Environmental triage decisions during a drought

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Abstract

The Murray Darling Basin Current is currently in drought. There are low water levels in most dams, and increased uncertainty about future rainfall. As a result management of the ecosystems in the basin that depend on river flows involves some hard decisions about what assets to save and what assets to let go. This paper models this triage problem using a stochastic and dynamic programming approach. This model is used to identify how optimal management is affected by hysteretic and irreversible effects of drought on ecosystem assets and uncertainty about future climate.

Key Words: Triage, irreversibility, climate change.

1 Introduction

This paper looks at the problem of allocating environmental water among different ecosystems during a drought. The key feature of this problem is that failure to allocate adequate water to a particular ecosystem may result in irreversible or hysteretic changes in the nature of ecosystem such as the death of key populations of some species. This problem is applicable to a range of environmental flow decisions in the Murray-Darling Basin (MDB) and at several scales. For example the Murray-Darling Basin Commission's living Murray program identified six "Icon sites" as the focus of its environmental water management strategy, and is currently exploring options for how to provide water to maintain the health of these sites.

The aim of this paper is to develop an understanding of optimal management strategies of environmental water during drought. We calculate optimal water management decision rules for a simple model and compare optimal management to a decision rule that aims to keep as many ecosystems alive for as long as possible by always providing water to an ecosystem that would otherwise die. The analysis therefore focuses on the value of a strategy that deliberately does not provide water to some ecosystems that need it in order to store water for future use. The problem therefore has a useful analogy to medical triage problems.

Triage

Triage means to sort. The concept of triage has been applied to biodiversity conservation (Bottrill et al, 2008; McDonald-Madden et al, 2008). In this context the basic triage problem involves ranking individuals so that a fixed amount of conservation resources can be allocated to where they are of most benefit. As such the concept does not differ from the standard economic problem of choice under scarcity. However we use the concept here because we are interested in the military triage category called expectant. Expectant are those expected to die, and refers to the critically wounded for which there is no effective treatment, or the probability of effective treatment is very low.

A simple model using a military casualty example illustrates the triage concept and the expectant category. Define a condition score for casualties (c) that varies from zero to one with one being perfect health. The condition score provides two pieces of information:

1. The probability that the patient will survive without treatment.
2. The probability that treatment will be successful

Suppose that the probability that a patient will die without treatment is proportional to the condition score. Also suppose that the probability that treatment is successful in saving a patient who would have died is proportional to the health of the patient. If the value of treatment is the increase in probability of survival given treatment, then this is proportional to $(1-c)c$, that is the probability that the patient is dying times the probability that the treatment will work. If there are is a fixed amount of resources for treatment, and each treatment takes the same amount of resources (simplifications from many actual triage procedures) then the triage decision involves classifying patients into three categories as illustrated in Figure 1.

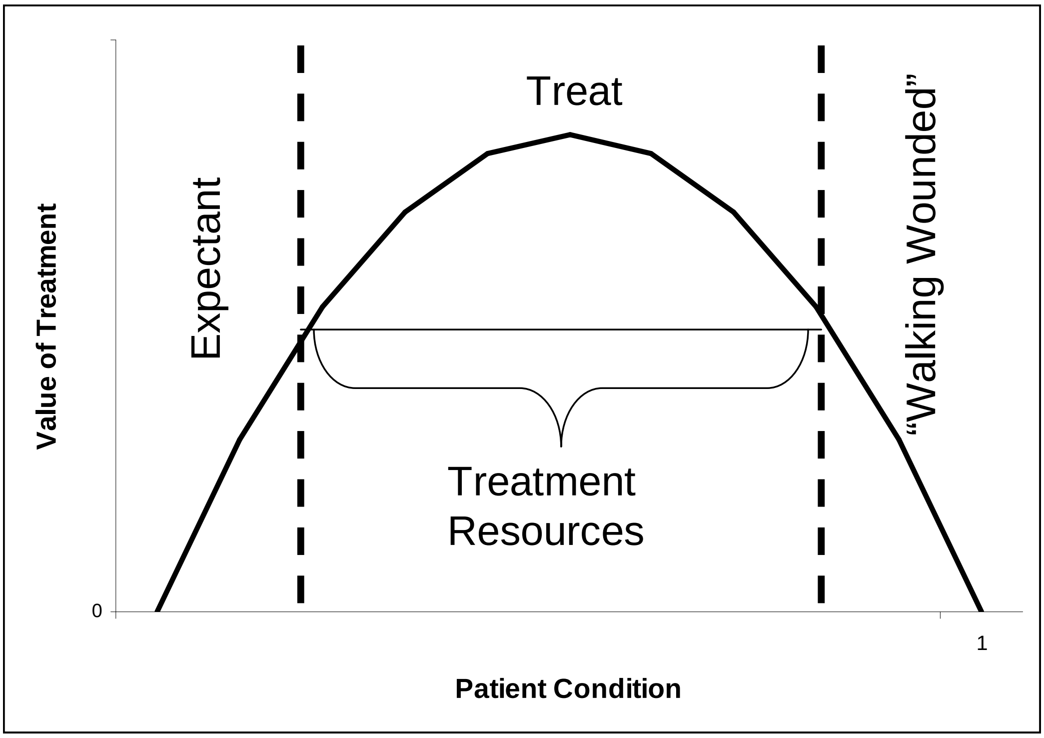

Figure 1. An example of triage and the expectant classification

This model provides a simple illustration of how the triage expectant category relates to the problem of optimal allocation of scare resources.

Nature of the problem

The problem of interest here differs from the static triage problem described above in two regards. First the scarce resource, water, may be allocated to future time periods as well as to current use. Second, the benefits from providing water to any ecosystem will depend on the future supply of water to an ecosystem and it's subsequent prospects for survival. Managing water is also inherently a problem of decision making under uncertainty. This uncertainty is exacerbated by climate change, which reduced the value of complex formal modelling of decisions under uncertainty that rely of historical data to provide information about probability distributions. Uncertainty also exists about the nature of the ecological response to water. This uncertainty may be partially reducible by investment in research, however uncertainty is likely to remain due to the complexity of the ecosystems, the existence of other threats and stresses, and a history of flow regimes that have been altered from their natural state by dams and irrigation. Uncertainty may also exist about the probability that an ecosystem will cross an important threshold, the likely state and behaviour of the systems once it has crossed a threshold, such as the loss of a key species, and the values that people are likely to ascribe to the new system.

Another aspect of the problem is that allocation of water to ecosystems tends to involve lumpy decisions, as minimum river-flow rates are often required before an area can be flooded (however technologies such as pumping are also being used to deliver water more effectively). In some circumstances synergies between different ecosystems exist as they may depend of similar flow regimes.

Analytical approach

We use stochastic, dynamic programming (SDP) to analyse a simple stylized model of the environmental water management problem in order to understand the characteristics of optimal management. The model has a single dam that is used only to provide water to two ecosystems (A and B). Each ecosystem has a level of health that, without water declines from full health to death in a specified number of years. Water can be allocated to neither, either or both ecosystems in each year. Each ecosystem requires a fixed, separate amount of water. Watering results in the ecosystem recovering to full health. We ignore uncertainty related to the ecosystem response for now and focus on uncertainty about future rainfall.

In order to understand the nature of optimal management of this system, we first look at how optimal management is affected by the presence of thresholds. We do this by comparing optimal management under two scenarios, first where an ecosystem dies if its health level reaches zero, and a second where the health of the system can recover once it reaches zero. We focus on how the probability of a rainfall event affects these results, as this is one way in which climate change may affect the system. The questions addressed are:

a) Do circumstances exist where optimal management involves abandoning some ecosystems before absolutely necessary?

b) How does the (lack of) ability of an ecosystem to recover from zero health affect the optimal decision rule?

We focus on the decision about the use of water when storage levels are low, but still sufficient to provide water to both ecosystems in the current year. We confirm that circumstances may exist where it is valuable to classify some ecosystems as "expectant" and withhold water from them. In the case examined, this result does not hold for the system where recovery is possible. This suggesting that a threshold for irreversible change is important in determining the value of the expectant triage approach.

A second section uses simulation modelling to explore the value of the expectant triage approach in situations where water storage levels are low. We compare a triage decision rule, which lets one ecosystem die in the first year, with a decision rule that always waters an ecosystem when it is required to stay alive. We ask "under what rainfall patterns in the triage decision rule valuable?" and examine how the probability of different environmental outcomes changes under the two decision rules.

2 Overview of the Model

The model specifies state variable defining the amount of water in the dam, and the health of each of two ecosystems (A and B). The dam level is increase by an amount of runoff from random rain event r_t that can occur one per year with probability *p*. The dam level is decreased by water released to ecosystems (w_t^a, w_t^b). The amount of water allocated to an ecosystem can take one of two values: $w_t^i, = 0$ or w^i . Therefore the amount of water in storage at the beginning of year t is given by:

$$w_t = \min\left(w_{\max}, w_{t-1} + r_{t-1} - w_{t-1}^a - w_{t-1}^b\right).$$

The capacity of the dam ($w_{\max}$) is set to be relatively high, (greater than the maximum annual rainfall) so that loss of water by overflow is not a major consideration for water use at low water storage levels. The rain event is assumed to occur after the release of environmental flows so the constraint imposed on the water decision by the amount of water available each year is:

$$w_t \geq w_t^a + w_t^b$$

The health of the ecosystems (h_t^a, h_t^b) is defined as an index [0,1] that declines by an amount $\beta_i, i = a, b$; for each year that it is not watered, returning to one if it is watered but remaining at zero if it reaches zero. That is the equation of describing the change in the health of each ecosystem is:

$$h_t^i = \begin{cases} 0 & h_{t-1}^i = 0 \\ \max\left(0, h_{t-1}^i - \beta_i\right) & w_{t-1}^i = 0, h_{t-1}^i > 0 \\ 1 & w_{t-1}^i > 0, h_{t-1}^i > 0 \end{cases}$$

The objective function is assumed to be to maximise society's direct utility from the ecosystems over time. This is assumed to be of the form:

$$V = \underset{w_t^i}{Max} \sum_{t=1}^{\infty} (1+r)^{-t} \left(\alpha_a h_t^a + \alpha_b h_t^b\right)$$

Where *r* is the discount rate. This objective function is maximized subject to the equations of motion for water levels and ecosystem health defined above. The problem was solved using stochastic dynamic programming (Bellman, 1957) using code developed by Miranda and Fackler (2002). The solution provides the expected value of problem, the optimal decision, and the probability transition matrix given the optimal decision for each specified combination of values for the state variables. Since the equilibrium solution to the model degenerates to the health of both ecosystems being zero, that is eventually the threshold will be crossed, we explore the long run properties of the solution by simulating multiple runs (80 iterations) of a long time horizon (60 years), and report average values across all runs at t=60 for variables of interest.

A simulation model was programmed in Microsoft Excel® in order to explore the implications of different decisions rules for the probability of survival of the two ecosystems.

For both models we specify the parameters of the problem so that ecosystem A is typically conserved and ecosystem B is possibly sacrificed under a triage management system. In the base case the model parameters are specified so that both ecosystems have the same characteristics, ($w_t^a = w_t^b = 2$, $\beta_a = \beta_b = 0.2$) but ecosystem A is valued twice as highly as ecosystem B ($\alpha_a = 20, \alpha_b = 10$). A discount rate of 1% is assumed, consistent with a focus on future value in the conservation of ecosystems. The dam capacity is set to 15 units.

3 Results

We focus on the problem of decision making under a drought, that is when water storage levels are low, and the health of the ecosystems are also likely to be low. Figure 2 show select results from the model run under optimal management. It reports average values after 60 years for ecosystem health and dam levels for 80 simulation runs under optimal management and favourable starting conditions (health and water level starting values equal to 50% of maximum values). Results are shown for a range of scenarios that vary the annual probability of a rainfall event from 0 to 0.85. Figure 2 also show the excess water: this is the average expected annual rain fall minus the average annual water requirements of both ecosystems. (These values are reported on the right hand side axis, and this second Y-axis is truncated at zero, however values at rainfall probabilities less than 0.2 the excess water figure is negative, reflecting the fact that on average there is not enough rainfall to meet the needs of both ecosystems.

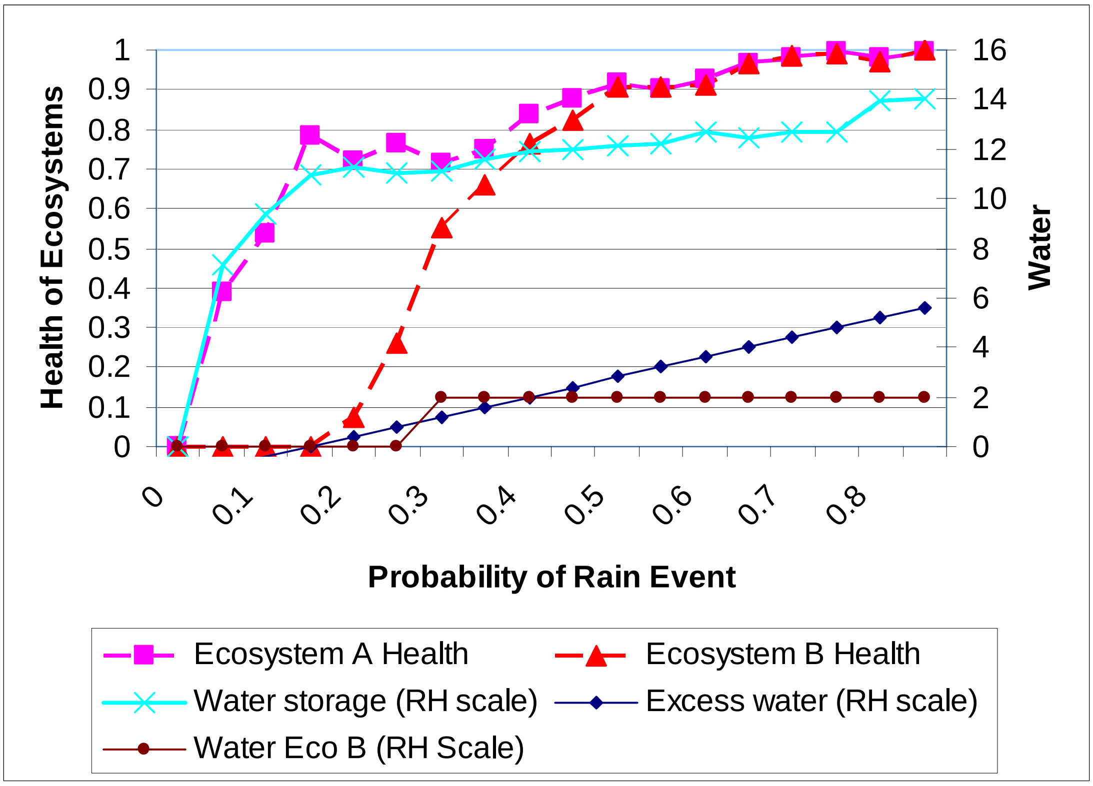

Figure 2. Ecosystem health and water use under optimal management as a function of the annual chance of rainfall.

Finally Figure 2 reports the amount of water applied to ecosystem B when the dam level= is equal to four units (where there is just enough water to both ecosystems) and where the health of Ecosystems A is equal to 0.4.

The results in Figure 2 indicate that, at high rainfall probabilities and expected rainfall levels, both ecosystems are maintained at almost full health. However as the probability of rain and the expected rainfall decreases, a decision is made to not supply water to the less valuable ecosystem (B). This occurs where the expected level of rainfall is still sufficient to provide water to both ecosystems. That is where the measure of excess water is still positive.

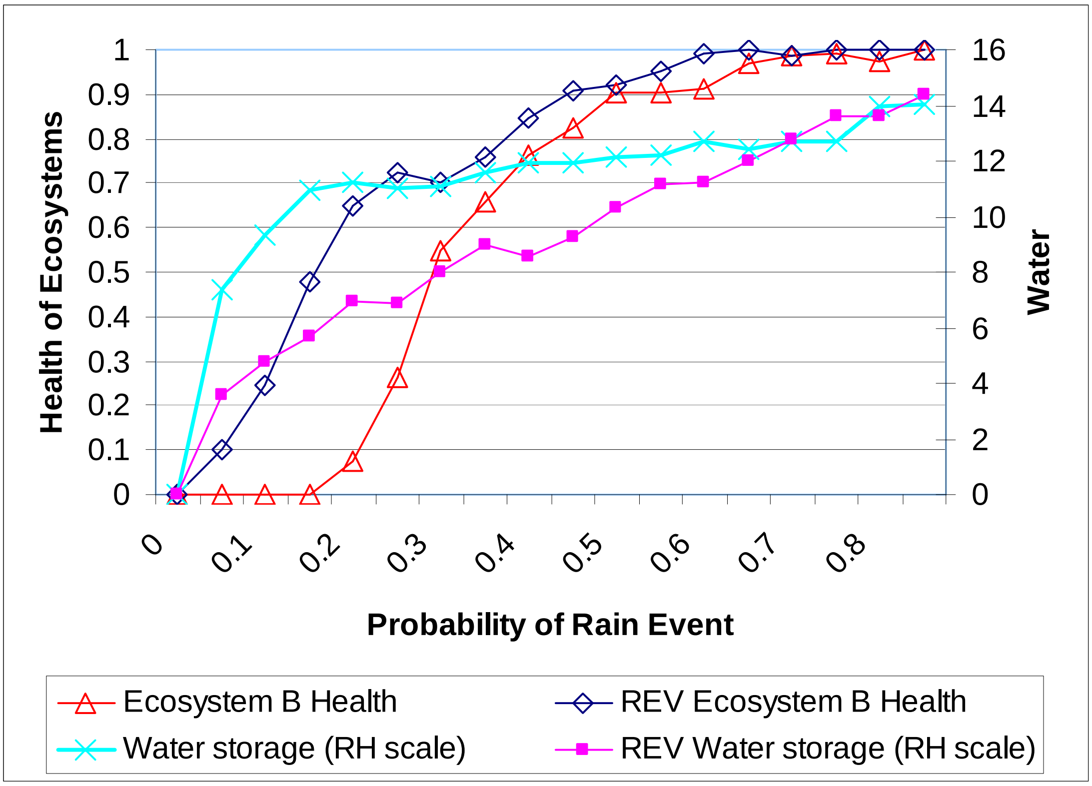

Figure 3. The average dam levels and expected health of ecosystem B with reversible (REV) and irreversible health thresholds at h=0.

Figure 3 shows the same based model values for average dam levels and the health of ecosystem B as shown in Figure 2. However here they are compared with equivalent results from optimal management of the system when there is not an irreversible change in ecosystem health at h=0. Output from this scenario, with reversible changes where health is zero are marked "REV". We can see that when loses are not reversible, dams are run much more conservatively, that is they are keep a higher level on average.

The irreversible threshold also results in the health of ecosystem B declining at higher rainfall probabilities. This is a result of water not being applied to Ecosystem B. Optimal management of the system therefore involves withholding water from ecosystem B at higher rainfall probabilities (and expected rainfall values) when there is an irreversible threshold, than when the health of the ecosystem can readily recover.

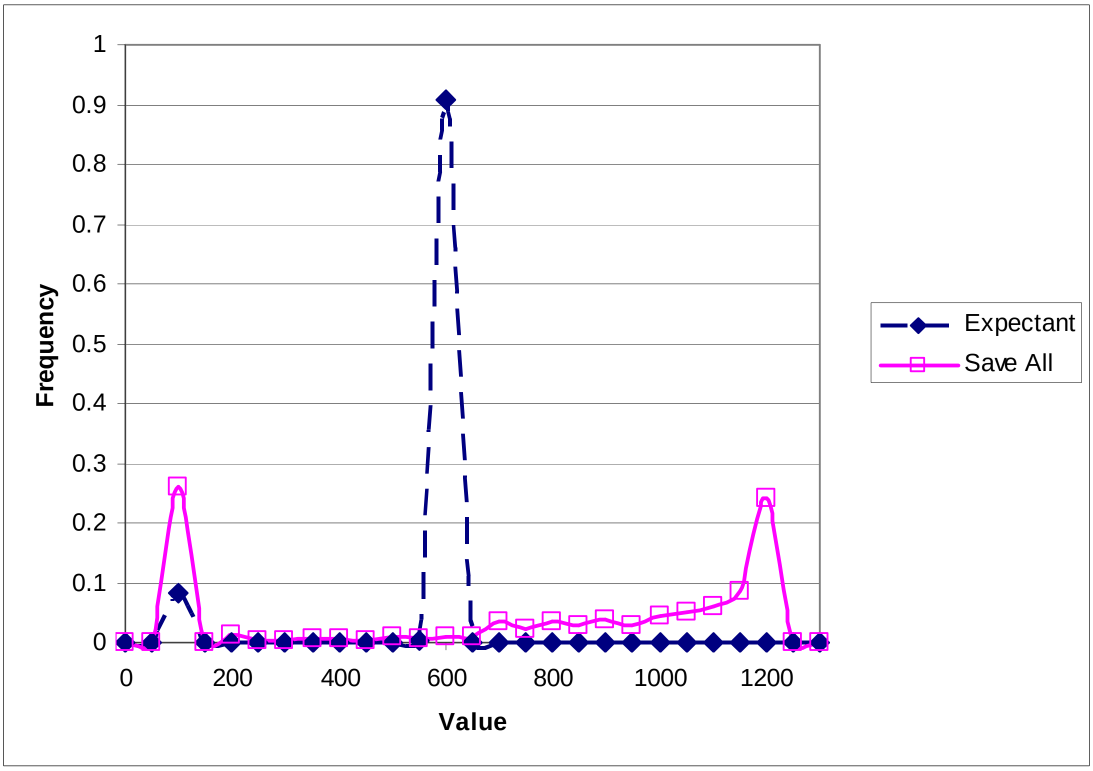

Figure 4 Distribution of present value under two management strategies.

Figure 4 shows the distribution of present values that occurs when the simulation model is run under two different management strategies. The initial value of the model runs specifies the grim situation where the “expectant” tirage strategy was shown to be useful by the SDP modelling. Specifically, just enough water is in storage in the first year to allow water to be made available to both ecosystems, and both ecosystems require water in that year in order to survive. The “Save All” management strategy is to provide water, where possible to both ecosystems when it is required to prevent death. The “Expectant” management strategy deliberately provides no water to ecosystem B in the first year, ensuring that it dies. This ensures more water is available to try and maintain ecosystem A in subsequent years. After the first year the “Expectant” strategy uses the same strategy as “Save All” of only providing water when it is required to keep Ecosystem A alive. Figure 4 shows the bimodal nature of the distribution of outcomes under each strategy. The large peak at 600 under the “Expectant” strategy represents the situation where Ecosystem A survives the drought, and dam levels can be maintained at high enough levels in the future to ensure its survival. The smaller peak at a value of 100 reflects the situation where Ecosystem A does not survive the drought. This peak is higher under the “Save All” strategy, reflecting the fact that water applied to Ecosystem B reduces the changes of Ecosystem A surviving. Conversely, the “Save All” strategy has a probability peak at 1200, reflecting the situations where enough rain fell in the early years to save both ecosystems, and small positive values between 600 and 1200 reflecting situations where ecosystem B survived the initial drought but had to be abandoned in later more prolonged droughts.

The bimodal nature of the distribution is hidden in the SDP analysis by a focus on expected values. Given this bimodal distribution, information on how the different decisions affect the probability of the different outcomes may be more useful than information on the expected values. In Figure 5 we present this information as the probability of achieving a benefit and the probability of incurring a cost from using the “Expectant” decision rule as compared to the “Save All” decision rule.

The possible benefit of the expectant strategy is the increased chance of saving Ecosystem A in the future due to holding more water in reserve. This is calculated as the probability of death of Ecosystem A in the first 20 years of the model run under the “Save all’ management strategy, minus the same probability under the “Expectant” management strategy. The possible cost of the Expectant management strategy is the forgone opportunity to save Ecosystem B. The probability of incurring this cost is the probability that Ecosystem B will survive under the “Save all” management strategy. Figure 5 shows how the probability of incurring these benefits and costs are affected by the chance of rainfall.

Choosing between the two strategies based on the information presented in Figure 5 requires weighting the value of each ecosystem and relative probability of each outcome. If the ecosystems are given equal weighting, then the decision to use the Expectant management strategy can be based on if the probability of the benefit is greater than the probability of the cost. We can see for the example in Figure 5, that under these circumstance the Expectant strategy would only be optimal for rainfall probability levels where, on average there is not enough rainfall to provide water for both ecosystems.

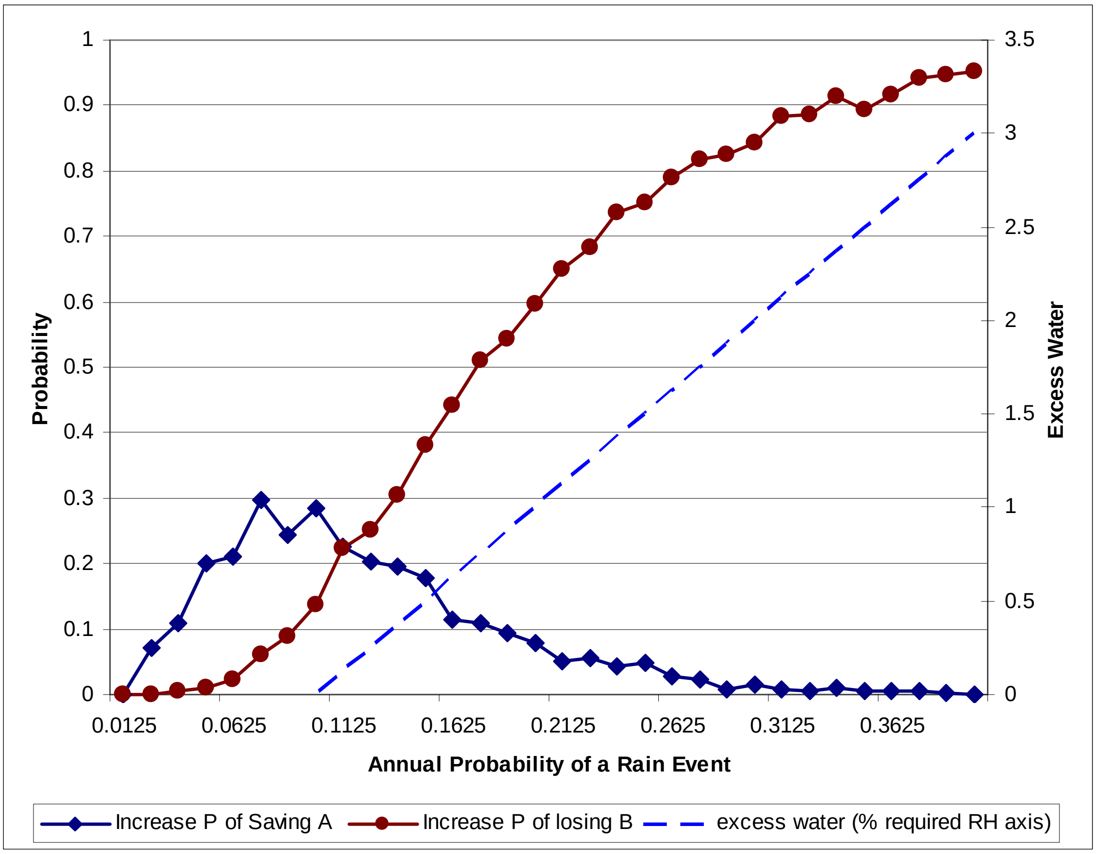

Figure 5 Probability (P) of Cost and Benefits of Triage with Medium Size Rain Events (*rn*=8)

This result is however not universal. Figure 6 shows equivalent results for the case where the rainfall event is larger (*rn*=16). In this case there is a range of rainfall probabilities, where average rainfall is sufficient to provide for average water needs (approximately 0.0625-0.1125) where the Expectant management strategy is optimal.

A range of factors determine the shape of the curve describing the probability of achieving a benefit by using the Expectant triage decision. One point to note is that the benefit is still relatively large at medium rainfall probabilities. In other words in trying to save critical ecosystems, the “Save all” strategy, by running down dam levels can imposes a significant, and reducible, risk on the future survival of ecosystem A.

On the other hand the probability of ecosystem B surviving under the “Save all” strategy increases rapidly with the probability of rainfall. The result in figure 6 therefore indicates that the optimal choice is sensitive to the probability of rainfall. As discussed below this may be important given uncertainty about future rainfall due to climate change.

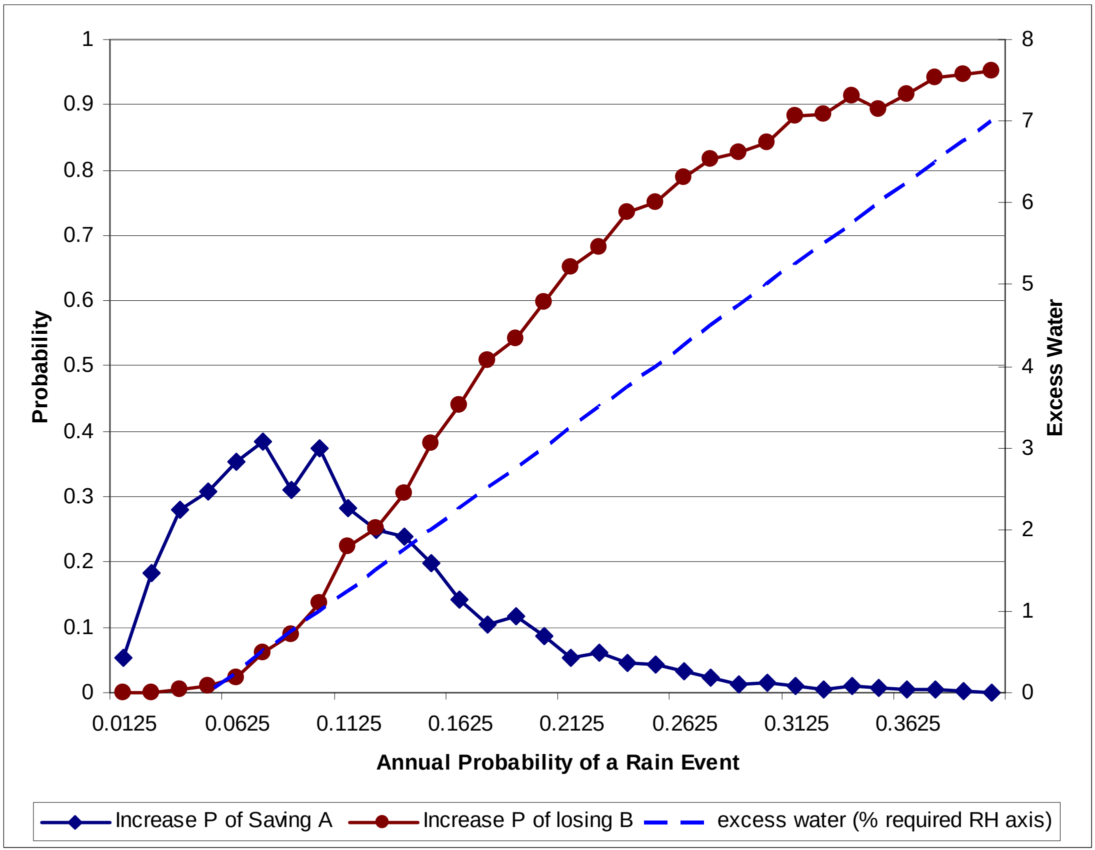

Figure 6 Probability (P) of Cost and Benefits of Expectant Triage with Large Rain Events (*rn*=16)

4 Discussion

This paper examines the problem of how to allocate limited environmental water among alternative ecosystems. First we ask, if, when water stores are low- but sufficient to provide all water needs in that year, it can be optimal to deliberately let some ecosystems die in order to save water for future years. The analysis confirms that this strategy, analogous to the triage practice of classifying severely sick casualties as expectant, can be optimal, in the sense of maximizing expected value. This can be the case even when we expect there to be enough rainfall, on average, to maintain all ecosystems. Next we show that this result can be attributed to the existence of a threshold, that is the potential death of an ecosystem that does not receive water.

A notable result is that if assets that are dependent on water storage can suffer irreversible change then management of water storage should be very conservative. That is, optimal management implies that large water stores are maintained, even when the system is under significant stress.

The focus of dynamic programming on the expected value of the outcome however hides the bimodal distribution of outcomes and the nature of the trade-off involved. Both the decision to let an ecosystem die, and the decision to save it can lead to large regrets depending on how future rainfall events unfold. The decision not to save an ecosystem may be regretted if there is significant rain that follows. Alternatively deciding to run down water storage to save all ecosystems risks not having enough water in future years to save any ecosystems if future rainfall turns out to be unfavourable.

We present results from a simulation model to help develop an understanding of how the probability of these different outcomes is affected by different management strategies. Preliminary results indicate that the optimal choice of a management strategy is not clear cut. Specifically the probability that an ecosystem that we save today will survive into the future is very sensitive to the probability of rainfall. Depending on the rainfall probability both the costs and the benefits of the Expectant triage decision can be large. More work is required to see how sensitive this result is to other factors, such as the rate of decline of ecosystem health, the relative water requirements, and other real world complexities such as synergies in applying water to both ecosystems.

Applications and future work.

This work is designed to be applied in two ways. First we hope to improve the intuition of river managers about the merits of triage decisions, and the associated implications for managing water storage levels. Future work will focus on the value of carry-over water, and look to see if triage rules are valuable and robust across the range of future rainfall patterns that may occur under climate change.

The second domain for application of this work is in our future work using agent-based simulation models to explore the trade-offs between irrigated agricultural production and environmental outcomes at the basin scale. Agent based modelling has the potential to identify opportunities for improved management of the system, while taking into account the behaviour of producers and environmental managers. The present work will enable us to specify simple decision rules for environmental management that take account of the need to keep the ecological system away from critical thresholds. Similar thresholds exist in the irrigation industry, where lack of water can cause the death or permanent reduction in the productivity of perennial crops. This simplification of the human decision making problem in the presence of thresholds will therefore help make modelling of trade-offs and policy responses in this complex human-ecological system tractable.

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