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The Use of Agent-Based Modelling in the Evaluation of Future Scenarios for Water Use in the Tropical Savannas of the Northern Territory

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Abstract

Water use in a tropical savannas region of the Northern Territory, Australia is guided and governed by the physical conditions of the aquifer and river system, the attributes of the community, and the rules embedded in legislation and in social norms. The current policy direction throughout Australia is driven by the National Water Initiative, one aspect of which is movement towards the use of water markets. This represents a change in the rules governing water use, and may have a range of impacts in the region. This paper describes a research project that evaluates how changes in the rules that guide and govern water use in the region could impact on social and environmental outcomes. The project is based around the Institutional Analysis and Development (IAD) framework, and makes use of agent-based modelling to model the responses of outcome variables to changes in the rules by which water is allocated. The agent-based model enabled modelling of future scenarios to support and inform different groups' evaluation of the impacts, by revealing the key interactions between social, economic, political and ecological systems that might result from a water market.

1. Introduction

Whenever we make decisions about how to run our lives and our work, we are guided and governed by a set of rules. Some rules are 'formal', in that they have been devised through formal processes and are recorded in legislation, regulations or by-laws, for example. Some rules are 'informal', in that they are cultural or social guidelines – called 'norms' or 'shared strategies' – that we see in the people around us and that we choose to follow for one reason or another.

This paper describes and analyses the interactions between the formal and informal rules that guide and govern water allocation in the Katherine-Daly River region in the Northern Territory (NT), and how these interactions contribute to certain outcomes. This is an important exercise because most resource use issues – for example, the equitable allocation of water to competing uses within environmental flow requirements – are due, in part, to the existing set of rules about water use. Modifying these rules may be able to bring about more acceptable outcomes. This paper uses a technique called agent-based modelling to simulate changes in allocation rules, and in so doing, enables the evaluation of possible future scenarios for the region and its institutional arrangements.

One particular set of rules that is under consideration for the water allocation process is a water trading system. Water trading is not currently occurring in the Katherine-Daly River region; however its consideration is being driven by a national program of water reform, known as the National Water Initiative (NWI). Water trading is a tool that can be used to help coordinate the allocation of ground and surface water to different uses. The rationale for using trading markets is that they can facilitate water being diverted to high value uses, thus bringing about the more profitable use of water, and they can also make it easier to recover water for environmental purposes while compensating those who decide to sell. While water trading has been operational in other parts of Australia for the past two decades, very little is known about how the interactions between buyers and sellers in a tropical savannas setting may play out and the outcomes they may lead to.

The objectives of this research are to document the patterns of interaction between irrigating growers under the current set of rules about water allocation, given existing physical/material conditions and the attributes of the community, and then to analyse the patterns of interaction that may occur under a new set of allocation rules, which include the rules of a water market, and the outcomes these interactions may lead to. The metrics by which these scenarios are evaluated are the total amount of groundwater extracted for irrigation and total profit from irrigated production.

These interactions are explored based on the Institutional Analysis and Development framework (Ostrom 2005) and through an agent-based model (ABM), which enables simulation of the real world system and the testing of changes to that system without risking the potentially negative effects of real world experimentation. The ABM models future scenarios by revealing the key interactions between social, economic, political and ecological systems that might result from a water market. This can then be used to support and inform evaluation of the outcomes.

The paper proceeds as follows. Section 2 introduces the real world context of the institutional change for the Katherine-Daly River system. Section 3 discusses agent-based modelling and the model specified to enable evaluation of potential future scenarios. Section 4 reports results of the modelled scenarios, and section 5 concludes with a discussion of the usefulness of modelling for the evaluation of scenarios.

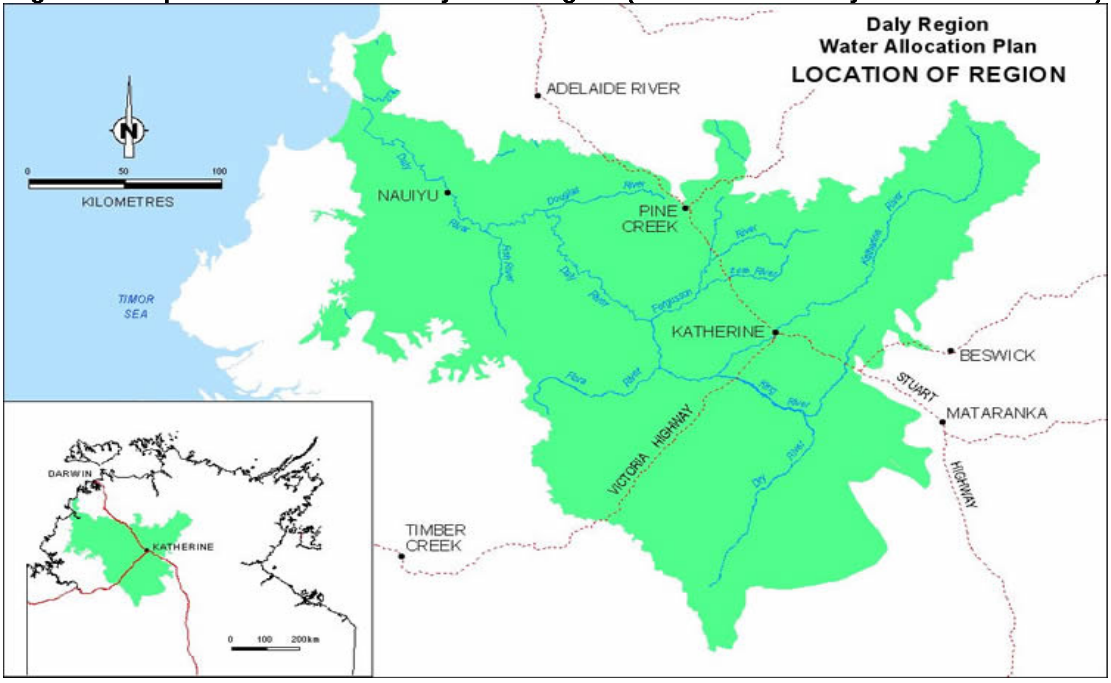
2. Institutional change in the Katherine-Daly River system

The Katherine-Daly River region is a set of tropical river sub-catchments in the Top End of the NT (Fig. 1). It is home to approximately 14,070 people (Griffith 2004), is popular with local and international visitors, especially as a recreational fishing spot, and supports both pastoral and emerging agricultural and horticultural enterprises. The Daly has the largest flow of all rivers in the NT, and the vast underground aquifers supplying the river ensure that relatively reliable flows of good quality water are still available during the dry season (Northern Territory Government 2003, p.3).

Both this and the availability of high potential soils (Begg, van Dam *et al.* 2001, p.ix) underpin the consideration of further agricultural development in the Region.

These year-round flows also contribute to the unique ecological nature of the Daly River system (Hatton and Evans 1998) and to the existence of certain habitats that support significant biodiversity and conservation values. Yearly monsoonal flooding delivers water and nutrients to the huge floodplain wetlands that provide habitat for a plethora of important species, including freshwater wetland birds. The river system also provides habitat to some rare and endangered species including the pig-nosed turtle (Georges, Webster *et al.* 2003; Blanch, Rea *et al.* 2005; Chatto 2005). Many of these species also provide for the nutritional needs and customary activities of the Aboriginal people living in the region (Jackson 2004), and the river system is also central to the identity, culture and lifestyle of Aboriginal and non-Aboriginal people (Stoeckl, Stanley *et al.* 2006).

Figure 1: Map of the Katherine-Daly River region (Northern Territory Government 2004)



The values and management of the river system are currently under consideration by the NT Government in the preparation of an Integrated Regional Land Use Plan and a Water Allocation Plan for the region, and this is being influenced by development and conservation aspirations, and by other, uniquely Indigenous, objectives.

Currently, water allocation decisions in the Katherine region are governed most directly by a licencing process decided and implemented by the NT's Controller of Water as an agent of the NT Government and in line with the *Water Act (Northern Territory) 2004* and *Water Regulations (Northern Territory) 2002*. This process includes an application by a potential extractor that details their proposed crop and water needs per month for up to ten years. The NT Government reviews the application and, if accepted, grants an entitlement, monthly allocations for up to ten years (and beyond if acceptable) and a use licence. Many aspects of daily water use decisions are mostly left up to each individual irrigator, and are based on their own crop requirements, soil conditions, technology, costs and benefits, experience and expertise.

Resources such as groundwater aquifers are described by economists as ‘common pool resources’. This means that: (a) it is difficult and costly to exclude people from extracting from the resource – the resource is ‘public’ in that it is difficult to assign complete private property rights, and (b) every person’s extraction impacts on the overall quantity and quality available for others, imposing group-shared costs on the community. For resources with these characteristics, it can be especially challenging to coordinate people’s activity, yet coordination is also especially important because the continued quantity and quality of water resources is critical to social, ecological and economic health. Randall (1978) and Common (1995) suggest that the management of common pool resources is likely to require a combination of economic instruments and community involvement in coordinating aggregate extraction strategies.

The challenge of coordination of a common pool resource can be met with four types of policy responses: (1) regulation only, (2) taxation or a levy, (3) implementing a market, (4) community governance, or a combination of responses (all of which include some form of regulation). The implementation of markets is being considered as part of the Australia-wide National Water Initiative (NWI)[1], and has been on the table in various forms in different parts of Australia since 1983.

Water trading may allow water entitlements to move (within certain conditions) to users who make the highest marginal returns from water use. Water trading may allow those who are not currently using their entitlement to realise the capital value of their asset through selling it permanently, or to earn an annual income through leasing it temporarily (depending on the rules of trade). Water trading may be part of a strategy to allow growers flexibility in responding to changing conditions, which, in combination with environmental water requirements backed up by a Water Allocation Plan, may ensure that unacceptable environmental impacts do not arise. Whether the benefits of water trading will arise in the Katherine-Daly region, however, and how a water market might interact with existing rules in the region are not yet certain.

To evaluate the potential impacts of a hypothetical water trading scheme, we analyse how changing some existing rules of allocation might impact on water use and on social, economic and environmental outcomes. The changes to be considered are from a system without a water market to one with a water market, and then of different water market designs. The different water market designs are based on the allocation of new water licences to new users or not, and the allocation of potential pumping restrictions in dry years to all users versus new users only. The following describes the ABM process and operation used to develop these scenarios for water use in the Katherine-Daly region.

3. The Tindall Aquifer Water Trading Model

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[1] See http://www.pmc.gov.au/nwi/index.cfm for more details on the NWI.

The model developed to empirically analyse changes to the Katherine-Daly system is called the Tindall Aquifer Water Trading Model (named after the aquifer from which water extraction is of interest). It simulates a population of horticulturalists (n = 18 or 59, depending on scenario specifications) involved in production of irrigated crops such as mangoes, melons and citrus. The Tindall aquifer is mostly responsible for recharging the Katherine River, particularly in the dry season, so plays a central role in providing for many ecological, social and cultural values expressed for the region. Concerns have been raised by community members and stakeholders about the potential impacts of further groundwater extraction on these values and the trade-offs that may have to be made between irrigation-based agriculture and the provision of environmental flows and their related benefits.

As discussed, a water trading system for water allocations is under consideration as an instrument to improve water use efficiency, to capture the full value of water, and to coordinate the use of the Katherine-Daly River system as a common pool resource. The specific simulation technique used to simulate changes to the institutional arrangements of the Katherine-Daly system is called agent-based modelling Parker, Manson *et al.* (2002) gives an overview of agent-based models applied to land use questions). In an ABM, the actors of interest are referred to as ‘agents’ who exhibit a range of behaviours that mimic the behaviours of their real-world counterparts. The agents in this model are irrigating growers in the Katherine-Daly region.

The model is written in the programming language, Java, and uses the Repast simulation toolkit[2] (Heckbert, Smajgl *et al.* 2006). Each time period represents a fortnight, during which events take place throughout the production year. These events involve three major activities. First, agents decide how much water they need to produce their crop and compare this with how much water they actually have – their water allocation (in megalitres). As the model simulates a water market, this first step reveals whether each agent has water allocations surplus to requirements that can be sold or whether they have a deficit in water allocations that they would like to buy.

Second, potential sellers and buyers of water calculate how much they would bid in a market to sell or buy a quantity of water. They then enter the market, which in this case is a double call market in which potential buyers randomly access an offer to sell and compare the price on offer with their own bid. Water is bought if the amount the buyer is willing-to-pay is higher than or equal to the selling price, and they may purchase a volume of water up to their demanded volume. If the buyer has not bought the full volume they demand from that seller, they proceed to the next seller’s offer and repeat the process. Once an agent’s full demanded volume has been purchased, or there are no offers to sell with a sufficiently low price, the next buyer agent goes through the same process until all demand is satisfied, all volume for sale has been purchased, or there are no more transactions. Once the buying and selling activity is completed, the water allocations for that month for each buyer and seller are updated according to how much each individual bought or sold. Agents then use their water allocation for that month.

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[2] http://repast.sourceforge.net/

The third step of the model calculates production based on the outcomes of the water market and the use of water allocations on crops (in this model all agents grow mangoes). The application of water to mangoes impacts on the growth rate of the crop, and hence the amount of mangoes harvested. The costs of production include variable and semi-fixed costs calibrated from horticultural literature, the costs of water purchased in the water market described above, and labour costs. Agent profits are realised through crop revenue, based on the volume of produce taken to market, and any revenue earned through selling water in the water market. The overall profits realised by agents are taken into consideration when they make decisions about the future development of their business including any potential changes in land use.

These three major steps of agents' behaviours as described above are embedded in, and rely on data relating to the broader social-ecological system of the Katherine-Daly region. There are three issues that define the scenarios of interest in this study. First is the introduction of a water market as discussed above. Second, there are currently 60 applications for water allocations from the Tindall aquifer that have been received by the Controller of Water. The Department of Natural Resources, Environment and the Arts wants to know the potential impacts of granting these allocations.

Third, there is an '80:20 rule' that states that at least 80% of the natural environmental water flow must flow in the river at all times, and thus that no more than 20% of annual aquifer recharge can be extracted for use. Extraction from the Tindall aquifer is about to reach this limit, which signifies the potential for restrictions to be placed on users when volumetric allocations exceed the 20% allowable extraction rate as they may in particularly dry years. The aquifer's volume and amount of discharge into the Katherine-Daly system and the potential for water pumping restrictions are measured based on patterns of rainfall and recharge and discharge values as described in Puhalovich (2005, Appendix C, Fig. C2).

If the total allocated volume of water is greater than the maximum volume that is extractable (i.e. 20% of the annual aquifer recharge) at any time of year (due to the year being particularly dry, for example), individual water allocations may be reduced by a certain amount and distributed between irrigators in a certain way. A second policy question is of how to distribute these pumping restrictions

Each scenario will investigate the impacts of interactions between these three factors and thus describes a different set of institutional arrangements defining the design of the hypothetical water market. The outcomes of each of these scenarios are measured through two metrics:

- Total amount of groundwater extraction for irrigation (ML); and
- Total profit derived from irritation production ($).

4. Results for potential future scenarios

Each simulation of the model was run for 528 time steps, each representing a fortnightly period, extending over 22 years of historical rainfall data for the region. Figures 2 to 6 depict the mean outcome for 100 simulation runs per scenario. The mean value for each of the runs is depicted by the prominent line (confidence intervals are not reported in this paper).

This is one critical caveat to state at the outset. Caution should be used in interpreting quantitative results from this style of modelling. This is because agent-based models are models of complex adaptive systems, which are characterised by two central attributes: sensitivity to initial conditions and the presence of non-linearities and feedbacks (Holland 1998). Because of this, complex adaptive systems exhibit emergent phenomena that cannot be observed in the individual parts, only in the whole system when the parts interact. As such, the prediction of state variables (specific model outcomes) at a certain point in time during the simulation is accompanied by a degree of uncertainty. The level of uncertainty depends on assumptions made in the model and increases as time passes in the simulation. Therefore, the results of this type of modelling are best interpreted through comparisons of multiple scenarios, and the differences between each set of outcomes. Therefore, we explore dynamics of the system, and compare one scenario outcome to another (where all other parameters are held constant) rather than present a given outcome at time t for a single simulation run. This caution applies to all of the modelled scenarios presented here.

The first scenario examined here models grower activity as described above, but without agents having the ability to trade water allocations. It also models the situation where no new water licences have been granted. The number of agents is thus 18.

This is the 'baseline' scenario and results are shown for the total amount of groundwater available for extraction (ML) by irrigators, annual rainfall (mm) and volume of groundwater actually extracted (ML) (Fig. 2). Based on historical rainfall data, there is an initial period of abundant rain in years 1-6, followed by a number of dry years (approx 6 to 14) where rainfall levels are not sufficient to recharge the aquifer. Rainfall again becomes generally abundant from years 15 onward. The available extraction volume increases and decreases with the wet and dry seasons of each year, and trends in line with rainfall. The times when baseline actual extraction is higher than the available extraction volume signals the potential need to introduce pumping restrictions in those years.

Figure 2: Groundwater available for extraction (20% of annual aquifer recharge), rainfall and total groundwater extraction by simulated agents for scenario 1

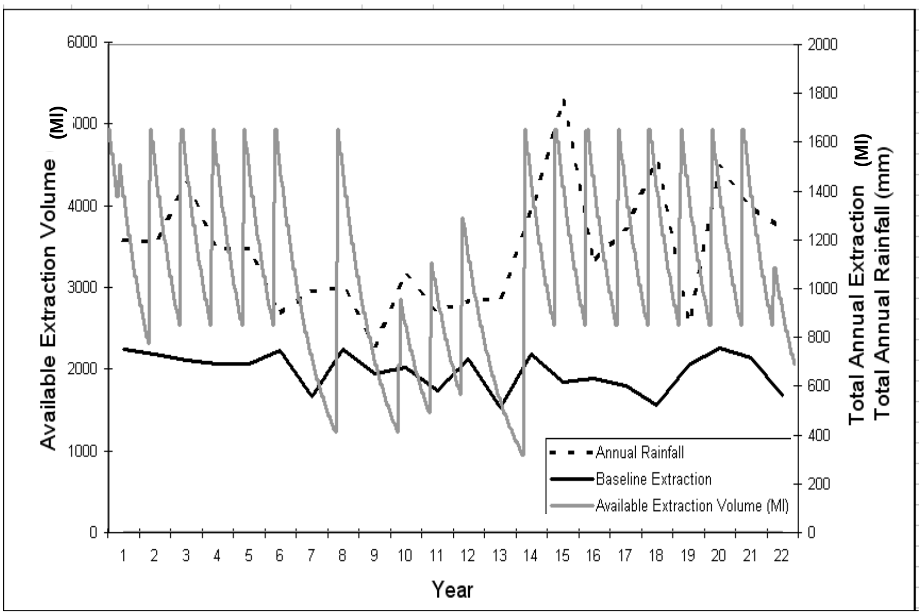
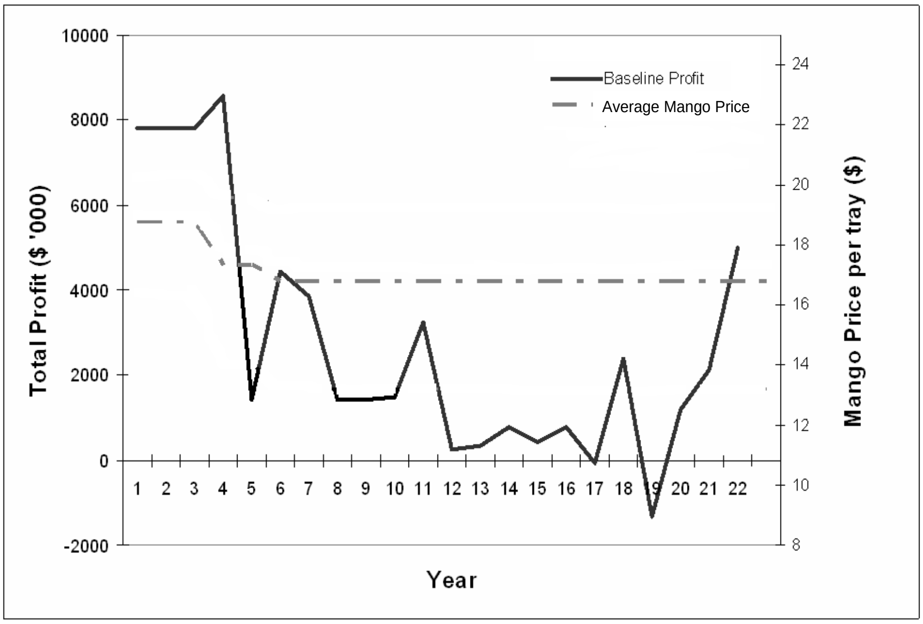


Figure 3 depicts total profit under the baseline scenario. The downward trend is explained partially by forecasted mango prices, which are predicted to decrease to 2013 (year 6) and then level out. The profit trend is also affected by the amount of crop produced (which is affected by rainfall) and the availability of labour during harvest time.

Figure 3: Total profit derived by simulated agents for scenario 1 and average mango price/tray



The following figures introduce scenarios where all pending applications for allocations are granted (the number of irrigator agents is now 59) and a water market is introduced. In scenario 2, pumping restrictions in dry years are borne by all irrigators. Figure 4 depicts total groundwater extraction volumes from the Tindall aquifer comparing scenarios 1 and 2. As would be expected, extraction volumes are higher when all pending allocations are granted and they converge to the same as for the baseline scenario, indicating that the cap of 20% of annual aquifer recharge becomes operational in both scenarios in particularly dry years. Pumping restrictions are applied to all irrigating agents in the model for this scenario, and growers face restrictions of up to 60% in the dry seasons of particularly dry years, and 40% otherwise.

Figure 4: Total groundwater extraction by simulated agents for scenarios 1 and 2

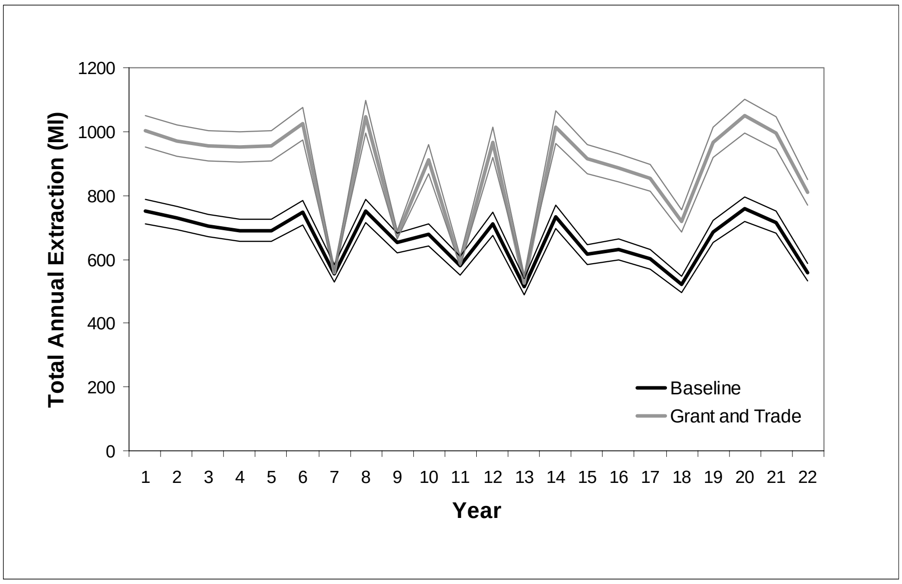
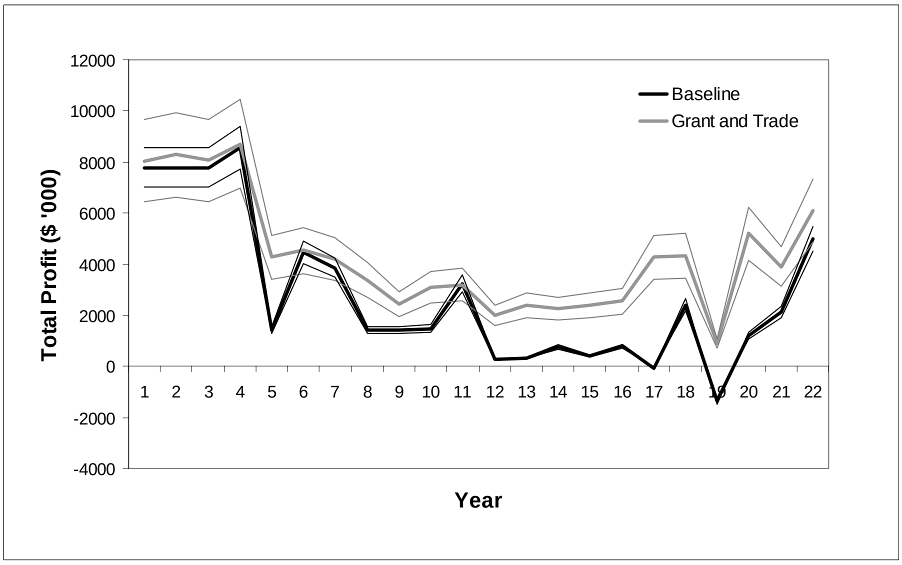


Figure 5 illustrates aggregate profit in scenarios 1 and 2. The greater profits in scenario 2 are a result of the increase in growers and water allocations being applied to a larger area of crop. It is more likely that the increase in profit reflects the presence of more growers in the industry, rather than that individual farms are operating more profitably. The trajectory follows similar dynamics to the baseline scenario, decreasing in dryer years, and recovering in the wetter years.

Figure 5: Total profit for simulated agents for scenarios 1 and 2



The total profit curve for a scenario where all applications are granted and there is no water market is not statistically different from the curve for scenario 2 where all applications are granted and there is a water market. The fact that there are no pumping restrictions in the former scenario indicates that the downward influence of pumping restrictions on profit in the latter scenario is offset by the existence of the water market.

Figure 6 shows total groundwater extraction from the Tindall for scenarios 2 and 3, the difference between the two being that pumping restrictions are borne by all growers in scenario 2, and only by those with newly granted allocations in scenario 3. Total extraction levels are higher when newcomers bear pumping restrictions, and extraction does not converge to the 20% limit in dryer years. This is because when newcomers are restricted, sometimes by up to 100% of their licence, existing licence-holders can still pump their entire licenced allocation, which occasionally pushes their total extraction over the 20% limit (in the baseline scenario, existing licence-holders would face restrictions of up to 50% in some years). Thus this set of rules cannot maintain extraction at or below the 20% limit.

Figure 6: Total groundwater extraction by simulated agents for scenarios 2 and 4

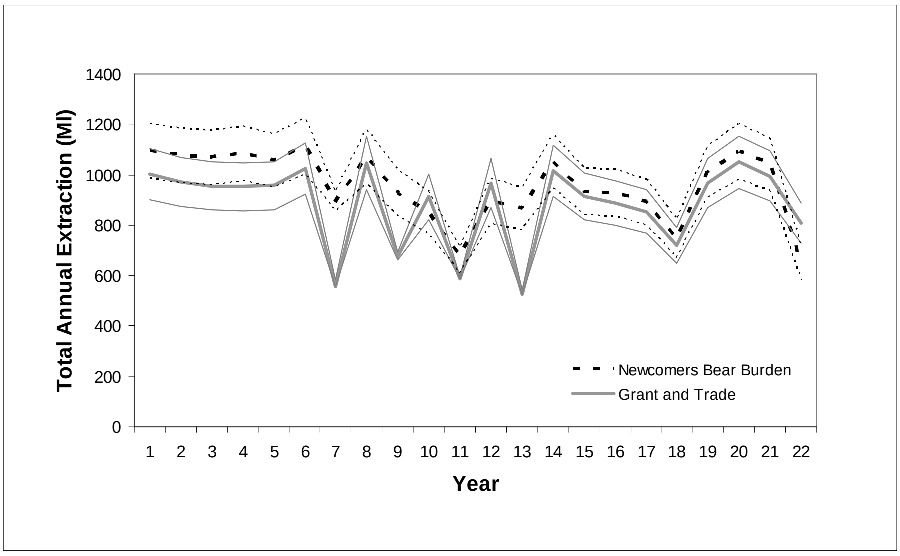


Figure 7 depicts the outcomes for total profit for the population of agents for scenarios 2 and 4. The higher overall levels of extraction in scenario 4 result in higher profit levels.

Figure 7: Total profit for simulated agents for scenarios 2 and 4

5. Conclusions and discussion

While none of these results can be taken as precise estimates, they do reveal some interactions between ecological, economic and social conditions in the Katherine-Daly River region and the rules that guide and govern water allocation and use. For example, the model reveals how the interactions between dry year rainfall, trading in the water market and rules about the allocation of pumping restrictions impact on the behaviour of newcomers and on environmental outcomes.

The granting of all pending applications and implementation of a cap and trade system combine to result in the need for pumping restrictions in each of the 22 simulated years. These restrictions reach up to 80% of each grower's licence in dryer years when borne by all, and up to 100% when borne only by newcomers. When pumping restrictions are borne by all growers, the 20% cap can be maintained, while extraction can sometimes overshoot the 20% limit when only newcomers bear pumping restrictions.

Total profit is influenced mainly by the number of licenced hectares and the amount of water applied to crops. When all pending applications are granted and there is no cap and trade system, total profit is not significantly different to when all pending applications are granted and there is a cap and trade system. This indicates that the downward influence of pumping restrictions on profit is offset by the existence of the water market. Even when extraction is not capped, however, profit is not higher than when extraction is limited to 20% of annual aquifer recharge due to the labour constraint. Therefore, both water and labour availability impact negatively on profit.

In summary, even without the granting of more licences there is a need for a cap to come into play to ensure extraction stays at or below the 20% limit of the 80:20 rule. It is important to note that this result has been simulated based on a particular hydrological model of the Tindall aquifer and data for current licenced allocations. The cap enables risks to the environment and non-extractive values of the Katherine-

Daly River system to be managed. The cap also imposes risks on growers, and a water market has here been simulated as an instrument to help growers manage their risk and to ensure water flow to the highest value uses. The scenario that maintains both the 20% limit and maximises water revenues is that where all pending licences are granted and pumping restrictions are borne by all growers.

The use of simulation modelling in this research has provided a tool to analyse the net impacts of institutional change. As such it is a heuristic, rather than a predictive tool, that enables the identification of patterns of interaction between variables in the support of scenario evaluation. Agent-based modelling relies on consultation with land managers and resource managers and the availability of data, and should also be 'groundtruthed' with these stakeholders to check that results seem reasonable to those whose actions are being modelled. These consultations are valuable exercises. Also of benefit is the visual nature of the ABM output, which can better enable stakeholder to perceive and think through scenarios.

Due to the making of assumptions and the limitations in computing power, an ABM will not be able to model all important variables or reveal all relevant interactions. As such, an ABM will need to be designed and interpreted based on theory and reality. For example, the Tindall ABM could not reveal that the success of a market-based instrument is dependant on a range of preconditions, such as wide agreement about the nature and extent of the resource and about the environmental target; monitoring schemes that are cost effective, transparent, consistent and credible to all participants; a clear link between land management actions and resulting environmental outcomes; and transferable, enforceable and tradeable private property rights (Ward, Tisdell *et al.* 2006).

In sum, however, the simulation of future scenarios through an ABM can be used to support and inform different groups' evaluation of the impacts by revealing the key interactions between social, economic, political and ecological systems that might result from a water market implemented in the Katherine-Daly River region.

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