How to Solve Our Water Crisis: a Demo Spot Market for Ground Water

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ABSTRACT

We show how to set up a physically and economically correct market for ground and surface water, using a modified version of MODMAN. MODMAN uses MODFLOW to produce a response matrix, which in turn becomes part of a linear program (LP). Greenwald showed how to use this mechanism to optimize various groundwater problems. We show how to use MODMAN to create an LP suitable for sustainable water trading. The LP includes required environmental conditions (e.g., head levels, flow to streams) as constraints, guaranteeing sustainability. The objective is to maximize consumer surplus. The objective coefficients are taken from users' bids to buy/sell from their water allocation, ensuring that no water users lose from the auction.

Our approach implies an institutional arrangement for a water market in which a regional agency acts as a broker for a given catchment. Users bid for water through a web page, thus virtually eliminating transaction costs. The agency then solves the LP, which gives the optimal prices and allocations. We will demonstrate our software, and provide preliminary results using data from New Zealand's Marlborough district. We believe that this approach can help solve the world water crisis.

INTRODUCTION

The world crisis of fresh water appears to be intractable. A casual survey of the literature shows that the economists believe that a market approach is the way to solve this crisis, and they give suggestions regarding attributes for a proper design. Such attributes include fair prices that adequately address externalities, low transaction costs, and constraints for sustainability. Unfortunately, none of them put forward a market design that satisfied their requirements. In Raffensperger & Milke (2005), we gave a market design that appears to satisfy all requirements. We also gave a literature review, which we shall not repeat here.

The critical new aspect is that our design allows a market for ground and surface water. The market design is for a single catchment. To model and optimize ground water movement and abstractions, the market system relies on MODMAN (Greenwald 1998), or similar software. We will not go into detail regarding MODMAN here, but instead concentrate on details of the market system. In a second paper (Raffensperger & Milke 2006), we gave a detailed example of how the market would work, using textbook data. Among other things, that paper shows that all rational traders gain from the market system. While this is no surprise to economists who well understand the gains of trade, it remains a point of confusion with the general public.

In this paper, we describe results from our water market system with an example using real-world hydrology from New Zealand's Marlborough region. Bids are notional.

PROBLEM DESCRIPTION

MODMAN can model and optimize water abstraction in a single catchment, given a valid MODFLOW-96 model (Harbaugh and McDonald, 1996). The main insight into developing the market system was simply this: replace MODMAN's objective of maximizing total abstraction with an objective based on users' bids for water. The linear program requires some additional variables and constraints to manage the bids, but the operations research is straightforward.

Following development of the technical modeling, our market design specifies a *market manager*, who may be a government authority. The market manager must have authority to adjust users' water quotas, particularly to reduce those quotas in drought. Assume without loss of generality that a user is associated with a particular well.

As described in our earlier papers, the market manager follows these steps to operate the market:

(1) The manager uses MODMAN to find a response matrix.

(2) The manager inputs environmental constraints into MODMAN, such as constraints preventing salt water intrusion, maintaining minimum river flows, and limiting aquifer drawdown.

(3) The manager checks whether existing quotas will meet all environmental standards, and if they do not, the manager has a method to reduce quotas. We assume proportional reduction, and have a method to choose the proportion (Raffensperger & Milke 2006).

(4) The manager accepts bids from users to buy or sell water from their quotas. Bids could be made over the internet.

(5) Using MODMAN, the market manager sets up a linear program (LP). The objective coefficients are the users' bids. The LP allocates water to users to maximize the sum of buyer and seller surplus, while ensuring environmental standards are met. The solution specifies the allocation of water x_l to each user l. The solution gives the market price of water at each potential abstraction point, p_l.

(6) The manager gives each user a definite right for the allocated water, for an allocation period (such as a week). The manager pays net sellers and charges net buyers at their local price.

If the users wish, the manager can run several tentative auctions, to give users an opportunity to see what will happen before they commit. Most likely, users will want to change their bids somewhat after discovering the initial allocation and the tentative prices for water quota. Following the final auction, the cost to the user is calculated as p_l*x_l.

In fact, our system can do slightly better than MODFLOW, in that we can allow more than one trader within a given MODFLOW grid cell. These traders cannot be distinguished hydrologically, but they can be distinguished economically, as though two people each had quota for a given well, and bought and sold from each other. The market price will be uniform throughout the grid cell.

THE MARLBOROUGH EXAMPLE

Marlborough is beautiful bowl-shaped region on the north end of the New Zealand's South Island. Years ago, the land was considered rubbish for farming. In the 1970's, someone discovered that grapes grow very well in the coastal gravel. Now the area produces some of the finest wines, especially white wines, in the world.

With the growth of the viticulture industry, demand for irrigation water has risen dramatically. Government estimates are that about 30% of available water is in use, and this is projected to 43-45% over the next few years. Unfortunately, users are far from surface water, so they take groundwater, which is now exploited almost at the maximum sustainable. Indeed, local government hydrologists want to know how far the aquifer can fall, and still be considered sustainable.

With the development of our work, the Marlborough District Council graciously gave us permission to study their catchment. They made available to us hydrology data from 1997, and details of users' quotas (called *consents* in New Zealand). Figure 1 shows a map of the area under study.

Figure 1. Map of Marlborough, showing wells, the MODFLOW grid, rivers, and roads. The coast is at the right side. The city of Blenheim is a bit right of middle. The labels A1, B3, C1, D3, and E3 are environmental control points, with their MODFLOW layer. The small gray dots correspond to the lowest volume wells, which were fixed in the simulation and optimization. The larger black dots are wells that trade. The inset shows Marlborough highlighted within New Zealand.

The region contains 623 wells of interest. The smallest 265 of these were set to have fixed flows in MODMAN, of between –1.4 and –107 m^3/day. The remaining 358 wells have quotas of between –180 and –1,349,280 m^3/day, the latter being associated with the city of Blenheim near the center of the figure. The area in Figure 1 is about 21 by 26 km (13 by 16 miles).

We used the notional bids shown in Table 1. The quantities are calculated as fractions of the user's quota. Negative quantities are sell bids; positive quantities are buy bids. For example, at a price of \$0.60/m^3, a user would be willing to half of his water. At a price of \$1/m^3, a user would be willing to sell all his water. For a price of \$0.40, a user would want to buy up to 50% of his quota, in addition to his quota.

Quantity:	–16.67%	–33.33%	–50%	50%	25%
Price	\$1.00	\$0.80	\$0.60	\$0.40	\$0.20

Table 1. Notional bids used in the market model.

MODMAN produced a linear program (LP) that corresponded to maximizing abstraction, but the LP did not have the bid information. Our software read the associated LP file, added the bid information, and then solved it. The final linear program contained 1,009 constraints, 8,885 continuous variables, and 81,769 nonzeros. By typical operations research standards, this is quite an easy model.

RESULTS

Figure 2 displays the results of the market system, with the interesting bit enlarged.

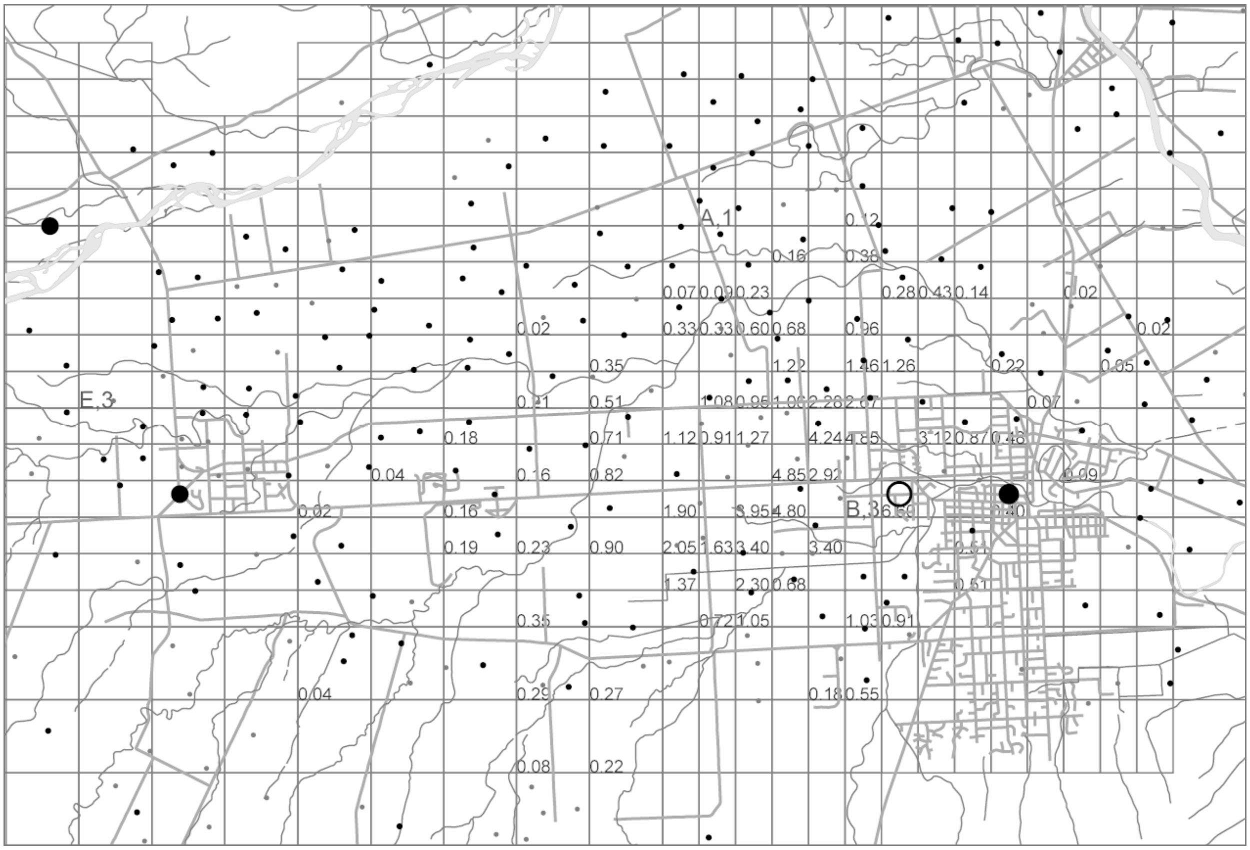

Figure 2. Results of the market software. Positive prices are shown by grid cell. Prices are zero at all other MODFLOW grid cells, including all those not shown. The three large black dots are wells that are major buyers of water. The circle near B3 is a well that is a major seller of water.

In the solution, the only binding environmental constraint is associated with control point B3, near Blenheim city. This LP constraint has a shadow price of $29 million, implying that a unit change in the associated head would improve the local economy substantially. Because of this binding control point, prices are high near the city, but fall away from the city. The price is zero far from the city (omitted to avoid clutter in the graph). None of the constraints for the other control points are binding.

It is easy to see which wells buy and which wells sell, simply from the prices. Wells sell everything if the local price is ≥ $1. They sell some if $1 < price ≤ $0.68. They buy if $0.40 ≤ price. Trades include one large sale and a few large purchases. The one large sale is by a well immediately adjacent to the B3 control point, because the price must be high there to protect the environment. Interestingly, just a couple grid cells to the east of the tight control point, a well makes a large purchase, at $0.40/megaliter. The other two large purchase are at the left of the figure, and those users get their additional water for free.

Net cash is $2,847,000, with the market agent paying users, almost all of which is for the one major sale near B3. Users in the donut-shaped region around B3 buy water from users right near the control point, while people far enough away from B3 get water for free.

Our software can change quotas dynamically to have a "user trades" scenario, where the market agent neither pays users nor is paid by users. However, this scenario would have the same prices and final quantities; it would just decrease everyone's initial consents a bit so that the market agent would net nothing.

Over the whole catchment, the net is 254,600 megaliters purchased above total consent. This suggests that (in 1997 anyway) total quotas could be raised, if some people near B3 were willing to sell. It looks like a classic city versus rural battle over water, exacerbated by the control point right next to the city, but mitigated by the market. Wells are overallocated near the city, and underallocated away from the city. The rational response to this market is to move water use away from the environmentally sensitive area at B3, which is exactly what is needed.

SUMMARY

A few caveats are in order. We have some uncertainties about the Marlborough quota database regarding well quotas and locations. We do not know whether the MODFLOW data models the water flow correctly, nor do we know whether the environmental constraints have been set correctly. These are data input issues. But given this experience with the data, we have shown that we can operate a market for ground water from a technical point of view. We see that the big flows are important, and little flows are not important, so a good approximation may be all that is needed. Furthermore, the prices tell us where to look to improve the data – around the B3 control point near Blenheim.

In this paper, we have shown the technical feasibility of a spot market for ground water that has correct prices and guaranteed sustainability. We demonstrated our market software with real hydrology data from Marlborough, NZ, and notional bids.

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