



**Protecting  
environmental flows  
through enhanced  
water licensing**

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# Protecting environmental flows through enhanced water licensing and water markets

**T. Erfani**<sup>1,2,\*</sup>, **O. Binions**<sup>2,\*</sup>, and **J. J. Harou**<sup>1,2</sup>

<sup>1</sup>School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester, M13 9PL, UK

<sup>2</sup>Department of Civil, Environmental and Geomatic Engineering, University College London, Chadwick Building, Gower Street, London, WC1E 6BT, UK

\* Authors contributed equally.

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Correspondence to: J. J. Harou (julien.harou@manchester.ac.uk)

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et al., 1996; Postel, 1998). Current water diversion practices lead to degradation of river environments in some areas, resulting in regional water scarcity and conflicts (Smakhtin et al., 2004).

Water trading developed in some countries as a response to water scarcity with the aim of allocating water efficiently (Bjornlund, 2003; Howe et al., 1986; Thobani, 1997). In the US, Chile, South Africa and Australia trading is permitted or encouraged in some regions. In US and Australia, government-allocated funds are used to buy back water allocations to leave water in the environment (Brewer et al., 2008; Wheeler et al., 2013; Wilkinson, 2008). These methods are short-term solutions to immediate water scarcity problems and such uses of public funds can be a contentious issue. Reforms of water allocation systems are under way in countries such as the US, South Africa, Australia, Russia and England and Wales to ensure environmental protection in the longer term (Gleick, 2011; Stern, 2013; Young, 2012). In England there are significant institutional barriers to water trading (EA and Ofwat, 2008; Hodgson, 2006).

The ability of water markets to help users adapt to water scarcity challenges is heavily dependent on the water resource management institutions (Grafton et al., 2011). The issues of fairness in water allocation between environmental and human uses, and between varying human uses have become controversial as economic considerations and market re-allocation may not result in a socially just outcome (Syme et al., 1999). Without appropriate regulatory ability to preserve shared ecosystem services there is a risk that over-abstraction will continue or worsen under market systems.

The objectives of water resource allocation systems is to regulate access to water resources, ensuring flexibility, security of access, predictability, and fairness, and to reflect public values and opportunity costs (Howe et al., 1986). More recently environmental protection has been added to those goals. One of the methods used to preserve adequate river flows is to set a minimum flow below which water abstraction must reduce or cease (Acreman, 2005). These static threshold or minimum flow methods of maintaining river flows often do not achieve ecologically or economically efficient results (Arthington et al., 2006; Katz, 2011). The aquatic environment relies

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Erfani et al. (2013) presented an efficient variant used by Erfani et al. (2014) to model a surface water spot market.

This paper applies and extends the Erfani et al. (2014) model to a case-study basin in Eastern England to assess possible outcomes of water trading under two licensing systems: (1) static minimum environmental flows with volumetric licenses; and (2) a share-based licensing system where water allocation is updated according to current flow conditions and dynamically updated environmental flows (EA, 2013; Young and McColl, 2005). While in the first system there is no license scaling, under the second system, the license volumes are scaled proportionally to abstractors' share. The next section describes the generalised river basin model formulation used to model both licensing regimes. Section 3 outlines the case study and additional constraints to represent the Ouse basin and its regulatory environment. Section 4 presents results followed by a discussion in Sect. 5 and conclusions in Sect. 6.

## 2 Methods

The model presented in this paper is an extension of the hydro-economic model of Erfani et al. (2013) which uses economic optimisation to simulate and track pair-wise water market transactions between individual water users. This paper introduces dynamic environmental flows and scalable "share" licenses into the pair-wise transaction tracking hydro-economic water market simulator to evaluate how they perform in a water trading context. The short-term spot water market considered here is a system where each user can observe the bid and ask prices of others, as could exist with an online transaction system. Model constraints are used to represent the physical, regulatory and water user-specific realities. The model formulation described in Sect. 2.1 and Appendix A summarise previous work (Erfani et al., 2014). In this paper, the model is further extended in Sects. 2.2 and 2.3 to model the dynamic environmental flows and scalable water licenses.

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## 2.1 Pair-wise trading model

The Erfani et al. (2013) model (see Appendix A for equations) uses economic optimisation subject to constraints to simulate a short-term (spot) market for water. The river network is modelled as a network of nodes (e.g. demands, junctions, reservoirs) and conveyance links (e.g. river reaches) and water balance is ensured at each junction or storage node. Economic benefit functions that quantify the economics gains from water diverted must be provided for each demand node at each time step. The maximized objective function is the sum of economic benefits from water use across all users in each individual time step, net of transaction costs. This objective functions identifies trades that make economic sense whilst meeting constraints that ensure regulations and agent behaviours are considered. For example it includes a penalty function for deviating from the target level of reservoir storage. Water user nodes consume some water using their own license or by buying from other license holders, and can sell the rest to others. Since most abstractors' water use is not fully consumptive, some water is returned to the river as return flow. The sum of volumes of water abstracted and sold by the users cannot exceed both their annual and weekly licensed allocation.

## 2.2 Dynamic environmental flows

The total amount of water across all users allowed for abstraction is the difference between the natural flow (excluding human water diversions and additions) and the minimum flow (MinFlow) at the downstream gauges. MinFlow is used in the following equation:

$$\sum_{CO_{ij}=1}^i x_{ij}^k + inFl_l \geq MinFlow_j \quad \forall l \in \text{Junction}, j \in \text{Gauge}, k \in \text{river} \quad (1)$$

for both the fixed and dynamic environmental flow water management systems.  $inFl_l$  is the external inflow at junction node  $l$ . The junction node  $l$  is connected to the gauge  $j$  to

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record how much water passes by the gauge  $j$ . With fixed volumetric water abstraction licenses, water available for abstraction is set using a fixed value of minimum flows ( $\text{MinFlow}_j$ ) regardless of the available flow recorded at the gauges. In the case of dynamic environmental flows,  $\text{MinFlow}_j$  is a function of naturalised river flows (flow without human water abstractions). Naturalised river flows are estimated from the river flow through the gauging stations, and the  $\text{MinFlow}_j$  is the sustainable minimum level of river flows.

### 2.3 License scaling

Under license scaling, the river basin is divided into sub-catchments separated by river flow gauging stations. The water available for abstraction at each gauge  $j$  is divided between the upstream license holders in that sub-catchment proportionally to their shares.

$$\text{WaterAbstracted}_j^k \leq \begin{cases} \theta_j \times \text{WkLi}_i, & \text{nFIGA}_j - \text{MinFlow}_j \leq \sum_{\substack{i \in \text{User} \\ \text{WIGA}_{ij}=1}} \text{WkLi}_i \\ \text{WkLi}_i, & \text{otherwise} \end{cases} \quad (2)$$

$\forall i \in \text{User}, k \in \text{river}$

where

$$\theta_j = \frac{\text{nFIGA}_j - \text{MinFlow}_j}{\sum_{\substack{i \in \text{User} \\ \text{WIGA}_{ij}=1}} \text{WkLi}_i}$$

In the above equation,  $\text{nFIGA}_j - \text{MinFlow}_j$  is the water available for abstraction for license holders upstream of gauge  $j$ .

### 3 Case study

#### 3.1 Water management in England and Wales

In England water diversions (“abstractions”) are regulated by the Environment Agency (EA). The abstraction licenses incur yearly charges based on the volumetric size of the license, and not on the actual abstraction volumes. The licenses state maximum daily and yearly abstraction volumes. Environmental protection is enforced through license-specific Hands-off Flow (HoF) restrictions which refer to minimum flow required through the relevant gauging station, below which the license is temporarily suspended. There are emergency provisions set out in Sect. 57 of the Water Resources Act 1991 which reduce spray irrigation in times of drought. Water trading is allowed, but rarely carried out. There is no water license spot-market; each transaction has to be assessed and approved by the EA over several months.

The current system was set up in 1960s and is not designed to manage competing water uses effectively. HoFs were introduced in an attempt to protect the environment from over-abstractions and were applied to newly issued licenses, with no change in allocations for legacy licenses. There is a lack of appropriate incentives or price signals for efficient water use and there are institutional barriers to water trading (Defra, 2011). The current licensing system in many areas results in over-abstraction and environmental damage: 18 % of river catchments are classed as over-licensed, and a further 15 % – over-abstracted (EA, December 2008). In around a quarter of water bodies in England and 7 % of water bodies in Wales new consumptive abstractions cannot be provided with reliable water supply (EA, 2011). Nationally, over a third of licenses are not utilized and kept as a reserve in case of a drought, making 20 % of the licensed volume unused, but which could have otherwise been licensed to new uses requiring water (EA and Ofwat, 2012). Water trading could provide flexibility in regional water resource management and is being considered in individual water resource management zones (Acreman and Ferguson, 2010).

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resulting in lower benefits from water use for the water company and the consumers. This loss of benefits is reflected in the reservoir deviation penalty factor  $\alpha$  ( $y$  axis in Fig. 2, left panel):

$$\text{Deviation}_j = \alpha \left| \text{tRes}_j - \sum_{k \in \text{Owner}} \text{Res}_j^k \right|, \quad (3)$$

where  $\text{tRes}_j$  is the seasonal storage target level (Fig. 2, right panel).

Water companies can implement demand reduction measures during droughts and temporarily restrict non-critical water uses to ensure that key water demands are satisfied. To reflect this in the model, the volume of water abstracted from the reservoir is reduced when storage levels are low using a hedging constraint (Appendix A).

When the PWS Reservoir storage volume is low and demand reductions are implemented, the PWS intake license manager is not expected to sell any water. This leads to the following trading rule: when the reservoir level is 50 % below target, water sales by PWS the following week are prohibited, until the level recovers.

### 3.3.2 Water trading

Agricultural users require water for the irrigation season and will in many instances be unwilling to sell their license before it. To represent varying degrees of water market participation, a limit on volumes sold by agricultural users was set in both the fixed and dynamic water management system modelling. For this a constraint (Appendix A) implicitly sets aside a portion of the yearly license for own use and ensures the user does not sell prematurely, exposing themselves to requiring water purchases later in the year. A “trade reluctance coefficient” is used to represent the degree to which farmers keep licensed water for their own use, and can be customized for each user enabling the analyst to consider diverse market participation. If the coefficient is set to 0, the user always prefers to trade whenever it is economically beneficial, regardless of likely own future water needs. Conversely, users with coefficient of 1 are conservative and

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will not sell water until they fully satisfy their yearly demand (at the end of the irrigation season).

### 3.4 Parameterizing dynamic environmental flows

The model was applied to the River Great Ouse basin using hydrological data from one of the driest years on record, characterized by low river flows for the first 8 months of the year, followed by wet autumn and winter (“naturalized” flow in Fig. 3). Using the Environmental Flow Indicator method discussed in Sect. 2.3, and taking into consideration the Abstraction Sensitivity Band of the river basin, the allowable water abstractions are calculated as proportions of naturalised flow (Table 1). In Table 1, percentile naturalised flow is the percentage of time flow historically exceeded a given flow value provided by the England’s Environment Agency (EA, 2013).

## 4 Model results

Below we review model results focusing on how the two licensing systems diverge in protecting environmental flows, water allocated to each sector, and plausible trades under a short-term spot water market.

### 4.1 Protection of the environment

Figure 3 compares modelled river flow exiting the river basin under the two licensing systems. The current system leads to large variability in river flows through the year, decreasing to low levels incompatible with recent regulations such as the European Water Framework Directive (Acreman and Ferguson, 2010). This is the result of the asymmetric impact of environmental hands-off-flow (HoF) conditions on individual licenses. HoFs were assigned to new licenses in the past to prevent over-abstraction of rivers but were not applied retrospectively to early licenses granted in the 1960s (see

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Sect. 3.1). As a result, some (large) licenses are not affected by HoFs and the system is not effective at ensuring environmentally acceptable abstractions during the drought.

The drought river flows are improved with the proposed licensing system (Fig. 3) and its higher environmental allocation. Whereas the current licensing system brings the flow to nearly zero for over 40 % of the dry year, the proposed licensing system never falls below 680 ML week<sup>-1</sup>.

## 4.2 Water diversions

With the more stringent environmental protection enforced by the proposed scalable licensing system all users face a lower amount of water available for diversion. The total annual volume of water diverted decreases by over 40 % (from 88 000 ML to 50 000 ML). All water users except industry decrease their diversions: PWS Reservoir by 44 %, PWS Intake – 8 %, power station – 38 %, agriculture sector – 26 %, private water supply – 14 %. Industrial user increases its abstraction by less than 1 %.

The large decrease in the PWS Reservoir abstraction is the main enabler of the higher river flows under the proposed system (Fig. 3). Under the current system there are no Hands-off Flow conditions imposed on the PWS licenses and the reservoir diverts heavily during the drought to stay within 50 % of its storage targets (Fig. 4, top panel). Under license scaling the reservoir's weekly water license is scaled down to less than a quarter of the reservoir's historical weekly diversion for most weeks of the year causing a rapid decrease in reservoir storage volumes that almost empties the reservoir (Fig. 4, lower panel).

## 4.3 License trading results

Figures 5 and 6 show which sectors are buying and selling water under the current and proposed licensing systems respectively.

Lower diversion allowances under the proposed system lead to a more active water market, with the number of trades more than doubling (127 % increase) and the volume

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traded increasing by 77% (see Table 2). Trading between users from different sectors also increases. Figure 7 shows the proportion of total yearly volumes transferred between sectors. Under the current licensing system the largest transactions by volume are from public water supply (PWS) to the power station (94%). Under the proposed shares-based system the power station is the largest buyer until autumn (Fig. 6), purchasing from both the PWS intake and agricultural businesses, followed by transfers from the power station to the PWS Reservoir in autumn and winter. Agricultural users also sell to the PWS Reservoir towards the end of the year, after the growing season. The purchases by PWS Reservoir are made to re-fill the reservoir which was depleted through the year under the proposed licensing system.

In the current volumetric licensing simulation, license-holders generally either sell or buy water through the year, and rarely switch from one status to the other. In the proposed shares-based system however, some users who buy at the beginning of the year become sellers at the end of the year, and vice versa. Under the current system some license holders are affected by the drought more than others because of the stricter HoF conditions on their licenses, and are therefore systematically disadvantaged during droughts. With the proposed shares system as simulated, all users are affected by reductions in the available resource, and short-term leasing enables them to manage their water needs effectively: selling in weeks when they have no or low demand for water and purchasing from other users when they have relatively high economic water demands unmet by their allocation.

Under proposed licensing, when the PWS Reservoir storage volume reaches half of the target level by mid-April, PWS intake ceases selling water due to the trading constraint outlined in Sect. 3.3.2, PWS Intake becomes a buyer in July–August, purchasing small volumes from private water supply license holders and farmers taking advantage of the first opportunity to start filling its reservoir. Under the current licensing system water trading stops as river flow recovers in mid-September whereas in the shares-based system, trading continues until the end of the year. The reason for this is the large impact of license scaling on the PWS Reservoir as discussed in Sect. 4.2. Low

storage volumes activate demand reduction measures which impose an opportunity cost on the water company and its customers and the marginal value of stored water increases (as represented by the penalty function defined in Sect. 3.3.2). The reservoir is refilled late in the year using its own license and purchases from other users.

## 5 Discussion

The model tracks individual transactions allowing the analyst to assess how water markets could operate under different water licensing regimes and how individual abstractors could be affected. The aim of the model is to inform the policy makers of the potential outcomes of water management regulations and assess the effectiveness of a proposed licensing system in increasing environmental protection whilst reducing economic costs of water scarcity.

Gross economic benefits from water use are estimated for each abstraction license holder using their economic water demand functions (see Erfani et al., 2014, for details). For each week, the benefits generated from water use by each abstractor were aggregated into sectoral benefits. Figure 8 compares the economic benefits by sector generated from water use for the two licensing systems in conjunction with the modelled water market. The energy sector sees the largest decrease in benefits with the introduction of the increased environmental protection associated with the proposed licensing system. Compared to the current licensing arrangement plus a market, the loss in benefits through the dry year across all sectors is estimated at £94 million (a 15% reduction, from £611 million for current licensing to £517 million with the proposed system, both with the modelled surface water market). Erfani et al. (2014) estimated the total annual economic benefits for the same system and year with current licensing and without trading at £575 million. In this case, the estimated opportunity cost of improved environmental flows is £58 million, a 10% loss in economic benefits.

These opportunity costs for improving environmental flows may appear large. Our analysis uses catchment inflows from one of the driest years on record so this cost

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can be considered an upper-bound on potential costs imposed on water users for enhanced environmental performance. Also, if the power station had an alternative supply to its surface water licence, its opportunity costs would decrease. To put the value in perspective, a survey by NERA (2007) estimated the present value of improvements in water environment of all water bodies in the UK to be between £18bn and £29bn (benefits incurred for an indefinite period), or between £618 and £1020 million per year. Garrod and Willis (1996) estimated the annual value of alleviating low flows for River Darent (river catchment area is 14% of the Great Ouse) at around £37 million (£2011).

Our model uses a single-objective (“aggregate”) optimisation formulation that maximises the total social welfare of all water users to simulate the water market. Single-objective optimisation emulates centralised water allocation but is appropriate to model regulated water markets “as long as interactions between agents and competition for resources can be interpreted in a competitive market paradigm” (Britz et al., 2013; Erfani et al., 2014).

Several model limitations and simplifications should be mentioned. Groundwater resources were excluded from the model because we focus is on the effects of changing the surface water licensing system. Abstraction license holders sometimes possess more than one license, sometimes for both surface water and groundwater abstractions. In this case, they will likely draw strategically from across their asset base (e.g. a water company will cost minimise when choosing sources), and such strategic abstraction would increase in a market – this is not considered in our current model where each abstraction point is modelled independently. Some abstractors, particularly agricultural ones, have small “winter storage” reservoirs to enable inter-temporal water management. Such users would likely switch between different water sources during droughts and involve reservoirs in sophisticated and diverse ways. At the time of the analysis, we did not have data on locations and capacities of small reservoirs and so this detail is left to later work. Most strategic behaviours across different assets





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abstraction regime based on volumetric licensing. Flows under the proposed system don't reduce below  $680 \text{ ML week}^{-1}$  whereas under current licensing flows reduce down to nearly zero for over 4 months of the year. With more water left to the environment, less water is available to satisfy human water demands leading to a more active water market. The number of trades under the scalable licenses system is more than double the number under current system and the volume traded is 77 % greater. Still the more active water market is not able to compensate for the loss of abstraction (increases in environmental flows); the opportunity cost of the increased environmental quality in the dry year is a loss of about 15 % compared to the current licensing system with a water market, or 10 % when compared to current system without a market (the current situation).

As pressure on water resources increases, water licensing systems will be expected to balance human and environmental water uses in increasingly effective and sophisticated ways. The English water allocation regime is currently being re-designed to protect environmental flows whilst minimising the societal economic cost of water scarcity. Water markets are viewed as part of the solution as they allow short-term economically efficient re-allocation of water during scarcity events. In designing new water allocation institutions regulators will want to assess how new water allocation systems could work in conjunction with water trading to manage droughts. Customized hydro-economic models, such as the one applied in this paper, help simulate coupled human-environmental systems, predict plausible behaviours and impacts, and assess proposed policies.

## Appendix A

### Formulation details

In this appendix we reproduce the formulation from Erfani et al. (2014) for reader convenience. Section headers specify which section of the current paper the equation relates to.

### Pair-wise trading model

The pair-wise trading model follows the multi-commodity modelling framework with an extra index  $k$  on the flow variable to represent water ownership (Erfani et al., 2013). The objective function of the model is

$$\text{NetBenefit} = \sum_{i \in \text{User}} \text{totalBenefit}_i - \sum_{i \in \text{User}} \text{totalCost}_i - \sum_{j \in \text{Reservoir}} \text{Deviation}_j \quad (\text{A1})$$

subject to the following mass balance constraints:

$$\sum_{\substack{j \\ \text{CO}_{ji}=1}} x_{ji}^k + \text{inFl}_i + \sum_{l \in \text{User}} \text{ReturnFlow}_{li} = \sum_{\substack{j \\ \text{CO}_{ij}=1}} x_{ij}^k \quad (\text{A2})$$

$\forall i \in \text{Junction}, k \in \text{Owner}, \text{DW}_{ji} = 1$

$$\sum_{CO_{ij}^i=1} x_{ij}^k + pRes_j^k = Res_j^k + \sum_{CO_{ji}^i=1} x_{ji}^k \quad \forall j \in \text{Reservoir}, k \in \text{Owner} \quad (\text{A3})$$

$$\sum_{CO_{ji}^j=1} x_{ji}^k = \sum_{CO_{ij}^j=1} x_{ij}^k + \text{WaterAbstracted}_i^k + \text{Trade}_i^{k \text{ river}} \quad \forall i \in \text{User}, k \in \text{Owner} \quad (\text{A4})$$

$$\text{Trade}_i^{k \text{ river}} = \sum_{CO_{ij}^j=1} x_{ij}^i \quad \forall i \in \text{User} \quad (\text{A5})$$

$$\text{ReturnFlow}_{ij} = \sum_{k \in \text{Owner}} (1 - \text{consFactor}_i) \text{WaterAbstracted}_i^k \quad \forall i \in \text{User}, DW_{ij} = 1 \quad (\text{A6})$$

$$\sum_{k \in \text{river}} \sum_{CO_{ij}^i=1} x_{ij}^k = \text{Discharge}_j \quad \forall j \in \text{Discharge} \quad (\text{A7})$$

### Current license restrictions

At the beginning of each week, the river flow is checked and if the value is below the HoF limit, the license is suspended for the upcoming week (Erfani et al., 2014). This is imposed using the following constraint:

$$(\text{flGA}_j \leq \text{AIGA}_j) \longrightarrow (\text{WaterAbstracted}_i^{k \text{ river}} + \text{Trade}_i^{k \text{ river}} = 0) \quad \forall i \in \text{user}, j \in \text{Gauge}, \text{RuGA}_{ij} = 1 \quad (\text{A8})$$



where WaterUse is the sum of water diverted and sold,  $c_i$  is a value ranging from 0 to 1, and

$$sL_j^0 = YrLi_j - c_j \times EWN_j. \quad (A14)$$

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**Table 1.** Allowable river diversions under the EFI system, defined as a percentage of river flow (source: EA, 2013).

Percentile natural flow at downstream gauge of the sub-catchment	Q30	Q50	Q70	Q95
Percentage of naturalised flow allowed for abstraction (%)	26	24	20	15

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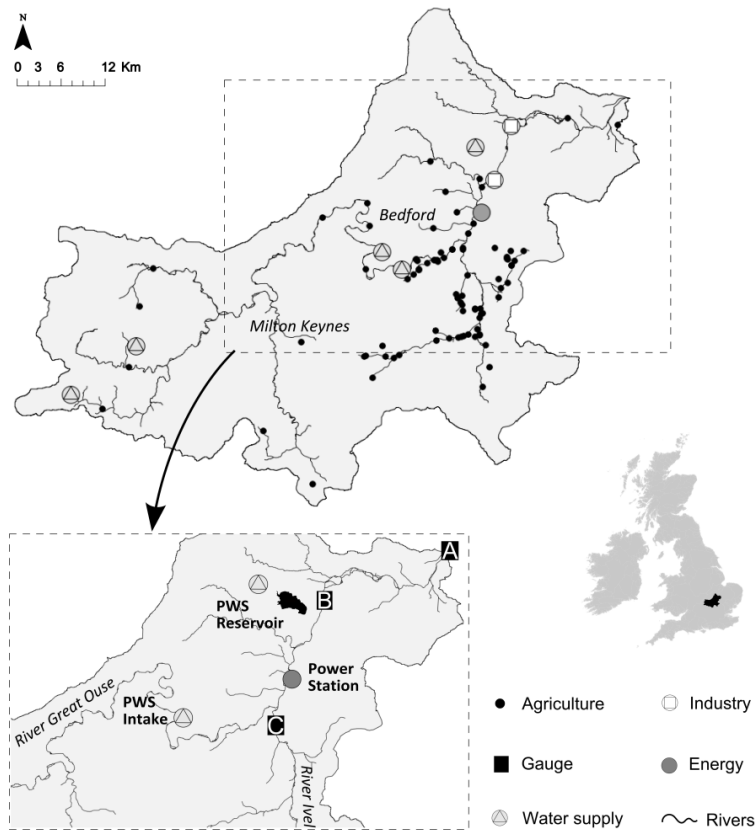
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**Table 2.** Numbers of trades, buyers and sellers, and volumetric annual totals under the 2 licensing regimes for a simulated historical dry year.

	Volumetric licenses	Sharing system
Number of trades	299	678
Sellers	48	90
Buyers	19	32
Total volumes traded, ML	2750	4860





**Fig. 1.** Map of the Great Ouse river basin showing approximate locations of water users and main river flow gauging stations: A – last flow gauge in the basin (sink), B – Offord gauge defining license scaling for PWS Reservoir and Power station, C – gauge defining license scaling for agricultural users located in the River Ivel tributary.

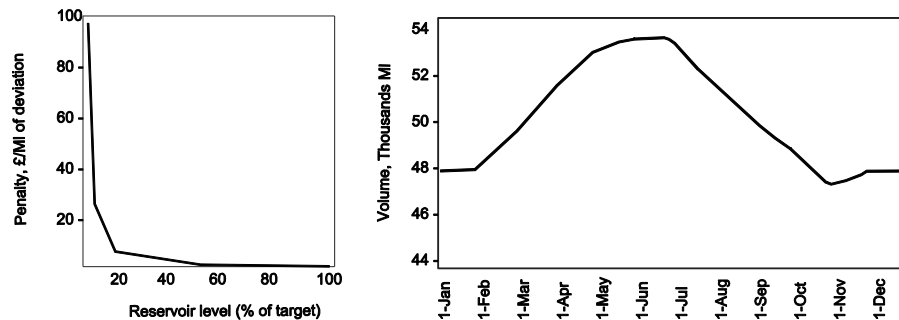
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**Fig. 2.** Reservoir storage deviation penalty (left panel), PWS Reservoir storage targets (right panel).

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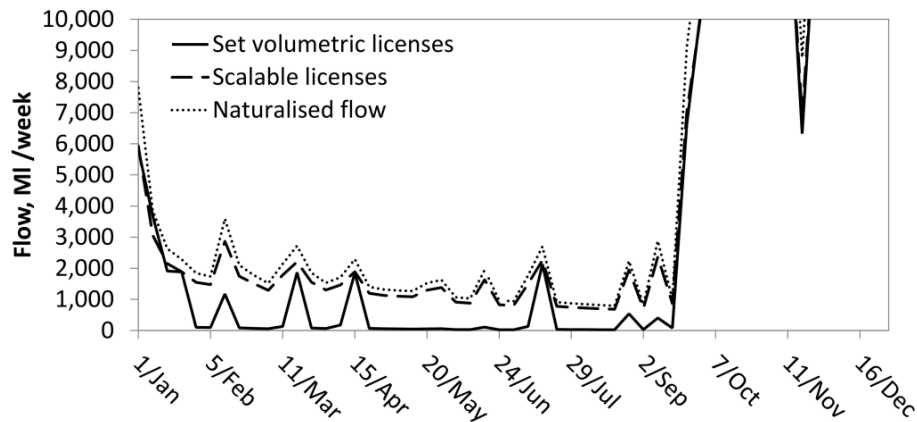


Fig. 3. River flow at the last gauge in the basin (marked A in Fig. 1).

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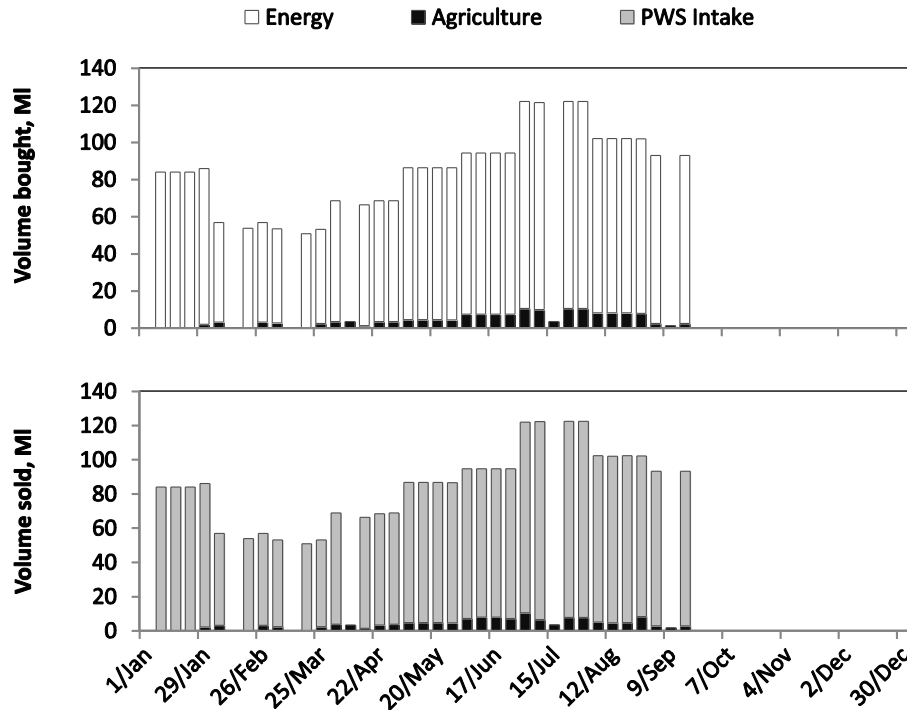
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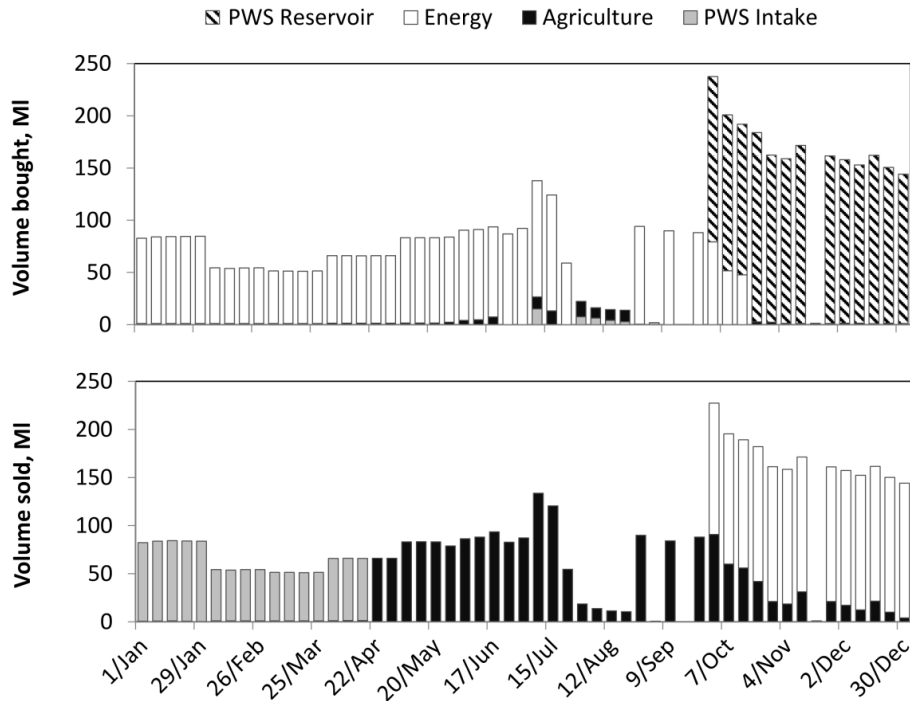
**Fig. 5.** Water volumes bought (top panel) and sold (bottom panel) in millions of litres per week by sector under the current licensing (volumetric) system.

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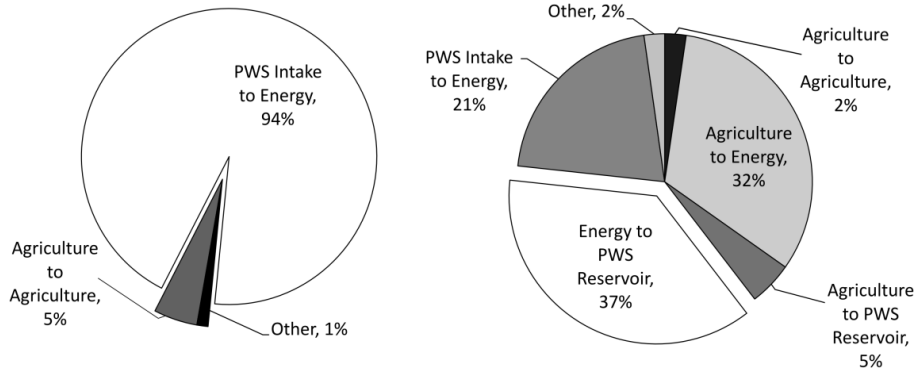
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**Fig. 6.** Water volumes bought (top panel) and sold (bottom panel) in millions of litres per week by sector under the proposed (scalable) licensing system.

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**Fig. 7.** Proportion of the total annual volume of trade transactions between sectors under the current (left panel) and proposed (right panel) licensing systems as simulated in a dry year.

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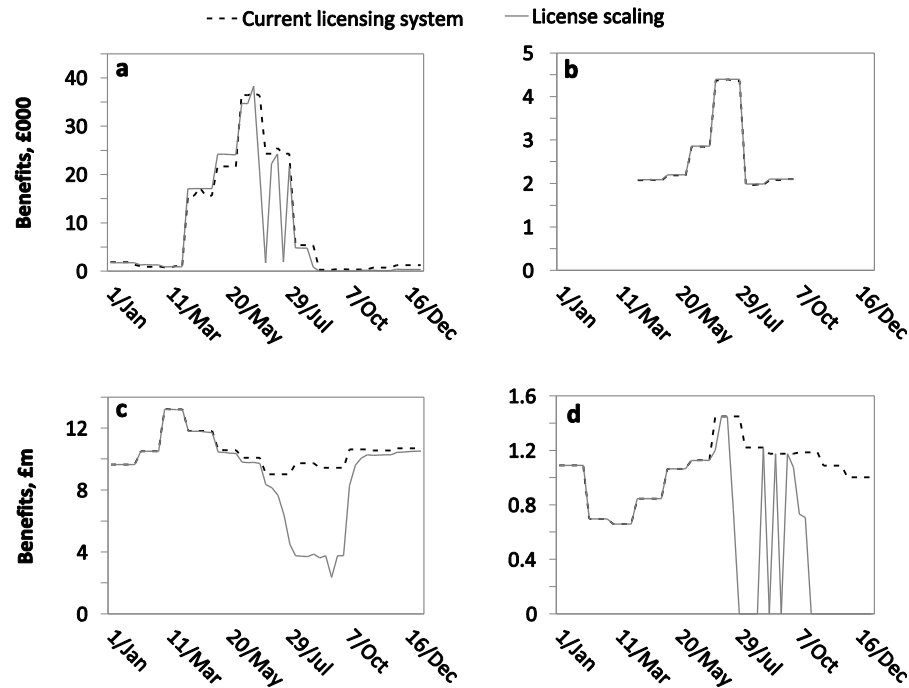
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**Fig. 8.** Comparison of gross economic benefits by sector from water use under the current and proposed licensing systems acting in conjunction with a short-term water market. The results are aggregated by sector: **(a)** agriculture; **(b)** industry; **(c)** water supply; **(d)** energy. The top panels show benefits in thousands of pounds and the bottom one in millions.

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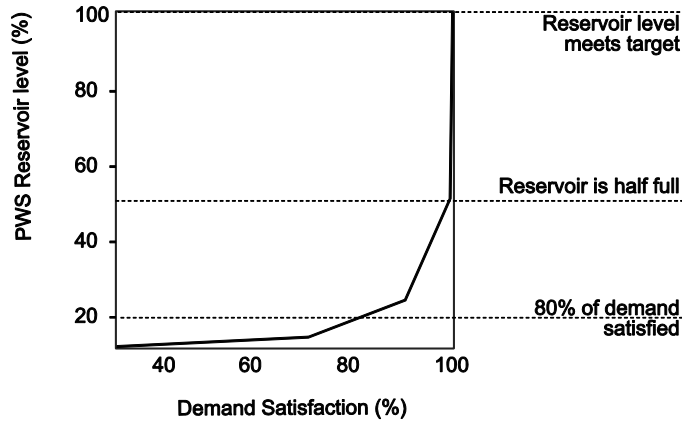


Fig. A1. Public Water Supply company hedging rule.

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