A design for a fresh water spot market

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Abstract This paper proposes a design for a fresh water spot market. The design has the groundwater of the New Zealand Canterbury Plains in mind, but would be appropriate for almost any region. In our market design, a market manager will operate a hydrology model and a Linear Program (LP), based on widely available software. The hydrogeology model calculates the effects of users' proposed abstraction rates. The LP finds allocations that maximise the sum of buyer and seller surplus, while satisfying environmental constraints expressed in terms of hydraulic heads and gradients in specific locations. The model produces a price for every location of interest. The price at a given location is the shadow price on the associated user's supply of water. Users are then charged their allocation times the market price at their location, and the market clears. We have written the software and are beginning testing.

Keywords Fresh water; linear programming; market models; sustainability

Introduction

This paper proposes procedures so that government can task a manager with allocating water, while protecting third parties and the environment. Our current research focuses on groundwater allocation, but we expect this can be extended. In our market design, a market manager will operate a hydrology model and a Linear Program (LP). The hydrology model calculates the effects of users' proposed abstraction rates. The manager solves the LP to find the allocations that maximise the sum of producer and consumer surplus. The allocations must satisfy environmental constraints. The market price at each location is the amount that the surplus value would increase per unit of additional water available at that point in the system. Users are then charged their allocation times the market price at their location, and the market clears.

A market for fresh water must first and foremost ensure a sustainable supply and protection for the environment. Secondly, a market must allocate water to maximise benefit to society. Where users can be made better off by trading, trading should be possible. Without individual incentives to improve water management, individuals will waste water. Lesser goals for a market include simplifying the resource consent process, simplifying planning of new developments, and improving calculation of costs of environmental damage.

Markets for water were first cogently discussed by Hirshleifer *et al.* (1960). They recommended that a market be set up with clear property rights, a basis for trade of those rights, and protection against externalities of trade. Except for mentioning externalities, they did not discuss environmental issues. Many other researchers have also highlighted the benefits of water markets (Thobani, 1997; McCann and Zilberman, 1999; Iglesias, Garrido *et al.*, 2001; Bate, 2002; Holland and Moore, 2003; Chakravorty and Umetsu, 2003; Gleick, 2003; Foellmi and Meister, 2004; Sharp, 2004; and many others). Following an extensive literature review, we conclude that empirical and theoretical research overwhelmingly endorses a market approach to water allocation, with the caveat that the market must be correctly designed. Unfortunately, no one seems to have proposed

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a satisfactory design. Most of the negative comment on water markets arises from the Chilean experiment (Bauer, 1997; Thobani, 1997). These negative impacts, including problems of externalities, unclear property rights, and ineffective enforcement, appear to come from errors of market design and operation.

Though not specifically for water markets, McCabe *et al.* (1991) suggested that computers could improve market operation. This was correct, as in 1995, New Zealand used computers for the first modern electricity market (Ring, 1995; Hogan *et al.*, 1996; Alvey *et al.*, 1998). Our market design follows the New Zealand electricity market in its use of (a) a market manager who solves a linear program to maximise buyer and seller surplus as specified by users' bids, and (b) pricing based on marginal costs by location.

Until recently, research in water allocation has focused on either hydrology or economic optimisation, without combining them. Becker (1995) used an LP with estimates of crop values. Garrido (2000) and Calatrava and Garrido (2003; 2004) studied market behaviour using non-linear programming without bids. Chakravorty and Umetsu (2003) developed analytical models for water management in a basin. Newlin *et al.* (2002) and Draper *et al.* (2003) have a sophisticated hydrology model with quite simple optimisation, using estimates of economic value. Similarly, Tisdell *et al.* (2004) and Yu *et al.* (2003) appear to have a sophisticated hydrology model but simple optimisation that finds a single price of water for a large region, with estimates of economic value. These tools help choose water policy, but do not involve users directly in a water market. While not using bids, Wang *et al.* (2003) developed thorough models of hydrology (with pollutants) and optimisation, and a game-theoretic framework. Their approach finds Pareto-optimal allocations to aid negotiation among co-operating stake-holders. The work that uses bids thus far appears to have simple or non-existent hydrology (Murphy *et al.*, 2000; Cummings *et al.*, 2004), and nothing intended for on-going real world markets.

As far as we can tell, no market model for fresh water exists that guarantees protection from externalities to the environment and third parties, and calculates different prices at each location. The objectives of this paper are to provide a theoretical background for this ongoing research, and stimulate discussion on market mechanisms for water allocation. This remainder of the paper gives the proposed market design, the associated hydrology model and linear program, and a discussion.

Methods – proposed market design

Our market design operates under a few reasonable assumptions. Water is generally short; our model is not intended for flood conditions. Users are given resource consents (permission to use up to a fixed amount of water), and government has the right to adjust the resource consents. Water use is metered.

A buyer and a seller cannot simply trade, because of the externalities that their trade may induce for others and the environment. No one can declare to whom a seller is selling, or from whom a buyer is buying, because water use in one place affects many places. Thus, the market requires a coordinating manager, selected by government. We assume the manager has a sufficiently accurate hydrology (e.g. MODFLOW, Harbaugh and McDonald, 1996) model for the region, which can evaluate the effects of water use. The manager accepts payments from buyers and disburses payments to sellers. In some cases, a seller may sell for environmental protection. In such a case, the manager serves a custodial role on behalf of the government by buying water. Government must set the preferred level of environmental protection.

The auction

At regular intervals, at least seasonally, the manager would operate a multi-round auction. Any owner or tenant of land in the market area has the right to bid (a) to sell water from an existing resource consent, (b) to buy water to add to a resource consent, or (c) to buy water without a resource consent. The manager receives the bids, and allocates water using the hydrology and LP models. The manager grants users the right to use the allocated water over a specific allocation period.

Notation (extended below):

α: fraction of the resource consent available (ideally identical to all users). This varies from 0 to 1.

p_l: spot price of water at location l. This is the marginal cost to the economy of supplying another unit of water at location l.

R_l: current resource consent held by the user at location l.

x_l: quantity of water that the manager has allocated to the user at location l.

Operation of the auction has the following steps.

- Before the auction, the manager runs a modified model to find the total amount of water available to be traded. This is declared as the proportion α of each user's resource consent.
- On auction day, users can bid to sell water from their resource consents, and can bid to buy more water. A user could bid a combination, selling for a high price and buying for a low price.
- The hydrology model finds a response matrix, how each user's demand affects other locations.
- The manager writes an LP with the response matrix, the bids, and environmental constraints.
- The LP allocates water to users to maximise the sum of buyer and seller surplus, while ensuring environmentally secure flows. The LP will also calculate the spot price at each location. Spot prices may differ by location because hydrology and demand differ by location.
- The manager then notifies users of tentative spot prices and their tentative allocations. Most likely, users will want to change their bids somewhat after discovering the initial allocation. By running several rounds (steps 2 through 6) at a given auction with only the last being firm, the users get clearer signals as to the outcome (Cummings *et al.*, 2004).
- The manager runs a final auction and clears the market. The manager gives each user a definite right for the allocated water, for the allocation period. The manager pays net sellers and charges net buyers at each location at their local spot price p_l. Cost to the user is calculated as $p_l * x_l$. Resource consent holders who do not trade get their proportional allocation $\alpha * R_l$ without cost or payment. The manager notifies them of the spot price of water at their location, and invites them to buy or sell water at future auctions. Our model with a simple modification calculates α.

The allocation x_l is a license to use any amount of water up to x_l for a specific period of time, drawn from location l. If the user does not take all of x_l before the end of the period, the user loses it.

The hydrogeology model

Groundwater flow is described by the theory of flow through porous media (Freeze and Cherry, 1979). Various groundwater models can be used in an allocation system. For a market model, requirements include speed, because the region may have thousands of wells; reliability, so bidders trust that the model will deliver timely results; versatility, because needs vary over time and space; public defensibility, since models could be challenged; and an interface to an LP.

We selected the software MODMAN (Greenwald, 1998). MODMAN was developed to optimise pumping of wells to solve management problems related to contaminated groundwater containment and removal. MODMAN uses a modified form of the USGS MODFLOW-96 to evaluate the flow network based on user-defined inputs. MODMAN adapted MODFLOW so that flow rates from wells are set by an LP, rather than considered as fixed MODFLOW inputs. Otherwise, MODFLOW operates normally with user-defined inputs such as boundary conditions, initial conditions, aquifer storage and aquifer transmissivity. Regionally, the market for fresh water naturally decomposes by watershed. Therefore, we can in principle set up a water market for any region that has a valid MODFLOW model.

First, MODMAN uses MODFLOW to evaluate a steady-state solution to the user-defined inputs for the case when no pumping occurs. Second, MODMAN executes the model with one well being pumped and finds the change in steady-state water levels at all points of interest. MODMAN repeats this process for all wells in the system. This provides a response matrix giving the draw down in water level at a series of points from pumping at each particular well. The response matrix can be used to calculate the anticipated draw down at each point of interest. The governing equation for groundwater flow is linear, so the total effect at one location from pumping at multiple locations is the weighted sum of the effects.

If given the following notation:

n: number of wells,

q_{it}: pumping rate from well i at period t,

F_{ijt}: draw down response at location i due to pumping at well j at period t,

then $s_{it} : \sum_{j=1}^{n} \sum_{u=1}^{t} F_{iju} q_{ju}$ =the draw down at location i in period t.

The linear program

Using the response matrix, MODMAN creates an LP. The flow rates from individual wells, $q_{1t},\ldots q_{nt}$, are decision variables, which must satisfy constraints. (If flows are non-linear, MODMAN has procedures for re-running MODFLOW with the $q_{1t},\ldots q_{nt}$ output from the LP to update the response matrix.) Our model can include any constraint that MODMAN can create, including:

- head limits, to ensure that the overall groundwater resource is not overly depleted;
- head difference limits, to ensure a minimum rate of surface water flow into a body;
- total flow, to limit total pumping to some fraction of the estimated aquifer recharge.

The input data for the linear program include unmanaged natural head at location i, the initial head at location i, upper and lower bounds on heads at each location and in each time period, upper and lower bounds on head differences between each pair of locations in each time period, the users' reservation prices for their bids, the users' resource consents.

Besides the flow rates q_{it}, additional decision variables include the bid quantities that should be accepted by the market, and the market prices (which are the shadow prices on well abstraction constraints). The sum of the accepted bid quantities is x_{it}, the water allocated to location i at period t.

In words, the linear program has the following components:

- Maximise consumer surplus + producer surplus.
- Bids are bounded by their marginal quantities. Sell bids are negative; buy bids are positive.

- The well abstraction plus bid amounts equals the resource consent. The dual variable of this constraint is the ($ gain)/(unit increase of the resource consent).
- Balance of flow at each location, in each time period.
- Bounds on well heads, relative to both the unmanaged head and the initial head.
- Difference constraints. To create gradient constraints, the head difference parameters can be scaled by distance to have a gradient limit. Vertical gradient constraints cannot be defined with the software, but these head constraints can be used in place of vertical gradient constraints. To create velocity constraints, the head difference parameters can be scaled by coefficients for hydraulic conductivity, porosity, and retardation.

Using a web page, the user at each location enters bids as five pairs of quantities and reservation prices. The web server stores the bids in a database. In a separate process, MODMAN generates an LP formulation in standard MPS file format. To run an auction, the server reads the bids in the database, adds the bids to the MPS LP file created by MODMAN, and then passes the modified MPS file to the LP solver. The model finds the well flow rates that maximise the sum of buyers' and sellers' surplus. When the LP solver completes, the server writes the amount of water allocated and the prices to the database, which users can view by refreshing the web page. Figure 1 shows part of the web page for one water user, with a set of notional bids.

Discussion

Our model is "time aware" – use of water now will affect the future. Each user may enter bids for any future auction. If the user omits a bid for an auction, the software re-uses the user's previous bid. The system therefore accepts the user's future value for water to any degree of accuracy that the user desires. Hence, the current price at a location reflects users' present and future reservation prices within practicable limits, and assuming forecasted rain.

Our model deals with the uncertainty of rainfall by clearing the market only for the immediate period, when the forecast is best known. Future periods are assumed to have the forecasted rainfall, but users have an opportunity to bid again when the forecast is better known. In dry times, the manager should operate the market relatively frequently. A local rain can change prices from day to day. In wet times, the manager can run the market less often. The manager will have the responsibility of being responsive to users, and to operate the market when an auction would improve welfare.

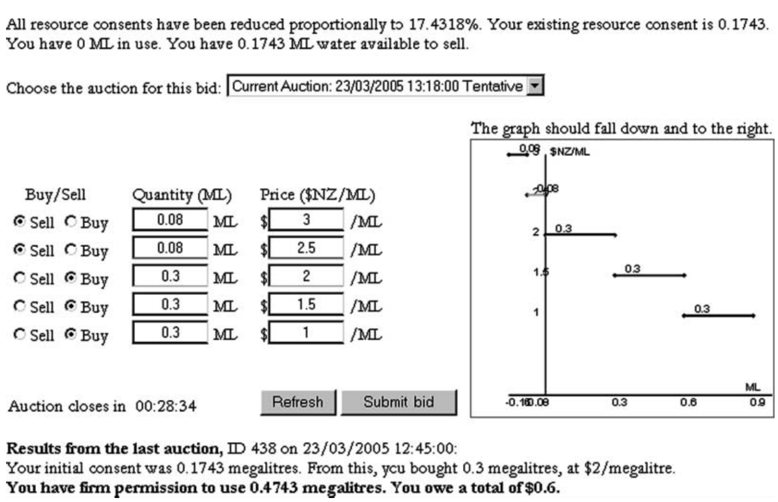

Figure 1 Sample input screen for a bidder named "well01"

Our software allows better resolution economically than hydrologically. In a given MODFLOW grid location, MODFLOW treats all wells as a unit. That is, only one flow can be identified for one MODFLOW grid location. If the grid location has more than one user, we simply add multiple bids. Trading can therefore occur between users in the same grid location.

The model requires protection of the environment. Who pays for that protection is largely controlled by the initial resource consents. If resource consents are too high, relative to the available water, the market manager must buy water from users to protect the environment, as with Cummings *et al.* (2004). If resource consents are low relative to total water available, net payments to the manager will be larger than net payments to sellers. In this case, users will pay for use of the water and for the externalities of their demands. A user near an environmentally sensitive region will be penalised. If resource consents are allowed to expire, the auction becomes a pure user-pays scheme.

Figure 2 shows a map of prices for a small example. The data is from Greenwald (1998). In this example, all users have bid identically as in Figure 1. Even though bids were identical, prices vary because the hydrogeology varies. Well 12 is the "driest" well, as the market manager has imposed head constraints to prevent salt water incursion from the coast. Similarly, active drawdown constraints raise the price a bit near wells 01, 16, 03, and 18.

What are the implications of errors and uncertainty in the hydrology model? The first order approximation – of getting the overall quantities of water about right – would seem to be an improvement. The hydrology model will need on-going development, and users must have access to a complaints process. However, New Zealand regional councils are already making water allocation decisions based on hydrology models (or without them!). Our model produces prices by location, which would motivate the manager to model areas with high-priced water more carefully.

How should water be allocated to the environment? Users will easily agree to some environmental constraints, such as prevention of incursions of coastal salt water into an aquifer. Other constraints will be more troublesome. For example, how much water should be allocated for river kayakers? The government will have tools to price

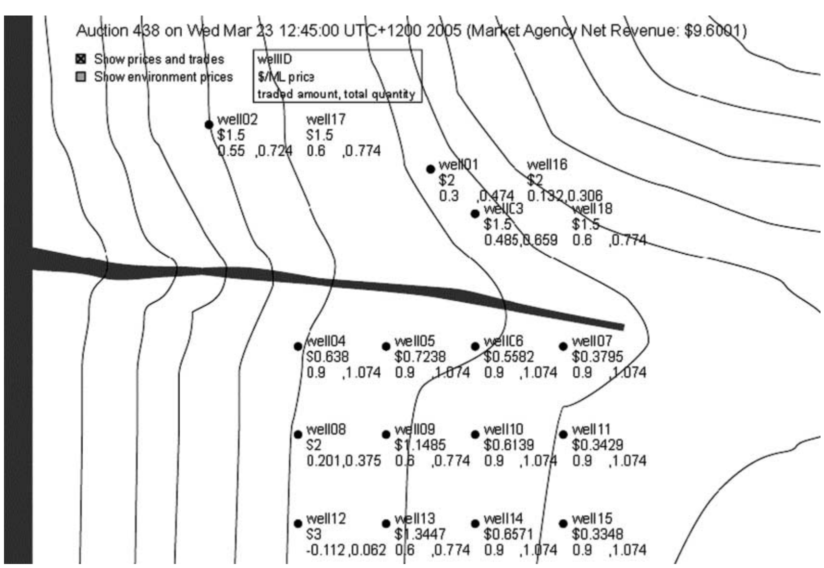

Figure 2 Map of prices and allocations. Wells 01 and 16 have the same location, as do wells 03 and 18. A negative trade is a sell. A positive trade is a buy

the water, and could choose to subsidise or charge the kayakers. In dry times, agricultural users will want to lower their costs by reducing environmental flows. Allocation of water to the environment must be chosen politically, with community involvement.

Conclusions

In this paper, we have described a design for spot market in fresh water. We described software that we have written to operate the market. The market is operated by a market manager. The manager first uses a simulation of the hydrology to calculate the response matrix, to show the effects of each user on all other users and the environment. Next, the users give their bids for marginal amounts of water. Based on users' bids, the hydrology, and environmental constraints, the manager constructs and solves a linear program to allocate water to users and to determine prices at every location. Users get accurate price signals to maximise the economic use of the water, while protecting the environment. Future work includes relatively easy extensions to surface water and discharges.

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