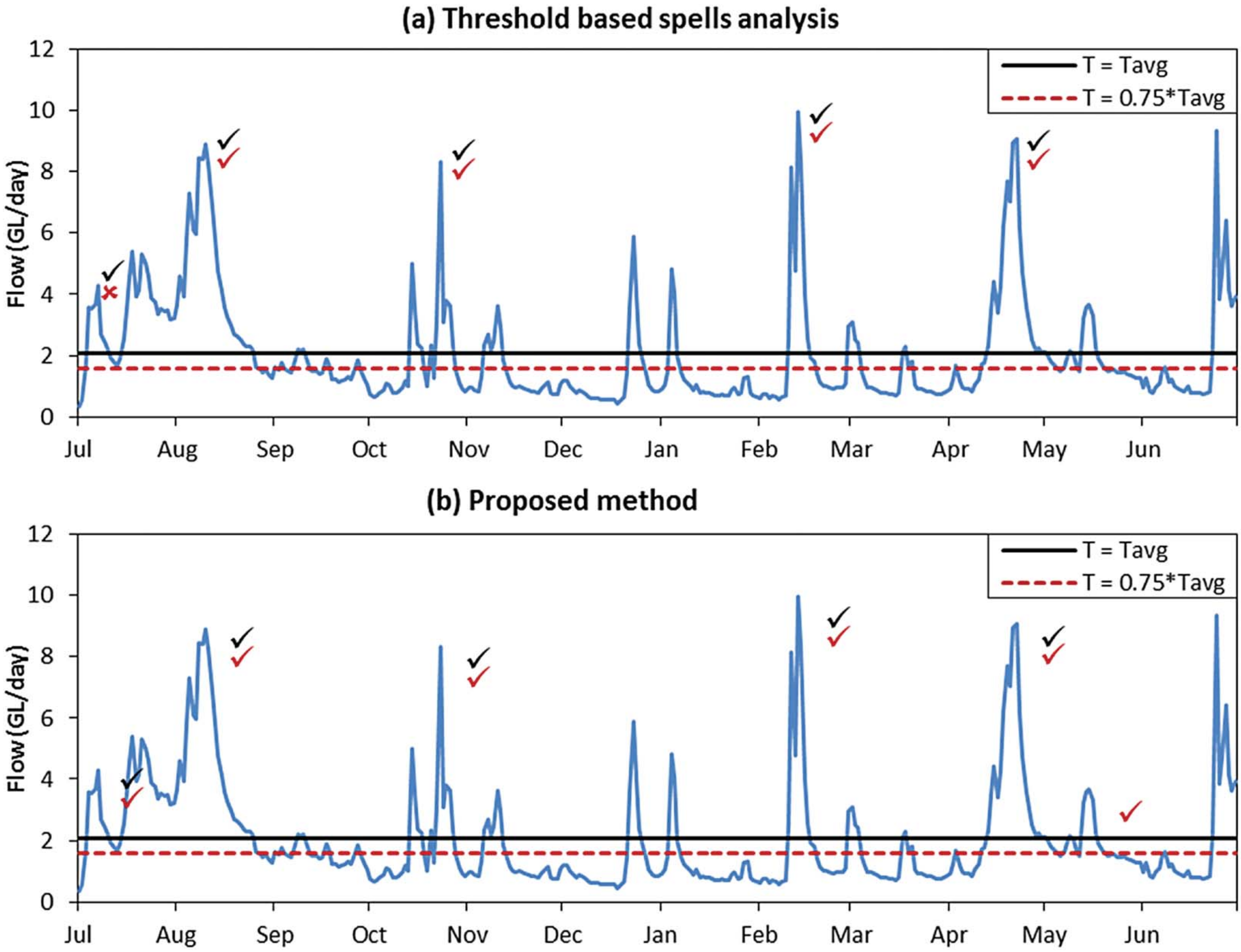

Figure 5. Flow in the Yarra River at Warrandyte showing independent flow spells of minimum duration of 6 days identified using (a) independence criteria based on days below threshold and (b) proposed independence criterion. Using a threshold-based independence criterion (a), only one spell is suggested at the threshold of $0.75^{*}T_{\mathrm{avg}}$ as flow does not fall below the threshold of $0.75^{*}T_{\mathrm{avg}}$ between the two spells. Using the proposed independence criterion (b), spells identified at the higher threshold being maintained at the lower threshold.

The second expert chose to identify spells for a low-growing stand of riverbank vegetation with the aim of looking after the growth and survival of established plants. Here the threshold identified is 2.5 GL, with a minimum duration of 1 day. Figure 8 shows the proposed method outperforms the threshold-based method (with K fixed to 0.9 in Example 1 and 0.715 in Example 2).

The analysis for the flow spells supporting low growing riverbank vegetation highlights the potential

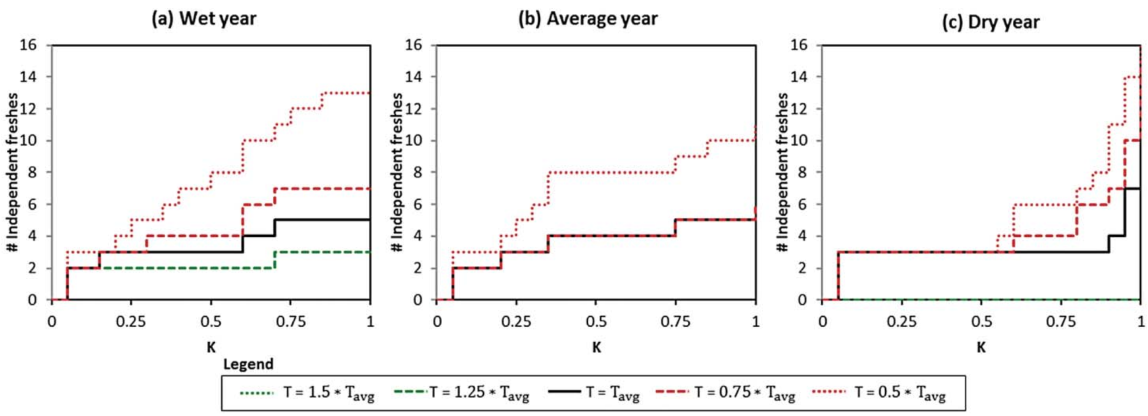

Figure 6. Sensitivity of parameter K on frequency of independent spells separated by at least 3 days and minimum duration of 7 days in regulated flows in (a) wet year (1995), (b) average year (1969) and (c) dry year (2006). As K increases, the total number of independent high flow spells also increases. The choice of K is less sensitive to identification of spells at higher thresholds as compared to spells at lower thresholds (as seen by the smaller gradient of the slope at higher thresholds).

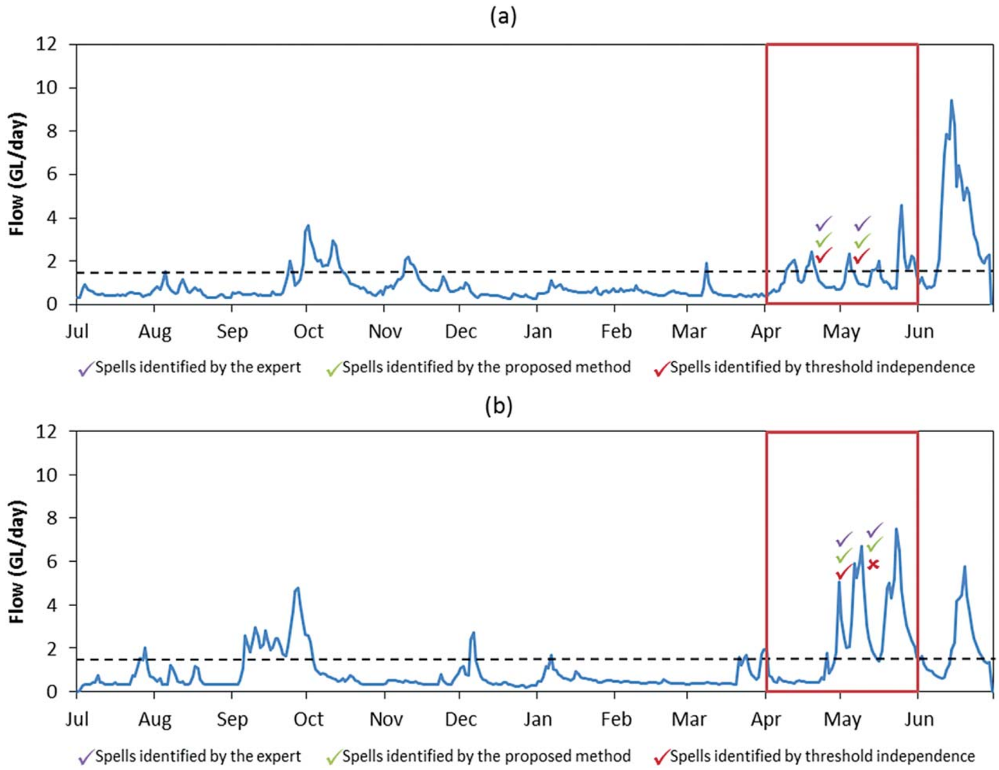

Figure 7. (Color online). Identification of flow spells for Australian Grayling Spawning in April and May.

challenge in selecting an appropriate value for the parameter K to ensure the correct spell events are selected for a given ecological endpoint. For 7 out of the 10 flow series tested, a K value of 0.6 correctly matched the flow spells identified by the expert. For the remaining three years of data, K values were between 0.7 and 0.9. As discussed previously, the parameter K represents the ratio between flow volumes in spells and the flow volume over their separation period: in some series this ratio is very low for the spells identified by the expert, whereas in others this ratio is quite high. The above illustrates the way in which the parameter K can be selected to be consistent with the ecological function of most relevance to the analysis. With increasing experience, we believe that experts should be able to derive a value or range of K

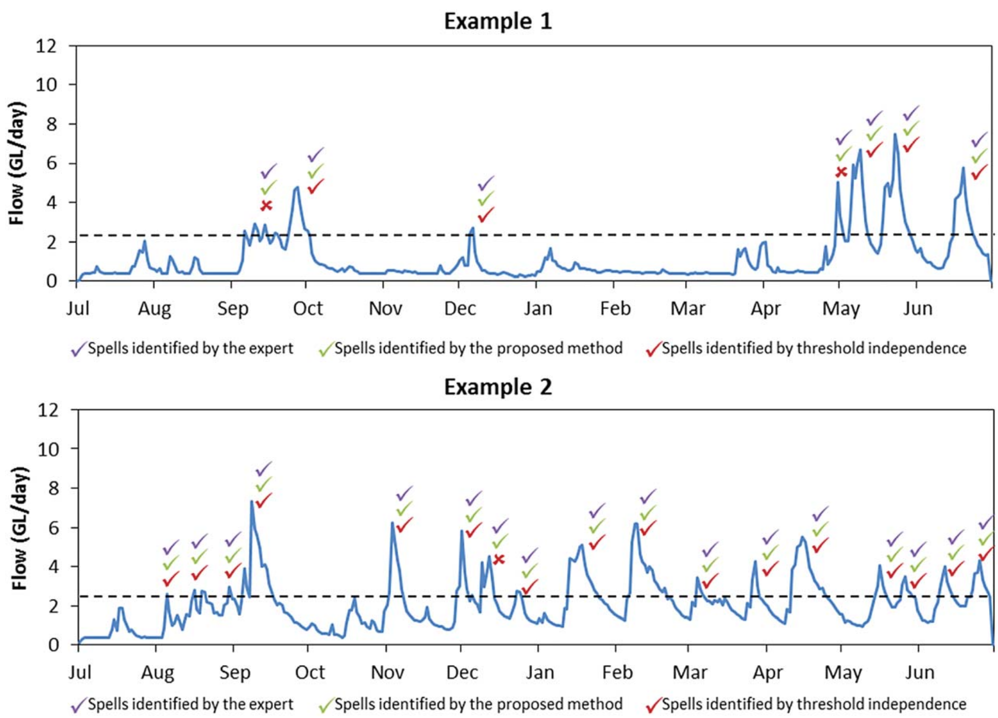

Figure 8. (Color online). Identification of flow spells for low growing riverbank vegetation.

that is relevant to the ecological endpoint under consideration. Over time, with more applications, it may be possible to derive default values for specific ecological endpoints.

6. Conclusion

The importance of flow spells for the ecological health of river systems is well-recognized (Poff et al. 1997). However, the commonly used statistical methods for analysis of flow spells are based on simple independence criteria that can confound attempts to meaningfully assess changes in spell frequency with different flow thresholds, as is required when inferring the ecological significance of a flow regime.

In this paper, we have developed a simple method that avoids the inconsistencies that can arise when using the traditional method of spells analysis, whilst remaining easy to implement. Importantly, this method includes a parameter K (which controls the ratio between the average flows in two independent flow spells and the average flows over the period separating them) that can be selected to help ensure that the results are relevant to the ecological processes of most interest. Selection of the parameter K requires input from the ecologists with site-specific knowledge, but such interaction between hydrologists and ecologists is a necessary part of any environmental flows study.

Hydrological indicators, such as flow spells analysis, play an important role in environmental flow assessments and compliance. However, as our management of environmental flows and understanding of flow-ecology relationships improves, it is important to revisit some of these indicators to ensure that they represent the ecological processes as best they can, and are inclusive of recent research. The proposed method in this paper retains the fundamental concepts of a spells analysis, but introduces a new independence criterion that ensures the spells analysis captures the specific events in a consistent manner and in a way that matches our current ecological knowledge.

Management of environmental flows to obtain best ecological outcomes in river systems has been recognized as an active area of research, with a number of decision support tools available to do the same. The simplicity and the analytical transparency of the proposed method make it easy to incorporate in such decision support tools. Furthermore, the proposed method provides greater precision in doing a spells analysis in such tools without decreasing their computational efficiency.

Note

1. Using publicly available flow data and environmental flows account volumes at McCoy's Bridge (gauge 405232), near the lower end of the system. Environmental water contributing to a high-flow event was defined as amounts debited to the environmental account on any day when total volume was greater than 940 Mld^{-1} (the highest baseflow recommendation for this part of the river; GBCMA 2014. Goulburn River: seasonal watering proposal 2014–2015. Goulburn-Broken Catchment Management Authority, Shepparton.), beyond that necessary to take total discharge in the system to 940 Mld^{-1}, i.e. only environmental water used beyond the high baseflow threshold. We appreciate the irony of calculating this statistic using the type of arbitrarily defined metric that this paper sets out to replace.

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