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Ivana Huskova

Julien J. Harou

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An agent model to simulate water markets

Ivana Huskova, **Julien J. Harou**
University College London (i.huskova@ucl.ac.uk, j.harou@ucl.ac.uk)

Abstract: In many catchments in England no further licenses are available from the Environment Agency (EA). The possibility of trading water between license holders has been recognized as a potentially effective and economically efficient strategy to mitigate increasing scarcity. However it is not clear what potential trading has to meaningfully address the supply-demand imbalance in over-abstracted areas. A screening tool that could assess the potential and effectiveness of water trading in any catchment would be useful. We propose an optimization-driven water market simulator that predicts economically efficient pair-wise trade and represents its interaction with natural flows and engineered infrastructure. The model emulates license-holders' willingness to engage in short-term trade transactions. In their initial form different 'agents' (license holders) are represented using an economic benefit function of water use. The working hypothesis is that trading behavior can be partially predicted based on differences in marginal values of water over space and time. A case study based on the river Dove Basin (UK) is made to test the model. The model which simulates the catchment weekly over several years can also consider user interactions with infrastructure (e.g. reservoirs) and user-defined transaction costs between user-types or specific license holder pairs.

Keywords: water market, water rights trade, transaction costs, trading water, hydro-economic modelling

1   INTRODUCTION

Many catchments in the UK, particularly in South East England, are considered over-abstracted by the environmental regulator which results in restrictions on existing abstraction; no new abstraction licenses are available. Water rights markets have been recognized as potentially part of the solution to address increasing water scarcity. It is not clear what potential trading has to effectively address the supply-demand balance. A screening tool would help characterize the potential and effectiveness of markets in a certain region.

We propose an optimization driven water market simulator that represents pair-wise water trade within a catchment and its interaction with hydrologic flows and engineered infrastructure. The model extends an existing flow-path water resource network model (Cheng, 2009) which allowed tracking the start and end of different water volumes thus allowing to track trade-type transactions. We integrate that formulation to economic drivers – water abstractors execute those trades that maximise economic value and are worth it given the cost of engaging in the trade transaction. To attempt simulating markets we combine a flow-path optimiser with a hydro-economic approach (Harou et al., 2009). The model treats water demands as elastic, with the value of water to each user represented with economic benefit functions. Transaction costs shape market behavior by preventing some otherwise optimal transactions and ensuring that a trade takes place only if the incurred social benefits exceed the associated social costs (Colby, 1990). The model promotes water resources to be allocated in the most economically efficient way within the catchment.

Cheng et al (2011) applied their original flow path model to a options purchase optimization problem for two municipal water agencies in Taiwan. Their approach uses fixed water demands and minimizes the purchasing of options. The agencies purchase options from one supplier; trade between the agencies was not considered. This application demonstrated the flow path model's usefulness in representing situations involving water trading.

To demonstrate the use of a flow path model to simulate pair-wise trading we propose a modified hydro-economic flow-path formulation and apply it to the River Dove catchment in Central England. Section 2 describes the flow path water market simulation model extension and filter algorithm to identify possible pair-wise trades. Section 3 describes the model formulation. In Section 4 we apply the model to the Dove catchment case study to demonstrate its applicability.

2   MODIFIED FLOW PATH MODEL

The flow path model proposed by Cheng et al (2009) is able to identify the particular supplier, receiver and the path of delivery within the water network system composed of nodes and directed arcs. The model proposed here makes 3 changes to the original formulation: 1. a single storage node is used, 2. water demands are elastic, with decreasing returns to water deliveries, 3. custom transaction costs between individual license pairs can be set, and 4. deviations from storage targets are penalized to encourage the pragmatic operation of reservoirs.

Cheng et al. (2009) use 2 dummy nodes, a reservoir supply node and reservoir receiving node (Figure 1), to represent storage nodes. The inflows into the reservoir are treated as the inflows into the receiving node while outflows from the reservoir as outflows from the source node. The former at time step t becomes water available for distribution at the reservoir source node at time step t+1 (dashed line in Figure 1). This requires two equations to handle the storage mass balance. We simplified this mass balance down to 1 equation where the storage at each time step is calculated simply as inflows – outflows + previous storage; the single-node representation is shown in Figure 1.
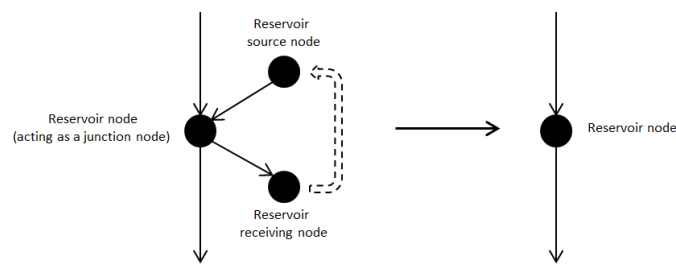

Figure 1. Reservoir representation in flow path model (left) and in the proposed model (right).

The water demand was changed from fixed to elastic by allowing it to vary according to water availability and marginal benefits. Water deliveries are the difference between the inflows and outflows to and out of a demand node within the same time step. Deficits are not allowed to promote trade between water users. The modified model was then linked to Hydroplatform.

A barrier to water market simulation is the complex and hard to quantify aspect of transaction costs as potentially transactions between individual users at different times could engender different institutional costs. The costs represent effort by regulators and/or transaction participants to agree to the transaction and its terms. The proposed formulation includes a transaction cost function between each unique pair of licenses which can be set with a unique initial cost (setting up a

transaction, no matter the size has a startup cost) and linear slope (to account for the fact that larger trades are likely to be more costly to engage) for each pair of traders. Alternatively, transaction costs can be homogenized between different user types (so that for example all agricultural to industrial trades have the same transaction cost function). The initial costs of transactions are represented with a step linear function using a binary variable.

Finally the deviation of reservoir storages from storage targets are minimized to encourage the realistic use of reservoirs compatible with other uses including water supply, flood control, recreation, etc. Target storage varies seasonally. In this model reservoirs are included in the subset of nodes that can engage in water sales. This is meant to represent the economic gains of having reservoirs under consortium ownership where users can bid for reservoir water (perhaps managed by a utility or 3rd party).

3 MODEL FORMULATION

The model was developed by improving and extending the original flow path model (Cheng, 2009). The decision variable is the magnitude of flow through each flow path represented as X_r. The start and end nodes of a flow path define the type of delivery, i.e. river flow, abstraction, or trade. The important parameters are *value*$_{i,k,t}$ and *volume*$_{i,k,t}$ = benefit and volume value of the piece-wise linear benefit function for node i at interval k at time step t, respectively, *cont*$_r$ and *linCoeff*$_r$ = constant and linear coefficient of the transaction cost function for each trade flow path, and the seasonal target storage volume of reservoirs *targetStor*$_{i,t}$.

The objective is to maximize the total net benefits generated by trade while minimizing the weighted deviation between actual and target storages:

$$Maximize\ z = \sum_{i \in D_i} \sum_t b_{i,t} - \sum_{r \in AT_r} \sum_t c_{r,t} - \Omega_i \sum_{i \in R_i} \sum_t (targetStor_{i,t} - Stor_{i,t})$$

(1)

where

$$t = 1, \dots, T$$

$$b_{i,t} = \sum_k (\lambda_{i,k,t} \cdot value_{i,k,t})$$

(2)

$$bought_{i,t} + \sum_{j \in R_j} resBought_{j,i,t} = \sum_k (\lambda_{i,k,t} \cdot volume_{i,k,t})$$

(3)

$$\sum_k \lambda_{i,k,t} \leq 1$$

(4)

$$\forall i \in D_i; t = 1, \dots, T, k = 1, \dots, K$$

$$c_{r,t} = X_{r,t} \cdot linCoef_r + const_r \cdot yTrans_{r,t} + X_{r,t} \cdot penalty_r$$

(5)

$$X_{r,t}/U_x \leq yTrans_{r,t} \leq L_x \cdot X_{r,t}$$

(6)

$$\forall r \in AT_r, t = 1, \dots, T; yTrans_{r,t} \in (1,0).$$

Subject to:
I. River source mass balance
II. Storage mass balance and capacity constraint
III. Abstraction mass balance and constraints
IV. License trade mass balance and constraints
V. Demand mass balance and constraints
VI. Catchment outflow mass balance and constraint
VII. Link capacity constraints

D_i is the set of all demand nodes, $b_{i,t}$ are the benefits generated by node i at time step t, AT_r is the set of all trade flow paths, $c_{r,t}$ are the transaction costs of path r at time step t, Ω_i *is the storage deviation penalty weight for reservoir i, Ri* is the set of reservoir nodes, and $Stor_{i,t}$ is the storage of reservoir i at time step t.

Equations (2) to (4) represent the piece-wise linear benefit function where *k* is the piece-wise interval, $\lambda_{i,k,t}$ is the interval proportion, *bought*$_{i,t,}$ is the licensed volume bought by node i at time step t from other demand nodes, and *resBought*$_{i,t}$ is the volume bought by node i at time step t from reservoirs.

Equations (5) and (6) represent the transaction cost function where *yTrans*$_{r,t}$ is a binary variable equal to 1 if $X_{r,t} > 0$, 0 otherwise, *penalty*$_r$ is the unit penalty cost for penalized trade paths, U_x and L_x are suitable upper and lower bounds on the $X_{r,t}$ variable respectively.

Constraints implement the following rules in an attempt to simulate trading activity:
1. The maximum abstraction volume a demand node is set by its license.
2. A minimum use can be set to prevent certain low value uses to trade all of their allocation during certain periods if this is found to be unrealistic.
3. Seasonal or time-step-specific minimum river flow requirements in the river are represented with minimum capacity constraints.
4. A demand node can buy from other connected demand nodes or reservoirs upstream.
5. Pair-wise trades are driven by benefits generated and transaction costs.
6. A demand node can either buy or sell a license in a single time step (but not both to discourage intermediaries).

The following model assumptions are limitations of the current approach:
1. Trades are chosen by the model to maximise the region-wide benefits. Individual gaming, rule-based or rent-seeking behaviour is not represented. This model proposed here does not benefit from advances proposed by adjacent fields such as game theory or multi-agent-based modelling.
2. Trade is allowed only in downstream direction even though in reality trades could be made upstream if a down-stream user would forego abstraction to allow an upstream user to abstract. Many of such upstream trades would be poorly perceived by regulators, as the environmental effects of trade typically worsen as abstraction moves upstream. In future work, 'virtual' (no cost – i.e. no pumping involved) connections between downstream and upstream users could be added to represent upstream trading when it is a realistic option.
3. Traders are myopic, they do not consider trading activity or water use in the past or future, this is particularly unrealistic for users whose decisions in past periods may cancel the need for water (e.g. farmer decisions may result in changed water use or none at all if fields are fallowed). Inter-period decisions are currently not modelled.

4   MODEL APPLICATION CASE STUDY

4.1   Dove catchment characteristics

The model was applied to a catchment modeled after the River Dove catchment in the UK (1020 km^2) (EA, 2006). Only surface water abstraction is modeled represented by 52 surface water rights holders (or licensees) of 5 use types: agriculture, amenity, industry, energy production and water supply. Each licensee is bound by a maximum allowed abstraction volume and holds a CAMS status (defined below). Two reservoirs, Tittesworth and Carsington are included in the study. The largest abstraction point is at the bottom of the catchment and belongs to the Severn Trent water company which provides commercial and domestic water services. The modeled time period covers three consecutive years from 1st January 2005 to 27th December 2007. This period includes critically dry conditions in 2005 that improved over the following 2 years. A weekly time step was applied

throughout the time horizon; the model considers trades each week. Minimum flows were introduced at Q70, the flow rate that is exceeded 70% of the time.

4.2   Identifying allowable trades

To establish which pairs of licensees are able and allowed to participate in trades we applied a filter algorithm illustrated in Figure 2. This filter attempts to emulate EA water trading regulations.

In England and Wales abstraction is managed through the Catchment Abstraction Management Strategies (CAMS) established by the EA. Every abstraction over 20 m^3 of water per day must be licensed (EA, 2010). Licenses are granted according to the water availability (taking into account the existing licenses within the catchment and environmental needs) and the purpose of abstraction. The CAMS level defines the level of abstraction stress the area is experiencing and is defined on scale from 1 to 6 (1 = area where granting of new abstraction licenses can still be considered, 6 = highly over-abstracted area where no further licenses can be granted) (EA, 2010).
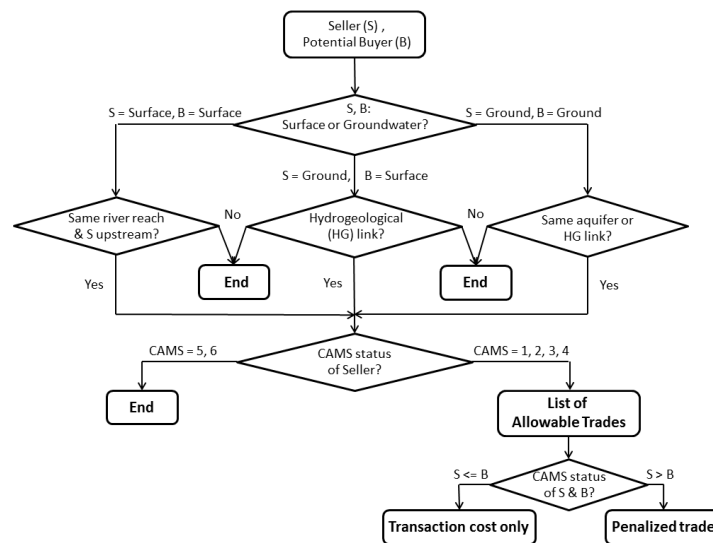

Figure 2. Filter algorithm to emulate which trades would be allowed by regulators.

The algorithm first evaluates if the pair of licensees is connected by a feasible hydrological link. Then environmental constraints are incorporated such that only trade possibilities where the seller has the CAMS status lower than 5 proceed into the list of allowable trades. Trades where the seller has higher CAMS status than the buyer to minimize the negative impact on the river are further penalized via increased transaction cost where the unit penalty cost is added to the transaction cost function (equation (5)).

4.3   Data on economic demands and transaction costs

The benefit functions of each licensee were derived using demand functions estimated by the point expansion method using licensed abstraction volume and literature water values (Table 1) for different water use types. Because each licensee has a different licensed abstraction volume the estimated benefit functions are unique to each licensee.

McCann and Easter (2004) recommend to analyze the types of transaction costs in water markets of similar physical and institutional composition to estimate the transaction costs for a new market. To further understand and measure these costs the process of water market establishment should be monitored and evaluated after the market's full implementation. Transaction cost functions between users of different types used in this study were postulated using data on actual trades effectuated between 2004 and 2009. The proportion of the total

traded volume during this period between different use types was consulted to guess feasible unit transaction costs. These are given in Table 2.

Table 1. Water values and price elasticities of individual purpose types

Purpose type	Characteristics	Water value p ($£/m^3$)	Reference	Price elasticity ε	Reference
Agriculture	Wheat	0.027	(Gibbons, 1986)	-0.29	(Scheierling et al., 2006)
	Barley	0.021			
	Sugar beet	0.066			
	Pasture irrigation	0.031			
Amenity	Golf course irrigation	0.128	(Watson, 2011)	-0.40	Assumed
Industry	Average of selected industries	0.144	(Moran and Dann, 2008)	-0.41	(Reynaud, 2003)
Energy	Hydropower	1.589	(Torcellini, 2003) and British Gas	-0.40	Assumed
Water supply	Commercial and domestic	0.435	(Aylward, 2010)	-0.41	(Dalhuisen et al., 2003)

Table 2. Transaction costs used in the study.

Fixed cost (£)			
Between agriculture users	200	Other trades	10,000

Unit cost ($£/m^3$)					
Seller	Buyer				
	Agriculture	Amenity	Industry	Energy	Water supply
Agriculture	0	50	15	50	50
Amenity	50	4	50	50	50
Industry	50	15	2	15	15
Energy	50	50	50	4	50
Water supply	50	50	11	70	9
Reservoir	5	5	5	5	5

4.4 Preliminary results

The interaction of trading activity with hydrological water availability and engineered infrastructure is demonstrated in Figure 3. There is a correlation between river flows, reservoir storage and trades volume; traded water increases during wet periods when reservoir storages can easily meet their target values. This suggests our winter water values may be too high or that transaction costs should be increased to discourage winter trades which are less likely for some sectors.
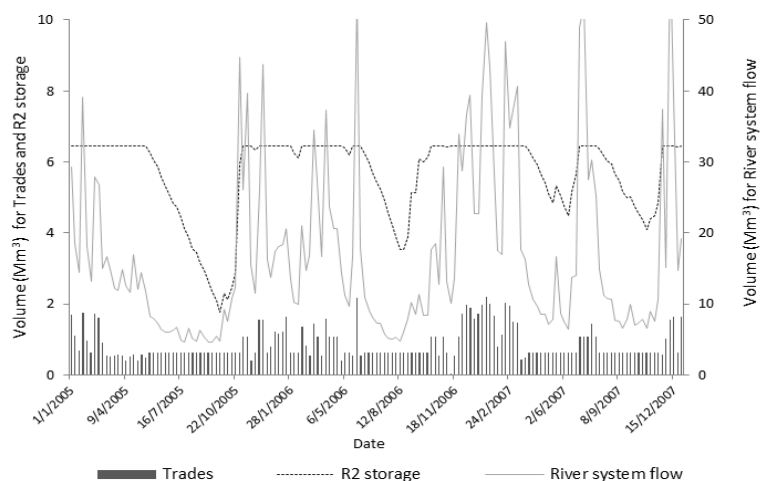

Figure 3. Trade, reservoir storages, and river flows over the modelled time horizon.

Storage targets were set to be 80% of the maximum storage in autumn, full storage in late winter, 70% in spring and 50% in summer. The behaviour of

individual licensees: abstractions, buying, selling can be also reviewed for each license or pair of licenses in each period. This behaviour is determined by the benefit functions and transaction costs. The benefit functions drive the trade towards downstream licensees with the highest marginal benefit from water use although transaction costs reduce the number of trades proposed. The model identifies the trades between individual market participants which can be aggregated to look at trade between different use types.

Figure 4a shows the total traded volume over the modelled period between the water use types and reservoirs. The energy production purchases the highest volumes due to its high values. The transactions between agricultural licensees are encouraged by their relatively lower transaction costs.

The influence of transaction costs on the market participants' behaviour can be observed by a basic sensitivity analysis. We increased the slope of the transaction cost function for trades between the same use types by 1. The corresponding trade volumes are illustrated in Figure 4a and 4b. The energy sector in Figure 4a is the largest buyer (from reservoirs mostly). These also trade with water supply users who purchase additional license from industry. There is also a small proportion of transactions between the same use types, namely agriculture, industry and water supply, due to lower transaction costs postulated between users of the same use type. The total traded volume in Figure 4b remained the same as in 4a but the pairs that perform trades change. Water supply licensees with low marginal values no longer trade their excess license with the same use type but instead sell to industrial users. The transactions between industrial users also slightly decreased. These changes occur because the marginal benefits of water use decrease in magnitude with increasing volume while the transaction costs increase linearly. Thus increasing the transaction costs makes some trades that previously generated benefits to become unprofitable. The model provides detailed information about which particular licensees engage in what trades in each time step.
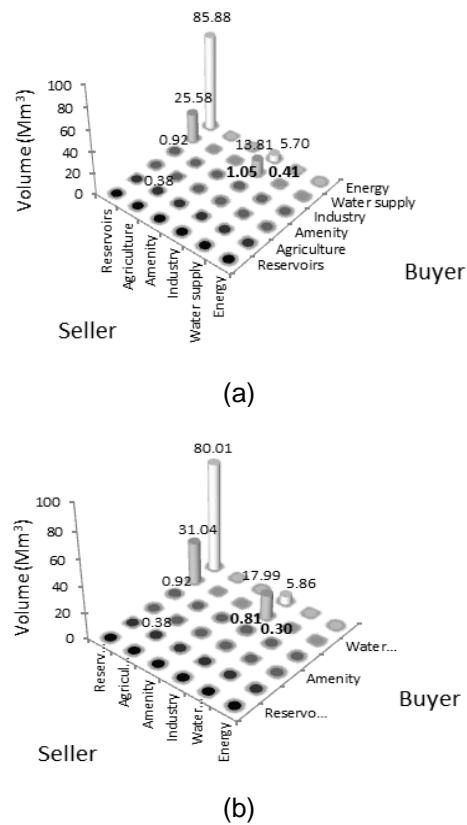

(a)

(b)

Figure 4. Total traded volume over the whole modelled time horizon between different use types and reservoirs (a). Total traded volume over the whole modelled time horizon with increased transaction cost for trade paths between same use types (b).

5   CONCLUSION

This study proposes a river basin simulator that attempts to integrate water rights or license trading considering pair-wise trading driven by economic benefits from water use and transaction costs. We demonstrated its applicability with a case study of the UK's Dove river basin. The model simulates trades that increase

regional economic benefits from water use whilst considering the interaction of trading with the catchment's natural hydrology and engineered infrastructure. The importance of benefit functions and transaction cost data as model drivers was illustrated on the magnitude and distribution of individual trades.

Future work could involve more sophisticated representation of individual water rights holders to reflect more realistic agent behaviour. The complexity of the model strongly depends on the spatial scale of the modelled water system; the current flow path approach requires further modifications and improvements to minimize this limitation. Economic benefit functions of water use and transaction costs need to be improved for results to better approximate realistic conditions.

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REFERENCES

EA, 2010. Managing Water Abstraction. Bristol: Environment Agency.

AYLWARD, B., SEELY, H., HARTWELL, R., DENGEL, J. 2010. The Economic Value of Water for Agricultural, Domestic and Industrial Uses: A Global Compilation of Economic Studies and Market Prices Ecosystem Economics LLC.

CHENG, W. C., HSU, N. S., CHENG, W. M. & YEH, W. W. G. 2011. Optimization of European call options considering physical delivery network and reservoir operation rules. *Water Resources Research,* 47.

CHENG, W. C., HSU, N.S., CHENG, W.M., YEH, W.W.G. 2009. A flow path model for regional water distribution optimization. *Water Resources Research,* 45**,** 2-8.

COLBY, B. G. 1990. TRANSACTIONS COSTS AND EFFICIENCY IN WESTERN WATER ALLOCATION. *American Journal of Agricultural Economics,* 72**,** 1184-1192.

DALHUISEN, J. M., FLORAX, R., DE GROOT, H. L. F. & NIJKAMP, P. 2003. Price and income elasticities of residential water demand: A meta-analysis. *Land Economics,* 79**,** 292-308.

EA 2006. Creating a better place - The Dove Catchment Abstraction Management Strategy. Bristol: Environment Agency.

EA 2010. Managing water abstraction. Bristol: Environment Agency.

GIBBONS, D. C. 1986. *The economic value of water,* Washington D.C., Resources for the Future, Inc.

HAROU, J. J., PULIDO-VELAZQUEZ, M., ROSENBERG, D. E., MEDELLIN-AZUARA, J., LUND, J. R. & HOWITT, R. E. 2009. Hydro-economic models: Concepts, design, applications, and future prospects. *Journal of Hydrology,* 375**,** 627-643.

MCCANN, L., EASTER, K.W, 2004. A framework for estimating the transaction costs of alternative mechanisms for water exchange and allocation. *Water Resources Research,* 40.

MORAN, D. & DANN, S. 2008. The economic value of water use: Implications for implementing the Water Framework Directive in Scotland. *Journal of Environmental Management,* 87**,** 484-496.

REYNAUD, A. 2003. An econometric estimation of industrial water demand in France. *Environmental & Resource Economics,* 25**,** 213-232.

SCHEIERLING, S. M., LOOMIS, J. B. & YOUNG, R. A. 2006. Irrigation water demand: A meta-analysis of price elasticities. *Water Resources Research,* 42.

TORCELLINI, P., LONG, N., JUDKOFF, R. 2003. Consumptive Water Use for U.S. Power Production Golden: National Renewable Energy Laboratory.

WATSON, P. A. T., D. 2011. Water-use efficiency in golf: An economic analysis of Colorado golf courses Environmental Institute for Golf.