Tindall Aquifer Water Trading Model: Technical Report and Scenario Results

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CSIRO Sustainable Ecosystems

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Table of Contents

List of Figures

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1. Introduction

This paper describes the functioning of the Tindall Aquifer Water Trading Model, developed by CSIRO Sustainable Ecosystems. The model is used for simulating a hypothetical market for water where irrigators in the Katherine region of the Northern Territory, Australia, may buy and sell their groundwater entitlements. The Tindall aquifer discharges into the Katherine River and is largely responsible for the flow of water occurring in the river throughout the year, and particularly in the dry season (Puhalovich 2005). The aquifer also provides water for irrigators for use in agricultural / horticultural production.

The introduction of water trading systems in Australia has been proposed as part of the National Water Initiative[1] as an allocation mechanism that may improve rural water use efficiency and help manage environmental outcomes as demand from irrigators increases. Increased groundwater pumping levels could potentially reduce the volume of water discharged into the river, and in turn affect environmental services which depend on the river's water flow.

The Tindall Aquifer Water Trading Model focuses specifically on extraction of groundwater from the Tindall aquifer for the purposes of horticultural production. Here we simulate a hypothetical water market for growers in the region, and use the simulation to examine outcomes that emerge depending on various scenarios of the market is implemented operated into the future.

Within the model, simulated growers are allocated a monthly licensed volume of groundwater for use in irrigated production, with model input data based on a number of real-world data sources from the region. Within the model, water can be applied to crops or sold to other growers for this purpose. The model considers water allocated to horticultural/agricultural uses, and does not consider water allocated to the public water supply, industrial use, or other uses. The model considers growers living in an area in and around Katherine and extracting from the Tindall aquifer, as depicted in the darker green area of Figure 1.

The model simulates conditions for a number of possible scenarios. Baseline conditions include n=18 growers, allocated a total annual volume of 18,990 Ml to

[1] See http://www.nwc.gov.au/NWI/index.cfm

be used in irrigated production. In this scenario (representing ‘baseline’ conditions), no market for water exists, and as such growers are not able to trade water allocations. In the baseline scenario, growers make their water use decisions based on their monthly allocation of water. Compared to this, a number of scenarios examine outcomes where further new licenses are granted (n=59 annually allocated a total of 35,107 Ml), a water market is introduced to allows trading of licensed allocations, and other constraints on the operation of the water market and the rules under which it operates are imposed. A range of scenarios within this range are explored and reported here.

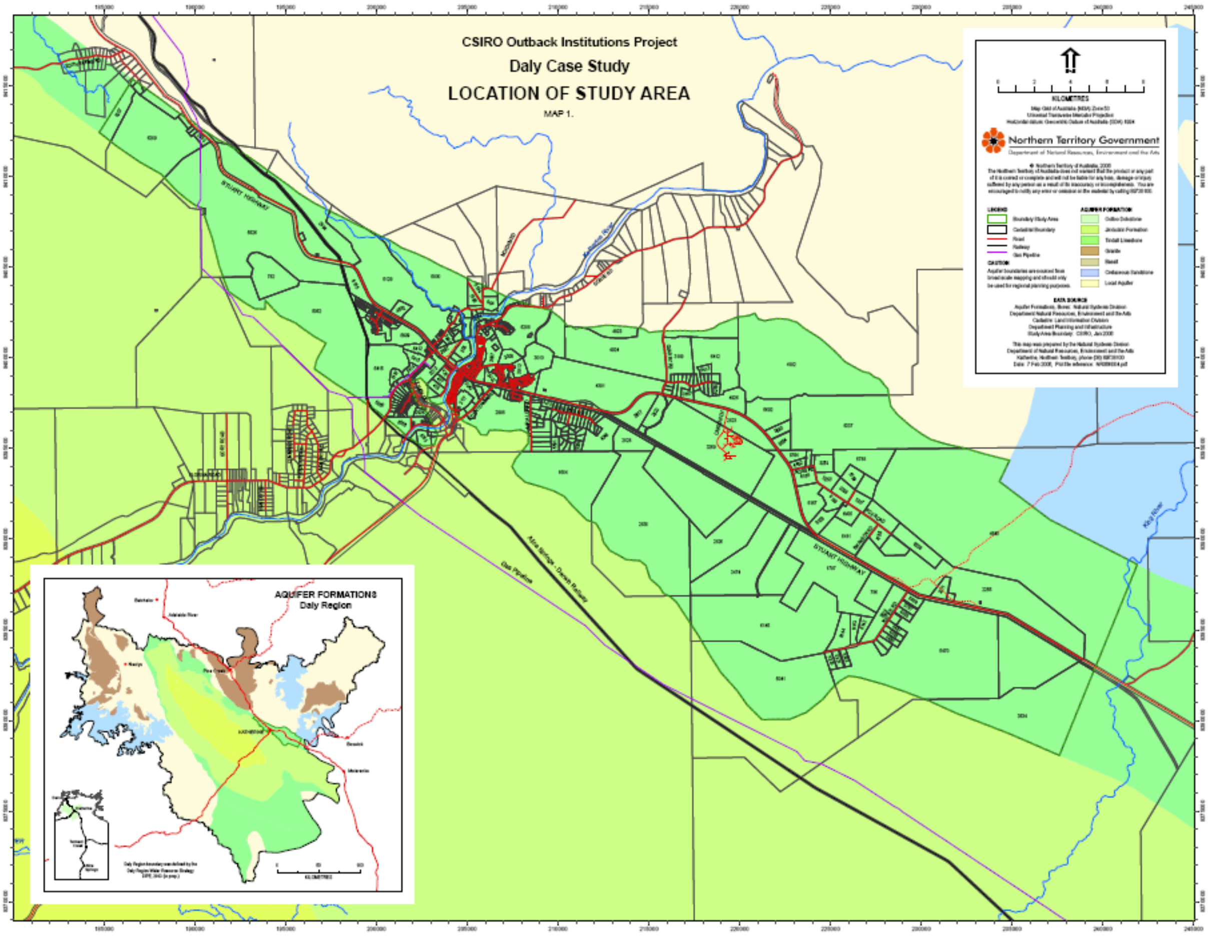

Figure 1: Farms included in the Tindall Aquifer Water Trading Model are shown here lying over top the darker-green area. The set of properties simulated is divided between East and West sections by the Katherine River (centre).

The model simulates the system involved, namely a connected system of irrigators and their crops, rainfall and the aquifer which supplies groundwater for irrigation. The model reports how this system changes in response to various potential policy options for the operation of a water market, and reports on a variety of indicators of the state of the system over time.

This report describes the model's operations and results according to a number of scenarios. Section 2 describes the model structure, including the program architecture, user interface and scenario specifications. Section 3 describes details of model operations, describing each program module, including equations, assumptions and calibration of the model. This section is organised according to the order of execution of the model. Section 4 describes simulation results of the water market for a number of scenarios. Section 5 offers discussion of simulation results.

2. Model Structure and Interface

The Tindall Aquifer Water Trading Model simulates a population of horticultural producers (n=59, and is dependant on scenario specifications) who are involved in horticultural production. The simulation technique used is that of agent-based modelling[2], with the simulated producers referred to as 'agents' who perform a variety of behaviours within the model that mimic real world behaviours of growers in the region. The simulation proceeds at a fortnightly time step[3], with events occurring during each time step throughout the production year.

Program Architecture

Technically, the model is written in the Java programming language, and uses the RePast simulation toolkit[4]. The model consists or four primary classes:

- *WaterModel.class* is the overall model controller and main class
- *GrowerListManager.class* creates the population of agents and tracks population level data
- *Grower.class* is an instance of a single producer agent, and performs agent behaviours during each time step
- *Space.class* maintains data items necessary for the model operation

[2] For an overview of agent-based models applied to land use, see Parker et al., (2002).
[3] It is assumed that each month consists of two fortnightly time steps, with 24 fortnights in one year. Fortnightly time steps are assumed as this was found to (generally) be the shortest time frame by which significant productions decisions, and events throughout the growing season occur.
[4] http://repast.sourceforge.net/

Further classes are included to support this basic structure. Upon initialisation, the model progresses through the steps outlined in this paper calling methods (functions) from the above classes where appropriate.

User Interface and Scenario Specifications

The Tindall Aquifer Water Trading Model uses the *Repast* user interface, as depicted in Figure 2, to allow the model user to control the simulation runs, and to set scenario specifications and initial conditions.

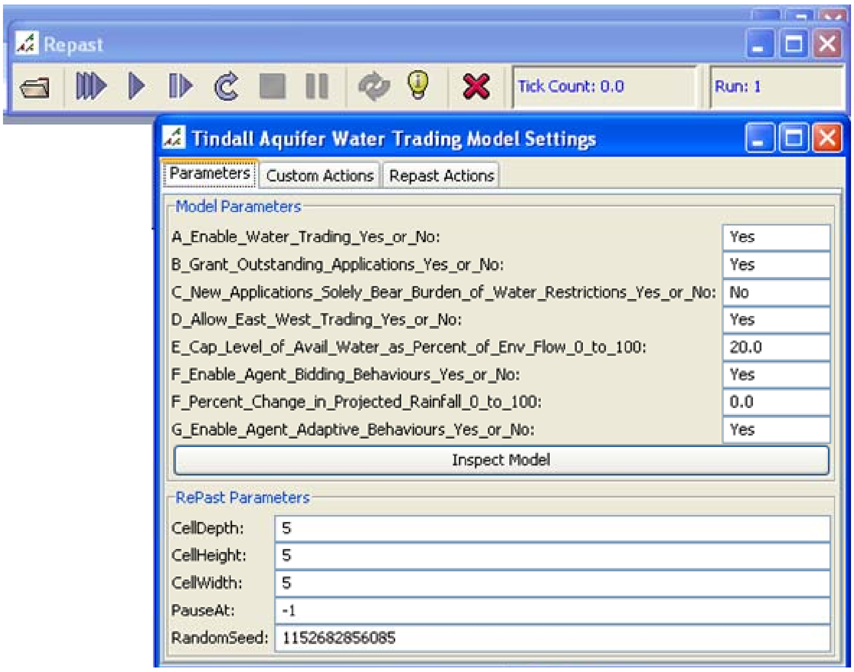

Figure 2: The Repast user interface of the Tindall Aquifer Water Trading Model. The top toolbar controls the simulation run, while the bottom window allows the model user to input scenario specifications.

Model users can alter the conditions under which the simulation proceeds by changing default values in the Repast user interface, including:

- *Enable_Water_Trading_Yes_or_No*
  - Determines whether producers are allowed to enter a water market (Yes), or not (No)
- *Grant_Outstanding_Applications_Yes_or_No*
  - Determines whether existing licensed users are the only users entitled to extract water (No), or whether those potential users who have submitted an application for extraction of water are approved

to pump ground water (Yes), as based on DNRETA[5] water license data

- *New_Applications_Solely_Bear_Burden_of_Water_Restrictions_Yes_or_N*
    - Sets whether 'newcomers' into the community of licensed water users are the only users affected by the imposition of pumping restrictions (Yes), or if all water users equally are affected (No)
- *Allow_East_West_Trading_Yes_or_No*
    - Sets whether producers located in the East Tindall area (n=32, including applicants) may trade with producers located in the West Tindall area (n=27) (Yes) or whether producers in the East and West may only trade amongst themselves (No)
- *Percent_Change_in_Projected_Rainfall_0_to_100*
    - Sets the increase or decrease in rainfall as a percentage change of the historical rainfall patterns
- *Cap_Level_of_Avail_Water_as_Percent_of_Env_Flow_0_to_100*
    - Sets the minimum percentage of natural environmental flows that must be maintained. The remainder is available for groundwater extraction.

3. Model Processes

Rainfall and Hydrological Conditions

Values of total monthly[6] precipitation (mm) were obtained from the Bureau of Meteorology, Darwin, as sampled at the Katherine Aviation Museum from 1975 to 2005. During model simulations, the historical data is run from 1975 to 2005, adjusted by the percentage change defined by the model user, as discussed above.

[5] Northern Territory Department of Natural Resources, Environment and the Arts
[6] To accommodate fortnightly time steps, monthly rainfall is equally divided between the 2 fortnights in any month.

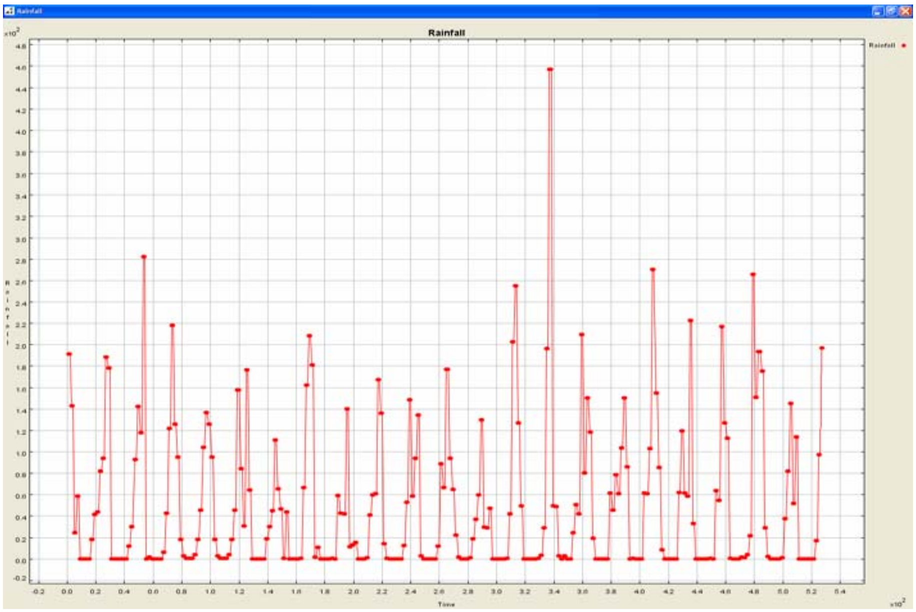

Figure 3: Repast graphical output of historical rainfall data for the Katherine Region, 1975 to 2005. Rainfall patterns are a major driver of model outcomes, hence the simulation is run using historical data.

In order to track how much water is available for irrigation extraction, the Tindall aquifer is modelled based on findings reported in Puhalovich (2005). The volume of water in the aquifer is calculated in a simple fashion such that:

Eq 1. $V_t = V_{t-1} + C_t - 0.015V_t$

Where V_t is the aquifer volume [Ml], C_t is the recharge volume [Ml], a volume of 1.5% of the aquifer volume is discharged per fortnight, and

Eq 2. $$C_t = \begin{cases} \mathit{If} \ \sum_t R_t < \min R \quad C_t = 0 \\ \mathit{If} \ \max R > \sum_t R_t < \min R \quad C_t = \left(\sum_t R_t - \min R \right) * RR \\ \mathit{If} \ \sum_t R_t > \max R \quad C_t = \max RR \end{cases}$$

Where $\sum_t R_t$ is the cumulative rainfall [mm] for the year[7], $\min R$ is the minimum cumulative rainfall [mm] required before recharge may begin to occur, $\max R$ is the maximum cumulative rainfall [mm] threshold where recharge rates reach their peak, RR is the recharge rate, and $\max RR$ is the maximum recharge rate possible[8].

[7] Cumulative rainfall is recorded from May to April after the end of the wet season.
[8] Values for $\min R$, $\max R$, RR, and $\max RR$ are calibrated based on Puhalovich (2005) in order to recreate the pattern of yearly aquifer volume recharge and discharge rates described

Regulating Groundwater Extraction Levels

A certain level of acceptable environmental flow of water into the Katherine River is defined by the model user through the user interface, as described in section 4, above. At least 80% of annual aquifer recharge is to be allocated for environmental use for the purpose of ensuring that requirements of all groundwater-dependent ecosystems are maintained. Annual extraction from aquifers will therefore be equivalent to no more than 20% of annual recharge (Faulks and Kirby 2004). This is known as the '80:20 rule'. This determines the minimum level of groundwater extraction. Past this point, extraction levels are 'capped'[9], thereby maintaining this minimum acceptable volume and hence the flow of water into the Katherine river.[10] The minimum aquifer volume is ensured through 'capping' the licensed extraction levels[11] from irrigators by the ratio of difference between total water licenses and maximum extractable water, such that:

Eq 3.
$$If \quad \sum_i E_{it} > V_t \times MinF \begin{cases} \xrightarrow{\text{True}} \mathrm{U_t} = \dfrac{\sum_i E_{it} - (V_t \times MinF)}{\sum_i E^c_{i\,t}} \\ \xrightarrow{\text{False}} \mathrm{U_t} = 1 \end{cases}$$

Where E_{it} are the licensed groundwater extraction levels [Ml] of producer i for $i = 1...n$ in time t, V_t [Ml] is taken from equation 1, $MinF$ is the specified minimum level of environmental water flow [%] as specified through the model user interface, U_t is the 'cap ratio' [%] which describes the percentage of restriction applying to agents' licenses, and $E^c_{i\,t}$ is the license volume [Ml] of agent

therein. This simplified version of calculating aquifer volume does not take into account many of the dynamic aspects of effective rainfall, groundwater flow, aquifer depth, and surface evapotranspiration.

[9] It is assumed that irrigators comply with licensed extraction volumes.

[10] If is assumed that the volume of the aquifer is directly correlated to the level of environmental flow discharged into the Katherine river, such that 80% of aquifer volume corresponds to 80% of environmental flow.

[11] The following equations use the term E_{it}, $E^c_{i\,t}$ and E_i', which jointly refer to a simulated producer's water entitlement (E), for producer i. If the producer faces a water restriction, the entitlement is 'capped', represented by the term c. The resulting restricted entitlement level is represented by the term E_i'.

i to which the cap c applies, again as specified by the model user. For example, if the model user has defined that only 'newcomers' are to bear the burden of water restrictions, $\sum_i E^c_{i\,t}$ represents the total license volume of only this portion of the agent population. Where no conditions of distribution for the burden of water restrictions exist, the burden is borne equally[12] for all agents in the population of irrigators. This process alters the licensed amount of groundwater an agent may extract, such that:

Eq 4. $$E_{i_t}' = \begin{cases} E_{i_t} \quad if \quad c = 0 \\ \\ E_{i_t} * U_t \quad if \quad c = 1 \end{cases}$$

Where E_i' is the adjusted licensed volume [Ml], and c is a binary variable (1 or 0) which is 'on' if restrictions apply to that agent, otherwise is 'off'.

The outcome of equations 2 and 3 is a specified volume of water that is restricted from being extracted by irrigators, and the determination of how that capped volume is distributed across the agent population (i.e. whether restrictions are borne equally or only by a certain group of irrigators).

Producer Characteristics and Behaviours

Data for farm attributes was acquired from DNRETA for calibration of simulated agents[13]. From this, the data set (held within the file 'ProducerData.csv') informs the model of attributes for each groundwater pumping license, including the details of each agent's water entitlements and other information pertinent to the farm's operation, including:

- Area[14]
- Location on either the east or west portion of the aquifer
- Whether the license is currently allocated or is in the application stage

[12] Licenses are adjusted by a percentage of the original license volume, where the percentage of the license is equal for all affected producers. I.e. all licenses could hypothetically be capped by 10% of their original volume, and hence larger licensed volumes would account for larger actually volume of water restricted from pumping.

[13] The data set was truncated to include only those licenses involved in irrigation activities, and excludes water use for industrial, cultural and public water use purposes.

[14] The spatial extend of the area under analysis is 33622.09 ha based on DNRETA data

- Current licensed extraction amounts (Ml) for months January through December[15]
- Area of land under production

Although a number of land uses exist in the study regions,[16] model operations are calibrated to mango production data. This assumption was required due to lack of consistent data.

Water Market Decisions

At this stage of the model process, the conditions for rainfall, aquifer condition, agents' water entitlements and associated restrictions has been set. Producers can now proceed with their production decisions, as described in this section. Agents determine their desired level of water use, ascertain if their entitlement and any restrictions satisfies this, and potentially enter into a market for buying extra volumes of water.

Watering Requirements

The first element in growers' water use decision is to compare crop watering requirements with the volume of their water use license for a given month[17]. Given the requirement to 'use it, trade it or lose it", the difference between requirement and license volume is the amount of water that growers can potentially supply to, or demand from a water market.

After adjusting the water license entitlement, as was described in equation 3, producers determine the level of water that they wish to use[18] (prior to entering a

[15] The original DNRETA data contains information on current and projected extraction levels, in which producers are able to increase their licensed volumes over time as farms develop to larger capacity for projected growth according to farm plans. The model uses the final farm capacity volumes, assuming production among farms in the region has already gone through this growth phase.

[16] Predominant land use in the area includes mangos (1101.7 ha), sorghum (710 ha), melons (including watermelon, rockmelon and pumpkin, 414 ha), citrus (275.8 ha), peanuts (150 ha). A number of other land uses contributes a smaller area under production, namely: forestry (hardwood, mahogany), nursery, cashews, sesame, vegetables, onion, annuals, hay, lawns / gardens, lucerne, Asparagus, banana and cotton

[17] Although the base time step is fortnightly, certain operations and data items pertain to longer periods, hence decisions which occur monthly.

[18] Assuming that producers are not constrained by capacity to pump, i.e. they have sufficient access to pumps, bores and other physical infrastructure necessary for irrigation.

water market to adjust this amount). Desired water use is based on crop water requirement data[19] for each crop, such that:

Eq 5. $N_{it} = \frac{Q_t - R_t}{100} \times A_i$

Where N_{it} is the total water [Ml] needed in time t[20], Q_t is the recommended minimum watering level [mm], R_t [mm/m^2] is the current rainfall, and A_i is the area [ha] under production for each crop type. The water use decision made by an agent will be the N_{it} value, up to the constraints of their individual water license.

Demand and Supply Volumes within the Water Market

Agents either provide (or require) a volume of water from the water market based on the discrepancy between crop requirements and licensed water entitlements, such that:

Eq 6. $D_{it} = N_{it} - E_{it}'$

Where D_{i_t} [Ml] is the discrepancy between desired water volume and licensed water volume (if negative, the discrepancy is the volume the agent's would potentially demand from the market, and if positive, the volume they may choose to supply[21] to the market), E_{it}' [Ml] and N_t [Ml] are derived in equations 3 and 4 respectively.

Growers in the simulated market can buy and sell water allocations based on a specific open call market structure (see Ward et al., 2006). In this set of market rules, all bids (asks and sells) are submitted simultaneously and a single and discrete market clearing price determined by the administrating agency. This market structure approximates that which has been proposed by DNRETA, where once a bid to sell is released, buyers can immediately purchase the

[19] As provided by Northern Territory Government, Department of Primary Industry, Fisheries and Mines (DPIFM)
[20] Water requirement data is presented on a monthly time scale by DPIFM.
[21] Given the requirement that producers in the real-world proposed water market must "use it, trade it or lose it" it is assumed that agents will supply all unused water to the market, as potential revenues can be made from water that would otherwise be 'lost'.

allocation volume on a ‘first-come, first-served’ basis. It is assumed that the ‘use it or lose it’ rule translates into ‘use it, trade it or lose it’, and that agents will supply all unused water to the market. In reality, however, all growers may not choose to participate in a market.

The modelled market organises potential buyers access a randomly selected offer to sell and compare the price on offer with their willingness-to-pay. A purchase would be made if the amount the buyer is willing-to-pay is higher than 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 the 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.

The water allocations for that month[22] for each buyer and seller are updated once the buying and selling activity is completed. Buyers incur costs based on the market price they paid and the volume they bought, and sellers receive the same in revenue. Agents then use their water allocation for that month.

Calculating Agents’ Market Price for Water

Agents’ market price for water, i.e. their willingness to accept an offer to sell or their willingness to pay to buy additional units of water, is determined by three factors, namely their marginal value for additional units of water, a ‘mark-up’ based on agent-specific behaviour. These two elements determine an agent’s price P_{it}, such that:

Eq 7. $P_{it} = MV_{it} * MU_{it}$

Where MV_{it} [$/Ml] is the marginal value and MU_{it} [%] is the mark-up. Each variable is described in each of the following two sections.

[22] Grower agents do not anticipate activity on the water market, or the possibility of water restrictions, but rather respond to their present water needs in any given time step.

Marginal Value

Grower’s marginal value for water [$/Ml] is the main determinant of their price for water when active in the water market. The marginal value for water is calculated for each grower depending on if they are buying or selling. Buyers calculate a marginal value based on the value of an ‘optimal’ volume of water[23], as compared to the current lesser available volume. Those growers supplying volumes of water to the market calculate their marginal value based on a production level that would be realised under decreased water use. In both of these calculations, The value of water is based on the difference between forecasted profit from the crop under current water use compared with profit from the crop under an altered water use regime. These forecasts are based on the growing season’s rainfall patterns (up to the present time step), and the crop growth already realised therein, as well as forecasted prices for harvests.

The marginal value of water is the dollar value that agents place on one unit of water [$/Ml]. This is the basis of the value that someone will bid to buy, or offer to sell water. As such the marginal value represents the agents’ willingness to pay for additional units of water, and / or willingness to accept payment for selling volumes of water. The marginal value of water is taken to be the base value from which an agent’s market bid value is set.

For buying agents, the marginal value of water is based on the shortfall volume of water they face (their demand, D_{i_t} from equation 4), and the potential profits if this volume were available, such that:

$$MV_{i\ t}^{d} = \frac{Max\pi_t - Current\pi_t}{D_{i\,t}}$$

Where

$$Max\pi_t = TR_{O_i'} - TC_{O_i'}$$

And

$$Current\pi_t = TR_{O_i} - TC_{O_i}$$

[23] Based on crop watering requirements for optimal growth, as discussed in section 3.8

And again where

$$TR_X = X * A_i * \frac{trees}{ha} * P_t$$

$$TC_X = X * A_i * \frac{trees}{ha} * C$$

where

$$X = either\ O_i\ or\ O_i'$$

Where , P_t is the price paid per tray of produce [$/tray], C is the unit cost per tray of produce [$/tray]. The central calculation is that of potential output X [trays/tree] under optimal water use O_i' and output under current water use O_i. The agent thus calculates the value of the water in the current period, considering the entire growth path during that growing season, taking into consideration existing growth and therefore incorporating feedbacks from previous time periods' water use decisions.

$$O'_{i\,harvest} = \sum_t O_{i\,t}^{MaxW_i}$$

And

$$O_{i\,harvest} = \sum_t O_{i\,t}^{W_i}$$

Where $O_{i\,t}^{W_i}$ [trays / tree] is a logistic growth function whose growth rate is dependant on the water use, as described further in following sections (see section 3.8). In this calculation, the final output at harvest time is calculated based on the existing output volume, and either the optimal $MaxW$, or current water use W [Ml]. In this sense, the agent calculates the value of water based on the difference between outcomes. Profit under water use which gives optimal crop growth (demand satisfied) vs the same but calculated with current water availability is compared, resulting in the marginal value of water.

For supplying agents, if their water need is < license volume, theoretically their marginal value for water would be 0. However, we assume growers would be able to behave strategically, and determine a marginal value calculation they believe is reasonable. Here we assume this is the minimum loss volume, such that

Eq 8. $$MV_t = \sum_t \left(\left(O_{i\ t}^{w} - O_{i\ t}^{w-1} \right) \times P_t \right)$$

Where W is again current water use [Ml], and $W-1$ is optimal water use less 1 ML of water over the area of the farm. The resulting formula applies to the dollar value for the unit volume of one megalitre.

Price Mark-up

Each agent is also programmed with a price mark-up variable, which represents a variety of effects on price which are not otherwise captured in the marginal value calculation as described above. The marginal values calculated as above would be appropriate for traditional neo-classical assumptions regarding agent rationality, but is limited in its ability to capture some of the more interesting processes that may affect a real producer's behaviour towards pricing water (see Ward et al., 2006).

To better capture a reflection on real-world bidding behaviour, economic experiments have been undertaken with producers from the region in order to elicit their revealed behaviour in a realistic market setting (see Ward et al., 2006). From this, data describing producer's bidding behaviour shows how actual bid values deviated from the perceived marginal value. The deviation from the true marginal value is termed the price 'mark-up'.

In the experimental data, the range of marginal values was recorded with an associated revealed bid value on an open market structure. Observed bids were compared to marginal values, calculating the deviation from what one would expect from a perfectly 'rational' decision. It was found that 11 unique bidding strategies existed in the population of experiment respondents, as described in the following section.

Experimentally-calibrated Bidding Behaviour

Two important values required for the model in this second stage of the process are the first bid value, and the adaptation of the agent's bids as price signals are perceived. The available options to parameterise these values include secondary literature, expert opinion and historic data from other regions. Here we parameterise the behaviour of simulated growers based on data from a series of field experiments, discussed further in the next section. As such, decision making behaviours were elicited using experimental economics techniques with actual growers in the Katherine-Daly region[24].

The results of the economic experiments yielded data about the first bid and how bidding behaviour changed over time. The bidding strategies of the workshop participants are used to calibrate the bidding behaviour of agents in the model by superimposing the range of marginal values observed in the experiments over the range calculated for agents in the model. Eleven bidding strategies were observed within the experiments, and were related to the marginal value of water that experiment participants perceived, with a range of marginal values existing within the participant population. Simulated agents also calculate their marginal values for water (discussed further below), and their location within this range was located and assigned the related bidding strategy from the field experiment population.

The mark up for each agent's first bid was calibrated from the differences between workshop participants' marginal values and their first bids revealed in the field experiments. The further adaptation of growers' strategies over time is calibrated based on the identification of explicit rules that workshop participants followed when changing their bids in response to their experiences in the market. See Smajgl and Heckbert (2006) for further discussion on calibration from experiment results. The 11 bidding strategies observed in the economic experiments are as follows, and are summarised visually in the following associated figures.

[24] The sample population participating in the experiment is self selected.

Strategy 1 corresponds to agents within the range of the lowest observed marginal value. Hence, it was in their best interest to only make offers to sell water allocations to other bidders with potentially higher willingness to pay values. It was observed that the selling offers using this strategy were set at a constant rate of above the perceived marginal value.

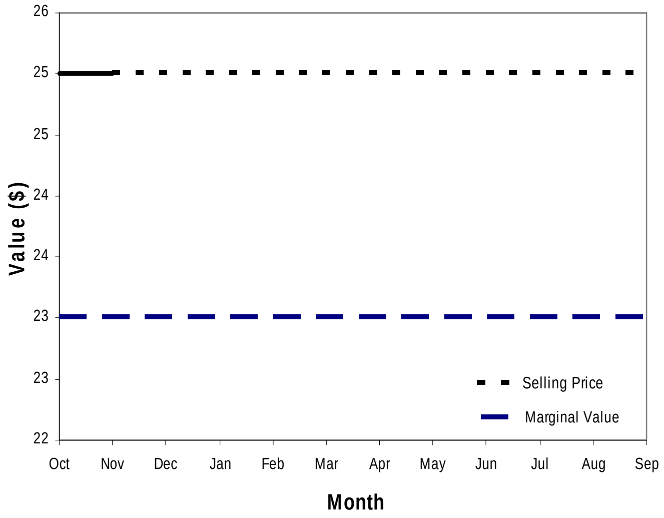

Figure 4: Bidding Strategy 1: Consistent mark-up value for selling bids

Strategy 2 and **strategy 3** again apply to only selling offers, and have an increasing value based on the success of market transactions. If a transaction occurs, the agent will proceed to raise the bid to the next highest level in an attempt to gain more revenue in the following potential transaction. If a transaction does not occur, they maintain their bid for 6 months. If still no transaction has occurred at this time, the bid value goes back down to the next lowest bid, repeating this process over time.

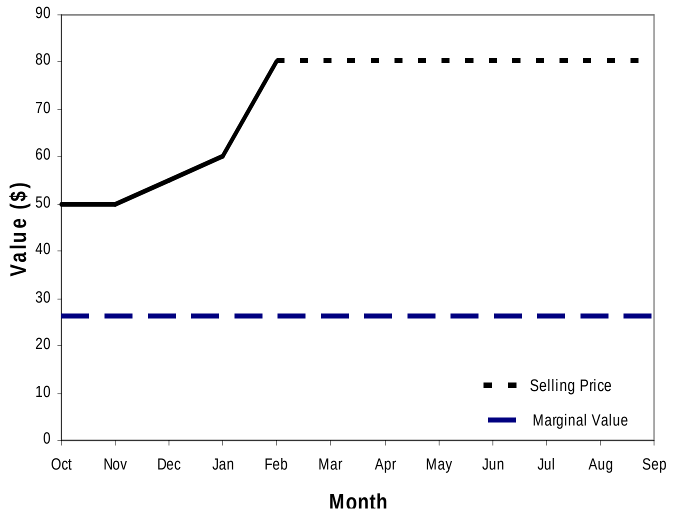

Figure 5: Strategy 2: Increasing mark-up value

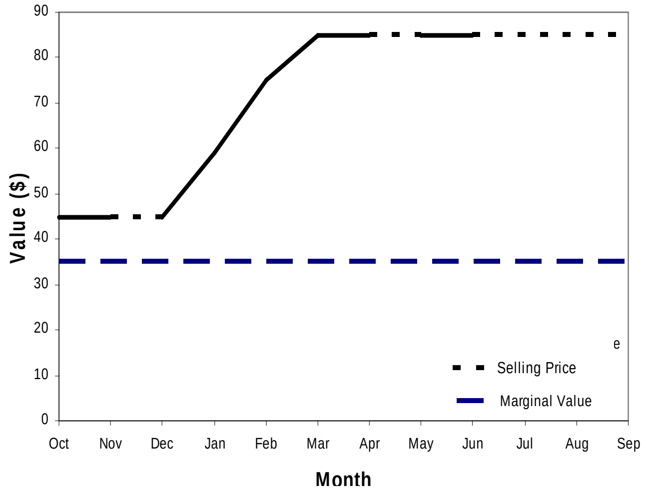

Figure 6: Strategy 3: Increasing mark-up value

Strategy 4 is the first of a number of 'converging' strategies observed. This strategy again only applies to selling bids. The agent begins with a large deviation from their marginal value (in an attempt to gain the most revenues from selling their allocation), and slowly proceeds to 'test' the market with an overall trend downwards, converging on the marginal value. In the following year, the difference between their marginal value and last period's bidding price is again subject to this pattern, such that a convergence continues to occur toward the marginal value over time.

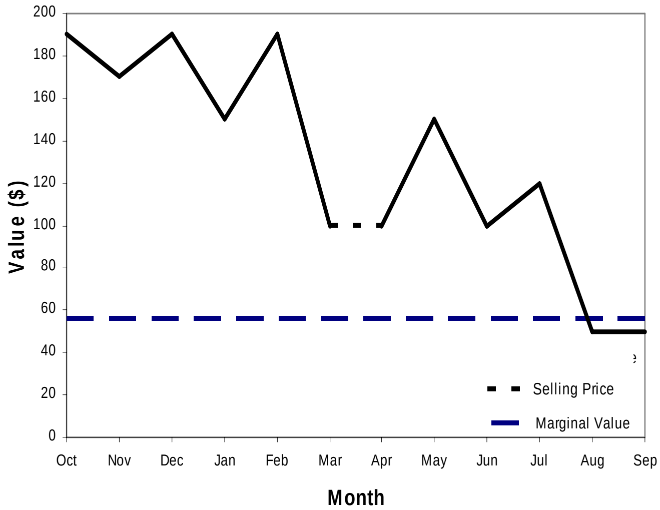

Figure 7: Strategy 4: Converging mark-up value

Strategy 5 is similar to strategy 1, in that there is a constant price value in relation to the agent's marginal value, and again only applies to selling bids. The difference is that the agent will attempt to sell water at a high price during the periods where water demand is likely to be highest, and failing a successful transaction, will revert to a lower value.

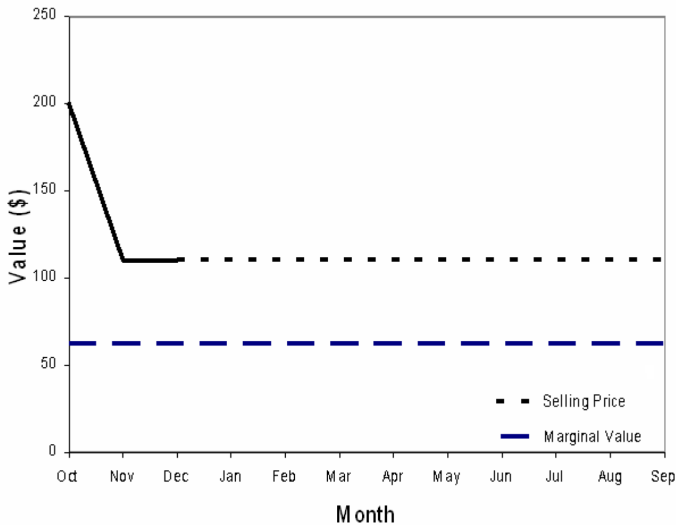

Figure 8: Strategy 5: Consistent mark-up value, attempting a higher mark up value in high-use periods

Strategy 6 is the first strategy with both a selling and buying component. It is similar to strategy 1, in that the offers to sell or bids to buy are set at a constant value throughout the year, depending on whether the agent is buying (price lower than marginal value) or selling (price higher that marginal value).

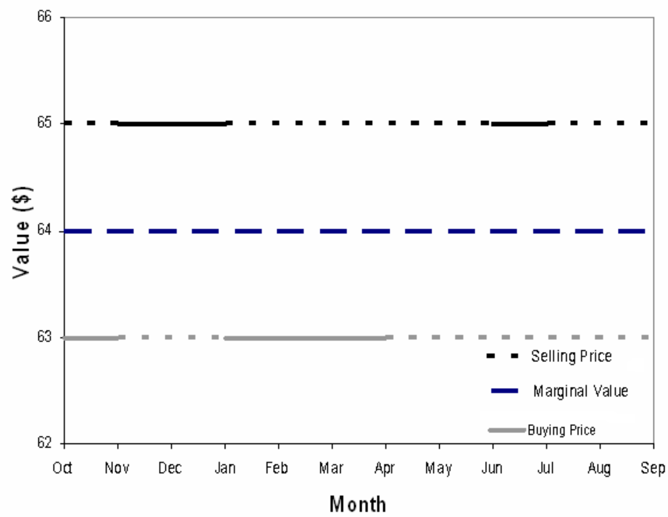

Figure 9: Strategy 6: Consistent mark-up value for buying and selling bids

Strategy 7 is similar to strategy 1, but applies only to buying bids. There is a constant mark-up value, and agents will maintain the bids to buy at this level below their marginal value.

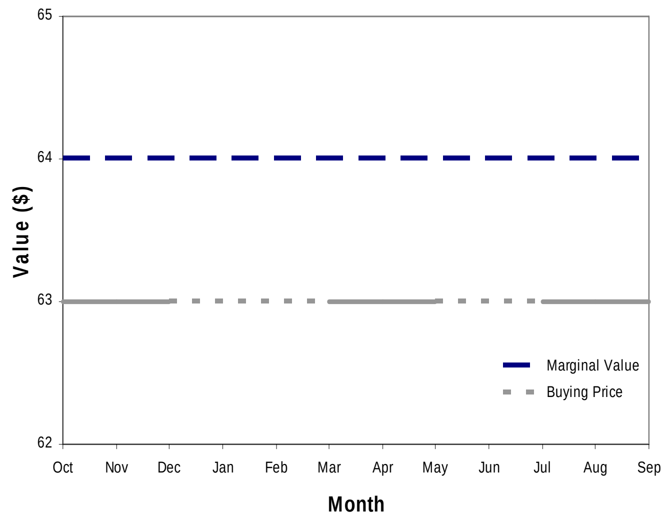

Figure 10: Strategy 7: Consistent mark-up value for buying bids

Strategy 8 Is a 'double convergence' strategy, in that the agent will make both offers to sell or to buy. Each strategy converges eventually towards their marginal value, in the same fashion described for strategy 4, above.

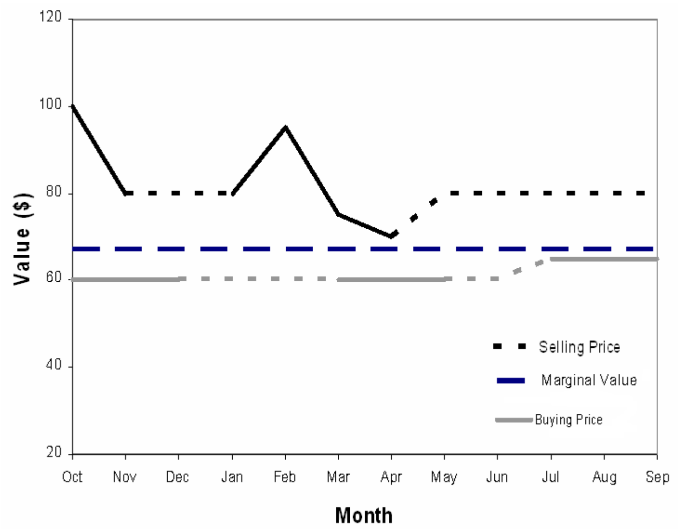

Figure 11: Strategy 8: Converging mark-up value for buying and selling bids

Strategy 9 is a buying only convergence strategy, similar to the prior convergence strategies described, except that it was shown in the experimental data that this agent overshot their 'rational' bidding value. Such behaviour articulates that this individual perceived a higher value than the economic marginal value communicated on the screen during the experiment. The strategy overshoots the marginal value line, but re-converges from the other side.

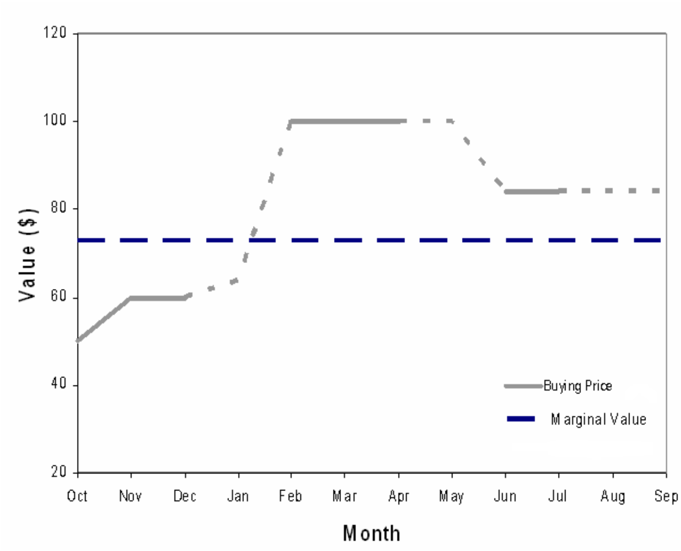

Figure 12: Strategy 9: Converging and overshooting mark-up value for buying

Strategy 10 is a buying only strategy with 2 components, the first is a convergence as described above, where bids to buy converge toward the marginal value, however, a very strong outlier was found in the experimental data, much lower than the converging trend seen for other data points. Hence, this strategy behaves like other converging strategies, with an addition of a stochastic 'shock' during one random month of the year, where the agent will offer to buy for a markedly lower price, as if testing to see how low they can go to buy water.

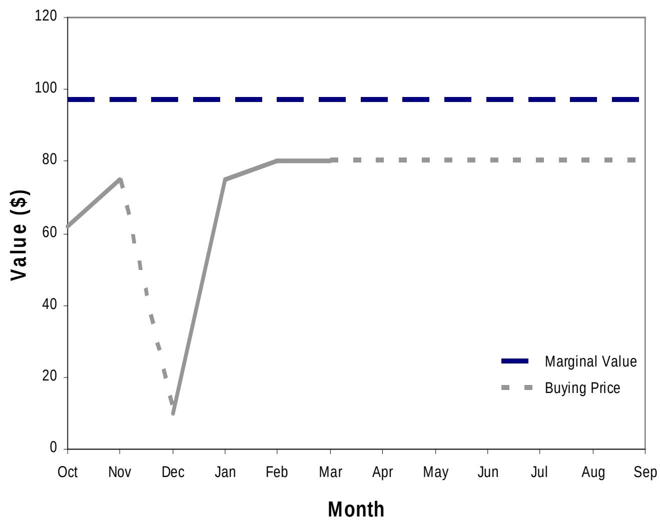

Figure 13: Strategy 10: Converging mark-up value and stochastic shock for buying bids

Strategy 11 is a 'double stochastic shock', in that a trend for buying and selling water, with non-rational outliers was seen. Hence, the agent will behave in a converging fashion for both buying and selling, but both have a number of stochastic shocks. On the buying side, they will buy once a year at well above their marginal value. On the selling side, they will sell several times during the year at 'rock bottom' prices.

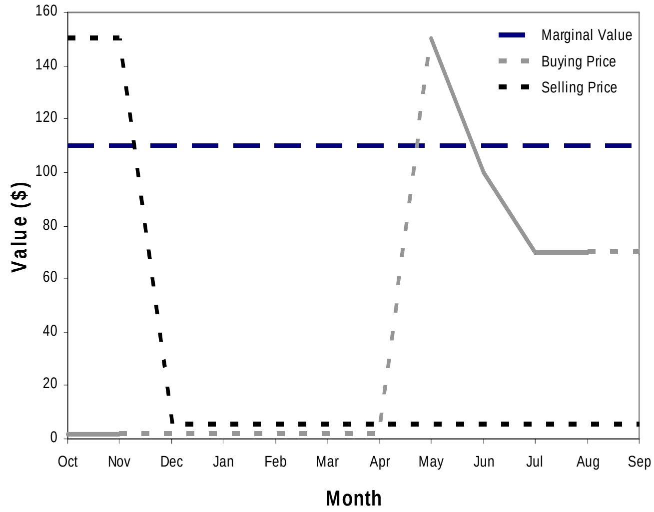

Figure 14: Strategy 11: Converging mark-up value and stochastic shock for buying and selling bids

The number of agents employing each strategy corresponds to the experimental data. Within the experiments, each observed behaviour corresponds with a calculated marginal value for water. The strategies in the ABM are distributed across the range of marginal values observed in the experiments, with the number of agents within each category being the proportion of agents whose marginal value lies within the corresponding range within the experimental data. As such the populations are normalised to each other, and the bidding strategy thus assigned. Figure 15 depicts the breakdown of how the number of agents employing each strategy. Here we see that the majority of agent strategies lie in the 1 – 4 range, which are 'price undercutting' strategies.. hence most agents are willing to accept payment below their marginal value level. The resutlt of this is to keep the price of water on the market down, as there are many bids on offer for cheap water.

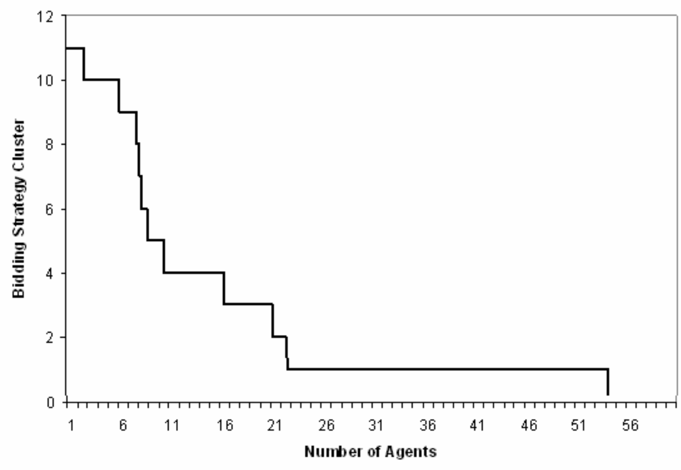

Figure 15: Number of agents employing the eleven bidding strategies.

Market Structure

Producers can buy or sell water through posting offers to sell and/or bids to buy volumes of water. The market structure is that of a double call market (see Ward et al., 2006). To mimic the processes in this market structure, the process begins with all agents who wish to place an offer to sell determining their desired selling volume and price, as described above. Once all offers have been placed, agents who wish to place a bid to buy water view the offers to sell.

An agent is randomly selected from the set of 'buyers', and views the offer of a randomly selected 'seller'. If the seller's willingness to accept price is lower or equal than buyer's willingness to pay, the buyer purchases the volume of water up to the their demanded volume. If the buyer purchases the seller's entire supply and has not fulfilled their demanded volume, the buyer proceeds to the next seller's offer and repeats the process.

Once the buyer has purchased their demanded volume or no offers to sell have a sufficiently low price, the next buyer agent repeats the same process until all demand is satisfied, all offers to sell are purchased, or no more transactions take place due to discrepancies in buying and selling price. Once water is bought/sold, the licensed water entitlements for the buyer and seller for that particular month are updated. The buyer incurs a cost according to the seller's offer price and volume demanded, and the seller receives and associated revenue.

The market process is now complete for the given month, and agents realise their actual water use levels, and the model may proceed to calculate the outcome of the agents' decisions.

Production Outcomes

After agents have made their water use decisions and any purchases have been made within the water market, crop production is realised for the given time period, such that:

Eq 9. $$O_t = O_{t-1} + \left(r_{wt} * \left[1 - \frac{O_{t-1}}{O_{\max}} \right] * O_{t-1} \right)$$

Where O_t is the output [trays / tree] production in period t, $O_{\max}$ is the carrying capacity, or full production limit, and r_{wt} is the growth rate [0-1], dependant on water use, such that:

Eq 10. $$r_{wt} = \left(\left[\frac{r^{\max W} - r^{\min W}}{W_t} \right] * \left[R_t + N_{it} \right] \right) + r^{\min W}$$

Where $r^{\min W}$ is the minimum productivity[25] W_t, and $r^{\max W}$ is the productivity associated with maximum output[26]. Hence, r is a linear function from lowest to highest productivity depending on moisture from irrigation and rainfall.

Harvest and Labour use

Harvesting occurs[27] once in the defined growing season[28]. In the model, harvesting occurs during one fortnightly time step. At this time the crop has progressed through its growth described in the previous section, and a final

[25] As provided by Northern Territory DPIFM. Minimum monthly optimal watering is set to DPIFM data. It is assumed that no watering yields the minimum growth of (3 trays per tree for mango). Maximum output is taken to be 15 trays per tree (White 2004).
[26] As calculated using the crop's minimum production and carrying capacity
[27] The 14 days in a fortnight is larger than the typical variation in harvesting time of 10 days for mango. The typical minimum contract for casual work is a two-week period. This may however overestimate the demand for labour in any one fortnight where in reality it could be spread across the previous and following fortnight.
[28] For example, the growing season for mango is 110 days, or 8 fortnights, commencing in the first week of July or August, depending on the early flowering conditions.

volume of output is ready to be delivered to market. The harvest requires a level of labour input, such that:

Eq 11. $L'_{it} = \frac{O_{it} * \lambda}{8} - f$

Where L_{it} is the labour need [persons] for time t, λ are the labour hours [hour/tray] required per unit of output[29], and f is a value of family labour [persons] that does not need to be purchased from the labour market. An 8 hour days is assumed.

The labour market is represented as a pool of labour from which agents subtract a given amount of labour, at a given price. It is assumed that labour contracts run on a two week basis, and are renegotiated at that time; hence the labour pool is updated with new people (units of labour).

Eq 12. $L_t = L_{\max t} - \sum_i L_{it}$

Where $L_{\max}$ is the maximum labour pool[30] [number of employable persons] in time t, and L_t is the current labour availability.

Note that if the labour pool is exhausted, growers will not be able to hire sufficient labour to bring produce to market, such that:

$$L_{it} = \begin{cases} L'_{it} \;\; if \;\; L_t > L'_{it} \\ L'_{it} - L_t \;\; if \;\; L'_{it} > L_t \\ 0 \;\; if \;\; L_t = 0 \end{cases}$$

Where L_{it} is the actual labour use. The final volume of output that is taken to market, $O_{i\,tHarvest}$ [trays], is then calculated such that:

Eq 13. $O_{i\,tHarvest} = O_{it} * \frac{f + L_{it}}{L'_{it}}$

Which is the volume of output harvested by paid labour and family labour.

---

29 For mangoes, the value of 0.2 hours per tray is taken from White (2004). An 8 hour work day is assumed.

30 Set at 4500 labourers, as reported in White (2004)

Profit Calculations

The final step in production outcomes is calculating the agent's profit which is realised by the volume of output brought to market. Profit, π_i, is calculated from total revenues, TR_i, and total costs, TC_i, such that:

Eq 14. $\pi_i = TR_i - TC_i$

Where

Eq 15. $TR_i = \left(O_{itHarvest} * A_i * \rho_t\right) + \left(P_{i\ t}^{w} * W^{s}{}_{t}\right)$

Eq 16. $TC_i = \left(VC * A\right) + \left(P_{i\ t}^{w} \times W^{b}\right) + I_i$

For total revenues, ρ_t is the market price paid [$/tray], P^w [$] is the price paid on individual exchanges in the water market, and W^s [Ml] is the volume of water sold. For total costs, VC [$/tray] is a fixed level of variable cost[31] of production, W^b [Ml] is the volume of water bought in the water market, and I_i [$] are interest payments made on fixed capital, such that:

Eq 17. $I_i = K_i \times \frac{(\gamma - 1)}{\left(1 - \gamma^{-m}\right)} \times 12$

Where K_i is the value of fixed capital assets[32], and is assumed to be funded through a bank loan, hence K_i is the balance on the loan principal with a term of m[33] repayment periods, and γ is a monthly amortisation factor which is a function of interest rates, such that:

Eq 18. $\gamma = 1 + \frac{\alpha}{12}$

Where α is the current interest rate[34].

[31] Calculated from White (2004) for mangos.
[32] Calculated from White (2004), using capital costs per ha of $26,771.82, $18,407.37, and $17,119.50 for small, medium and large farms respectively.
[33] Average loan term is assumed to be 15 years, assigned to agents at a 30% standard deviation.
[34] Interest rate of 7.5% is assumed.

The above calculations calculate the total profit earned by each agent from the production year. The profit calculation after the crop's harvest is sold to market can then be used to calculate the agents' overall cash flow θ_i, as a measure of the economic sustainability of the farm, such that:

Eq 19. $\theta_t = \sum_t \pi_{i_t} - \frac{V_i}{26}$

Where V_i is an internal payoff threshold representing a minimum desired level of disposable income[35] above the break-even point.

Adaptive behaviour

Agents in the model have the capacity for adaptive behaviour, which is an important inclusion given that the simulated agents' behaviours are a modelled attempt to represent actual real world behaviour of irrigators. Representing the system as an agent-based model allows for this interesting behaviour to be incorporated. In this section, three adaptive behavioural processes are described which involve the process of agents learning to perform better within the modelled environment. The first two refer to the variables for expected price for output brought to market (defined in equation 8) and expected price for water (defined in equation 9) which use reinforcement learning. Each of these allows the agent to create dynamic expectations based on past outcomes, thereby improving performance as learning occurs.

The third adaptive behaviour is the ability of agents to evaluate hypothetical outcomes that might occur were they to make changes to their overall farm enterprise. Here, agents have the capacity to examine other agents' decisions, and determine whether they might be better off (through receiving higher profits) were they to adopt these behaviours themselves.

The fictitious play process involves a series of iterated calculations which compares current profit levels against possible profits calculated from a hypothetical change in the agent's decisions. The equations used to calculate these hypothetical outcomes are the same as those defined in equations 4

[35] Disposable income of $30,000 per year is assigned with a uniformly distributed variance of 17%

through 20 above, as appropriate for the variables the agent is hypothetically altering to explore potential outcomes.

The first step in fictitious play learning is to perceive behaviours or characteristics of other agents. Within the model this is accomplished by agents exploring options that are used by other, relatively profitable agents. Hence, if one agent is receiving high payoffs, others will emulate their behaviour. However, in realty we might not expect one producer to know the specific details about someone else's profit. Therefore it is not reasonable to simply allow simulated agents to have open access to other agents' profit levels. Nevertheless, someone making a healthy profit is likely to 'self-express' their financial condition through a variety of signals, such as making investment or purchasing goods that would otherwise be out of reach for less financially successful agents. Therefore, simulated agents in the model self-select to 'flag' themselves as having been successful if their profit is relatively higher than the rest of the population, such that:

Eq 20. $$If \quad \pi_{\mathrm{i}t} > \frac{\sum_i \pi_{\mathrm{i}t}}{\mathrm{n}} + \sqrt{\frac{\sum \left(\pi_{\mathrm{i}t} - \frac{\sum_i \pi_{\mathrm{i}t}}{\mathrm{n}} \right)^2}{(n-1)}} \xrightarrow{then} \text{flag} = \text{true}$$

Where the first element is the mean profit value, and the second element is the standard deviation of profit across the population. In other words, if an agent's profit is greater than the average plus one standard deviation[36], they 'flag' themselves as having been successful.

The possible adaptation strategies used here include:

- Change in off farm income –decreases family labour available for production, increases off farm income
- Change production area – new areas under production, need to buy water off market
- Exit market – sell water, no revenue from crop output, can pursue off farm income

[36] Normally distributed population, scores above the mean plus one standard deviation would amount to approximately 17% of the population.

- Change water use – buy or sell water on market, r in output is changed

Agents perform a series of iterated calculations to determine if any of the adaptive strategies is expected to improve financial performance. If the option do so, they are selected. Otherwise the agent continues the search until options are selected, or exhausted.

4. Results

Scenario 1: Baseline Conditions: No-trade , no new licenses granted

The baseline scenario (n=18) describes the current licensing and extraction situation on the Tindall aquifer. In this simulation, the original license holders are simulated with their monthly allocations un-capped, and no water market exists for trading. Fig. 16 shows results for total groundwater extraction (Ml) by irrigators, annual rainfall (mm) and volume of groundwater available for extraction (Ml). The historical rainfall data shows 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 fully recharge aquifer volumes. Rainfall again becomes generally abundant from years 15 onward. Accordingly, extraction volumes correspond with this pattern, with peaks in extraction matching low rainfall years.

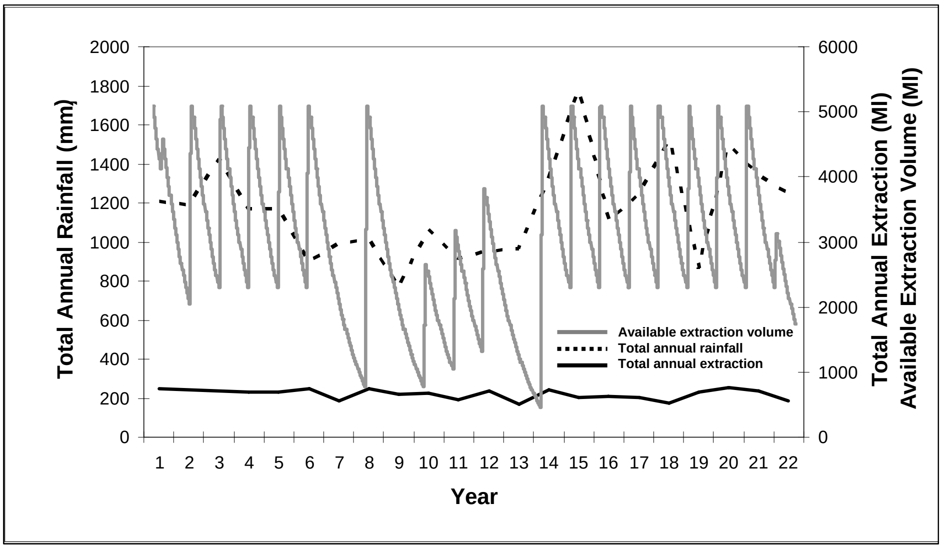

Figure 16: Total groundwater extraction by irrigating growers, showing rainfall and available extraction volumes, and the associated extraction levels for Scenario 1, showing baseline conditions.

Figure 17 depicts total profit under the baseline scenario for the agent population over the 22 year simulation run and forecasted prices[37]. Production and profit also depend on the natural phenological cycle of mangoes. The downward trend in profit is explained partially by forecasted prices (for mangos, prices are set to decrease to year 6 before levelling out). Once accounting for the price trends over time, profit levels are affected mainly by water availability. The lower profit values in the middle years of the simulation correspond to a period of dryer years. By the time rainfall increases in the later years, lower prices serve to keep the total profit from production depressed.

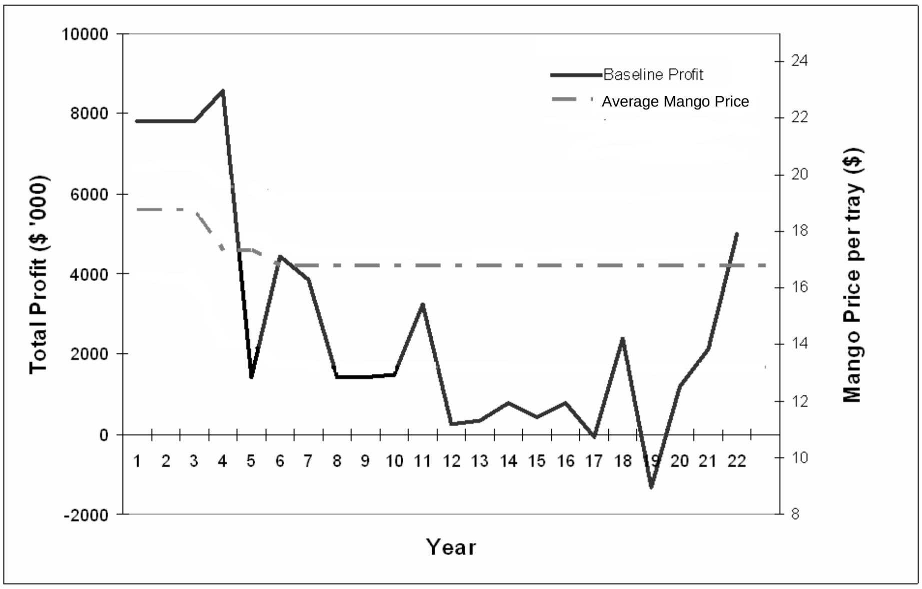

Figure 17: Total profit from irrigated horticulture, Scenario 1, showing baseline conditions and prices for produce (mangoes)

Labour shortages have been identified as having a significant impact on enterprise profitability. White (2004) reports that estimated economic losses (including direct and indirect benefits) for the Northern Territory as a whole due to lack of labour range from $5.8 million to $26.1 million.

The baseline simulation assumes there are 4,500 labourers available during the harvesting season. In order to determine the impact of labour availability within the study region, this is compared with the situation where labour availability is unlimited. As shown in Fig. 18, simulated economic losses due to shortfalls in labour availability can reach up to $7.4 million (year 17).

[37] Based on White (2004).

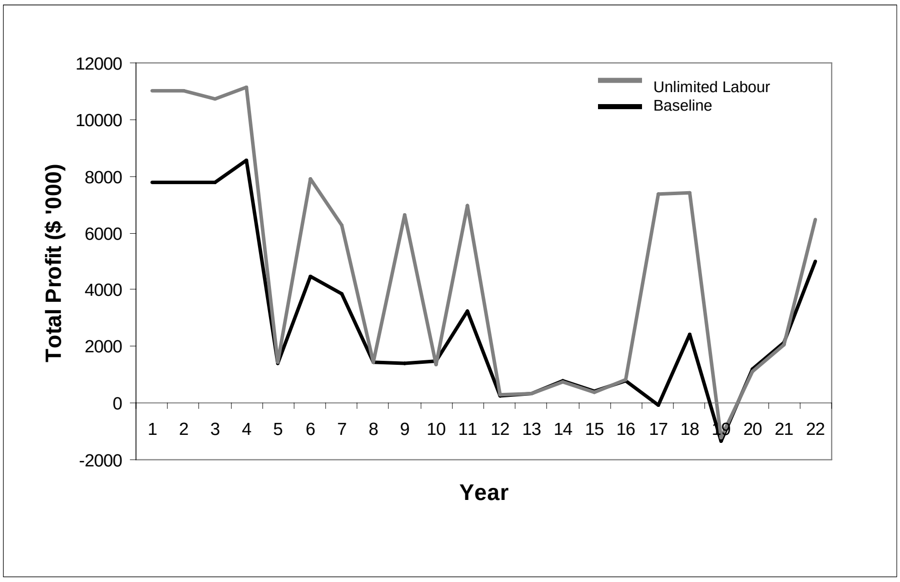

Figure 18: Total profit under the baseline scenario compared to profit levels possible with unrestricted access to labour. The distance between the two trajectories represents economic losses due to labour shortfalls.

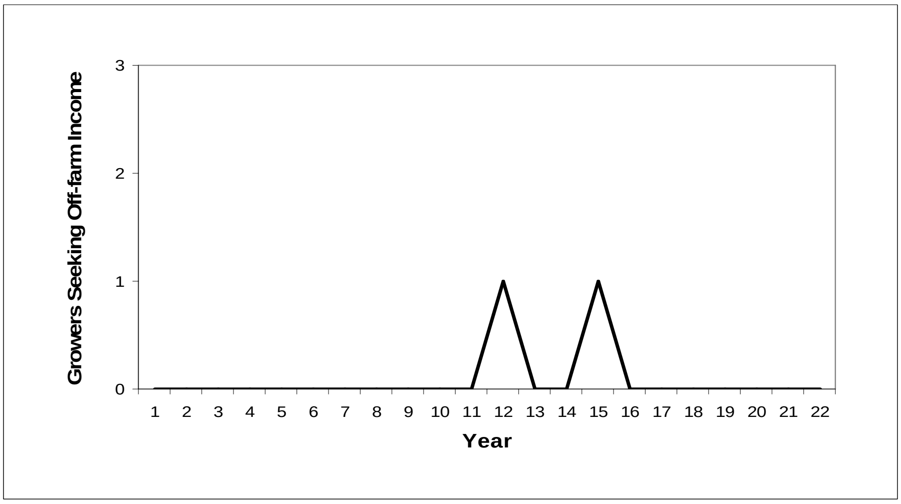

Figure 19: Number of growers who seek off-farm income through the modelled adaptation process under the baseline scenario

From this point, we can begin to compare results of the baseline scenario with other scenarios, where new applications for groundwater extraction are granted, and where a water market and its operating rules are examined.

Scenario 2: Limited applications granted, no trade

This scenario simulates the granting of all pending applications for water (scenario 2a), and also just the five largest license applications in terms of volume of water (from a total of 41 applications; scenario 2b). Note that there is no cap and trade system in these scenarios. The aggregate amount of water these five applications account for is 90% of the aggregate of all current applications. Fig. 20 depicts two years (years 3 and 4) of the whole 22-year simulation.

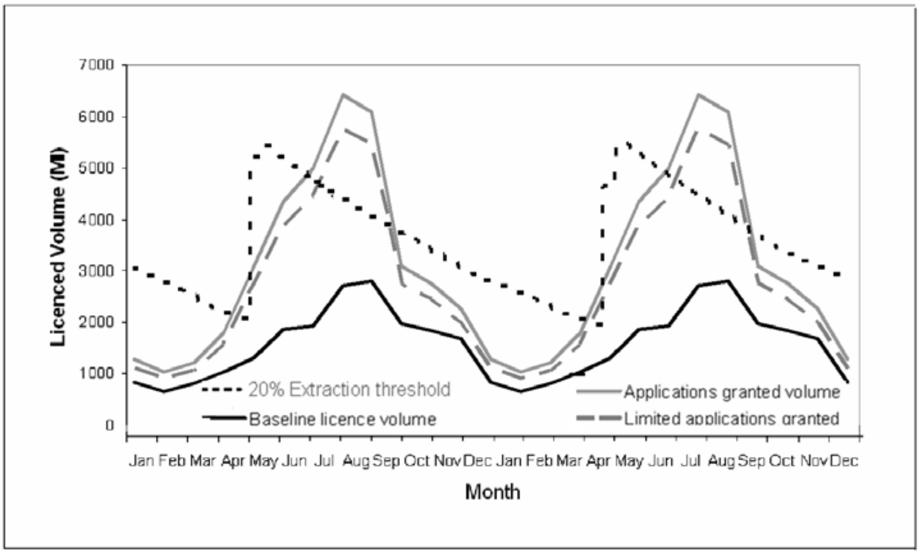

Figure 20: Groundwater volume available for extraction and licensed volumes for three scenarios

The baseline license volume is the current simulated aggregate amount of water allocations throughout the year with only 18 licenses. The 20% extraction threshold illustrates the volume corresponding to the 20% of annual aquifer recharge that is available for extraction according to the 80:20 rule described earlier. The shape of this curve depicts the way in which the aquifer is replenished quickly during the wet (although after a time lag) and recharges into the river system at a slower rate through the dry. Given assumptions about aquifer levels and dynamics, the amount available for extraction is generally sufficient to supply the current volume of water that is licensed for extraction, except for a number of dry years in the middle of the simulation (see years 6 to 14 in Fig. 16).

If all pending applications for water allocations are granted (scenario 2a), the total volume of water extracted will be 85% higher than the baseline scenario in all of the 22 simulated years. The demand for water in July, August and September of most years is greater than the 20% of annual aquifer recharge that can be supplied. This indicates that a cap on water extraction will need to come into play in these months and that there may need to be an additional mechanism for allocating water at these times. This is where the water market may become useful.

The result is similar when only the five largest volumetric applications for water are granted (scenario 2b). Again, there is not sufficient extractable water to cover licensed volumes in July, August and September. Groundwater extraction levels for this scenario over the 22-year period are depicted in Fig. 21. Extraction levels are higher for this scenario, given the increased licensed volumes. As was shown in Fig. 20, a cap would come into play in certain months to maintain the 80:20 rule, although the cap is not depicted in the figure below.

In the following figures, mean outcomes for 100 simulation runs are depicted. Confidence intervals are calculated for α=0.05 and are depicted in lighter lines, surrounding their associated mean.

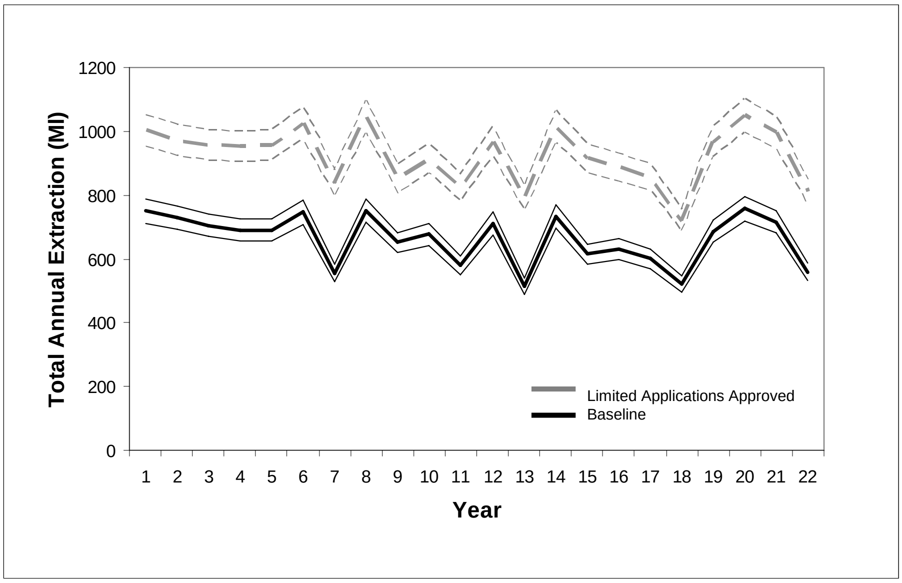

Figure 21: Total groundwater extraction by irrigating growers, showing mean values and associated confidence intervals, Scenarios 1 and 2b

The outcomes for profit under this scenario are depicted in Fig. 22, showing a higher level of overall profit than for the baseline scenario. This higher total profit level is particularly pronounced during the dry middle years of the simulation and the latter years where profits remained depressed under the baseline scenario. Important to note here is that individual enterprises are not more profitable under this scenario, rather there are simply more growers producing mangoes.

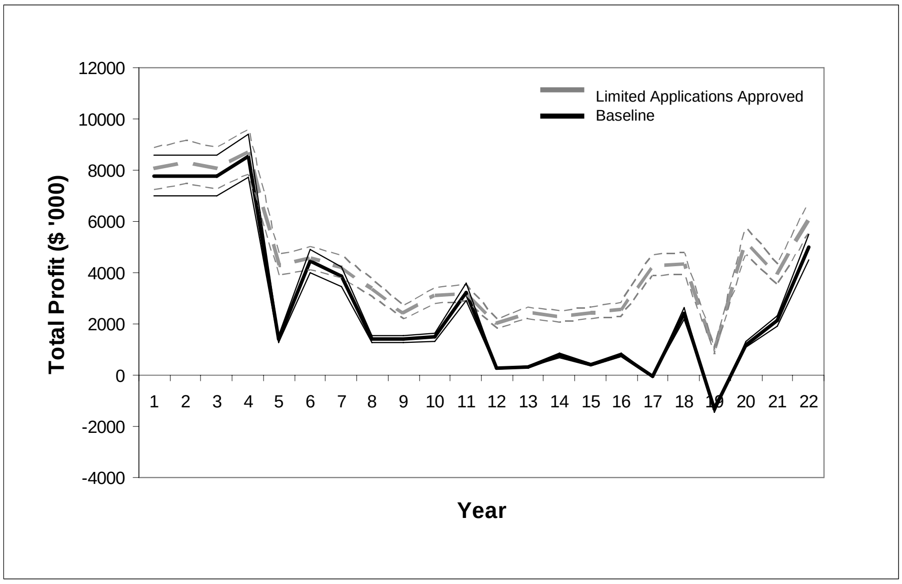

Figure 22: Total profit from irrigated horticulture, Scenario 2b, showing mean values and associated confidence intervals.

In summary, the simulation of current outcomes reveals that total extraction from the Tindall aquifer is always beneath the 20% of annual aquifer recharge available to be extracted. Baseline profit for the industry is affected mainly by water availability, and is impacted also by labour shortages and decreased prices. For year 19, although there was enough rainfall in the simulation, it came at the wrong time of the year. Granting all or some of the pending applications for water allocations will result in total extraction exceeding the 20% limit in all years. This indicates the need for a cap to be placed on extraction in these periods and an instrument for allocating the reductions in allocations on licenses.

The following sections report the results of scenarios where a water market is implemented. The questions of interest are: what are the impacts of this change in the way water is allocated throughout the hydrological cycle of the aquifer and river system, and what are the impacts on total water extraction, profit and other outcome indicators?

Scenario 3: Applications granted, water market implemented, all growers bear risk of water restrictions

As seen in scenarios 2a and b, approving some or all license applications may result in an allocated volume that sometimes exceeds the threshold identified in the 80:20 rule. A cap-and-trade system is explored as a mechanism to enable demand for new groundwater extraction licenses to be met while also maintaining environmental flows. Here, a market for trading water allocations is simulated, and total water extraction is ‘capped’ when it reaches 20% of annual aquifer recharge. Each individual license-holder must then face pumping restrictions of a certain percentage of their monthly allocation.

Fig. 23 shows the extraction volumes for scenario 3, where applications are granted, and the cap-and-trade system is implemented. This is compared to the baseline scenario. Note the convergence of values in these two scenarios in the dryer years in the middle of the simulation. These points indicate where a cap has been implemented to maintain minimum environmental flows. The implementation of the cap means that the greater number of growers can extract more groundwater in wet years when the aquifer is fully recharged, but that minimum volumes for environmental flows during dryer years are still maintained. For comparison, the total annual extraction curve for scenario 2a where all applications are granted and there is no water market, sits above the baseline, reaching a peak of approximately 1,100 Ml in year 8.

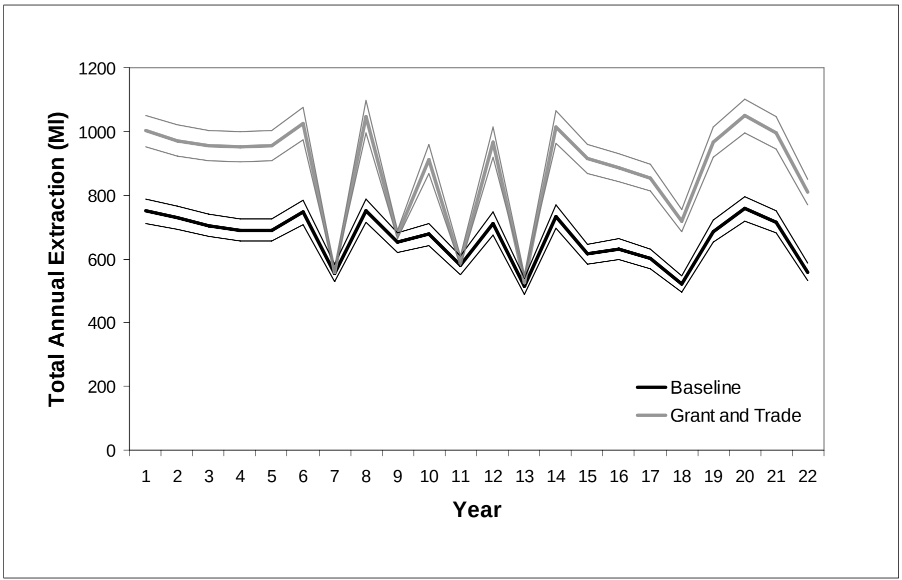

Figure 23: Total groundwater extraction by irrigating growers, Scenarios 1 and 3, showing mean values and associated confidence intervals.

Fig. 24 compares the profit outcomes under scenario 3 with the baseline scenario. The greater profits are a result of the larger amount of water applied to mango production (the total profit in this scenario is the sum of 59 individual licenses, versus 18 in the baseline scenario). The trajectory follows similar dynamics to the baseline scenario, maintaining a slightly lower level through dry years, and recovering in the following wet years.

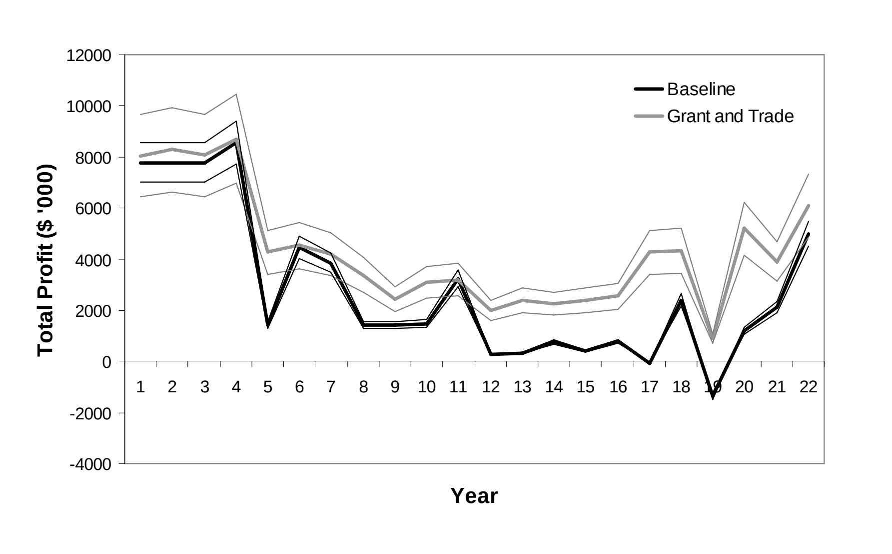

Figure 24: Total profit from irrigated horticulture, Scenarios 1 and 3, showing mean values and associated confidence intervals.

The total profit curve for scenario 2a where all applications are granted and there is no water market is not statistically different from the curve for scenario 3 where all applications are granted and there is a water market. The fact that there are no pumping restrictions in scenario 2a indicates that the downward influence of pumping restrictions on profit in scenario 3 is offset to some degree by the existence of the water market.

As outlined in Fig. 23, the granting of new applications without another instrument to limit groundwater extraction to the 20% available results in an over-allocation of available water in dryer periods. Scenario 3 simulates a cap and pumping restrictions on every grower's license. The level of restrictions depends on the volume by which licensed allocations exceeds 20% of annual aquifer recharge. When licensed allocations exceed this 20%, all licenses are reduced by a given percentage.

Fig. 25 depicts the percentage by which licenses will be restricted to comply with the 20% cap over the 22 years of the simulation. What this figure shows is that if the cap were operational in the baseline scenario, all growers would have to restrict their pumping by as much as 50% in dry periods, and in scenario 3, the cap is operational in the dry seasons of all years, and will require greater pumping restrictions (up to 80%) in dryer years.

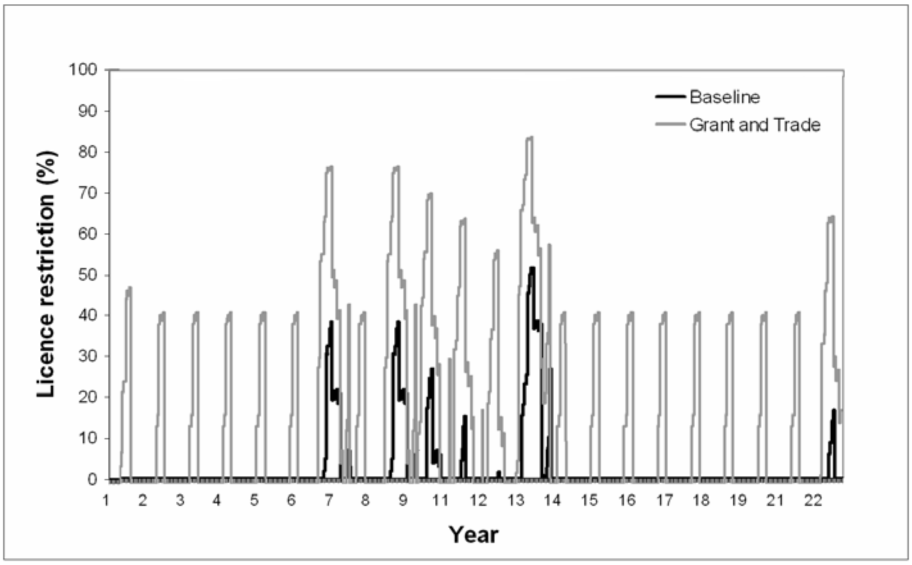

Figure 25: Percentage by which licenses will be restricted, Scenarios 1 and 3

The water market enables growers to purchase water subject to affordability and availability in these highly restricted periods. Hence, while the cap manages environmental risk, the market provides a mechanism for growers to manage their own risk.

Fig. 26 depicts the volume of water demanded and supplied within the water market under scenario 3. These trajectories again correspond with rainfall patterns over the 22 year simulation. Note that Fig. 26 suggests that sufficient supply of water allocations exists to meet demand in any given year.

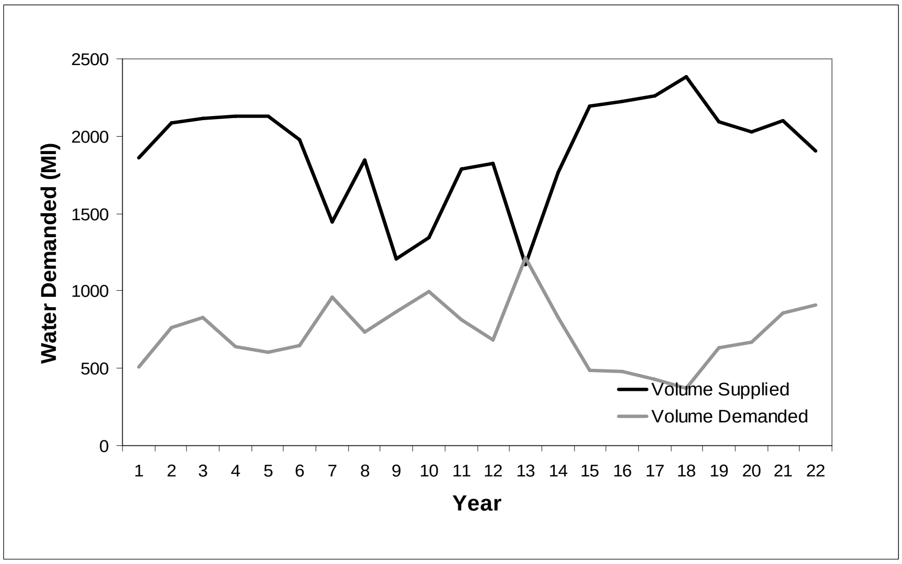

Figure 26: Volume of water demanded and supplied within the water market, Scenario 3

Fig. 27 depicts the total volume of water purchased on the market (Ml) and the bids, either to buy or to sell, made for water (note this is not the equilibrium price). As would be expected, the volume purchased is higher when bids are lower and vice versa. The spike in average bids made for water in the early years may reflect that growers are learning about the water market and testing it out. The lower points of volume purchased in years 10, 11 and 13 correspond to dryer years, indicating that growers are trading less in these years. The lower volumes purchased in years 2 to 4 may indicate that growers are learning about the market in these years and increase their purchases as they become more familiar with its operation. The volume of water purchased increases in later years of the simulation as rainfall increases.

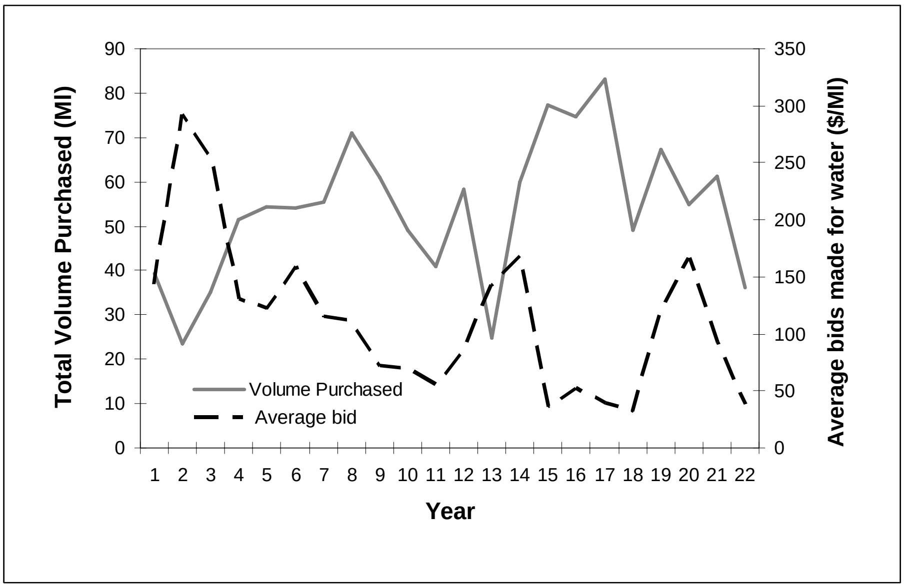

Figure 27: Volume purchased on the water market and average bid per Ml of water, Scenario 3

Fig. 28 illustrates the outcome of actual activity in the water market. Trading in water allocations yields revenue ranging from less than $2,000 in year 18 up to $10,000 in year 14. Here we see a level of trading of $7,000 to $10,000 in years of higher rainfall, and depressed market activity in extremely dry years as growers are less willing to part ways with their licensed volumes.

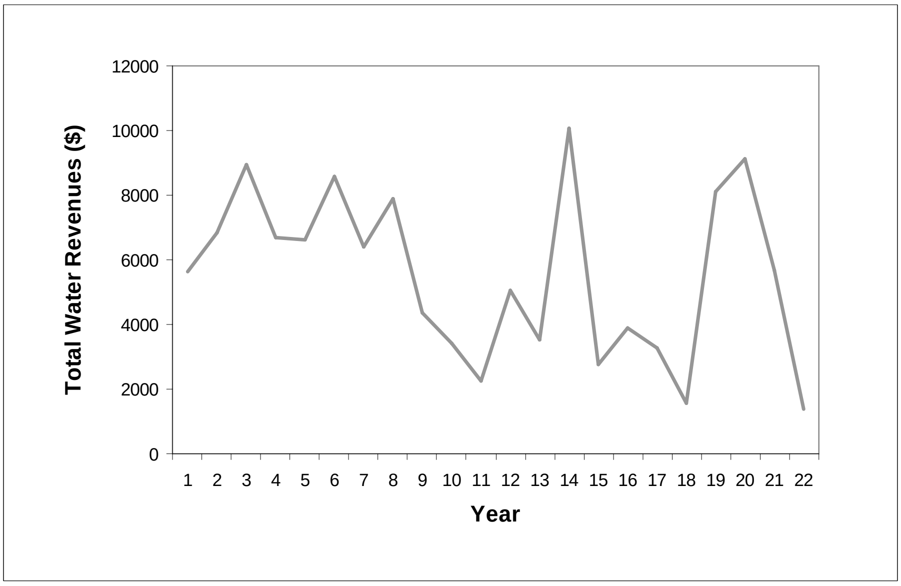

Figure 28: Revenues realised from activity in the water market, Scenario 3.

The impacts of the cap and pumping restrictions on crop production are illustrated in Fig. 29 showing aggregate production across growers between scenario 3 and a situation where unlimited water is available. If unlimited water is available, all growers can harvest 15 trays per tree. If all growers can harvest 15 trays per tree, the total number of trays for one of each grower's trees aggregated across all growers is 840 trays. Fig. 29 indicates that capping water use and allocating pumping restrictions is impacting negatively on the number of trays each tree can produce.

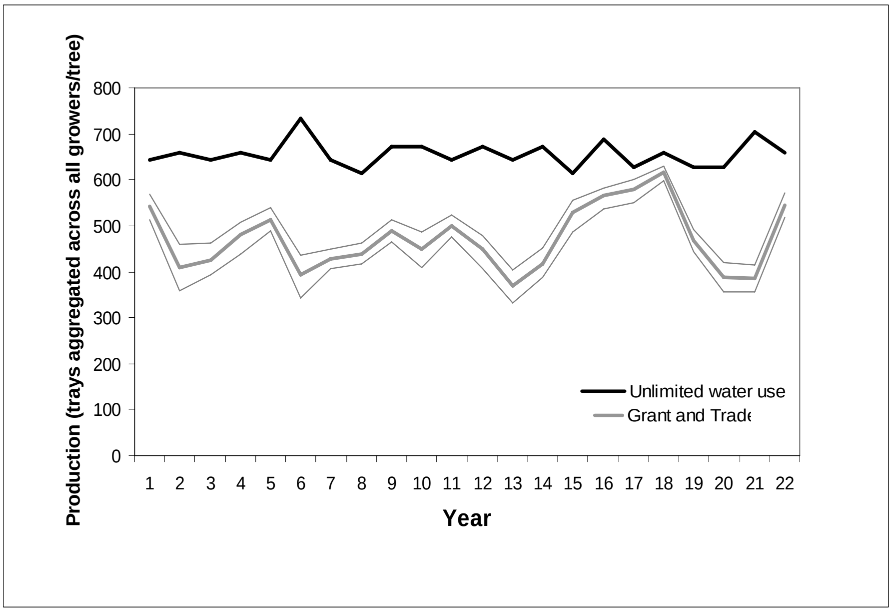

Figure 29: Aggregate production levels, Scenario 3, compared to unlimited water availability, showing mean values and associated confidence intervals.

However, even when extraction is not capped, as in scenarios 2a and b, meaning that greater numbers of trays could come from each tree, profit is not higher than for scenario 3 due to the labour constraint (shown in Fig. 17 for the baseline scenario).

Fig. 30 shows that six growers discontinue farming and seek off-farm income from years 12 to 15 and a further two in year 19, which is an increase from the baseline scenario.

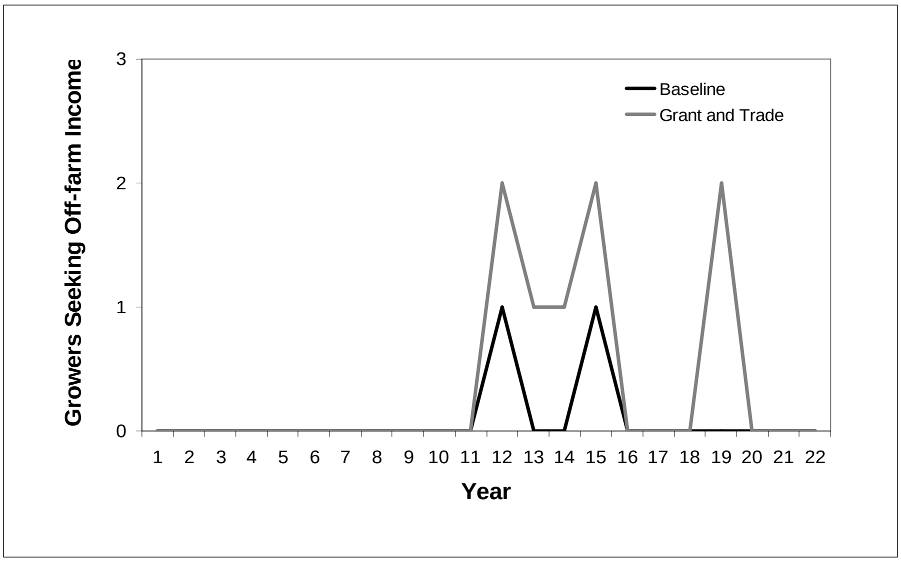

Figure 30: Number of growers who seek off-farm income, Scenarios 1 and 3

In summary, when all pending applications are granted, a cap and trade system is implemented, and pumping restrictions in dry periods are allocated to all license-holders, extractions from the aquifer are greater than the baseline scenario, although they converge to the 20% cap when it comes into play in dryer years. Total profit is higher than for the baseline scenarios, although this is accounted for by the increase in license-holders rather than increased profit for each individual. Total profit is the same for simulations of 59 growers whether there is a water market or not. To comply with the cap, pumping restrictions are implemented in each year of the simulation and reach up to 80% in dryer years. In the water market, sufficient supply of water allocations exists to meet demand in any given year. The results of this scenario indicate that capping water use and allocating pumping restrictions across all growers is impacting negatively on the number of trays each grower can produce from each tree. Even when extraction is not capped, however, profit is not higher than for scenario 3 due to the labour constraint. Therefore, both water and labour availability impact negatively on profit. As a result of their observations of their own profits, eight growers exit the industry in comparison to the two who leave in scenario 1.

The next scenario simulates the granting of all pending licenses, water trading and allocates any pumping restrictions to new license-holders only rather than to all.

Scenario 4: Applications granted, market created, newcomers bear risk of pumping restrictions

A difficulty that exists in implementing a new policy mechanism such as a water market is how to deal with people who have already been operating under the previous policy regime, and whether to treat them differently to 'newcomers', who enter the arena after changes are made. In this scenario we examine the situation where pumping restrictions in dryer periods apply only to the 'newcomers' and existing license-holders may continue to use their pre-existing allocated volumes without the risk of water restrictions being imposed.

Fig. 31 compares trajectories of extraction volumes for scenarios 3 and 4. Scenario 4 sees an increase in groundwater extraction compared to scenario 3. Existing license owners do not have their allocation capped. This means that in some years the existing license owners extract all available water and this can even exceed the 20% limit (as seen in the baseline curve of Fig. 25. This will mean that in some years 0% of their licensed extraction is available to new license holders. With a 20% cap imposed, even existing license-holders would face restrictions of up to 50% in some years were the cap applicable to them as well.

When the licensed extraction of all (existing and new) license holders exceeds the 20% allowed then the burden of reduced allocation falls on the newcomers and their allocation is reduced. This means that newcomers will rely more heavily on water in the market to meet their desired water use.

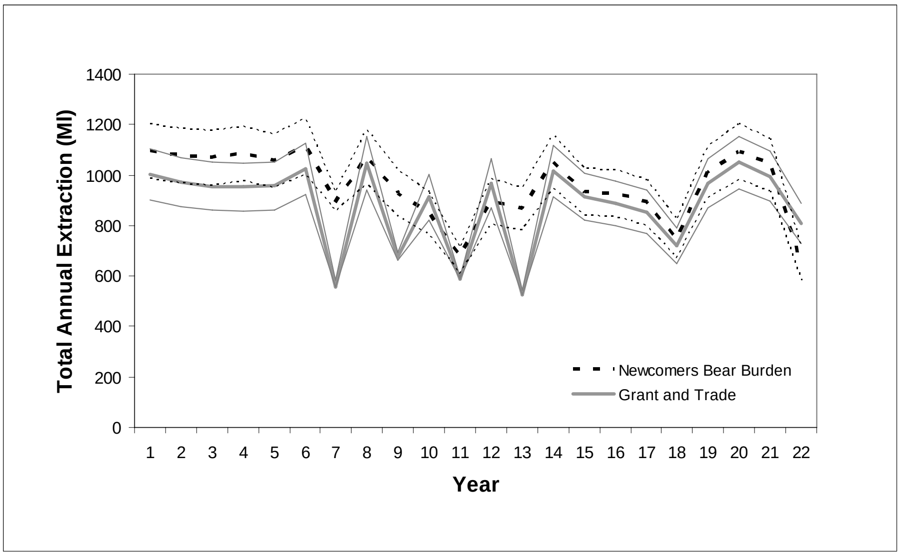

Figure 31: Total groundwater extraction by irrigating growers, comparing scenarios 3 and scenario 4, where newcomers must solely bear the burden of water restrictions, showing mean values and associated confidence intervals.

Comparing Fig. 31 to Fig. 16 (which showed a scenario where all growers face pumping restrictions) we see that the 'newcomers bear burden' scenario over-shoots capped license volumes according to the 80:20 rule (for example in years 7, 9, 11 and 13). This suggests that a rule stating that newcomers bear the burden of pumping restrictions diminishes the ability of the policy instrument to maintain minimum environmental flows; namely because there is a group of growers who may continue their operations without contributing to the maintenance of minimum environmental flow requirements.

Figure 32 shows outcomes for profit comparing these two scenarios. The higher overall levels of extraction result in higher profit levels

Figure 32: Profit from irrigated horticulture, Scenarios 3 and 4, showing mean values and associated confidence intervals.

Fig. 33 depicts how this profit is distributed within the population of growers. The Shannon Diversity Index[38] reports on the distribution of profit within the community of growers. A larger index value corresponds with a more even distribution across agents. Comparing scenarios 3 and 4, we see approximately four periods during simulation runs where the distribution of profit within the agent population is significantly different between the two scenarios (approximately years 9-10, 12-13, 16-17 and 18-21), particularly occurring in the middle dryer years. The distribution of profit across growers starts more evenly and then becomes less even.

38 $S = \frac{\pi_i}{\sum_i \pi_i} * \left(1 - \log\left(\frac{\pi_i}{\sum_i \pi_i}\right)\right)$ where π is profit [$] realised at the end of harvest.

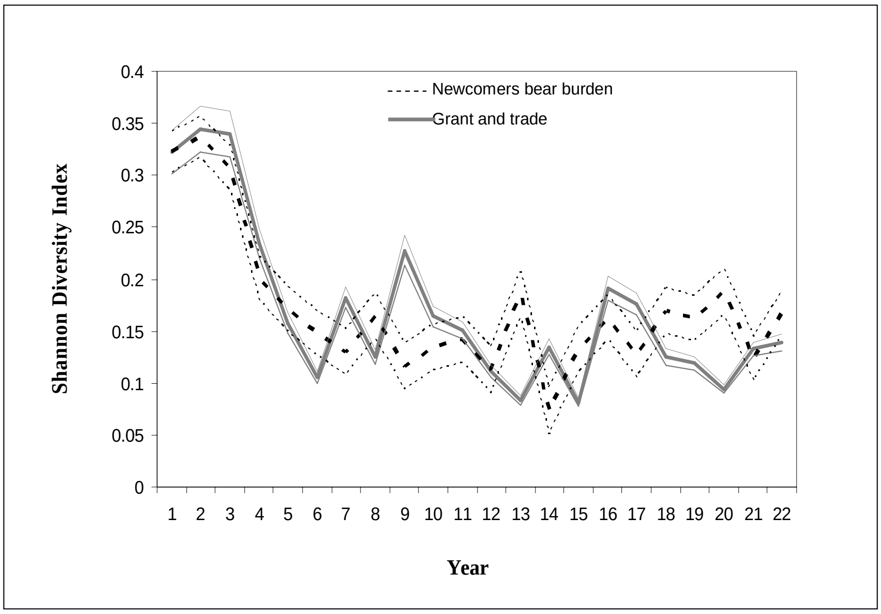

Figure 33: Shannon Diversity Index of profit, Scenarios 3 and 4, showing mean values and associated confidence intervals.

Fig. 34 depicts the average profitability of farms from an exemplar year (year 16, scenario 3). Farms are categorised as small, medium and large according to White (2004), where small farms are less than 2 000 trees , medium, 2 000 to 9 999 trees, and large greater than 10 000 trees

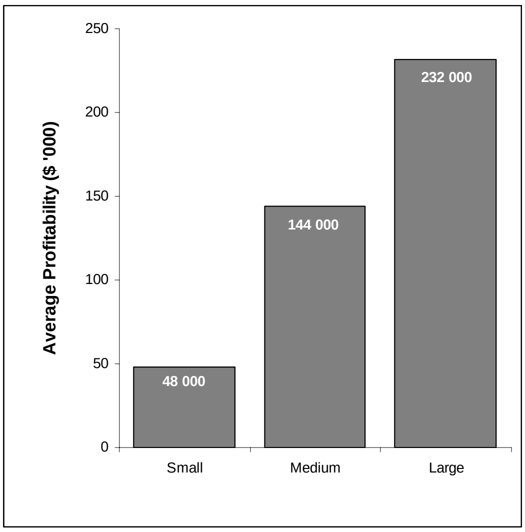

Figure 34 Average profitability by farm size for an typical year, scenario 3

Fig. 35 depicts the percentage by which pumping must be restricted during dryer periods. The trajectory for scenario 4 represents the percentage restriction faced by newcomers only. It is seen that the percentages by which pumping must be restricted are significantly higher than for scenario 3 where the volume of water that must be retained for environmental flows is spread across all 59 growers. In the dry years especially, this means that newcomers must restrict their pumping by up to 100% of their licensed allocation. Newcomers can still acquire water on the market, though there are no guarantees that the market will provide sufficient water. This introduces a high degree of risk for the newcomer population.

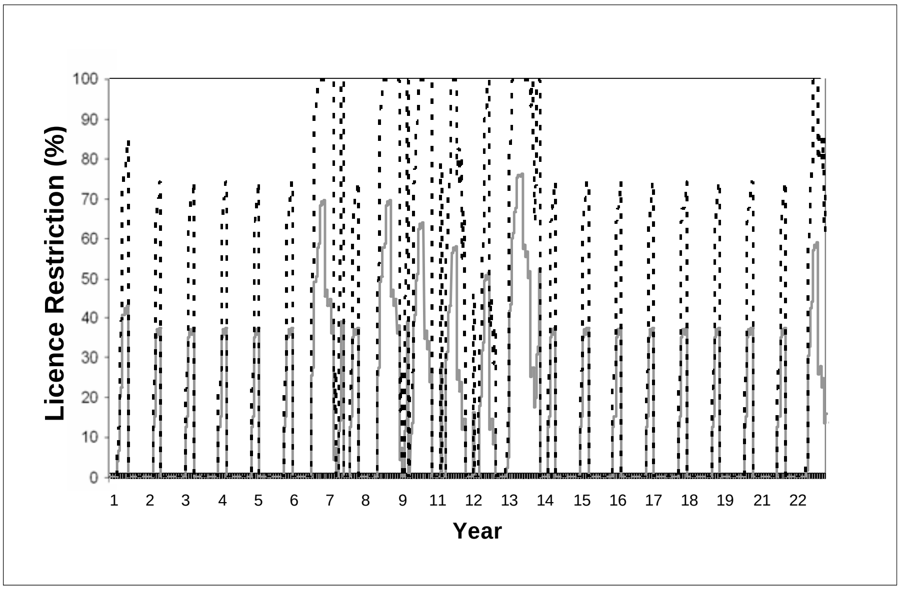

Figure 35: Percentage by which licenses will be restricted, Scenarios 3 and 4

Counter-intuitively, we see in Fig. 36 the volume of water demanded on the market is lower in scenario 4 compared to scenario 3, although this difference is only significant in year 13. This is explained by the fact that although a large portion of the population (newcomers) may be facing water restrictions, the overall demand from those with existing licenses is notably lower.

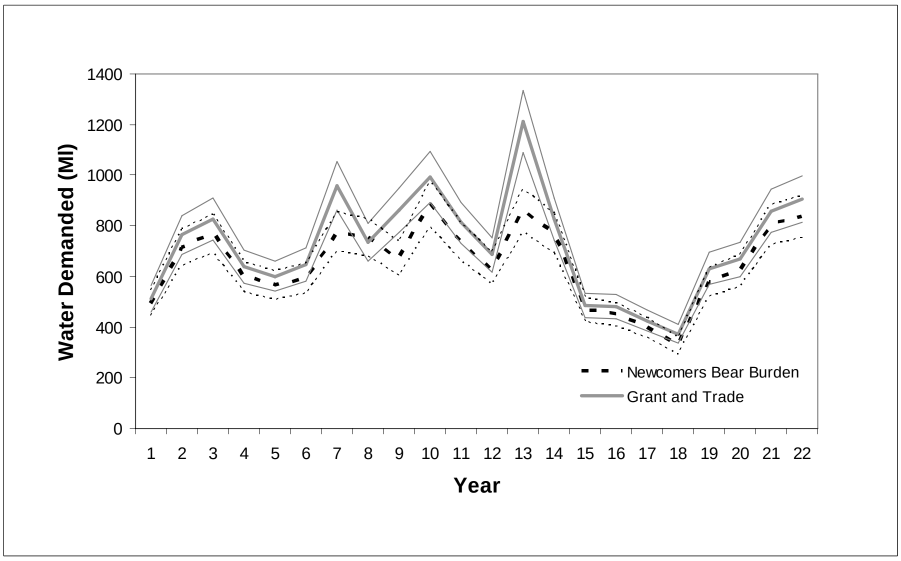

Figure 36: Volume of water demanded, comparing scenarios 3 and scenario 4 where newcomers must solely bear the burden of water restrictions, showing mean values and associated confidence intervals.

As seen in Fig. 37, there is a significantly larger volume of water purchased on the market in scenario 4 compared to scenario 3, less so but still pronounced in the dryer years. Newcomers' heavier reliance on the market results in higher trading volumes.

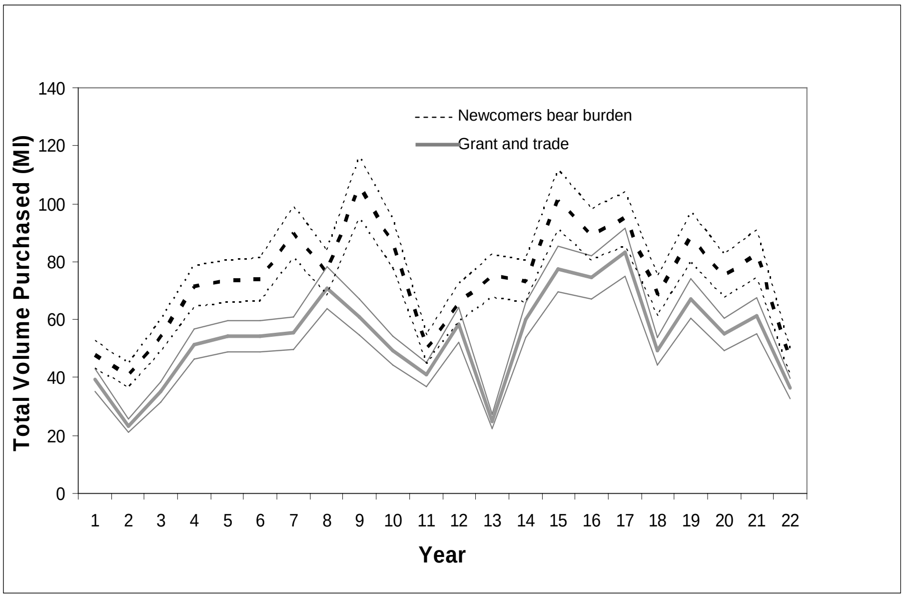

Figure 37: Volume of water purchased in the market, Scenarios 3 and 4, showing mean values and associated confidence intervals.

The volume of water supplied to the market is higher in scenario 4 compared to scenario 3 although this difference is not statistically significant. This indicates that existing license-holders are generally using the water they pump rather than increasing their supply to the market substantially.

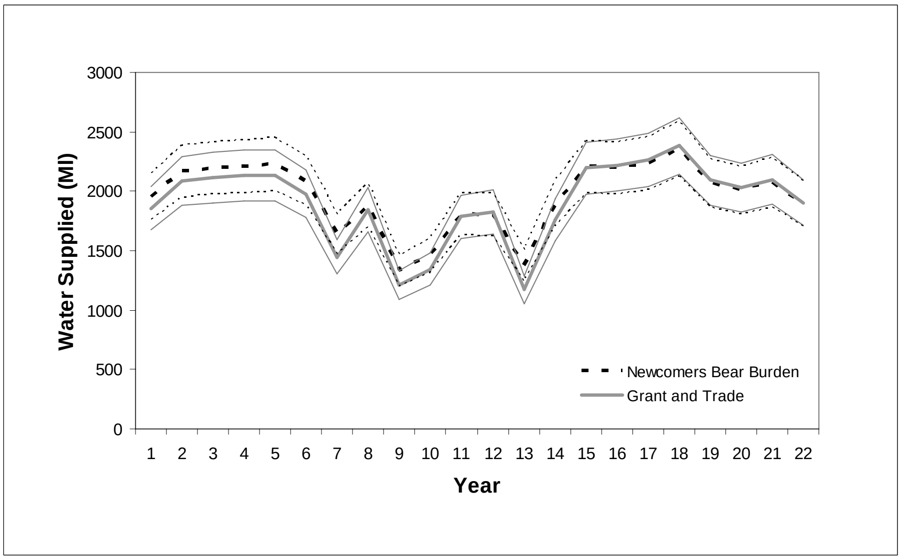

Figure 38: Volume of water supplied to the market, Scenarios 3 and 4, showing mean values and associated confidence intervals.

The average bid made for water is not significantly different between the two scenarios, as shown in Fig. 39.

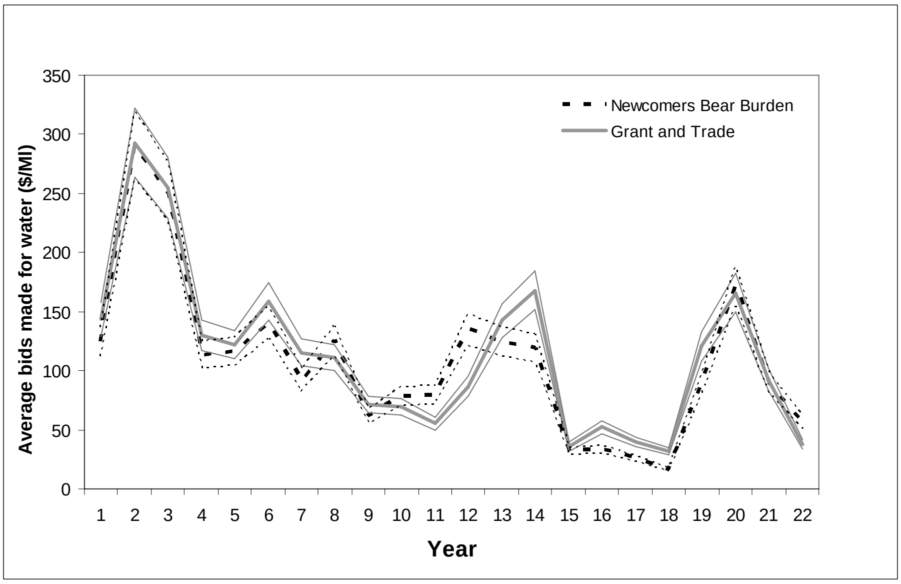

Figure 39: Average bid per Ml of water, Scenarios 3 and 4, showing mean values and associated confidence intervals.

The higher volumes of water traded result in an overall higher level of revenue from water sales as seen in Fig. 40.

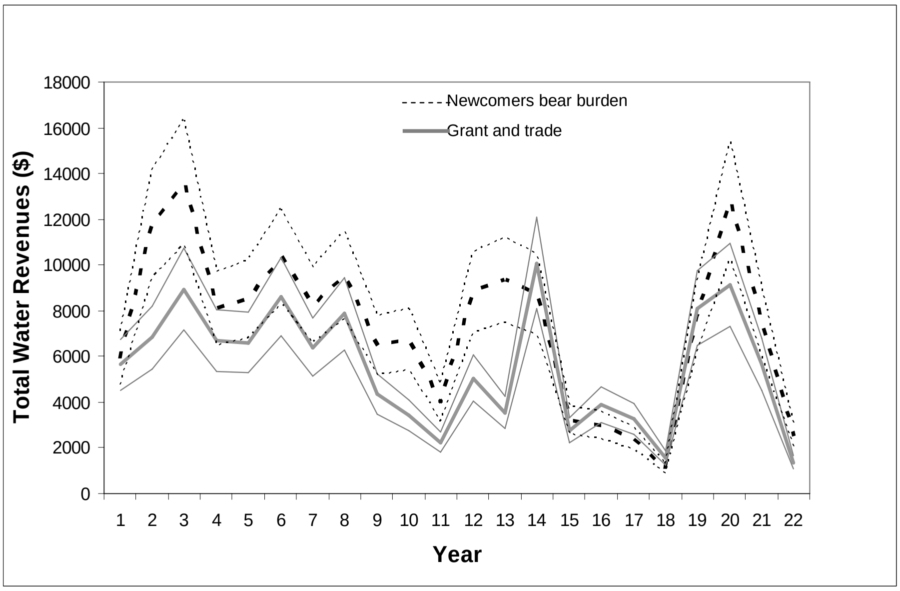

Figure 40: Total water revenues derived from the water market, Scenarios 3 and 4, showing mean values and associated confidence intervals.

The number of growers who seek off-farm income in scenario 4 is different to scenario 3 in that it occurs at an earlier period (years 7 to 9) as well as during the later half of the 22 year simulation (years 12 to 15). This indicates that four people exit the industry almost as soon as the dryer years in the middle of the 22-year simulation begin rather than at the later stage as for scenario 3.

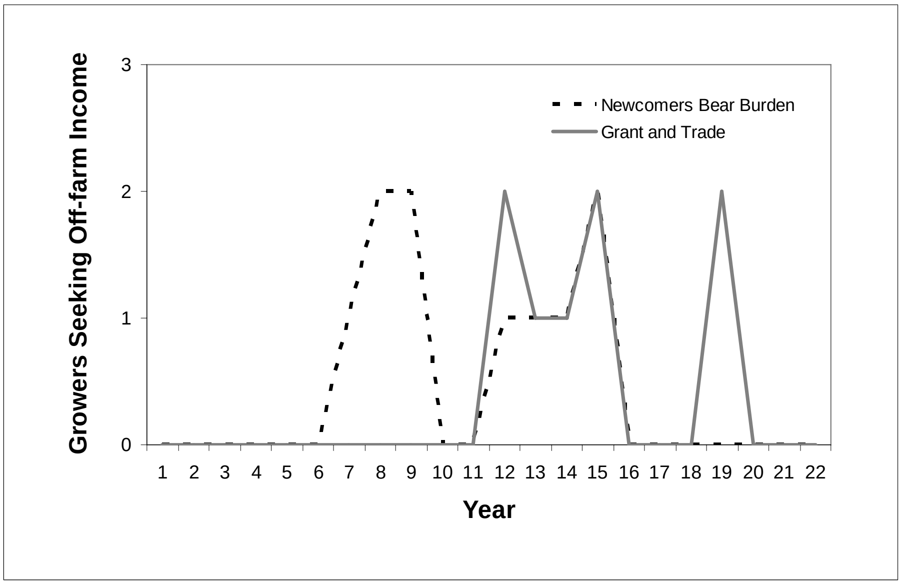

Figure 41: Number of growers who seek off-farm income, Scenarios 3 and 4

In summary, when only newcomers bear pumping restrictions, they can face restrictions of up to 100% in some periods. Total water extraction from the aquifer is higher in scenario 4 than scenario 3, meaning that the rule that only newcomers bear pumping restrictions doesn't enable the 20% limit on extraction to be met, especially in dry years when newcomers face restrictions of up to 100%. Existing license-holders don't necessarily supply more water to the market, and more growers exit the industry earlier than for scenario 3.

Scenario 5: Applications granted, market created, trading between east and west Tindall restricted

The final scenario considers the option of restricting trading in the region such that there is no trading between growers extracting from the east side of the Tindall aquifer and growers extracting from the west side of the Tindall aquifer. The Katherine River is the approximate dividing line. In this scenario, growers on the West Tindall may trade with other West Tindall growers, but not with growers on the East Tindall area (and likewise for the other location). In this scenario, it is seen that total extraction levels do not change compared to sceario 3, as shown in Fig. 42.

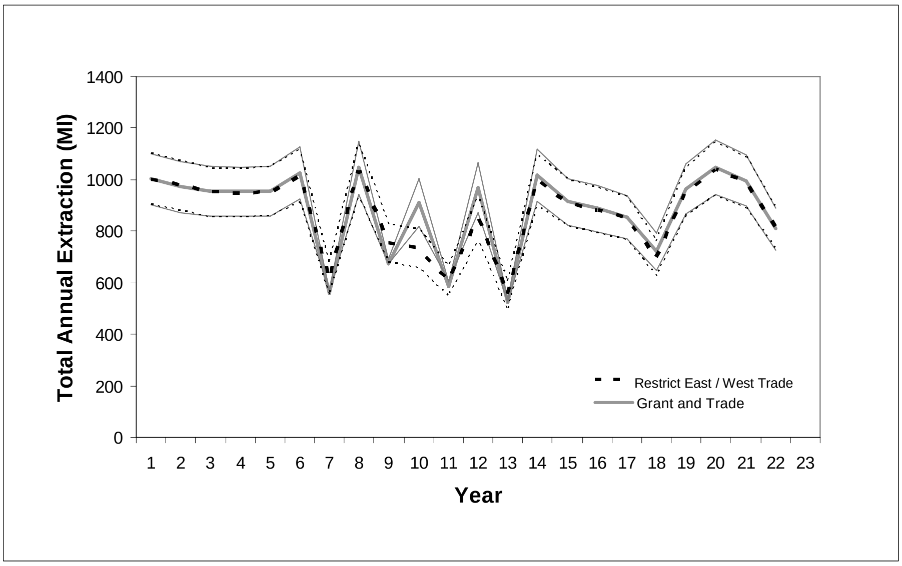

Figure 42: Total groundwater extraction by irrigating growers, comparing scenarios 3 and scenario 5, where trade between the East and West Tindall areas is restricted, showing mean values and associated confidence intervals.

The total profit derived by growers is less smooth and is sometimes higher in scenario 5 than in scenario 3, although these differences are seldom statistically significant (Fig. 43).

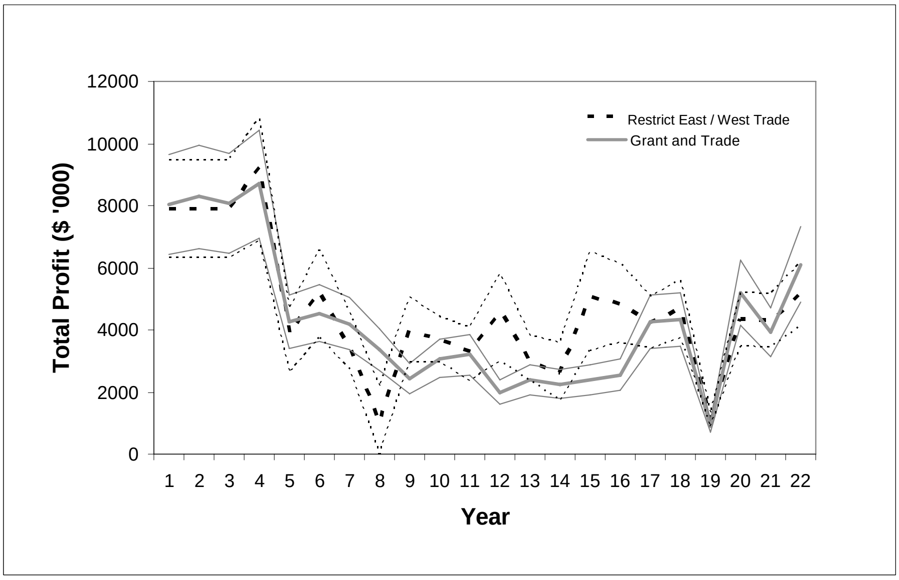

Figure 43: Profit from irrigated horticulture, Scenarios 3 and 5, showing mean values and associated confidence intervals.

Scenarios 3 and 5 are identical in the application of water restrictions, and the percentage of licenses that must be capped (see Fig. 25).

There is no significant difference between scenarios 3 and 5 in terms of volume of water demanded from the market, as depicted in Fig. 44.

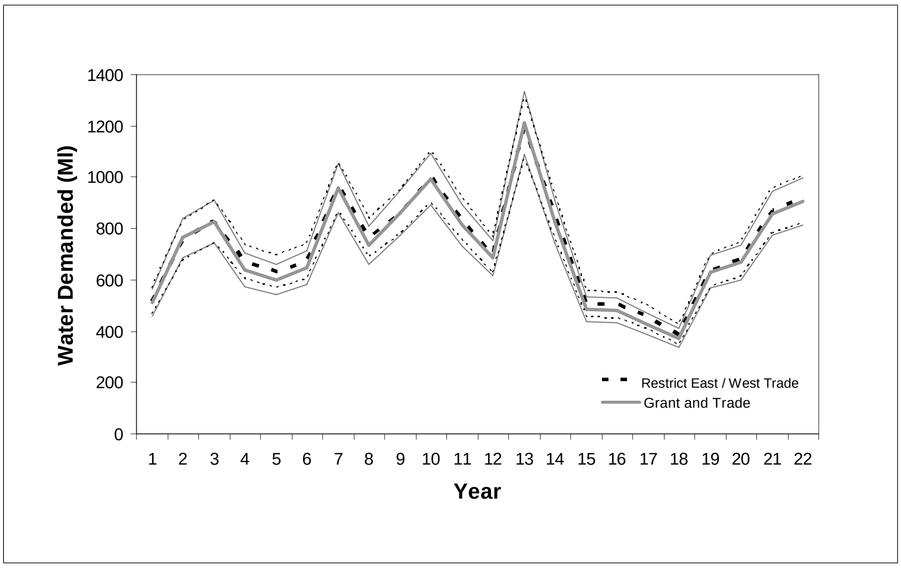

Figure 44: Volume of water demanded, Scenarios 3 and 5, showing mean values and associated confidence intervals.

Likewise, volume supplied is unchanged between the scenarios

Fig. 45 shows that the average bids made for water are again not significantly different between the two scenarios.

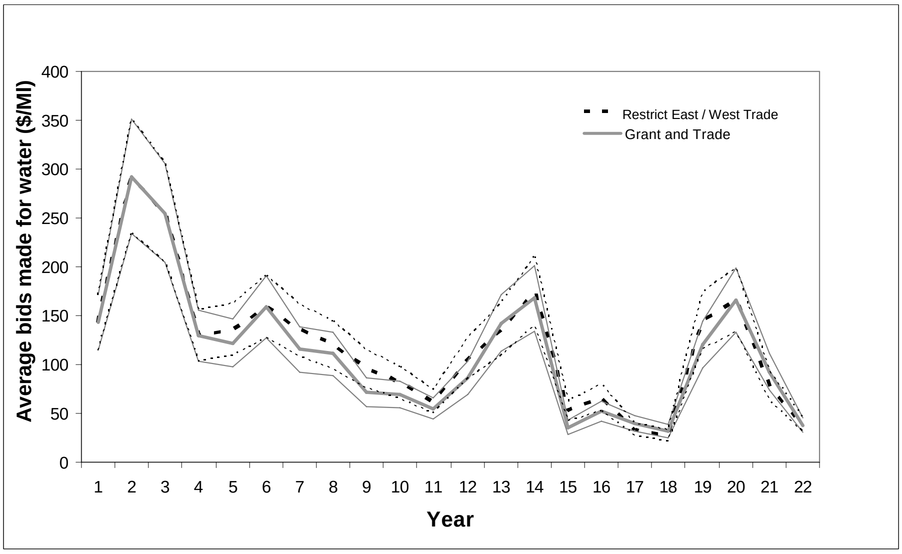

Figure 45: Average bid per Ml of water, Scenarios 3 and 5, showing mean values and associated confidence intervals.

The total volume purchased on the water market is mostly not significantly different between scenarios 3 and 5, as depicted in Fig. 38. The situation where there is no trade between the east and west portions of the aquifer results in less water being purchased because the number of buyers and sellers that can interact has been decreased.

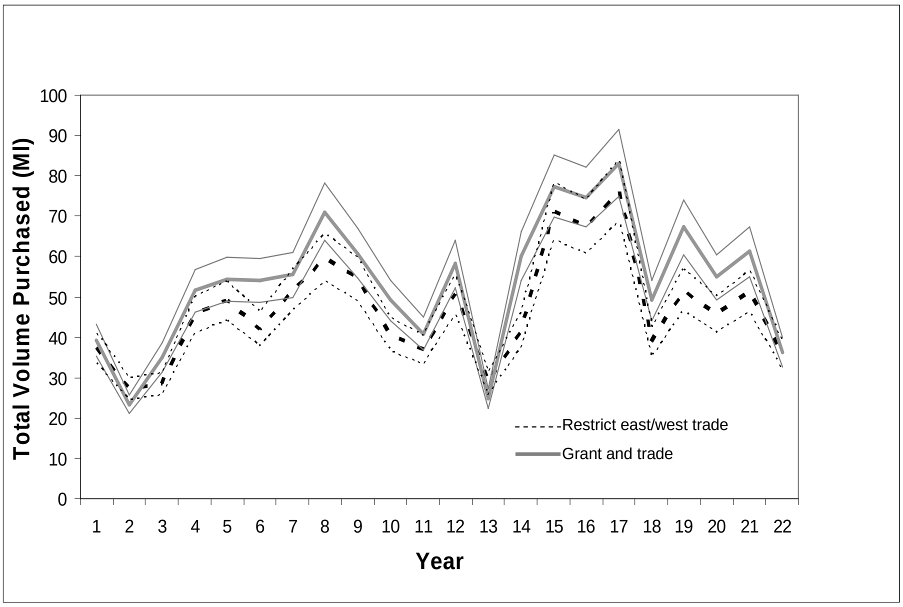

Figure 46: Volume of water purchased from the market, Scenarios 3 and 5, showing mean values and associated confidence intervals.

As a result of the decrease in volume purchased, revenues derived from the sale of water, as depicted in Fig. 47 are mostly lower for scenario 5 although not significantly so.

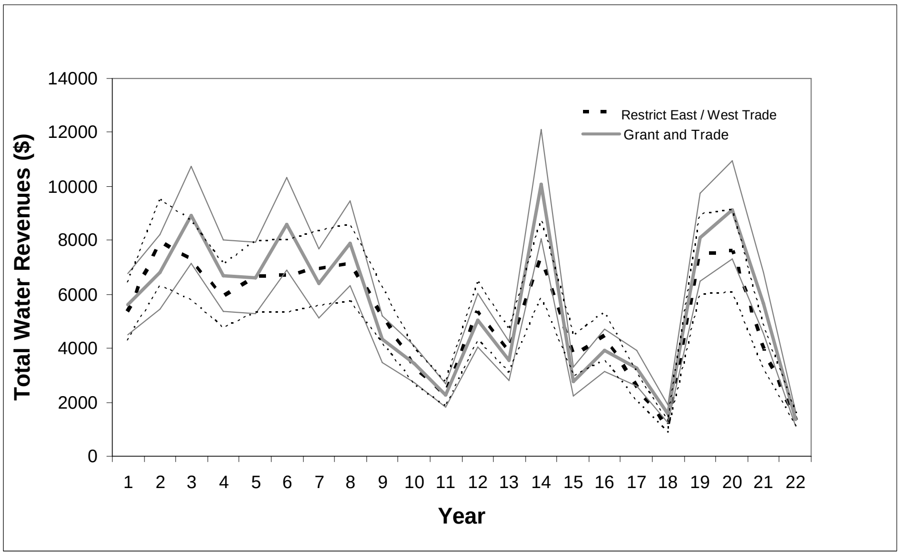

Figure 47: Water revenues derived from activity on the water market, Scenarios 3 and 5, showing mean values and associated confidence intervals.

There is no statistically significant difference in the number of growers who seek off-farm income between scenarios 3 and 5.

5. Discussion

The granting of all pending applications and implementation of a cap and trade system combine to result in the need for pumping restrictions during a portion of each of the 22 simulated years. These restrictions reach up to 80% of each grower's license 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 licensed 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. Labour restrictions are a major limitation in the modelled system to growers achieving higher returns. As such, the effects of the water market may not be fully realised if there simply isn't enough labour to bring the crop to market. Therefore, both water and labour availability impact negatively on profit, and therefore should realistically be dealt with under joint policy approaches in the real world.

The granting of all pending applications and implementation of a cap and trade system combine to result in eight or nine growers choosing to exit the industry after observing their profits over time. This amounts to over 10% of the number of growers in the community exiting the industry, with potentially notable social consequences, however these are beyond the scope of this study.

The volume of water purchased on the water market is lower when trading is not allowed between growers extracting from the east and west sides of the Tindall in the Katherine region.

In summary, even without the granting of more licenses 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 licensed allocations as report by DNREA. 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 licenses are granted and pumping restrictions are borne by all growers.

Attention now turns to the analysis of the development of a water resource management strategy for the Katherine-Daly region. This will take place through a theoretical analysis of the potential impacts of changes in the rules surrounding the role of the Water Controller and the role and composition of a Water Advisory Committee.

References

Faulks, J. J. and S. Kirby (2004). Water use within the Daly region. Darwin. Northern Territory Government Department of Infrastructure, Planning and Environment. Presentation to the Daly Region Community Reference Group.

Parker, D. Berger, T., and Manson, S., eds. (2002); Agent-based models of land use/land cover change. LUCC Rep. Series No. 6, International Human Dimensions Programme on Global Environmental Change (IHDP).

Puhalovich, A. (2005). Groundwater modelling of the Tindall Limestone Aquifer. Darwin. EWL Sciences Pty Ltd for the Northern Territory Government Department of Infrastructure, Planning and Environment.

Smajgl, A., and Heckbert, S., (2006). Simulating institutional dynamics in the context of water in outback Australia. IASCP 2006 proceedings.

Ward, J.R., Tisdell, J.G., Straton, A. and Capon, T., (2006). An empirical comparison of behavioural responses from field and laboratory trials to institutions to manage water as a common pool resource. IASCP 2006 proceedings.

White, K. (2004). The Northern Territory Mango Industry: a socio-economic perspective. Darwin. Horticulture Division, Primary Industry Group, Northern Territory Government Department of Business, Industry and Resource Development.

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