Water resource management and the age of uncertainty: Can science provide any answers?

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Introduction

The complexity, uncertainty and variability of Australian ecosystems raises the question whether science is able to deliver answers to water sharing problems. In the end, much of the decision making seems to be based on value judgements about the best use of water (Falkenmark 2003). In this paper we will argue that science has an important role to play. Science can help define the risks involved in using water for a certain purpose. Understanding these risks will allow better decision making.

The variability in rainfall, climate and water resources in much of Australia has resulted in a strong competition for access to water for irrigation, stock watering, domestic uses and the environment. In many inland areas, water is the life blood of communities and brings economic prosperity. This prosperity is based on the ability of water to support the growth of agricultural crops and native grasses, hence, this means that a high value is assigned to water. Similarly, on the coastal fringe, a glimpse of water in Sydney can make a house price jump $100,000, and that glimpse of water is not even usable by the buyer!

However, within a natural catchment, water is never lost. All water is used by parts of the ecosystem and extraction of water will, in the future, cause some degradation of the ecosystem (Falkenmark 2003; Kalff and Woolley 2005). As the environment has limited ability to speak up and demand its share of the water, the water management act 2000 in NSW and Queensland makes provisions for the environment. In the act and its implementation, there is increased emphasis on the “best scientific knowledge” to develop water sharing. The question is: What is the “best scientific knowledge” and is this good enough?

Scientific knowledge; our view of science and the way science is developed has changed dramatically over the last half century. Scientists and academics, in general, have done a good job in research and education. The general public is much more knowledgeable and the overall knowledge level has increased (Nowotny et al., 2001). However, this increase in knowledge and education has come with a catch. The problems we are facing are increasingly complex, and a cynic might claim that all scientists have done is create new, more complex, problems. In addition, the more knowledgeable public demands better answers and is willing to question the general outcomes that science presents (Nowotny et al., 2001) and this leads to increasing uncertainty about scientific outcomes. An example is the current debate about global warming, where all sides of the debate are well armed with scientific knowledge, but there is no clear evidence either way. This has led to the naming of the current period: “The age of uncertainty”.

In addition to this, the Australian climate delivers some significant further challenges to scientists working in natural resources. A highly variable climate echoes in water balance components which makes it difficult to quantify ecological water use, such as for groundwater dependent ecosystems (Fig. 1) (Vervoort and Thompson, submitted). Similarly, identifying useful indicators to monitor the degradation or health of ecosystems is a challenge (Fairweather 1999). Do we really understand the natural system, and will we ever fully understand the natural system to allow decisions to be made? From a positivist standpoint, which is still mainstream philosophy in science, the understanding of the system should increase with increasing knowledge. But earlier it was argued that increasing knowledge is increasing complexity and possibly not delivering answers. Does science have a role, or is it all a value judgement in the end, or is it a combination?

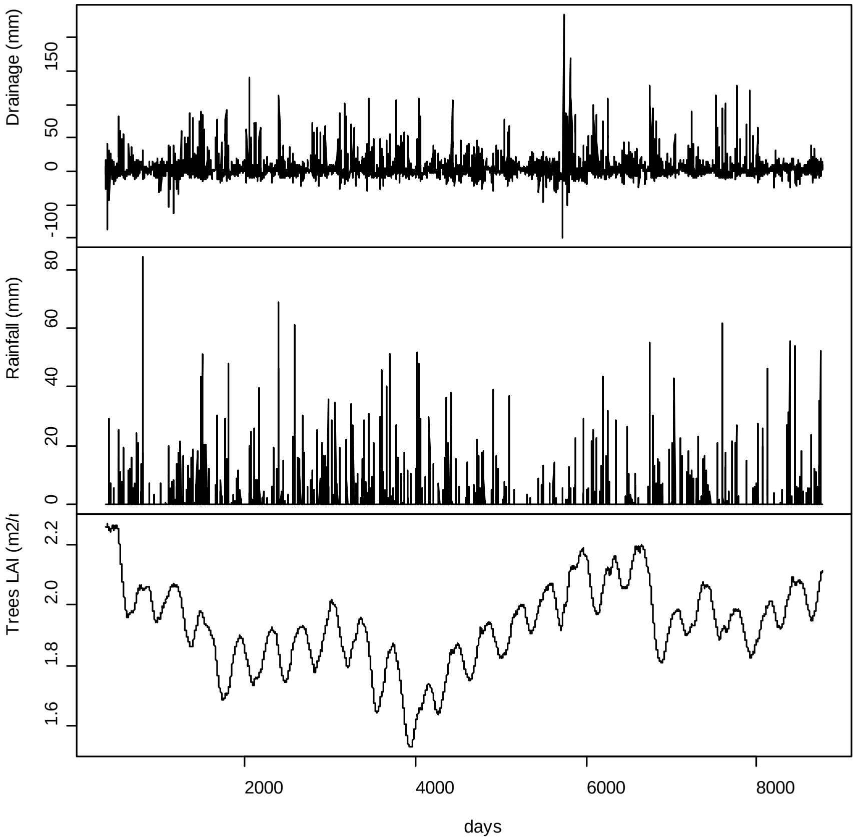

Figure 1. Example of high variability in rainfall and associated drainage and leaf area index for Eucalyptus Camaldulensis near Tamworth, NSW.

From an economic perspective water should be allocated to the highest value use (Young 2005). In the case of semi-arid regions it would be expected that the highest value use is the only use that could afford to pay for the water, where the highest value use is selected by the market. Moreover, where the value of water is high(er) it would be expected that trading of water would form a ‘lucrative’ trade, for example through investing in water saving technologies and thus selling excess water to a neighbour. Though, this may be ideal it is far from what happens in practice. The key to the failure is spatial and temporal variability of climate and water demand (Savenije and van der Zaag 2002) and thus more so in semi-arid regions. The reason for this is that the marginal utility of water increases due to the perception of the water user, where utility is defined as the satisfaction achieved by consuming goods and services. Rothbard (1957) defines utility theory as an analytical tool to assess the values and choices of an individual and welfare theory as a tool to assess the relationship between values of many individuals. These two theories lie at the heart of water valuation and are particularly useful when considering risks of actions of an individual, or group, based on utility and altruistic behaviour based on welfare. In the case of the utility of water in a semi-arid region, a farmer may decide to store as much water as possible in order to avoid ‘drying out’ during the growing season. Hence, the farmers perception of the utility of water is high. Furthermore, a high value of water leads to ‘hedging’ or other risk avoiding strategies that may convert into externalities being inflicted on downstream users and the environment.

Downstream water users can hold parliamentary inquiries; the question is what can a voiceless environment do? It does not have capital, does not trade and will not buy water for itself. Some argue that environmental groups and other altruists will buy water and this will provide water for the environment. Clearly this assumes some level of altruism in individuals, which we know exists in all of us, but is limited by wealth and security. In general, the less secure and less wealthy will be less inclined to be altruistic, and therefore there would be a need for the government to fulfil this role.

An additional problem, with markets to manage the environment, is that most environmental systems have a threshold with regard to disturbance or use (Fig 2a). Once the health of an ecosystem passes the threshold it is very difficult to return to ‘pristine’. Moreover, most returns are hysteretic (Murray *et al.* 2003). It is clear that if we would know how close we are to the threshold the value of the ecosystem will fall and the price of the commodity (i.e. clean water) should increase dramatically, but once the threshold is passed, the price of the commodity will fall (Fig 2c), as the resource is now useless (Fig 2b). An example of this is water quality degradation due to increased extraction. With imperfect information, it is difficult to assess how close we are to the threshold and it is difficult to assess whether we can rehabilitate a system. It is therefore difficult for a market to assess the price of water in relation to ecosystem health and future availability.

Finally, managers, or more broadly, decision makers consider that increased access to information or skill is a way in which to reduce, manage or control risk (March and Shapira 1987). This is based on the implicit assumption that more information gives better management, since management involves a weighing up of risks (Chavas and Pope 1984). However, this is only true if the information improves understanding of risk and thus allows better (more sustainable) outcomes. Here, the notion of ‘garbage in garbage out’ needs to be carefully considered thus avoiding the spread of misinformation. Hence, for example, the role of sensitivity analysis in the presentation of information to decision makers

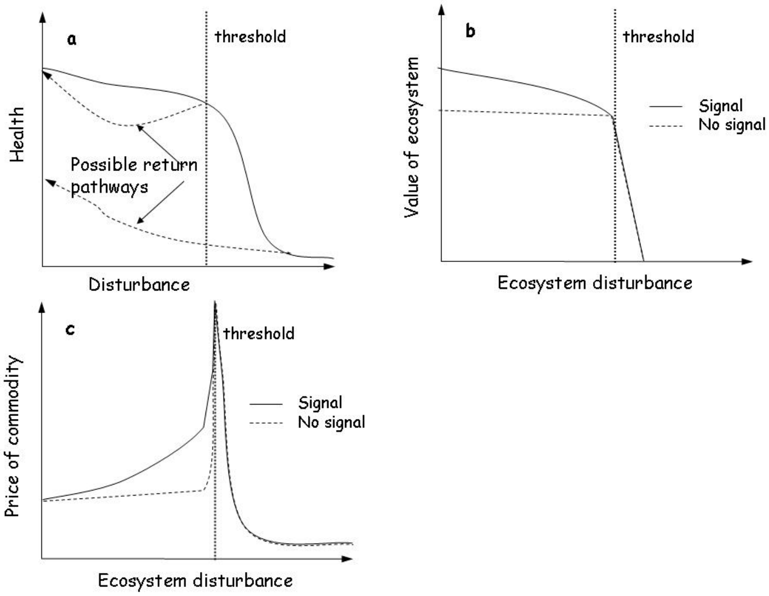

Figure 2. (a) The effect of disturbance on the health of an ecosystem, indicating the collapse of the health after a threshold and the hysteresis in the return paths. (b) The value of a ecosystem governed by a threshold and (c) the price of a useful commodity in this ecosystem (for example clean water). Two different possibilities are indicated. Either the system has some signalling capacity (i.e. a slow observed decline) before the threshold, or this is not available.

The role of science

This brings back the role of science in the water management arena. As pointed out, management hinges on managing risk. Risk in this case is understood as a general cumulative risk of taking a certain management decision. Risk can be defined in many different ways, but this paper will define risk as (van Ogtrop *et al.* 2005).

$$\boldsymbol{Risk} = \boldsymbol{chance} \times \boldsymbol{damage} \text{ or } \boldsymbol{Risk} = \boldsymbol{chance} \times \boldsymbol{effect}$$

This means that, to be able to calculate risk, we need to calculate both the chance or probability of an event occurring and the damage or effect of that event (sometimes called hazard). Probabilistic modelling and probability have a long tradition in science, particular in hydrology and meteorology (Krzysztofowicz 2001). This type of work takes into account the inherent variability in the processes to come up with probability of an event occurring. An example of this is the prediction of floods and extreme weather events. However, more recently, the recognition of high variability in many natural resource problems has led to an increase in probabilistic and stochastic modelling (e.g. Laio *et al.* 2001; Vervoort *et al.* 2004).

The damage or effect part on first glance appears to be all based on a value judgement, that is, it hinges on the perception of the utility of the resource and the decrease in that utility. However this decrease in utility has to be calculated based on a change in state of the system. Science is able to assess or predict the change in state of system. This is not always exact as this involves many uncertainties, as argued before. But luckily these uncertainties are included in the probability in the risk calculations. To return to the threshold system, while science is not able to predict when exactly the water quality in a river will become unusable, it can make probabilistic predictions of this occurring. For example, science can predict the probability that an ecosystem will cease functioning as a filter for water quality. Economics can then apply a value to the change in state and the risk can be calculated. Current developments in natural resource valuations and ecosystem services can help define these values.

We have argued that the uncertainties in many natural resource problems limit the deterministic prediction of damage to the ecosystem. We have also argued that economic markets in natural resource systems are imperfect as most systems are threshold systems and without information about when the threshold is reached these markets cannot operate. Risk calculations can be used as an information tool to make decisions, as this can assess the probability of a threshold being reached and value the change in state. Science through probabilistic and stochastic modelling plays a role in these risk assessments by being able to calculate the chance of occurrence and the probable change in state. We will now illustrate this with an example.

Example

We will use a simple example of a semi-arid floodplain system influenced by water extraction upstream. Flooding in these systems is important since it stimulates vegetation growth and might also have important fertility effects (Ogden and Thoms 2002; Sims and Thoms 2002). One of the problems in the prediction of floods is that the spatial and temporal dimensions are variable (i.e. Costelloe *et al.* 2003) and this makes it difficult to predict. However, it is well known that larger floods (spatially large) occur less frequent and vice versa and this can be described in terms of an exceedance graph (Fig. 3A). This graph indicates the probability of a flood exceeding a certain flow level. The probability is generally recalculated as the average recurrence interval (ARI), where ARI = 1/probability. As indicated, if extraction of water occurs, there will be a shift in the exceedance graph (Fig. 3A). For example, a flood of 100,000 ML/day has a probability of occurring of approximately 0.6 in the “natural” state and 0.2 and 0.4 under extraction levels 1 and 2, respectively. In this case the chance of such a flood occurring has decreased, or, to put it the other way around, the flood level at the same recurrence interval has decreased. At for example the 0.6 probability (or approximately 2 year recurrence) has moved from a 100,000 ML/day flood to a 80,000 or 60,000 ML/day flood. Note that this probability calculation only focuses on the chance of something happening, it does not say that a flood of 100,000 ML/day will happen. Similar to rainfall predictions, it only indicates the possible occurrence.

Of course this only gives a measure of the chance component of the risk. The real question is how this will affect the downstream. While there are ongoing ecological studies and ecosystem services calculations to calculate this relationship exactly, we will argue that this is also a probabilistic variable which cannot be precisely established. What needs to be calculated in this case is the probability of a biomass growth rate X conditional on the probability of a flood level Y and assuming independence (Clarke, 1998):

$$P[growth < X \mid flood < Y] = P[flood < Y] \bullet P[growth < X]$$

Conceptually the average biomass growth rate has a relationship with the recurrence of flooding (Sims and Thoms 2002). It has been suggested that the % observed green vegetation as a function of ARI follows a unimodel distribution (Sims and Thoms 2002) (Fig 3B). However, vegetation growth would not be even over the whole floodplain and this means that the variance of the vegetation growth rate also varies with ARI (Fig. 3C). The shape of the variance curve can be explained as follows: If only a small flood occurs, only part of the floodplain is wetted and also only certain species will be able to use this water. Some species need much more water before changes in vegetative growth occur, while others react really quickly and in an opportunistic way (i.e. annual grasses). At some optimal medium flood level (and related ARI) all species are given sufficient water to thrive this means the variance in the biomass production has a minimum. If the flood further increases, the flood water would also lead to destruction of biomass for which it will take time to recover. These models do not take into account the delayed response to large flood events and thus underestimate the value of such large events.

This thus gives a relationship between flood level and vegetation growth rate. However these curves still don’t express the probability of biomass growth conditional on flood level. A cumulative probability curve for vegetation can be derived similar to a flood level exceedance curve (Fig. 3D). Using data of biomass growth rates for different years and a cumulative probability can be constructed, which would be independent of the flood levels occurring in year. At present we actually do not know what these curves exactly look like, but we believe that this is the direction science should be moving towards in natural resource management. Monte Carlo modelling of local vegetation responses to water inputs using models such as GRASP or WAVES might allow construction of these relationships. We have assumed that the probability distribution follows a lognormal distribution, but other shapes can easily be used. Other examples would be a normal (Gaussian) or a gamma distribution.

As a worked out example of how these curves can be used let us assume that a policy decision is being made on what the effect would be to move from the “natural” state to extraction level 1 and extraction level 2. Using Fig 3A, we can calculate P[flood < 100,000ML/day] (Table 1). One way to tackle the effect part is to use Fig 3B and use the probability from step 1 to calculate the ARI. At 100,000 ML/day the ARI is 1.67 or almost every two years for this river. Using this in Fig 3B we can find the growth rate for each extraction level. We will assume a value of $100,000 for 1 unit of biomass growth/year (over a whole property). The change in growth rate is than the effect of the extraction. Multiplying the change in growth rate by the change in P by the value gives an estimate of the risk

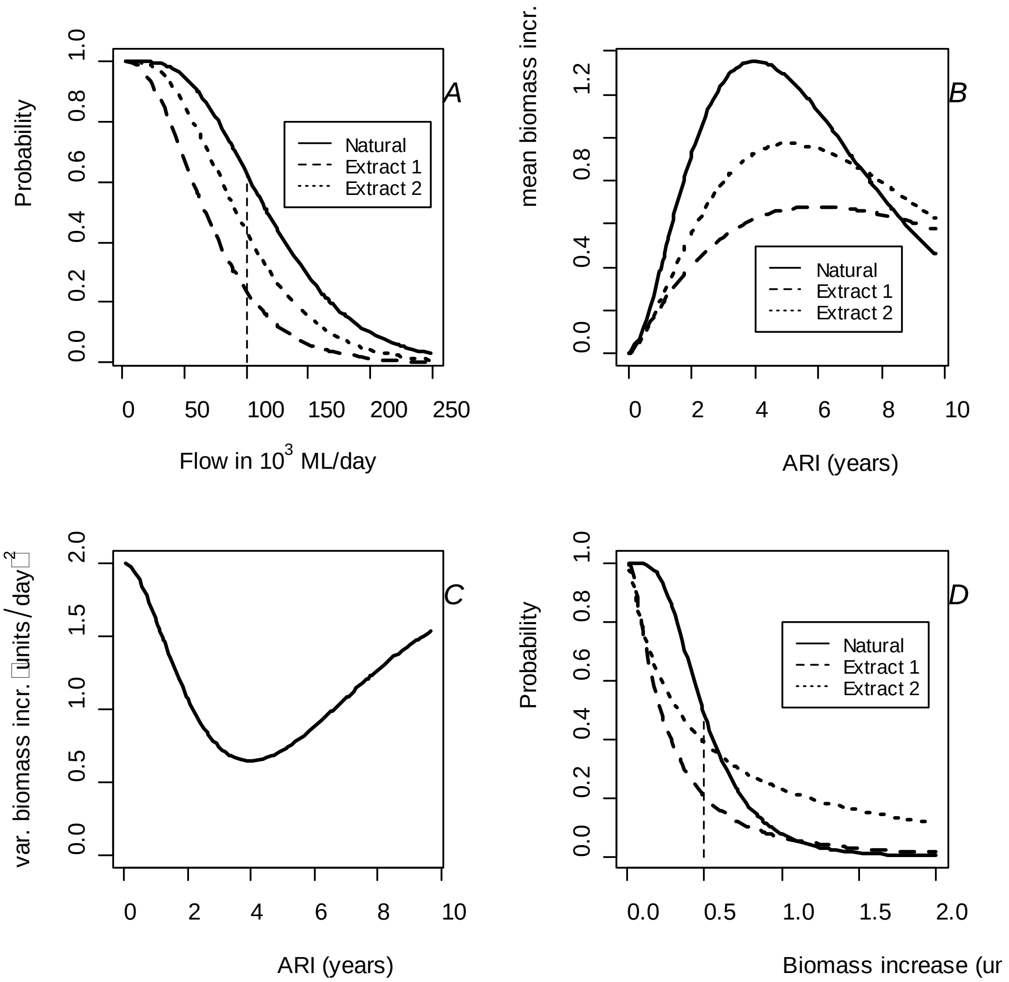

Figure 3 Conceptual relationships (A) exceedance plot, (B) mean biomass growth rate and return period, (C) variance of biomass growth rate and return period, and (D) probability of biomass growth rate

A second way of calculating the probability is to be aiming at a biomass growth rate of 0.5 units/day (Fig. 3D). This results in a conditional probability, achieving a growth rate smaller than 0.5 units/day and a flood smaller than 100,000 ML/day, of 0.20, 0.64 and 0.36 for the different states (Table 1). The change in probability for the different scenarios relative to the "natural" state can be used in the risk calculations to assess the risk of changing the extraction level. Using again 1 unit/day equal to $100,000 production, results in risks between $16,000 and $64,000 (Table 1).

The results are somewhat different but indicate a similar trend and order of magnitude. The differences are in this case probably purely due to the uncertainty in the estimation of the probabilities, which were read of the graphs rather than calculated.

Using these values a manager, water sharing process, or a policy developer can make decisions about extraction levels and their possible impacts. The other side of the coin is of course the increased production and value of the extracted water, which we have not taken into account in this example. This would have to be weighed up against the increase in risk at the downstream end.

Table 1. Example risk calculations for changes in biomass growth rate due to changes in flood level related to extractions

	Natural	Extract 1	Extract 2
Method 1			
P[flood < 100,000 ML/day]	0.4	0.8	0.6
Biomass growth rate (Fig 4B) at ARI = 2	0.9	0.4	0.6
Risk @ $100,000 for 1 unit/day		$40,000	$18,000
Method 2			
P[growth < 0.5]	0.5	0.8	0.6
P[flood < 100,000|growth < 0.5]	0.20	0.64	0.36
Risk @ $100,000 for 1 unit/day	$20,000	$64,000	$36,000

References

Costelloe JF, Grayson RB, Argent RM, McMahon TA (2003) Modelling the flow regime of an arid zone floodplain river, Diamantina River, Australia. *Environmental Modelling & Software* **18**, 693-703.

Chavas J-P, Pope RD (1984) Information: Its Measurement and Valuation. *American Journal of Agricultural Economics* **66**, 705-710

Clarke RT (1998) ‘Stochastic processes for water scientists. Developments and applications.’ (John Wiley and Sons)

Fairweather PG (1999) State of environment indicators of 'river health': exploring the metaphor. *Freshwater Biology* **41**, 211-220.

Falkenmark M (2003) Freshwater as shared between society and ecosystems from divided approaches to integrated challenges. *Philosophical transactions of the Royal Society of London B.* **358**, 2037-2049.

Kalff FRP, Woolley DR (2005) Applicability and methodology of determining sustainable yield in groundwater systems. *Hydrogeology Journal* **13**, 295-312.

Krzysztofowicz R (2001) The case for probabilistic forecasting in hydrology. *Journal of Hydrology* **249**, 2-9.

Nowotny H, Scott P, Gibbons M (2001) 'Re-thinking science: Knowledge and the public in an age of uncertainty.' (Blackwell Publishers Ltd.: Oxford).

Laio F, Porporato A, Ridolfi L, Rodriguez-Iturbe I (2001) Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress: II. Probabilistic soil moisture dynamics. *Advances in Water Resources* **24**, 707-723.

March JG, Shapira Z (1987) Managerial perspectives on risk and risk taking. *Management Science* **33**, 1404-1418.

Murray BR, Zeppel MJB, Hose GC, Eamus D (2003) Groundwater-dependent ecosystems in Australia: It's more than just water for rivers. *Ecological management and restoration* **4**, 110-113.

Ogden R, Thoms M (2002) The importance of inundation to floodplain soil fertility in a large semi-arid river. *Verh. Internat. Verein. Limnol.* **28**, 744-749.

Sims N, Thoms MC (2002) What happens when flood plains wet themselves: vegetation response to inundation on the lower Balonne flood plain. In 'International symposium on the Structure, Function and Management Implications of Fluvial Sedimentary Systems'. Alice Springs, Australia. (Eds FJ Dyer, MC Thoms and JM Olley) pp. 195-202. (IAHS Press). Available

van Ogtrop FF, Hoekstra AY, van der Meulen F (2005) Flood management in the Lower Incomati River Basin, Mozambique: Two alternatives. *Journal of the American Water Resources Association* **41**, 607-619.

Vervoort RW, Glendenning C, Odeh IAO (2004) Developing a deep drainage risk map for the Border Rivers area. In 'ASSSI and NZSS biannual conference Supersoil' Sydney, NSW.

Vervoort RW, Thompson K How do we assess the groundwater dependency and requirements of terrestrial phreatophyte ecosystems? submitted to *Hydrological Processes*