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# Quantifying environmental water demand to inform environmental flow studies

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**Abstract:** The process of undertaking an environmental flow study often results in the identification of ecologically important components of the flow regime, some of these flow components are ultimately implemented as formalised dam release or water harvesting rules. The quantification of environmental water is often not realised until specific flow rules or dam release rules are implemented within a detailed hydrologic model. However, this quantification of environmental water is valuable to the experts conducting the initial environmental flow study to 1) be able to communicate the priority of environmentally significant components of the flow regime; 2) consider undesired ecological effects such as unnatural looking saw-tooth flow regimes and 3) inform the dam release rules by advising on the ecological trade offs between release strategies such as augmenting existing high flows (often called piggy-backing) or relating the release rules to historical seasonal cycles.

We have developed a software utility 'eFlow tool', which can construct flow time series via augmentation of a current-case of flow by reconstructing environmentally important components of the flow. The user can adopt a range of flow augmentation strategies such as mimicking the natural frequency of events, augmenting existing flows, or waiting until the last possible day in the season of interest before allowing augmentation to commence. Augmentation strategies can also vary through time to reflect the observation that as the time since successfully achieving a specific flow component environmental flow increases, the importance in having the criteria met also increases.

The output from the eFlow tool allows users to quantify the additional water requirements of meeting specific environmental flow components and to then investigate the sensitivity of the water cost to different trigger flow thresholds or event durations.

***Keywords:*** *environmental flow, decision support, water demand*

## 1. INTRODUCTION

The environment is a significant 'user' of freshwater, and the environmental water requirements to restore or to maintain ecosystems are actively considered both in long term planning and in the year to year water allocation process. Where water resources have not been excessively prescribed such as in northern Australia, water resource planning can accommodate to 'quarantine' environmental water and ensure a proportion of the mean annual flow is reserved solely for environmental benefit. For these northern systems where the extraction of consumptive water is mostly through event harvesting, the management of environmental water is mostly by limiting the water extracted during events. The quantification of the environmental and consumptive components of the daily flow regime for water harvesting streams is relatively straightforward because the two components can be treated as separate additive components of the daily flow.

For catchments where water is much more tightly controlled through infrastructure such as dams, weirs and irrigation systems, like many of the southern Murray Darling Basin catchments, almost every mega litre of water passes through a water management structure, and as such could potentially be utilised for consumptive use. For these highly regulated systems, the pressures on using environmental water for consumptive use (irrigation and urban demand) are high and the economic benefits are directly measurable. The environmental benefit of allowing water to run free must be demonstrable and the limited amount of environmental water, particularly during drought years, means that it must be used in specific and targeted campaigns focused on high value environmental assets. Despite the smaller volume (proportional to flow) on using environmental water in highly managed regions, the large degree of water management infrastructure allows us to specifically time the release of environmental water. As such, we have a high degree of control over how flow may be augmented and therefore we have the opportunity to implement water saving strategies such as piggy-backing on tributary flows or consumptive water delivery to achieve the environmental benefits of high discharge events.

There are many variations in approach taken to conduct environmental flow studies (See AcreMan and Dunbar, 2004 and Tharme, 2003 for reviews). However, most approaches used in Australia will at some stage define important components of the flow regime. Cottingham *et al*., (2005) provide a good illustration of this by summarising the recommended flow components from environmental flow studies for the rivers of the state of Victoria (Australia). Environmental flow studies often compare flow alternative water management scenarios in terms of how well each scenario meets the recommended components of the flow regime and interpret the likely environmental consequences of each flow regime.

In this way the environmental flow assessment project team is provided with a series of flow scenarios and asked to recommend the least worst scenario, with limited opportunity to review the water cost of reinstating specific components of the flow regime.

The value of prioritising and reviewing the relative water cost is best illustrated with an example. The six key flow components in Table 1 are for the lower reach of the Werribee River (Victoria) (Ecological Associates, 2005), and each flow component is important for meeting between two and six environmental criteria. These environmental criteria relate to physical processes such as mobilising substrate or disturbing pioneer vegetation, or biological process such as queues to trigger spawning or movement, habitat such as providing pool space or connectivity between pools for fish or water regimes for riparian vegetation. The environmental criteria are not all of equal importance to be met for every year, and the social demands of ecological consequences mean that some of these are more important than others, or have a higher social value. Whilst not directly stated, the approach to preserving environmental assets is a risk assessment based model where the value of a particular environmental asset is arrived at through a social process of defining and prioritising environmental values. We should therefore continue this hierarchical priority in the delivery of water by providing clear preferences to the most important components of the flow regime. Thereby meeting all flow requirements in those years when water is available, but delivering water to the increasingly important environmental features in years of water scarcity.

The use of environmental water is essentially a trade off against consumptive use. Hence, the description of the environmental water need should be presented along with the amount of water required to meet that need, essentially allowing consideration of the forgone consumptive use to achieve that environmental benefit. It is relatively straightforward to create an augmented flow regime using a spreadsheet by considering one or two key flow components. However, this rapidly becomes a very difficult task when simultaneously considering multiple flow components as demonstrated in an example in section 3. A solution for determining the preliminary water cost of meeting a prioritised list of flow objectives is presented here in the form of the eFlow tool, the basic architecture and logic is described in Section 2 and its application demonstrated with the example flow components from Table 1. Before describing the tool we describe some of the key concepts which we have used in developing the computational procedures used in the tool.

### 1.1. Key features required to prescribe environmental water demand

The process of defining a daily environmental requirement is similar to the process of determining consumptive demand, whereby algorithms must be developed to determine the cumulative consumptive demand. The key features of algorithms to determine the environmental water demand which have been incorporated into the eFlow tool are:

1) Mutually beneficial flow components. For example: by achieving flow component 2 (Table 1), the requirements of flow component 1 are also partially met, so the water cost of meeting these rules is not additive.
2) Mutually exclusive flow components. For example: consider flow components 2 and 4 in Table 1 - in achieving flow component 2, a period of 14 days is required between events; if we are in a period between events and have the opportunity to provide an event to meet flow component 5, then a priority must be given to allow the most environmentally beneficial of the two competing flow components to be met.
3) Water availability. For example: to provide any additional water, one must maintain a budget of accessible environmental water available for release.
4) Operational Constraints. For example: to achieve flow component 6 (overbank flow) then the engineering constraints of maximum release on from the reservoir must be considered.
5) Reference to natural flow. For example: to highlight that a given flow component would not always be met under the pre-development conditions, prescribed environmental flow components are often only triggered if they would have occurred naturally (flow components 1-4 Table1).
6) Multiple year performance. For example: flow component 6 in table 1 (bankfull) is only required once in 10 years, hence the measure of the successful completion of flow components must be able to consider multiple years.
7) Flow augmentation strategies. For example: the cost of supplying water to meet a flow component will be reflected in the strategy used to meet the flow component. Consider the difference between adding water to extend an existing high flow to the required duration, compared to waiting until the last possible moment in the season (in case the flow requirement is met by natural storm events), and only augmenting the flow if the flow component has not been met.
8) Risk based approach: The flow component prescribed in Table 1 are absolute, consider flow component 3; if the flow falls below 36 ML/d for one single day between June and December then this flow component has failed, in the same way that if their was no flow for the entire period. Clearly there is some environmental value in almost meeting the flow requirement, hence the measurement of the success of flow components should allow a mechanism to report these sub-optimal but better-than-nothing conditions.
9) Realistic measure of Water Cost: The allocation of water is necessarily suboptimal because we do not know what the future conditions will be. Hence, operational decisions on water allocation are based on knowledge from previous years and the current demand. The determination of flow augmentation costs should, where possible, replicate this limitation.

## 2. EFLOW TOOL

In order to determine the environmental water demand to augment a flow scenario which is the modelled current climate including consumptive demands, we considered two alternative approaches. The first, and simplest to implement was to stochastically generate many flow scenarios, then assess how these scenarios perform against the desired flow components. This effectively allows an optimal solution where the cost functions of water use and flow component performance can be the focus for the optimisation. Whilst this would provide the minimum water cost result, we chose not to apply this stochastic approach because the conversion of the resulting optimal flow regime into operational flow rules is difficult and the value of the tool would remain a theoretical minimum water cost to deliver environmental water rather than inform the appropriate operational modes of flow augmentation. Instead, we started with the premise of using the constraints to flow augmentation such as reservoir delivery capacities along with delivery strategies such as piggy-backing on tributary flows, extending existing events and mimicking natural flow. From this point we have provided the user the ability to rank flow components and to choose the strategies of flow augmentation for each flow component. The prescribed augmented flow may not have the lowest possible water cost, but it does conform to current operational constraints and is therefore a more realistic measure of the cost of implementing environmental water than a stochastically generated and then optimised flow.

**Table 1** Werribee River below Melton Reservoir flow recommendations (Ecological Associates, 2005)

| **Flow** | | | | | **Rationale** |
|---|---|---|---|---|---|
| | **Season** | **Magnitude** | **Frequency** | **Duration** | |
| 1 | Jan - May | Low flows 10 ML/d or natural if natural is less | all years except extended drought | residual time after other flows | *Fish*: maintain pool refuge habitat<br>*Macroinvertebrates*: inundate in-stream macroinvertebrate riffle habitat; maintain pools for drought intolerant macroinvertebrate fauna<br>*Platypus*: maintain refuge pools in summer and Autumn; maintain stable undercut benches for burrows and feeding habitat.<br>*Geomorphology*: maintain natural variability in base flows to maintain bank stability |
| 2 | Jan - May | Low flow freshes 167 ML/d or natural if natural is less | 3 per year minimum event separation 14 days | 1 day | *Fish*: maintain pool water quality during low flows; allow passage of River Blackfish fry between pools.<br>*Macroinvertebrates*: flushing of fines or sands for macroinvertebrate habitat<br>*Platypus*: scour fine grain sediments from the base of pools and silt from riffles; maintain pool water quality during low flows |
| 3 | Jun – Dec | Base flows 36 ML/d or less if natural is less | annual | Residual time after other flows | *Fish*: allow passage of River Blackfish adults; provide deep spawning habitat in pools or submerged rocks and snags<br>*Vegetation*: in-channel flow to sustain in-channel macrophyte growth (including marginal vegetation) in winter and spring<br>*Platypus*: flow extends laterally to bench habitat during reproductive period from late winter into summer |
| 4 | Jun – Dec | High flow freshes 350 ML/d or natural if natural is less | 5 in Jul to Sep 2in Oct to Dec minimum event separation 5 days | 5 days | *Vegetation*: high flow to inundate shrub assemblages on benches and support growth in winter and spring; support the growth of emergent macrophytes in the riparian zone by providing falling water levels during the transition from spring to summer |
| 5 | All | Bank full flows 4000 ML/d | Natural (1 per year) | 1 day | *Vegetation*: disturb shrubby vegetation on benches<br>*Geomorphology*: scour pools / mobilise riffles, achieve " effective discharge" for sediment transport (equivalent to morphologically defined bankfull discharge) |
| 6 | All | Overbank flow 28,000 ML/d | Natural (1 in 10 years) | 1 day | *Macroinvertebrates*: intermittent turning over of substrate via bed mobilisation<br>*Geomorphology*: grass removal from benches to allow reworking of sediments in gross channel forms |

***Hydrologic Representation***

The eFlow tool has a very simple hydrologic representation and has been designed for future coupling to sophisticated hydrological models. The eFlow tool relies on simulated daily time-step time series of the natural (pre-development) flow sequence and the simulated developed flow sequence (D and E in Figure 1). Where water is to be supplied from a reservoir, the storage capacities, modelled inflows and outflow constraints of the reservoir can also be used as well as a simple representation of gains (tributary inflows) and losses (seepage, extraction) that may occur between the reservoir outlet and the target reach for the environmental flow (Figure1).

***Flow components***

Each of the flow components such as those described in Table 1, is defined in terms of either a high or low flow spell analysis (all of those in Table 1 can be presented as high flow spell analysis). The spell is defined in terms of the:

- Period of Interest - the time span in a given water year in which the rule should be applied.
- Spell definition criteria including the flow threshold, minimum spell length, total duration, spell independence (minimum period between spells).
- Measure of success - spell duration, flow volume, number of spells per period of interest).

***Flow augmentation methods***

Once the flow component is defined we can prescribe a preference for how the flow should be delivered. For example, the first flow recommendation in Table 1 describes the 'frequency' as all years except extended drought. That is, the flow delivery strategy for some flow components may require a given flow to be delivered each and every year. Others rely on reference back to what would have occurred under pre-development conditions in order to make a judgement as to whether the flow should be augmented. In the eFlow tool, we have implemented six alternative flow augmentation strategies (Table 2). Any combination of flow augmentation strategies 1-4 can be applied to each flow component, and augmentation strategies five and six can be applied uniformly across all flow components.

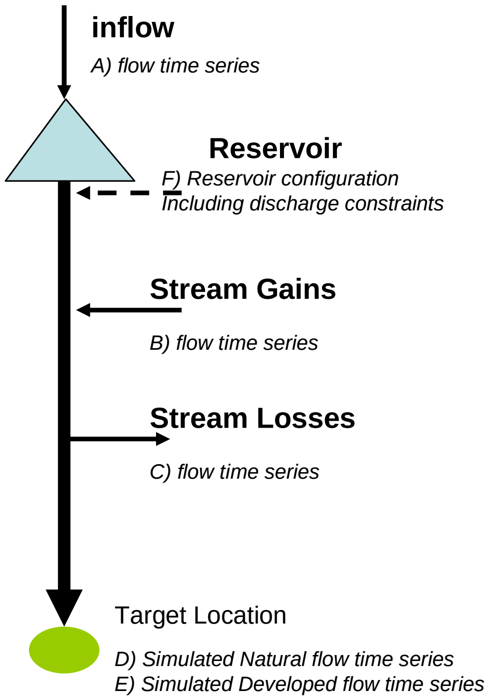


**Figure 1** Hydrologic representation used by the eFlow tool.

Firstly if the absolute is selected, the tool simply forces the flow objective to be met in each and every water year. However before forcing the flow objective to be met, one may choose to try other flow augmentation criteria and only force the augmentation as a last resort.

**Table 2** Alternative basis for flow augmentation

| Strategy | Description |
|---|---|
| 1) Extend Spells | If the spell threshold criteria has been met on the previous day, but the duration criteria has not been met, then release enough water on this day to allow the spell to continue. |
| 2) Would it occur naturally on this day? | Without regulation would there be a spell today? |
| 3) Force | If the flow component has not been met and we are approaching the end of the defined season then augment the flow to ensure the flow component is met. |
| 4) Force – variable years | This is the same as the 'Force' strategy although the user can choose the required return interval to force the flow. For example 'force this flow requirement every four years if the other flow augmentation strategies have not achieved the flow component.' |
| 5) On average did it occur on this day in previous years for the natural flow regime? | Without regulation was this day in spell for the majority of previous years? |
| 6) Would it occur under the Current regime on this day? | Where there are mutually exclusive flow rules, we choose to not augment the flow, this effectively adopts the least water cost approach where there is a conflict between flow requirements. |

The basic computational procedure for each flow component ('rule' in Figure 2) for each day of the record is diagrammatically shown in Figure 2. The 'constrained' cases in Figure 2 rely on reference to a definition of reservoir capacity, inflows and outflow constraints; the 'unconstrained' case places no limitation on water availability and may be utilised in a first iteration use of the tool, to gain a sense of the order of magnitude of water requirements before a more detailed investigation into all constraints.

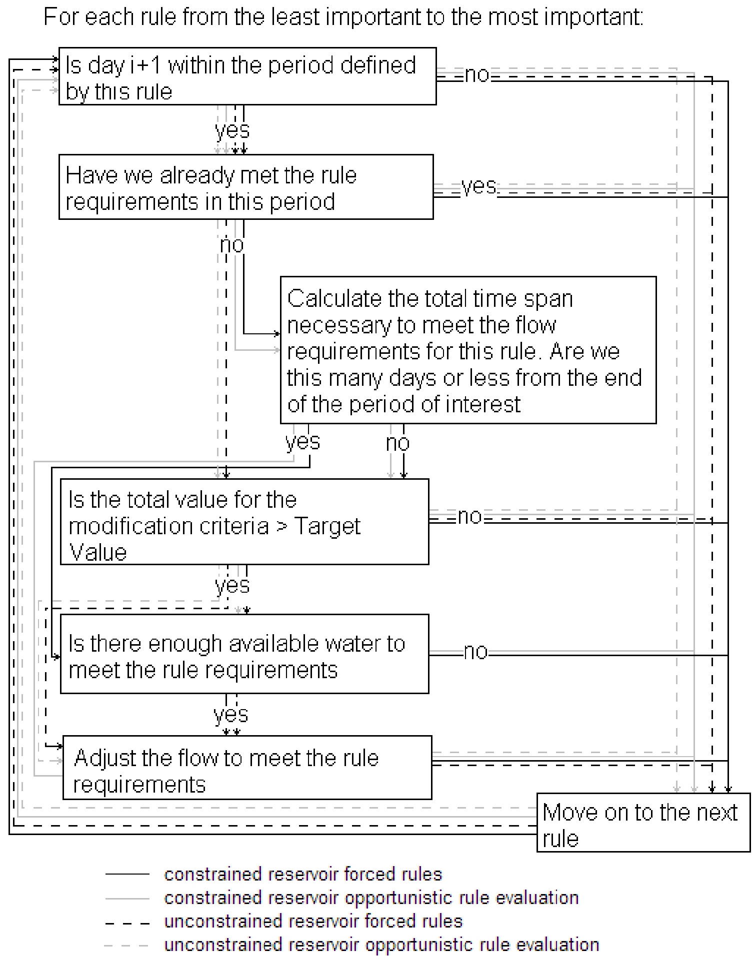


**Figure 2** Programmatic flow for assessing rules for all alternative cases

## 3. CASE STUDY EXAMPLE: WERRIBEE RIVER DOWNSTREAM OF MELTON RESERVOIR

To demonstrate the eFlow tool, the flow components for the lower reach of the Werribee River (Victoria) (Table 1) have been used along with example data sets which reflect simulated natural flow and flow under current diversions for the period 01/01/1960 to 31/12/1999.

The simulated pre-development regime has a mean daily flow of 271 ML/d compared to 218ML/d under the simulated regulated regime, due to upstream extractions. We set up the eFlow tool with a flow rule representing the first five of the six flow components in Table 1 (the overbank flow component (flow component 6) is met at the same frequency under the natural and regulated case hence we have excluded it from the analysis. The default settings for flow augmentation are to have flow augmentation strategies 1 to 3 on for all rules and to have augmentation strategies 4 to 6 off for all strategies. Run 1 (Table 2) demonstrates the results of flow augmentation for the default settings. The water cost for Run 1 was an additional 12GL/year, however we can see that all off the flow components are achieved more frequently under the augmented regime than would have occurred under pre-development conditions.  For Run 2 we have turned the ‘force’ requirement off for all flow components, and the total additional flow required has more than halved to 5.3 GL/year. However, the frequency of flow components 1 to 3 continues to be above the natural frequency. Consider the base flow components (1 and 3), rather than require these components to occur each and every day of the specified season we have relaxed the criteria in Run 3 and only require them to occur 80 percent of the time (although with the requirements that spells must occur for at least 20 days to avoid counting short spells which may have limited environmental benefit). For Run 3 the total additional water required to achieve these flow components and approach the natural frequency of occurrence was 5 GL/year.

Additionally, we can include the release constraints of the upstream reservoir (Melton Reservoir), such that the capacity to deliver the environmental flow component is further constrained by the outlet limitations and available water supply.

**Table 3** Lower reach of the Werribee River example results

| Flow component | Performance: number of times the flow component was successfully achieved (1960-2000) | | | | | |
|---|---|---|---|---|---|---|
| | Target number | Number achieved | | | | |
| | | Natural Flow | Current flow | Run 1 | Run 2 | Run 3 |
| 1) Jan - May 10ML/d minimum flow | 40 | 4<br>25* | 6<br>33* | 40 | 40 | 40 |
| 2) Jan-May 167 ML/d small freshes | 40 | 17 | 33 | 36 | 34 | 34 |
| 3) June-December minimum flow | 40 | 33<br>38* | 11<br>32* | 40 | 40 | 40 |
| 4) June-December 350ML/d Fresh | 40 | 30 | 12 | 34 | 30 | 30 |
| 5) 4000ML/d bank full flow | 40 | 28 | 21 | 40 | 28 | 28 |
| Water use summary | | | | | | |
| Mean Daily Flow (ML/d) | | 271 | 218 | 251 | 232 | 231 |
| Mean Annual Flow (ML/year) | | 98978 | 79545 | 91657 | 84883 | 84502 |
| Water Cost to move from current flow to scenario(ML/year) | | | | 12112 | 5338 | 4957 |

Run1: Flow rules as specified in Table 1;
Run2: modified Augmentation criteria (force turned off)
Run 3: relaxed the criteria for base flows in flow component 1 and 3
* How the relaxed base flow requirements in run 3 perform against the natural and current flow.

## 4. DISCUSSION AND CONCLUSIONS

When conducting environmental flow studies it is valuable to be able to investigate the water cost of reinstating different combinations of flow components so that the sensitivity of flow thresholds on the water cost can be established. The water cost of augmenting the flow to meet multiple flow components is not additive because when meeting some flow components others are also partially met. Hence, the process of augmentation is not a trivial additive process. The eFlow tool considers all environmental flow requirements for every day of the record, along with preferred augmentation strategies, to calculate a realistic water cost of augmenting the existing flow.

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