Developing a seasonal environmental watering tool

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Abstract

There is significant pressure on freshwater systems worldwide as consumptive demands for water increase relative to the available resource, severely affecting flow regimes, and hence negatively impacting river ecosystems. A key element of Australia's approach to improve the ecological health of these systems has been large public investment in water entitlements. Management of these entitlements to achieve the best possible environmental outcomes requires ongoing active decision making on a season by season basis. These decisions include the delivery of water to competing environmental assets, the timing of these deliveries, the carryover of water to provide for the next season or the trade of water. These decisions are complex due to the multiple temporal and spatial scales. How this environmental water is managed in an efficient and transparent way, especially in the face of uncertainty in future rainfall locations and volumes, presents challenges. A potential tool to assist environmental managers to understand and assess this complex decision space is optimisation. Optimisation has been used in water resource management, mainly in long term planning of environmental and consumptive water use, however there has been limited focus on seasonal environmental watering decisions, and scant attention to making decisions that hedge against possible future stream flow realizations. Thus this paper describes the seasonal decision space (including the objectives, drivers, constraints and decisions available), and demonstrates how uncertainty in future rainfall and streamflow can be incorporated into a decision support tool.

1. INTRODUCTION

The environmental water reserve, or environmental entitlements, require active and ongoing management by environmental water holders to ensure that the best possible environmental outcome is being achieved with the available resource (Horne et al. 2010). Decisions are needed around the timing and volume of environmental water delivery, along with the choice of water source and delivery pathways. When volumes of water are limited, adequate flow cannot be provided to meet all environmental demands. Trade-off decisions are frequently required between competing environmental objectives in different river reaches, or objectives achieved with different environmental flow components and timings (high winter flow rather than low summer flow) in the same reach. This spatial and temporal complexity makes it difficult for environmental water managers to process all available information and make transparent decisions. Current decision-making for environmental water delivery is based upon the accumulated experience of managers – so-called 'experience-based practice' (Cook et al. 2010).

The Seasonal Environmental Watering Decision Support (SEWDS) tool uses optimization to consider how best to release environmental water to meet a given set of environmental objectives. Optimization has previously been used for environmental watering decisions, however these studies have broadly investigated either short-term operational decisions (for example, Cioffi and Gallerano 2012), or longer-term planning decisions (for example, Grafton et al. 2011, Szemis et al. 2013). The SEWDS tool brings together information about the water resource system, ecological responses to flows and environmental objectives to inform seasonal watering decisions. This paper discusses one specific aspect of the tool, namely how uncertainty in future rainfall and streamflow will be considered. In order to tackle uncertain future climate conditions, a Multi-Stage Stochastic Mixed Integer Programming framework is adopted (see for example, Shapiro et al. 2014). The adopted framework models the possible realizations of the uncertain process (here streamflow) in the future by means of a discrete number of possibilities. The stochastic model provides contingency plans for all possible future scenarios, and importantly, at each time point in the planning horizon. Solutions obtained from the model implicitly consider all possible environmental futures, with their importance weighted by their relative probabilities. Assuming that the scenarios are broadly representative of what can happen in the future; this leads to decisions that hedge against future uncertainty. The stochastic programming model also embeds learning, automatically adjusting the likelihoods of future scenarios to take into account what has occurred so far during the planning horizon.

The paper begins with an overview of the seasonal planning process (Section 2) and then presents a demonstration model in Section 3. Conclusions and next steps are presented in Section 4.

2. THE SEASONAL PLANNING PROCESS

Figure 1 provides a high-level overview of the decisions available to an environmental water manager and the various factors that will influence these decisions. The decisions available include the decision to release, trade or carryover water and the decision to access unregulated or supplementary flows. In general, decisions to release water or access unregulated water occur at the monthly or sub-monthly timescale, while decisions on trade occur quarterly (or thereabouts), and carryover is an annual decision. The most significant factor to influence watering decisions is climate and resulting stream flow. This in turn influences allocation levels (and water available to both irrigation and the environment).

The current seasonal environmental water planning approach uses climate scenarios, with priority actions identified for different representative year types (MDBA 2012). This approach is a significant improvement on previous planning where a single suite of environmental flow recommendations was applied across all climate scenarios. By identifying priorities for different year types, the seasonal environmental watering approach is better positioned to achieve outcomes in extreme conditions. However, a practical challenge remains for environmental water holders. How does one know in advance whether the year will be very dry, dry, average or wet? In fact, if the year begins as an average year, this may well be followed by a dry season before returning to average late in the year. This is demonstrated in Figure 2, where the streamflow patterns are shown for each climate scenario (dry, average and wet based on 10^{th}, 50^{th} and 90^{th} percentile annual flows), with the actual observed streamflow shown to cross these.

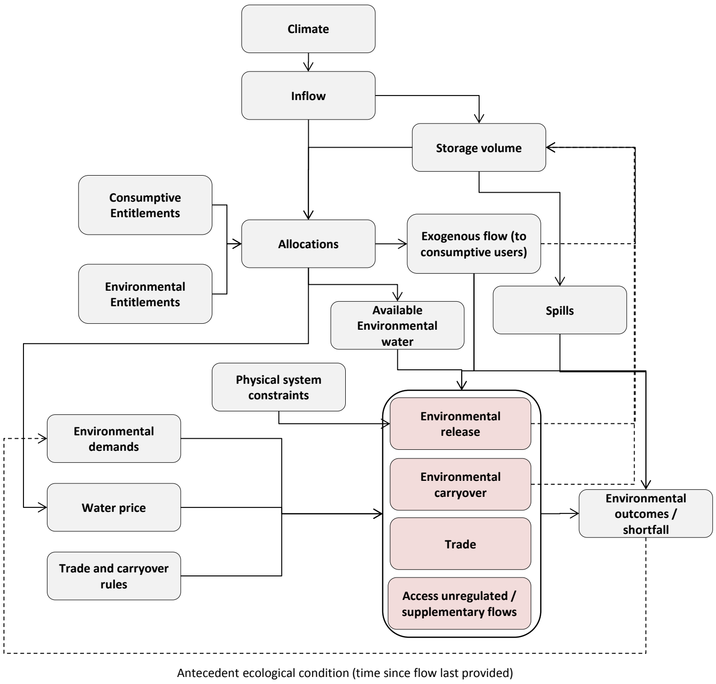

Figure 1 Overview of seasonal environmental watering decision space (decision shown in red)

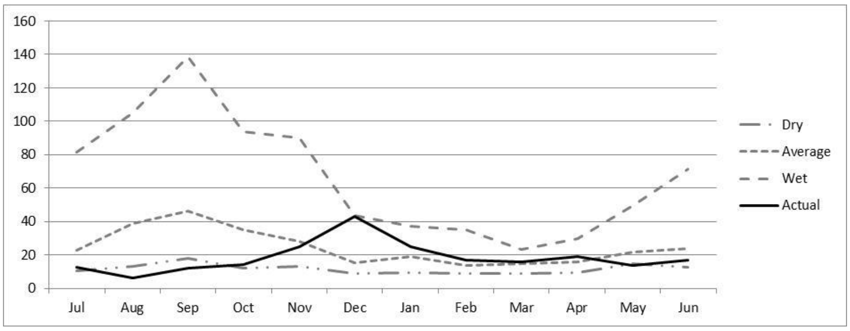

Figure 2 Seasonal planning scenarios

3. SEASONAL ENVIRONMENTAL WATERING DECISION SUPPORT TOOL

3.1. Model overview

SEWDS aims to be a flexible optimisation tool that can help the decision-maker evaluate a number of complex situations in a fast, transparent and consistent manner. The main outputs to be provided by the system are recommendations concerning monthly-scale environmental water release decisions. Importantly, this is a decision support tool, not a decision-maker. The tool is not aimed at providing “a solution”. Rather, it is anticipated that the tool will be used to test different conditions and scenarios, in order to help environmental water managers understand the likely ecological effects of different decisions, and how different environmental drivers may change the way that the environment responds. Summarising the information in the decision space shown in Figure 1 Overview of seasonal environmental watering decision space (decision shown in red)

the optimisation model can be described as a set of mathematical equations that represent the constraints and the objective function in terms of the decision variables. This general model is instantiated by using input data from the system at hand (see Figure 3). In the case of a deterministic model, all inputs are assumed to be known in advance while in a stochastic model, unreleased information (such as the streamflow in the future) is considered via a set of scenarios representing possible realisations of the data. In both cases, the proposed optimisation model aims to make environmental release decisions that minimize environmental risk over a 12 month seasonal planning period, given a known allocation, and across all environmental elements.

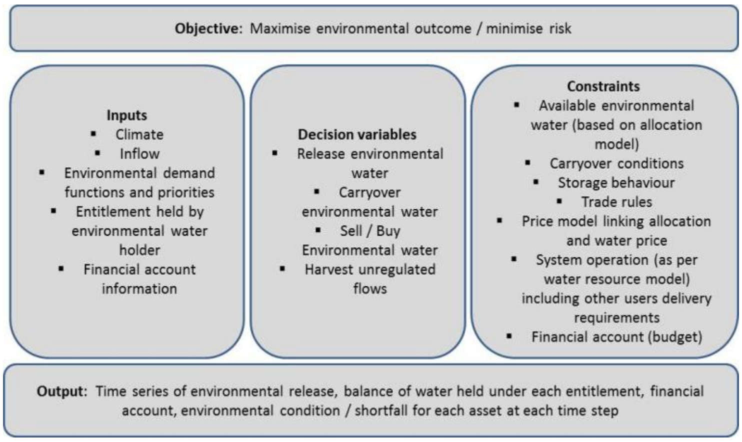

Figure 3 Overview of optimisation model

3.2. Demonstration case

A simple demonstration model is used to illustrate the potential for optimisation to assist environmental watering decisions, and the differences between a deterministic and stochastic approach. The system consists of two reaches, one immediately downstream of a storage and the other downstream of a weir. For the purposes of this demonstration, the model does not explicitly include storage operation, and a predefined inflow series is used instead. This assumes that there is no interaction between environmental decisions and storage spills or irrigation deliveries. Obviously this is a significant (and probably incorrect) assumption, and it will be addressed in the final model development process for the project by modelling the key aspects of the water resource system within the optimisation model. Similarly, the environmental allocation is known at the start of the modelling period. In development of the final model, this will be adjusted to match the current system where allocations are announced throughout the year.

The flows in the two river reaches caused by irrigation demands, local inflow and spills, differ significantly. There is a seasonal flow inversion in Reach 1, and flows are significantly reduced from natural conditions in Reach 2. The flows are shown in Figure 4 for dry, average and wet conditions, and low, medium and high storage levels. The flows vary both due to changes in natural inflow and due to changes in irrigation allocations and demands. The figures show the huge variation that can occur in a "dry" year depending on storage conditions (and similar outcomes for average and wet years). This is most apparent for Reach 1.

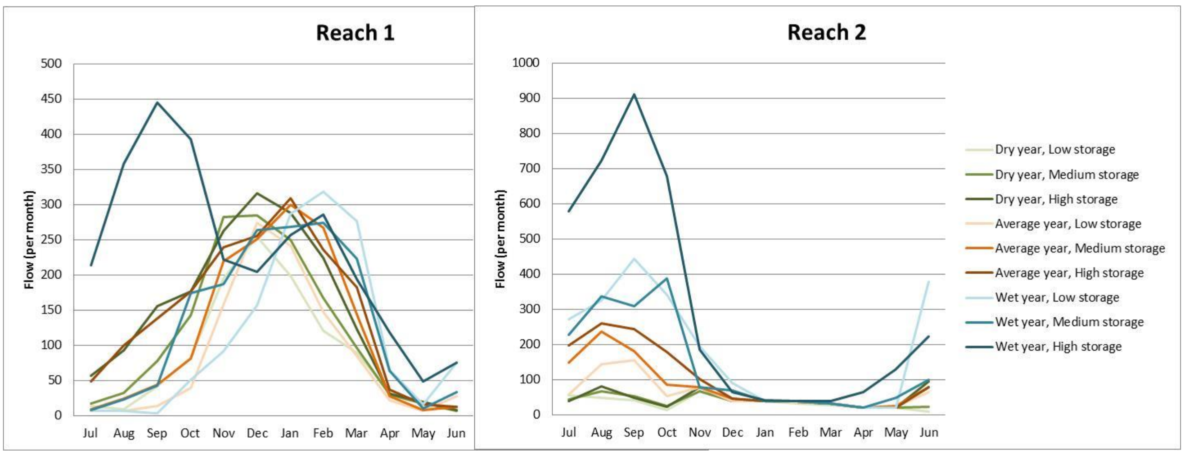

Figure 4 Exogenous flow (spills, runoff and irrigation releases) (a) Reach 1 (b) Reach 2

For this demonstration model, the objective function is calculated as the arithmetic mean of risk ratings for all flow components across both reaches. Many other methods can also be used to combine risks/benefits across different environmental elements and spatial units representing more complex interactions between components. The specific form of risk is not specified, but could be considered as either a failure of an annual event (e.g. breeding), or the risk of local extirpation of the taxon. The decision variables represent how much water to release from storage at the top of the catchment (one release location / decision) at each month, knowing that an environmental water release into Reach 1 also passes through Reach 2, providing additional flow at both locations (i.e. the release decision influences the outcome in both reaches).

3.3. Representing environmental demands

Environmental demands are represented in this case study as a series of environmental response curves based on habitat requirements (Figure 5, Figure 6). These curves were developed based on habitat rating curves (Horne et al. 2010). The varying shapes of the curves reflect that some elements of the ecosystem require flows to be within an ideal range, while others respond to trigger events. They also illustrate different environmental requirements at different times of year (summer and winter) for some species. These response curves are included for demonstration purposes and more complex and species based models will be developed as the SEWDS project progresses.

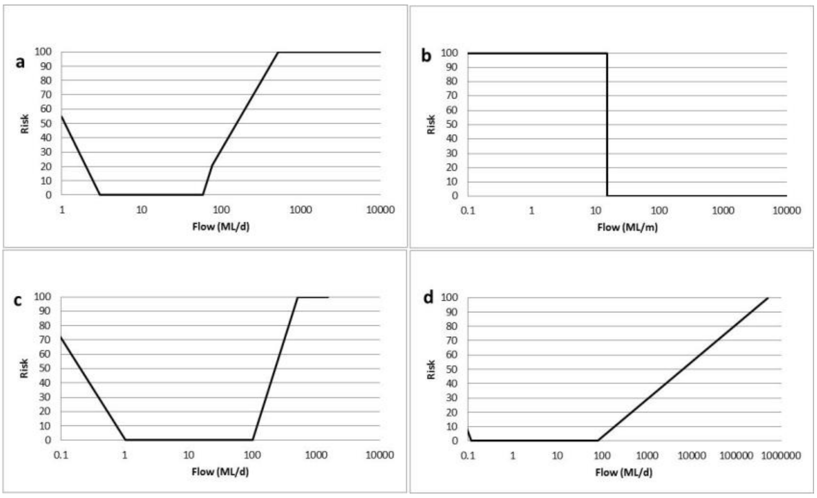

Figure 5 Reach 1 Environmental response curves for monthly flow (a) Shallow habitat required Jan - Mar (b) Wetland inundation requiring one flow event between Jul - Oct (c) Riffle habitat required Dec - May (d) Velocity required flow Dec - May

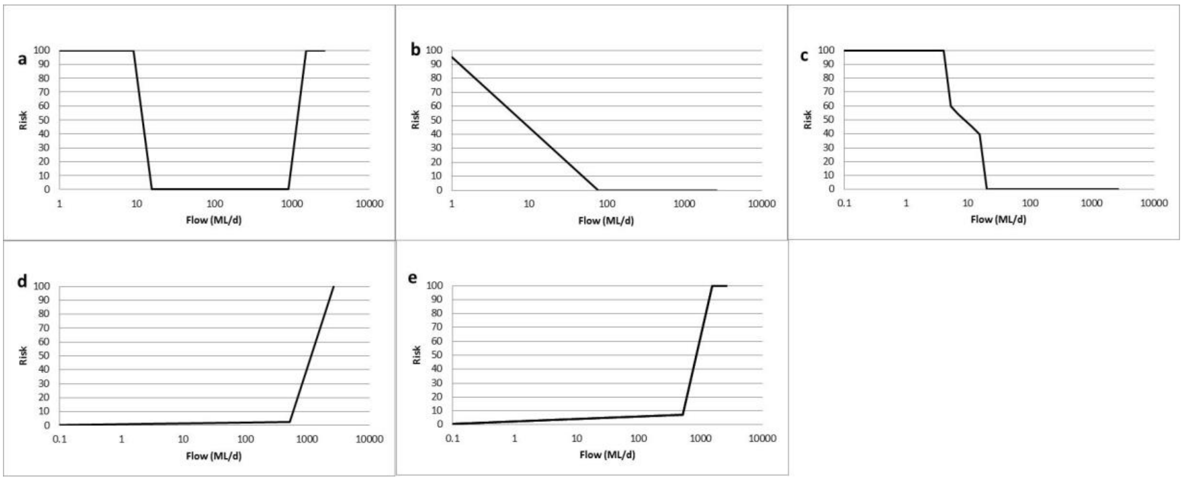

Figure 6 Reach 2 Environmental response curves for (a) Slow shallow habitat (Jan – Mar) (b) Deep water habitat winter (Jun – Nov) (c) Deep water habitat summer (Dec – May) (d) Shear stress causing flows (Jun – Nov) (e) Shear stress causing flows (Dec – May)

3.4. Incorporating a scenario tree

As described above, variation in climate is often considered in the context of water resources as a range of independent scenarios. We can apply a similar approach within the SEWDS tool when optimizing for environmental water releases. In Figure 7, 16 scenarios are shown with the rainfall (and streamflow) climate varying throughout the year on a seasonal basis.

Note that while the climate changes seasonally, the time-step for flows is still monthly. Even when the year commences as dry, there are different release decisions depending on how the remaining seasons unfold. If an optimisation model is run for each of these deterministic scenarios, the output will produce the optimal release pattern *provided* this is actually the climate sequence that eventuates. There is no way to average these results across scenarios to reach optimal decisions. This can be demonstrated comparing the suggested release patterns for Scenario 1, 2 and 6. In Scenario 1, the entire year remains dry. There is a large release late in the water year (June) to meet deep water habitat requirements in Reach 2. In comparison, in Scenario 2, the last part of the water year exhibits average rainfall and passing flows in Reach 2 provide for deep water habitat requirements in June without an additional environmental release. On this basis, the recommended release pattern has a high release in November to meet deep water habitat requirements at this time of year. In Scenario 6, the year commences dry, but then becomes wetter. This reduces the requirements for additional environmental water to meet deep water habitat requirements in June or November. Flows can therefore be released at the start of the water year for other environmental demands.

Instead, rather than thinking of these outcomes as individual scenarios, we can consider the possible future scenarios within a scenario tree that represents how the year may unfold. Figure 7b shows the same scenarios presented in a scenario tree, where the scenarios are grouped based on how the year unfolds. Note that this is a demonstration case and that in practice the probabilities assigned to each branch would demonstrate some correlation to previous streamflow. Scenarios 1 and 9 diverge in spring, while scenarios 1 and 4 diverge in autumn. Probabilities are associated with each branch of the scenario tree. If the model is run using a stochastic approach, the recommended decision at a particular time-step takes into consideration all the possible future scenarios from that point in time, and hedges the decision at that time-step against these possible futures.

The stochastic model assumes that some time is needed to observe differences in rainfall (streamflow) before the decision-maker can be sure that two scenarios are different, and respond accordingly. In the model, the length of time needed before learning occurs and the decision-maker can respond to differences observed, which we call the *learning lag*, is a flexible parameter. For the experiments discussed here, the learning lag was set to one season. Thus the environmental release decisions must be identical for all months in spring, since the differences between scenarios 1-8 and 9-16 in spring cannot be learned, or acted on, until the start of summer. Similarly, all release decisions made in the model for the summer months must be identical in all scenarios 1-8, but these can be different to the decisions made in scenarios 9-16.

(a) (b)

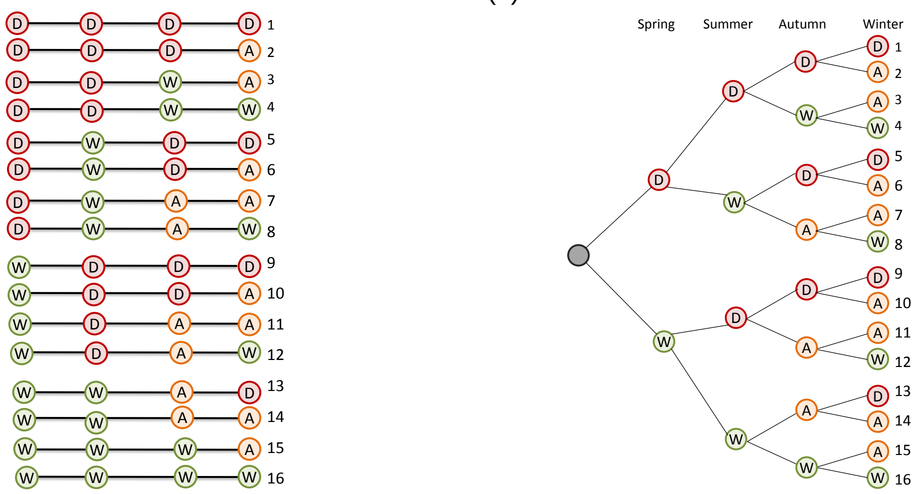

Figure 7 (a) Independent climate scenarios - 16 deterministic series showing seasonal variation in climate conditions (b) Scenario tree with seasonally changing climate conditions (note equal probabilities of each branch in this example)

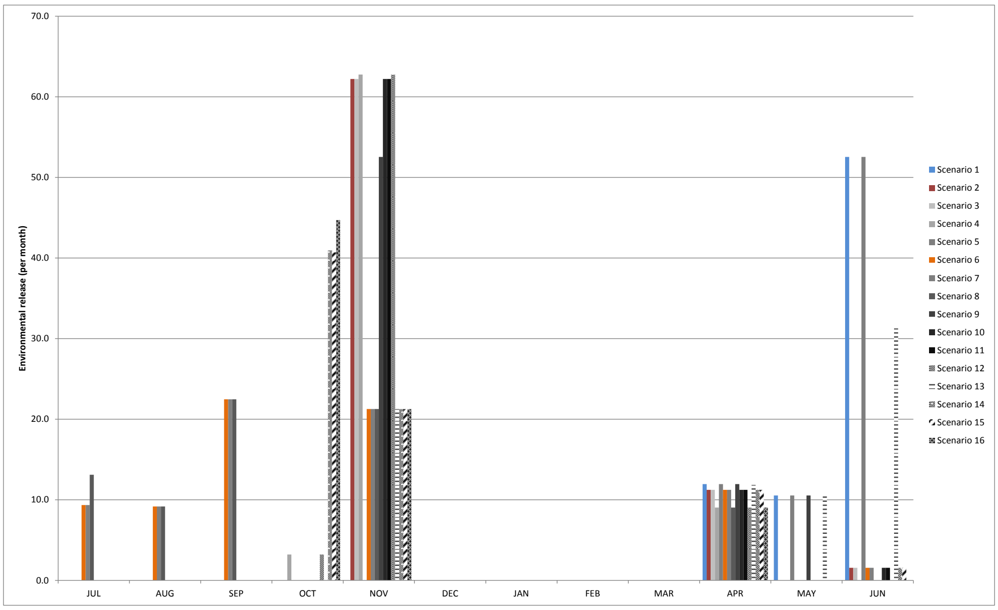

Figure 8 Recommended environmental release pattern for the 16 independent climate scenarios

The recommended release pattern generated by running this model prior to spring using a stochastic approach is shown below (Figure 9). It should be noted, that this will not be the optimal release pattern for what does actually eventuate (which cannot be known at the time the model is run). This can be seen when looking at the 12-month averaged environmental risk outcome for the single run of the stochastic model (9.14%) and comparing this to the average value obtained over all scenarios when perfect future knowledge is assumed at each one of 16 deterministic model runs (8.41%). While the risk itself is not a useful measure here, it does show that a model that hedges against future conditions will usually not be able to provide the single optimum solution for any specific scenario. This is expected, since the stochastic model is subject to the more realistic assumption that future climate is not known exactly, but can only be considered in terms of probabilities. At early stages, the same decision will be recommended for multiple scenarios, since we have no knowledge of which scenario will actually eventuate (as per the learning lag discussed above). The model copes with this limitation by obtaining somewhat malleable decisions at these early stages; good outcomes can still be obtained for each scenario, by adjusting later decisions, taken when more information is available. On the other hand, a deterministic solution obtained for a given scenario will not usually perform as well, if evaluated over all the possible scenario realisations. For example, if we solved the deterministic model for a dry year, and made release decisions on this basis, we can see that the performance across all scenarios should the climate pattern deviate would lead to an average risk of 10.3%. This pattern will repeat for any deterministic solution and demonstrates how hedging provides an improvement over assuming a single climate scenario.

The species-level ecological outcomes can be reported in the same manner as for the deterministic model above, by assessing the individual ecological responses to the recommended flow regime and the actual flow along the scenario that eventuates. For example, if it turns out that the year is as per scenario branch 6 or branch 12, the corresponding environmental flow regimes and environmental outcomes (Figure 9) are shown below.

If using a stochastic model in practice, rather than running the model a single time for the year, the environmental manager would, in each month or season, update the scenario tree based on their current knowledge, and run the model to make decisions about the next time-step, thus incorporating the new knowledge concerning what has eventuated in previous time-steps. The changes in decisions caused by this approach are likely to be substantially more incremental than the wholesale changes in decisions that occur using deterministic models and a scenario-based approach.

4. DISCUSSION AND CONCLUSIONS

Optimization provides a useful tool to assist in environmental watering decisions. As demonstrated in this paper, it allows uncertainty in individual inputs, such as exogenous stream flows, and the ability to obtain greater certainty (learn) about those inputs over time, to be embedded in the decision process, via the stochastic programming paradigm.

The model presented in this paper is a simplistic representation of a river system. Future versions of the model will be based on complex water resource systems and incorporate more detailed ecological response functions and complex objective functions. There is a challenge in getting the balance between the level of complexity and solvability of the tool. Similarly, a challenge exists in ensuring that the model operation and outputs are relevant to the way environmental managers make decisions and will therefore be useful in their day to day operations.

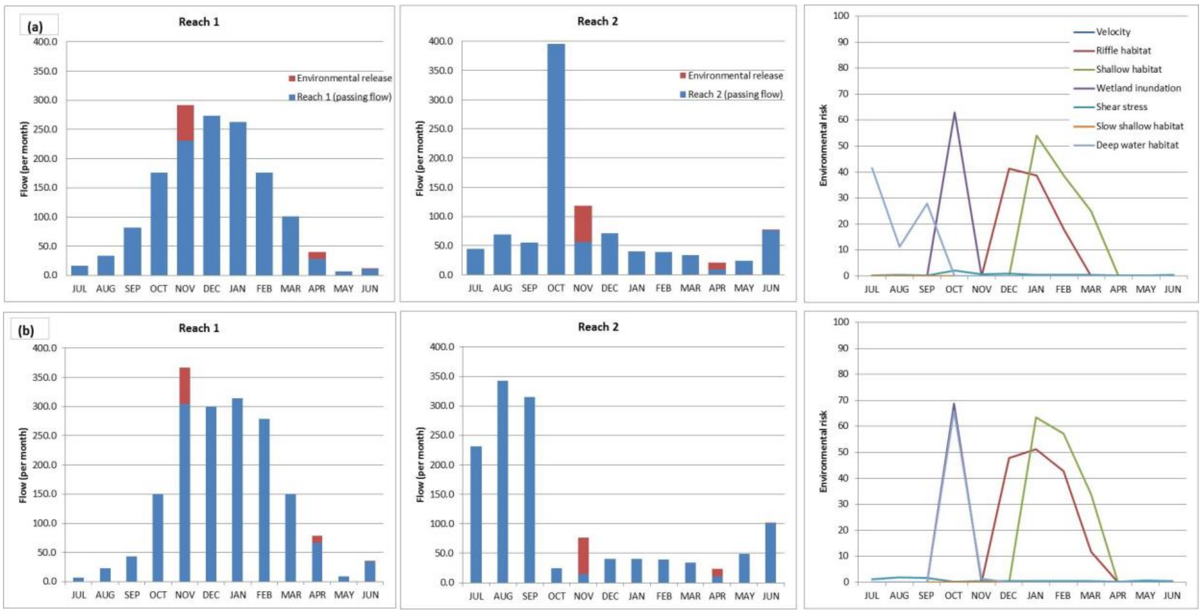

Figure 9 –Total flow (showing exogenous flows and recommended environmental release based on stochastic model) in reach 1 and reach 2, and environmental outcomes for (a) Scenario 6 and (b) Scenario 12

5. ACKNOWLEDGMENTS

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