

1 **Protecting environmental flows through enhanced water licensing** 2 **and water markets**

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12 **Abstract**

13 To enable economically efficient future adaptation to water scarcity some countries are revising
14 water management institutions such as water rights or licensing systems to more effectively
15 protect ecosystems and their services. Allocating more flow to the environment though can
16 mean less abstraction for economic production, or the inability to accommodate new entrants
17 (diverters). Modern licensing arrangements should simultaneously enhance environmental
18 flows and protect water abstractors who depend on water. Making new licensing regimes
19 compatible with tradable water rights is an important component of water allocation reform.
20 Regulated water markets can help decrease the societal cost of water scarcity whilst enforcing
21 environmental and/or social protections. In this article we simulate water markets under a
22 regime of fixed volumetric water abstraction licenses with fixed minimum flows or under a
23 scalable water license regime (using water ‘shares’) with dynamic environmental minimum
24 flows. Shares allow adapting allocations to available water and dynamic environmental
25 minimum flows can vary as a function of ecological requirements. We investigate how a short-
26 term spot market manifests within each licensing regime. We use a river-basin-scale hydro-
27 economic agent model that represents individual abstractors and can simulate a spot market
28 under both licensing regimes. We apply this model to the Great Ouse river basin in Eastern
29 England with public water supply, agricultural, energy and industrial water using agents.
30 Results show the proposed shares with dynamic environmental flow licensing system protects

1 river flows more effectively than the current static minimum flow requirements during a dry
2 historical year, but that the total opportunity cost to water abstractors of the environmental
3 gains is a 10 to 15% loss in economic benefits.

4

5 **1. Introduction**

6 Recent projections show that the amount of available water runoff currently appropriated for
7 human needs globally are around 50%, likely to rise to 70% by 2025 (Postel et al., 1996;Postel,
8 1998). Current water diversion practices lead to degradation of river environments in some
9 areas, resulting in regional water scarcity and conflicts (Smakhtin et al., 2004).

10 Water trading developed in some countries as a response to water scarcity with the aim of
11 allocating water efficiently (Bjornlund, 2003;Howe et al., 1986;Thobanl, 1997). In the United
12 States, Chile, South Africa and Australia trading is permitted or encouraged in some regions.
13 In US and Australia, government-allocated funds are used to buy back water allocations to
14 leave water in the environment (Brewer et al., 2008;Wheeler et al., 2013;Wilkinson, 2008).
15 These methods are short-term solutions to immediate water scarcity problems and such uses of
16 public funds can be a contentious issue. Reforms of water allocation systems are under way in
17 countries such as the United States, South Africa, Australia, Russia and England and Wales to
18 ensure environmental protection in the longer term (Gleick, 2011;Stern, 2013;Young, 2012).
19 In England there are significant institutional barriers to water trading (EA and Ofwat,
20 2008;Hodgson, 2006).

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

28 The objectives of water resource allocation systems is to regulate access to water resources,
29 ensuring flexibility, security of access, predictability, and fairness, and to reflect public values
30 and opportunity costs (Howe et al., 1986). More recently environmental protection has been
31 added to those goals. One of the methods used to preserve adequate river flows is to set a
32 minimum flow below which water abstraction must reduce or cease (Acreman, 2005). These

1 static threshold or minimum flow methods of maintaining river flows often do not achieve
2 ecologically or economically efficient results (Arthington et al., 2006;Katz, 2011). The aquatic
3 environment relies on a natural hydrological cycle, but human water abstractions alter the
4 natural flow variability which is important to sustaining riverine species, and minimum flow
5 regimes do not support natural flow regimes (Poff et al., 1997). Hence, fixed volumetric
6 allowances have evolved into allowances with reference to river flow conditions such as ‘per
7 cent of flow’ regime, with abstractions limited to a sustainable share of the natural river flows
8 (Richter et al., 2012). Environmental flow methods are used to determine the sustainable levels
9 of abstractions. Over 200 environmental flow approaches have been developed to provide the
10 policy-makers with tools to re-design water allocation systems ensuring that river ecology is
11 protected, whilst taking into account human water needs (Acreman and Dunbar, 2004).
12 Environmental flow methodologies have been developed and applied in 44 countries, spanning
13 6 world regions with the United States the most active proponent of the approach (Tharme,
14 2003).

15 Allocation of water across individual water abstractors, similarly, should be linked to water
16 availability. Examples of these new systems can be found in Australia (Libecap et al.,
17 2010;Young, 2012), Chile and Mexico (Hodgson, 2006). Water allocations in this system are
18 according to available water and river flow conditions. The shares are translated into
19 volumetric licenses for each abstractor.

20 In re-designing a water allocation system policy makers need to assess how well the new
21 system meets the objectives outlined above, and whether it promotes economically efficient
22 allocation whilst preventing negative externalities of water diversions on the environment or
23 other users. River basin modelling and integrated assessment (Loucks et al., 1981; Letcher and
24 Jakeman, 2003) can provide insights into potential environmental and water allocation
25 outcomes of the proposed changes. Hydro-economic models that incorporate hydrology,
26 institutions and economics are particularly relevant (Harou et al., 2009). Traditional hydro-
27 economic models can simulate aggregate regional results of water trading (Draper et al.,
28 2003;Ward et al., 2006). To determine market outcomes at the scale of individual water
29 diverters, however, it is important to simulate the transactions between individual water users.
30 Cheng et al. (2009) developed a flow-path model formulation allowing to track transactions
31 between users. Erfani et al. (2013) presented an efficient variant used by (Erfani et al., 2014)
32 to model a surface water spot market.

1 This paper extends the generic water market simulation model proposed by Erfani et al. (2014)
2 to assess possible outcomes of water trading under a share-based licensing system where
3 allocations (water rights) are updated according to current flow conditions and dynamically
4 updated environmental flows (EA, 2013; Young and McColl, 2005). The new model is applied
5 to a case-study basin in Eastern England. The performance of the proposed licensing system is
6 compared to the currently used licensing system which uses static minimum environmental
7 flows and volumetric licenses. The current system allocates fixed water volumes whilst the
8 proposed system scales weekly licensed volumes proportionally to each abstractors' shares
9 depending on flow conditions. The contribution of this paper is to represent a novel modern
10 water management licensing system within a hydro-economic water market simulator to assess
11 the hydrological and economic impacts of the new policies on a real-world complex multi-
12 sector water resource system.

13 The next section describes the generalised river basin model formulation used to model both
14 licensing regimes. Section 3 outlines the case study and additional constraints to represent the
15 Ouse basin and its regulatory environment. Section 4 presents results followed by a discussion
16 in Section 5 and conclusions in Section 6.

17

18 **2. Methods**

19 The model presented in this paper is an extension of the hydro-economic model of Erfani et al.
20 (2014) which uses economic optimisation to simulate and track pair-wise water market
21 transactions between individual water users. This paper introduces dynamic environmental
22 flows and scalable 'share' licenses into the pair-wise transaction tracking hydro-economic
23 water market simulator to evaluate how they perform in a water trading context. The short-
24 term spot water market considered here is a system where each user can observe the bid and
25 ask prices of others, as could exist with an online transaction system. Model constraints are
26 used to represent the physical, regulatory and water user-specific realities to try and incorporate
27 plausible trading behaviours. The model formulation described in Section 2.1 and Appendix B
28 summarise previous work by (Erfani et al., 2014). In this paper model extensions to model
29 dynamic environmental flows and scalable water licenses are presented in Sections 2.2 and 2.3.

30 **2.1. Pair-wise trading model**

31 The Erfani et al. (2014) model (see appendix B for equations) uses economic optimisation
32 subject to constraints to simulate a short-term (spot) market for water. The river network is

1 modelled as a network of nodes (e.g. demands, storage reservoirs, junctions where flow links
 2 converge or diverge) and conveyance links (e.g. river ‘reaches’, i.e., segments) and water
 3 balance is ensured at each junction or storage node (see e.g. Loucks et al., 1981, Loucks and
 4 Van Beek, 2005). Economic benefit functions that quantify the economic gains from water
 5 diverted must be provided for each demand node at each time step. The maximized objective
 6 function is the sum of economic benefits from water use across all users in each individual time
 7 step, net of transaction costs. This objective functions identifies trades that make economic
 8 sense whilst meeting constraints that ensure regulations are followed and plausible agent
 9 behaviours are considered. For example it includes a penalty function for deviating from the
 10 target level of reservoir storage. Water user nodes consume some water using their own license
 11 or by buying from other license holders, and can sell the rest to others. Since most abstractors’
 12 water use is not fully consumptive, some water is returned to the river as return flow. The sum
 13 of volumes of water abstracted and sold by the users cannot exceed both their annual and
 14 weekly licensed allocation.

15 **2.2. Dynamic environmental flows**

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

$$19 \quad \sum_{\substack{i \\ CO_{il}=1}} x_{il}^k + inFl_l \geq MinFlow_j \quad \forall l \in Junction, j \in Gauge, k \in river \quad (1)$$

20 for both the fixed and dynamic environmental flow water management systems. *inFl_l* is the
 21 external inflow at junction node *l*. The junction node *l* is connected to the gauge *j* to record
 22 how much water passes by the gauge *j*. With fixed volumetric water abstraction licenses, water
 23 available for abstraction is set using a fixed value of minimum flows (*MinFlow_j*) regardless of
 24 the available flow recorded at the gauges. In the case of dynamic environmental flows,
 25 *MinFlow_j* is a function of naturalised river flows (flow without human water abstractions).
 26 Naturalised river flows are estimated from the river flow through the gauging stations, and the
 27 *MinFlow_j* is the sustainable minimum level of river flows.

28 **2.3. License scaling**

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

$$4 \quad WaterAbstracted_i^k \leq \begin{cases} \theta_j \times WkLi_i, & nFlGA_j - MinFlow_j \leq \sum_{\substack{l \in User \\ WlGA_{lj}=1}} WkLi_l \\ WkLi_i, & otherwise \end{cases}$$

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6 $\forall i \in User, k \in river$ (2)

7 where

$$9 \quad \theta_j = \frac{nFlGA_j - MinFlow_j}{\sum_{\substack{l \in User \\ WlGA_{lj}=1}} WkLi_l}.$$

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10 In the above equation, $nFlGA_j - MinFlow_j$ is the water available for abstraction for license
 11 holders upstream of gauge j .

13 3. Case study

14 3.1. Water management in England and Wales

15 In England water diversions ('abstractions') are regulated by the Environment Agency (EA).
 16 The abstraction licenses incur yearly charges based on the volumetric size of the license, and
 17 not on the actual abstraction volumes. The licenses state maximum daily and yearly abstraction
 18 volumes. Environmental protection is enforced through license-specific Hands-off Flow (HoF)
 19 restrictions which refer to minimum flow required through the relevant gauging station, below
 20 which the license is temporarily suspended. There are emergency provisions set out in Section
 21 57 of the Water Resources Act 1991 which reduce spray irrigation in times of drought. Water
 22 trading is allowed, but rarely carried out. There is no water license spot-market; each
 23 transaction has to be assessed and approved by the EA over several months.

24 The current system was set up in 1960s and is not designed to manage competing water uses
 25 effectively. HoFs were introduced in an attempt to protect the environment from over-
 26 abstractions and were applied to newly issued licenses, with no change in allocations for legacy
 27 licenses. There is a lack of appropriate incentives or price signals for efficient water use and

1 there are institutional barriers to water trading (Defra, 2011). The current licensing system in
2 many areas results in over-abstraction and environmental damage: 18% of river catchments are
3 classed as over-licensed, and a further 15% - over-abstracted (EA, December 2008). In around
4 a quarter of water bodies in England and 7% of water bodies in Wales new consumptive
5 abstractions cannot be provided with reliable water supply (EA, 2011). Nationally, over a third
6 of licenses are not utilized and kept as a reserve in case of a drought, making 20% of the
7 licensed volume unused, but which could have otherwise been licensed to new uses requiring
8 water (EA and Ofwat, 2012). Water trading could provide flexibility in regional water resource
9 management and is being considered in individual water resource management zones
10 (Acreman and Ferguson, 2010).

11 In response to the shortcomings of the current English abstraction licensing system it is
12 currently being reformed. The aim is to allow water abstractors to more easily manage changes
13 in water availability and regulators to better guarantee environmental flows (EA and Ofwat,
14 2012). The new regime is due to be implemented by the mid- to late-2020s. In the meantime,
15 the EA has been assessing sensitivity of rivers to abstractions through the Restoring Sustainable
16 Abstraction program, and making changes to licenses on a case-by-case basis to help prevent
17 further damage.

18 Water licensing changes in England and Wales are designed to comply with the European
19 Water Framework Directive (WFD). The aim of the WFD is to bring the quality of rivers to
20 'good ecological status'. Methods to define environmental flow requirements have been
21 developed to enable policy makers to move away from the 'minimum flow' approach to a river
22 management approach that takes into consideration human water needs (Acreman and Dunbar,
23 2004). These informed the Environmental Flow Indicator (EFI) approach to dynamic
24 environmental flows developed by the Environment Agency. The EFI approach uses flow
25 duration curves to fix the percentage of flow that can be abstracted at different flow levels.
26 Each river in England and Wales has been assigned with an 'abstraction sensitivity band'
27 according to its sensitivity to changes in flow. With reference to the abstraction sensitivity, the
28 percentage of flow allowed for abstraction is assigned to each river (EA, 2013).

29 **3.2. Modelling the Great Ouse river basin**

30 To investigate the outcomes of potential license reform options, we apply the proposed model
31 to the 3000 km² Great Ouse River basin in eastern England (Figure 1). The largest towns are
32 Milton Keynes and Bedford. The basin is characterized by gently rolling land in the upper part

1 and flood plains and meadows in the lower part. Average annual rainfall varies from 540mm
2 in the east to 670mm in the west (EA, March 2005).

3 There are 94 active surface water licenses belonging to users from four sectors: Energy,
4 Agriculture, Public and Private Water Supply and Industry. Approximate locations of users are
5 shown in Figure 1. Around 95% of yearly surface water abstractions are appropriated by the
6 Public Water Supply (PWS) company and either stored in the reservoir (marked PWS
7 Reservoir in Figure 1) or input into treatment and distribution network (abstraction point
8 labelled PWS Intake in Figure 1). The second-largest water abstractor is the power station,
9 which uses 4% of the total volume abstracted for cooling.

10

11 **3.3. Case study-specific constraints**

12 In addition to the mass balance constraints described in Section 2, the constraints summarized
13 below are used to represent regulatory rules and water use behaviours in the basin.
14 Incorporating rules is possible since the optimisation model is solved separately for each
15 weekly time-step; abstractors have limited hydrological foresight.

16 **3.3.1. Current license restrictions**

17 Water abstraction restrictions under the current system outlined in Section 3.1 are implemented
18 to model the fixed volumetric water management system only. This is represented in the model
19 by constraints on license usage. When the river flows are below the threshold limit defined by
20 the hands-off-flow (HoF), the license is temporarily suspended, prohibiting abstractions or
21 trading of this license. The rule specified in Section 57 of the 1991 Water Resources Act
22 reduces spray irrigation water diversions when river flow reaches low levels. In our model a
23 50% rationing is imposed on farmers when river flows are below the flow historically exceeded
24 95% of the time at the downstream gauges (see appendix B for equations).

25 To model PWS Reservoir operation rules, the following set of instructions is employed for both
26 the fixed and dynamic water management licensing regimes. If reservoir storage is below the
27 minimum volume, withdrawals from the reservoir stop. Storage target seeking behaviour by
28 utilities is modelled by penalizing storage target deviations in the objective function. As the
29 reservoir levels get progressively lower, the more water-saving initiatives are implemented,
30 and the lower proportion of the demand is satisfied, resulting in lower benefits from water use
31 for the water company and the consumers. This loss of benefits is reflected in the reservoir
32 deviation penalty factor α (y-axis in Figure 2 (left)):

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$$Penalty_j = \alpha \left| tRes_j - \sum_{k \in Owner} Res_j^k \right|, \quad (3)$$

where $tRes_j$ is the seasonal storage target level (Figure 2 (right)).

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 B).

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 (half of target volume or less), water sales by PWS the following week are prohibited until the level recovers. Sensitivity analysis was carried out to test the impact on trading of more conservative policies where trading is stopped earlier (Section 4.4).

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

3.4. Parameterizing dynamic environmental flows

1 The model was applied to the River Great Ouse basin using hydrological data from one of the
2 driest years on record, characterized by low river flows for the first 8 months of the year,
3 followed by wet autumn and winter ('naturalized' flow in figure 3). Using the Environmental
4 Flow Indicator (EFI) method discussed in Section 2.3, and taking into consideration the
5 Abstraction Sensitivity Band of the river basin, the allowable water abstractions are calculated
6 as proportions of naturalised flow (Table 1). In Table 1, percentile naturalised flow is the
7 percentage of time flow historically exceeded a given flow value provided by the England's
8 Environment Agency (EA, 2013). Please see Klaar et al. (2014) for further information on the
9 EFI approach.

10

11 **4. Model results**

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

15 **4.1. Protection of the environment**

16 Figure 3 compares modelled river flow exiting the river basin under the two licensing systems.
17 The current system leads to large variability in river flows through the year, decreasing to low
18 levels incompatible with recent regulations such as the European Water Framework Directive
19 (Acreman and Ferguson, 2010). This is the result of the asymmetric impact of environmental
20 hands-off-flow (HoF) conditions on individual licenses. HoFs were assigned to new licenses
21 in the past to prevent over-abstraction of rivers but were not applied retrospectively to early
22 licenses granted in the 1960s (see Section 3.1). As a result, some (large) licenses are not
23 affected by HoFs and the system is not effective at ensuring environmentally acceptable
24 abstractions during the drought.

25 The drought river flows are improved with the proposed licensing system (Figure 3) and its
26 higher environmental allocation. Whereas the current licensing system brings the flow to nearly
27 zero for over 40% of the dry year, the proposed licensing system never falls below 680
28 Ml/week.

29 **4.2. Water diversions**

30 With the more stringent environmental protection enforced by the proposed scalable licensing
31 system all users face a lower amount of water available for diversion. The total annual volume

1 of water diverted decreases by over 40% (from 88,000 MI to 50,000 MI). All water users except
2 industry decrease their diversions: PWS Reservoir by 44%, PWS Intake – 8%, power station –
3 38%, agriculture sector – 26%, private water supply – 14%. Industrial user increases its
4 abstraction by less than 1%.

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

12 **4.3. License trading results**

13 Figure 5 and Figure 6 show which sectors are buying and selling water under the current and
14 proposed licensing systems respectively. Figure 5 shows that because of PWS’s lack of HoF
15 conditions, they are able to sell water to the energy sector throughout the year. Under the
16 proposed system as modelled (Figure 6), where sectors are on equal footing, these rents are not
17 available and PWS stops selling water at the end of April, at which point the energy sector
18 begins buying from farmers (with higher transaction costs due to the larger number of
19 transactions involved).

20 Lower diversion allowances under the proposed system lead to a more active water market,
21 with the number of trades more than doubling (127% increase) and the volume traded
22 increasing by 77% (see Table 2). Trading between users from different sectors also increases.
23 Figure 7 shows the proportion of total yearly volumes transferred between sectors. Under the
24 current licensing system the largest transactions by volume are from public water supply (PWS)
25 to the power station (94%). Under the proposed shares-based system the power station is the
26 largest buyer until autumn (Figure 6), purchasing from both the PWS intake and agricultural
27 businesses, followed by transfers from the power station to the PWS Reservoir in autumn and
28 winter. Agricultural users also sell to the PWS Reservoir towards the end of the year, after the
29 growing season. The purchases by PWS Reservoir are made to re-fill the reservoir which was
30 depleted through the year under the proposed licensing system.

31 In the current volumetric licensing simulation, license-holders generally either sell or buy water
32 through the year, and rarely switch from one status to the other. In the proposed shares-based

1 system however, some users who buy at the beginning of the year become sellers at the end of
2 the year, and vice versa. Under the current system some license holders are affected by the
3 drought more than others because of the stricter HoF conditions on their licenses, and are
4 therefore systematically disadvantaged during droughts. With the proposed shares system as
5 simulated, all users are affected by reductions in the available resource, and short-term leasing
6 enables them to manage their water needs effectively: selling in weeks when they have no or
7 low demand for water and purchasing from other users when they have relatively high
8 economic water demands unmet by their allocation.

9 Under proposed licensing, when the PWS Reservoir storage volume reaches half of the target
10 level by mid-April, PWS Intake ceases selling water due to the trading constraint outlined in
11 Section 3.3.2, PWS Intake becomes a buyer in July-August, purchasing small volumes from
12 private water supply license holders and farmers taking advantage of the first opportunity to
13 start filling its reservoir. Under the current licensing system water trading stops as river flow
14 recovers in mid-September whereas in the shares-based system, trading continues until the end
15 of the year. The reason for this is the large impact of license scaling on the PWS Reservoir as
16 discussed in Section 4.2. Low storage volumes activate demand reduction measures which
17 impose an opportunity cost on the water company and its customers and the marginal value of
18 stored water increases (as represented by the penalty function defined in Section 3.3.2). The
19 reservoir is refilled late in the year using its own license and purchases from other users.

20 **4.4. PWS trading rule sensitivity analysis**

21 PWS is the largest abstractor in the catchment, and the largest single seller of water licence in
22 the current system simulation, and the second-largest in the proposed system of scaled licences.
23 Sensitivity analysis has been carried out to test the effect of the PWS trading rule outlined in
24 Section 3.3.1 on model results. A more conservative attitude to trading is considered where the
25 PWS Intake stops selling water if 30% or 10% below the storage target. The impact of these
26 two scenarios on trades and sector benefits were assessed and compared to the original case
27 where PWS stops trading if storage goes below 50% of the storage target.

28 Figure 8 shows changes in volumes sold, by sector, under the 2 licensing systems with stricter
29 PWS trading rules. Under the current system, as the PWS Intake reduces its yearly volumes
30 sold, agriculture increases its selling. The volumes sold by agriculture with the 30% rule are 5
31 times the volume sold under the 50% rule. The number of sellers is increased from 48 to 69
32 with 30% below the storage target trading rule, and to 75 with 10% below the storage target

1 trading rule. The overall total volumes sold per year reduce by around 50% as the trading rule
2 is changed from 50% to 10% below the storage target.

3 Under the proposed system, the PWS Intake is not the largest seller, and the reduction in its
4 volumes sold does not produce as large of an effect on overall trading results. The number of
5 sellers remains at 90 because all water users with water to sell are already participating in the
6 market. The volumes sold by agriculture increase slightly (around 5% increase as the rule
7 changes from 50% to 10% below the storage target). The overall total volumes sold reduce by
8 around 10%.

9 The agriculture sector's and the power station's benefits from water use reduce as the PWS
10 Intake adopts a more conservative selling rule. Due to higher selling volumes by agriculture,
11 its benefits from water use reduce by 25% (current system) and 23% (proposed system). The
12 overall reduction in the volumes sold means a reduction in the power station's ability to
13 supplement its allocated water volumes by buying from other sectors, and its benefit reduces
14 by 30% (current system) and 21% (proposed system).

15 These results suggest that the water market under the proposed licensing system can be less
16 responsive to a single large user's attitudes to trading.

17

18 **5. Discussion**

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

24 Gross economic benefits from water use are estimated for each abstraction license holder using
25 their economic water demand functions (see Erfani et al. (2014) for details). For each week,
26 the benefits generated from water use by each abstractor were aggregated into sectoral benefits.
27 Figure 9 compares the economic benefits by sector generated from water use for the two
28 licensing systems in conjunction with the modelled water market. The energy sector sees the
29 largest decrease in benefits due to the increased environmental protection of the proposed
30 licensing system mostly due to the sector's inability to buy water from public water under
31 drought. The water company also incurs significant summer losses as it introduces restrictions.
32 English policy-makers are currently discussing the possible 'grandfathering' of the current

1 system priorities in the new licensing system; this would result in a multi-tiered scaling systems
2 where certain sectors have priority over others. As the details of such a system were not yet
3 established, these have not been modelled, but if PWS were given priority within the scaled
4 system, its loss of benefits would likely decrease.

5 Compared to the current licensing arrangement plus a market, the loss in benefits through the
6 dry year across all sectors in our case-study is estimated at £94 million (a 15% reduction, from
7 £611 million for current licensing to £517 million with the proposed system, both with the
8 modelled surface water market). Erfani et al. (2014) estimated the total annual economic
9 benefits for the same system and year with current licensing but without trading at £575
10 million. In this case, the estimated opportunity cost of improved environmental flows is £58
11 million, a 10% loss in economic benefits.

12 These opportunity costs for improving environmental flows may appear large. Our analysis
13 uses catchment inflows from one of the driest years on record so this cost can be considered an
14 upper-bound on potential costs imposed on water users for enhanced environmental
15 performance. Also, if the power station had an alternative supply to its surface water licence,
16 its opportunity costs would decrease. To put the value in perspective, a survey by NERA (2007)
17 estimated the present value of improvements in water environment of all water bodies in the
18 UK to be between £18bn and £29bn (benefits incurred for an indefinite period), or between
19 £618 and £1020 million per year. Garrod and Willis (1996) estimated the annual value of
20 alleviating low flows for River Darent (river catchment area is 14% of the Great Ouse) at
21 around £37 million (£2011).

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

27 Several model limitations and simplifications should be mentioned. Groundwater resources
28 were excluded from the model because we focus on the effects of changing the surface water
29 licensing system. Abstraction license holders sometimes possess more than one license,
30 sometimes for both surface water and groundwater abstractions. In this case, they will likely
31 draw strategically from across their asset base (e.g. a water company will cost minimise when
32 choosing sources), and such strategic abstraction would increase in a market – this is not

1 considered in our current model where each abstraction point is modelled independently. Some
2 abstractors, particularly agricultural ones, have small ‘winter storage’ reservoirs to enable inter-
3 temporal water management. Such users would likely switch between different water sources
4 during droughts and involve reservoirs in sophisticated and diverse ways. At the time of the
5 analysis, we didn’t have data on locations and capacities of small reservoirs and so this detail
6 is left to later work. Most strategic behaviours across different assets and over time (long-term
7 decisions) are not reflected and are beyond the scope of this paper.

8 Economic water demands were estimated using past literature and are indicative of the water
9 values across the different uses in our catchment. In our model water diversions and trading
10 are driven primarily by the spatially and temporally varying values of water as encoded in
11 weekly demand curves for each abstractor. In reality, economic considerations are not the only
12 drivers for human behaviour. Actual water markets would depend on the pre-existing social
13 networks within the basin, preferences and attitudes towards trading, as well as perceptions of
14 fairness and justice (Syme et al., 1999). Such motivations were not represented in our hydro-
15 economic model because they are not known. We take steps to represent some attitudes to
16 trading by introducing a trade reluctance coefficient for agricultural users and embedding water
17 company operating rules regarding their assets by a rule on trading. Furthermore, in our model
18 the propensity of different agents to trade with each other can be calibrated on a pair-wise basis
19 using transaction costs. In our application we set transaction costs by abstractor sector but a
20 more detailed study of transaction costs could be performed.

21

22 **6. Conclusions**

23 This paper uses a hydro-economic model to assess the performance of two water licensing
24 regimes in conjunction with surface water markets. The first regime is the minimum-flow-
25 based system with fixed volumetric licenses currently used in England and Wales. The second
26 one is a proposed licensing system based on scalable licenses where shares are translated into
27 actual permissible allocation volumes depending on minimum environmental flows that are set
28 dynamically to adapt to naturalised flow conditions. The model was applied to the Great Ouse
29 River basin in East England over a historically dry year.

30 Results suggest the proposed dynamic environmental flow with scalable licensing system is
31 better able to prevent very low flows during droughts than the current abstraction regime based
32 on volumetric licensing. Flows under the proposed system don’t reduce below 680MI/week

1 whereas under current licensing flows reduce down to nearly zero for over 4 months of the
 2 year. With more water left to the environment, less water is available to satisfy human water
 3 demands leading to a more active water market. The number of trades under the scalable
 4 licenses system is more than double the number under current system and the volume traded is
 5 77% greater. Also, the water market under the proposed system was less sensitive to a reduction
 6 in trading by one large agent (we tested this for PWS). Still the more active water market is not
 7 able to fully compensate for the loss of abstraction (increases in environmental flows); the
 8 opportunity cost of the increased environmental quality in the dry year is a loss of about 15%
 9 compared to the current licensing system with a water market, or 10% when compared to
 10 current system without a market (the current situation).

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

21

22 **Appendix A: Nomenclature**

<i>Junction</i>	No-demand and non-storage nodes which join 2 or more links in the network
<i>User</i>	The set of all licensed river abstractors including Agriculture, Industry, Water supply and Energy
<i>Owner</i>	The set of all water right holders, reservoirs and the river
x_{ij}^k	Decision variable, the water flowing from node i to j with license holder k

$inFl_i$	External hydrological inflow at junction node i
CO_{ij}	Connectivity matrix which contains 1 if node i is connected to node j , 0 if no connection
$pRes_j^k$	Reservoir j storage carried over from previous time step with water license k
Res_j^k	Reservoir j storage with water license k
$tRes_j$	Reservoir j target
$WaterAbstracted_i^k$	Water consumed by user i which is either bought from owner k or abstracted from river using user i 's license
$Trade_i^{k \in river}$	Water license leased for one time-step by user i
$ReturnFlow_{ij}$	Water returned back to the river at downstream junction node j of user i based on the consumption factor of user i
DW_{ij}	Junction node j downstream of user i
$consFactor_i$	Fraction of water evaporated relative to diverted for user i
$Discharge_j$	Discharge sink j at the mouth of the river
$WkLi_i$	Weekly license allowance for user i to abstract water from river
$YrLi_i$	Yearly license allowance for user i to abstract water from river
$Deviation_j$	Deviation of reservoir j from its target storage volume
$fIGA_j$	Flow at gauge j
$AlGA_j$	Allowable flow at gauge j
$RuGA_{ij}$	Information with regards to the hands of flow condition which equals one if user i abstraction is controlled with the level of flow at gauge j
$Q95GA_j$	Q95 flow level at gauge j

$UpGA_{ij}$	Agriculture user i upstream of gauge j
$WaterUse_i^t$	Water used by user i at time t including the abstraction and trading
sL_i^t	Selling limit for user i at time t
EWN_i	Historical expectation of water needs for user i

1

1 **Appendix B. Formulation details**

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

4

5 **Section 2.1.**

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

9
$$NetBenefit = \sum_{i \in User} totalBenefit_i - \sum_{i \in User} totalCost_i - \sum_{j \in Reservoir} Penalty_j \quad (B1)$$

10 subject to the following mass balance constraints:

11
$$\sum_{\substack{j \\ CO_{ji}=1}} x_{ji}^k + inFl_i + \sum_{l \in User} ReturnFlow_{li} = \sum_{\substack{j \\ CO_{ij}=1}} x_{ij}^k$$

 12
$$\forall i \in Junction, \quad k \in Owner, \quad DW_{li} = 1 \quad (B2)$$

13

14
$$\sum_{\substack{i \\ CO_{ij}=1}} x_{ij}^k + pRes_j^k = Res_j^k + \sum_{\substack{i \\ CO_{ji}=1}} x_{ji}^k \quad \forall j \in Reservoir, \quad k \in Owner \quad (B3)$$

15

16
$$\sum_{\substack{j \\ CO_{ji}=1}} x_{ji}^k = \sum_{\substack{j \\ CO_{ij}=1}} x_{ij}^k + WaterAbstracted_i^k + Trade_i^{k \in river}$$

 17
$$\forall i \in User, k \in Owner \quad (B4)$$

19
$$Trade_i^{k \in river} = \sum_{\substack{j \\ CO_{ij}=1}} x_{ij}^i \quad \forall i \in User \quad (B5)$$

18

$$ReturnFlow_{ij} = \sum_{k \in Owner} (1 - consFactor_i) WaterAbstracted_i^k \quad \forall i \in User, \quad DW_{ij} = 1 \quad (B6)$$

$$\sum_{k \in river} \sum_{\substack{i \\ CO_{ij}=1}} x_{ij}^k = Discharge_j \quad \forall j \in Discharge \quad (B7)$$

Section 3.3.1.

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:

$$(flGA_j \leq AlGA_j) \rightarrow (WaterAbstracted_i^{k \in river} + Trade_i^{k \in river} = 0) \quad \forall i \in user, j \in Gauge, \quad RuGA_{ij} = 1 \quad (B8)$$

In addition, the 50% rationing is imposed on farmers using the following set of check constraints:

$$(flGA_j \leq Q95GA_j) \rightarrow (WaterAbstracted_i^{k \in river} + Trade_i^{k \in river} \leq 0.5 \times WkLi_i) \quad \forall i \in Agriculture, j \in Gauge, \quad UpGA_{ij} = 1 \quad (B9)$$

For the PWS reservoir, the volumetric capacity constraint is as follows:

$$2627 \leq \sum_{k \in Owner} Res_j^k \leq 55450 \quad \forall j \in Reservoir. \quad (B10)$$

The hedging constraint for water company demand reduction is represented by:

$$WaterAbstracted_i^j = F \left(\sum_{k \in Owner} Res_j^k \right), \quad \forall i \in user, j \in Reservoir, CO_{li} = 1 \quad (B11)$$

where $F(\cdot)$ is the function shown in Figure B.1 which represents the relationship between the reservoir level, as a percentage of the target, and the proportion of demand that is satisfied.

1

2 **Section 3.3.2.**

3 At each weekly time period t of the modelling agricultural willingness to sell their license is
4 represented using:

5 $Trade_i^{kEriver} \leq \max\{0, sL_i^t\} \quad \forall i \in user \quad (B12)$

6 This limit (sL) applies until the farmer abstracts a proportion c_i of their expected water needs
7 (EWN_i) which is based on their historical yearly water use. For each user i ,

8 $sL_i^t = \begin{cases} sL_i^{t-1} - WaterUse_i^t, & \text{Sum of abstraction up to time } t \leq c_i \times EWN_i \\ WkLi_i, & \text{otherwise} \end{cases} \quad (B13)$

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

10 $sL_i^0 = YrLi_i - c_i \times EWN_i \quad (B14)$

11

12

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

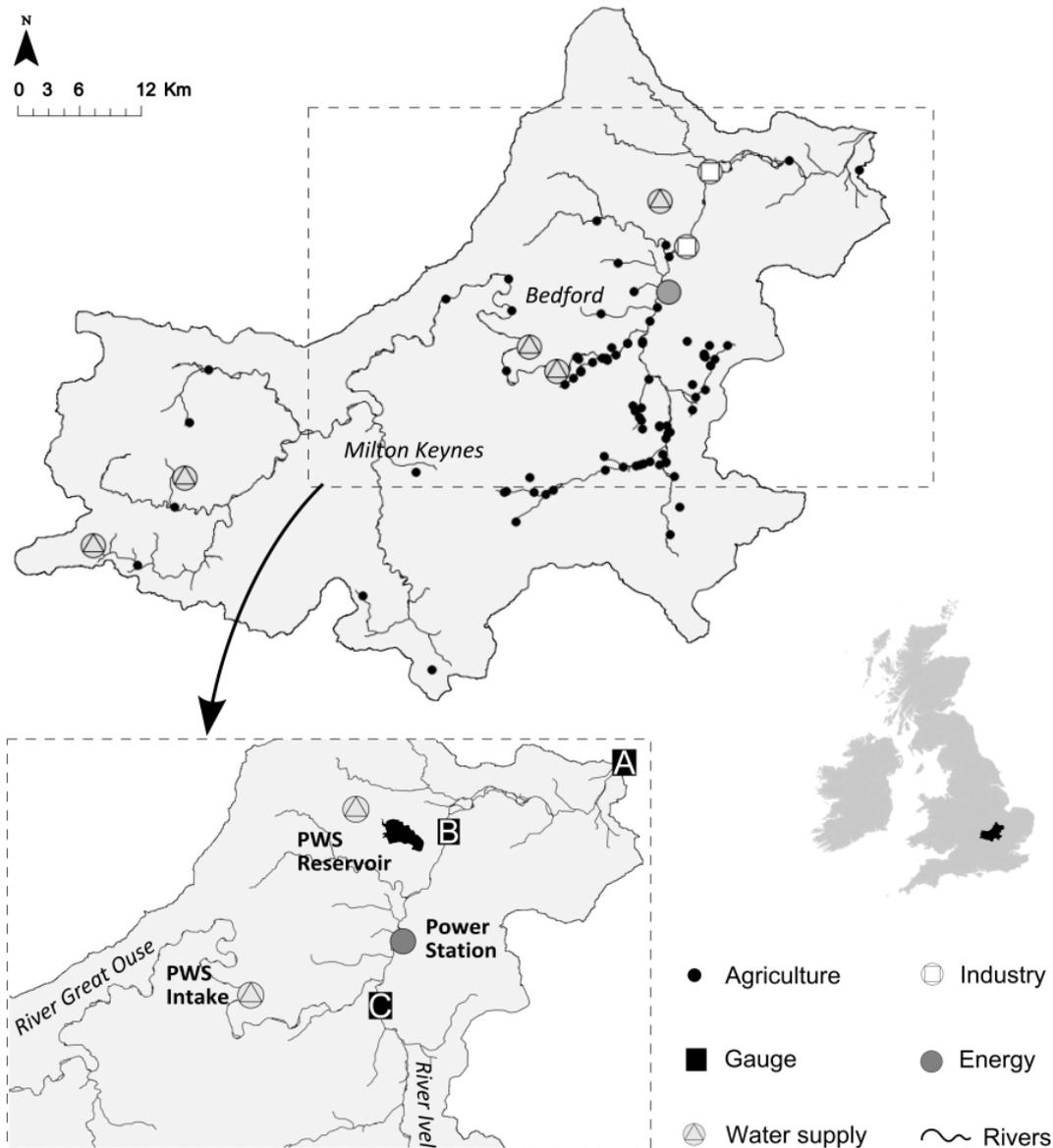
Percentile natural flow at downstream gauge of the sub-catchment	Q30	Q50	Q70	Q95
Percentage of naturalised flow allowed for abstraction (%)	26	24	20	15

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

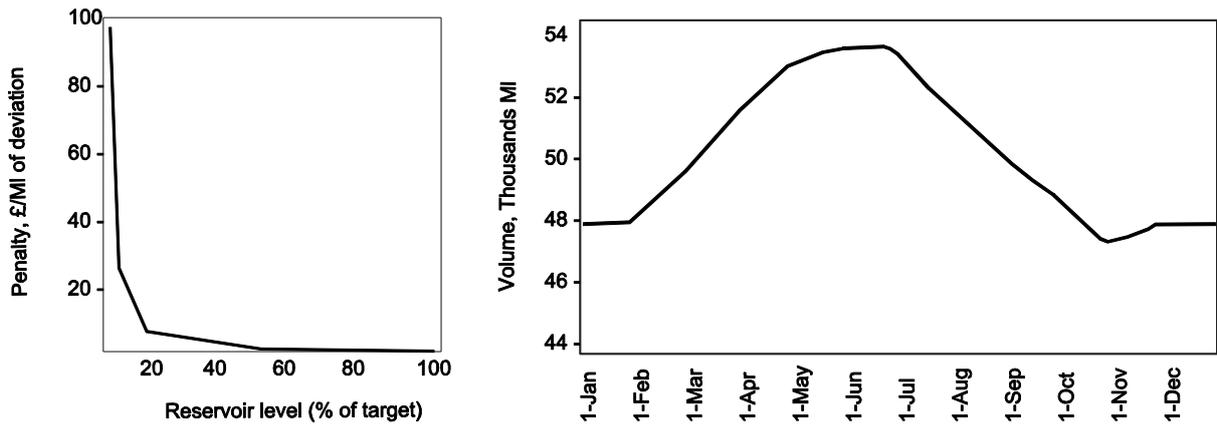
	Volumetric licenses	Sharing system
Number of trades	299	678
Sellers	48	90
Buyers	19	32
Total volumes traded, MI	2750	4860

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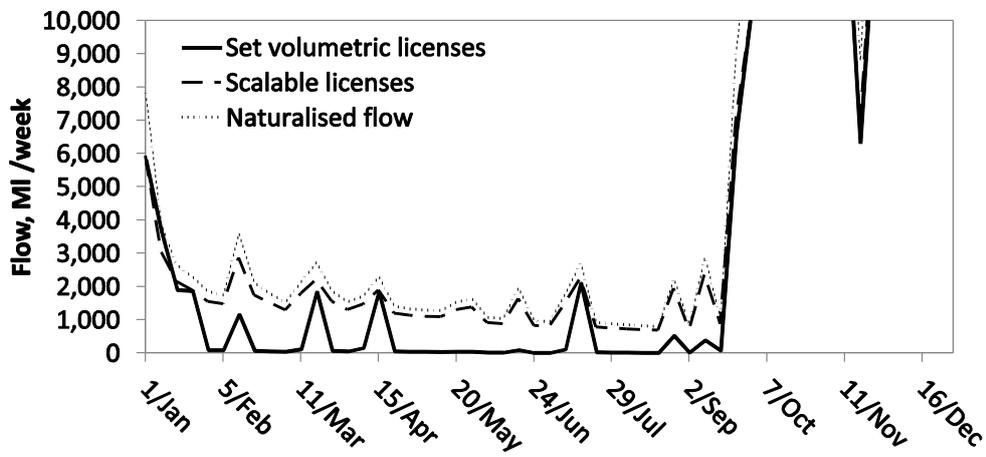
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2 **Figure 1** Map of the Great Ouse River basin showing approximate locations of water users and
 3 main river flow gauging stations: A – last flow gauge in the basin (sink), B – Offord gauge
 4 defining license scaling for PWS Reservoir and Power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



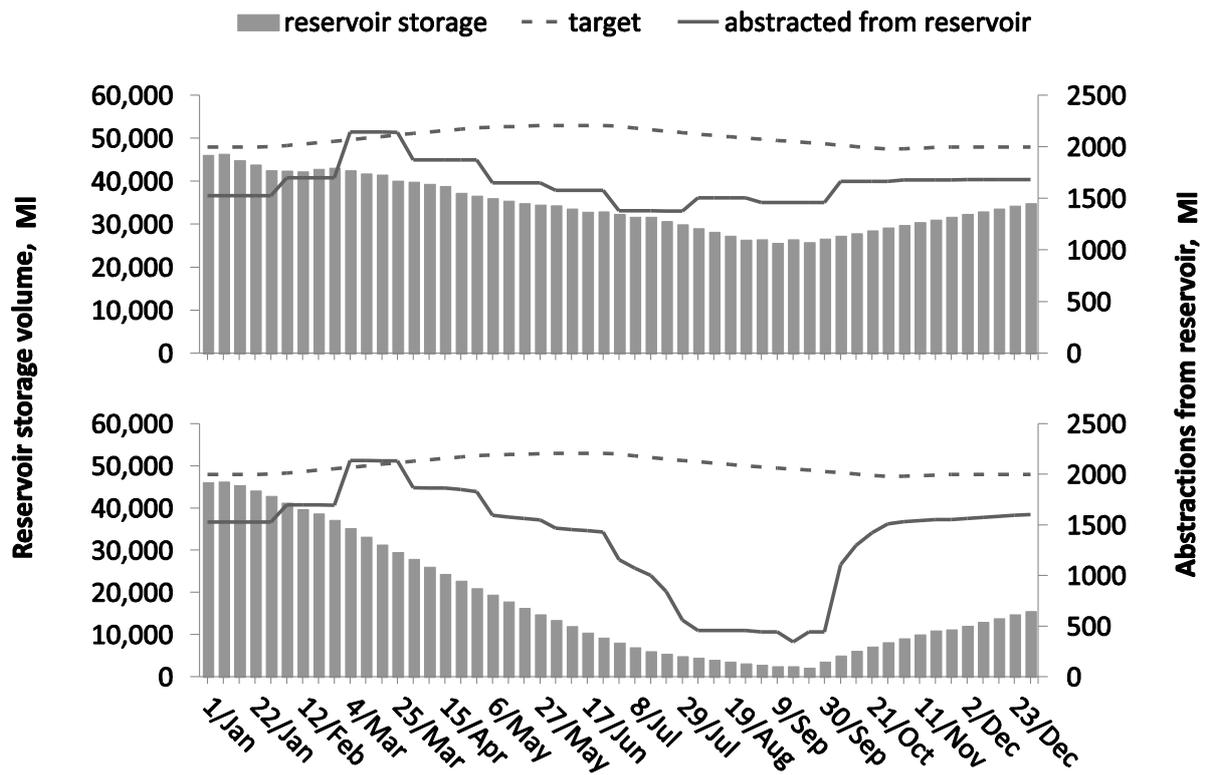
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Figure 2 Reservoir storage deviation penalty (left), PWS Reservoir storage targets (right)



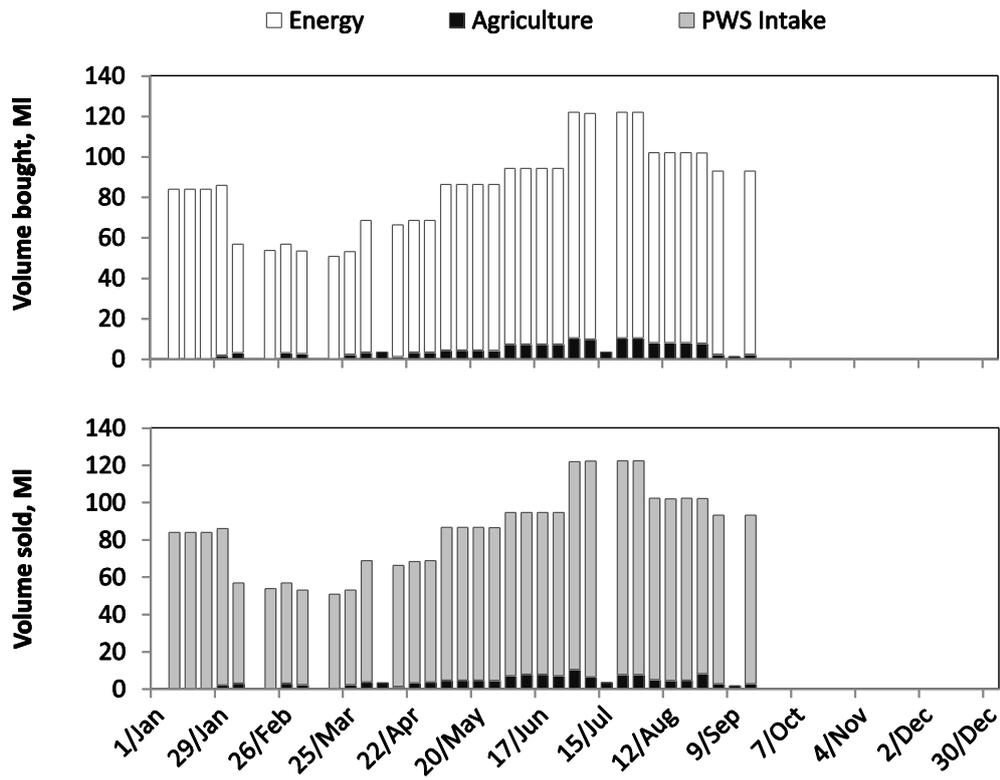
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Figure 3 River flow at the last gauge in the basin (marked A in Figure 1).



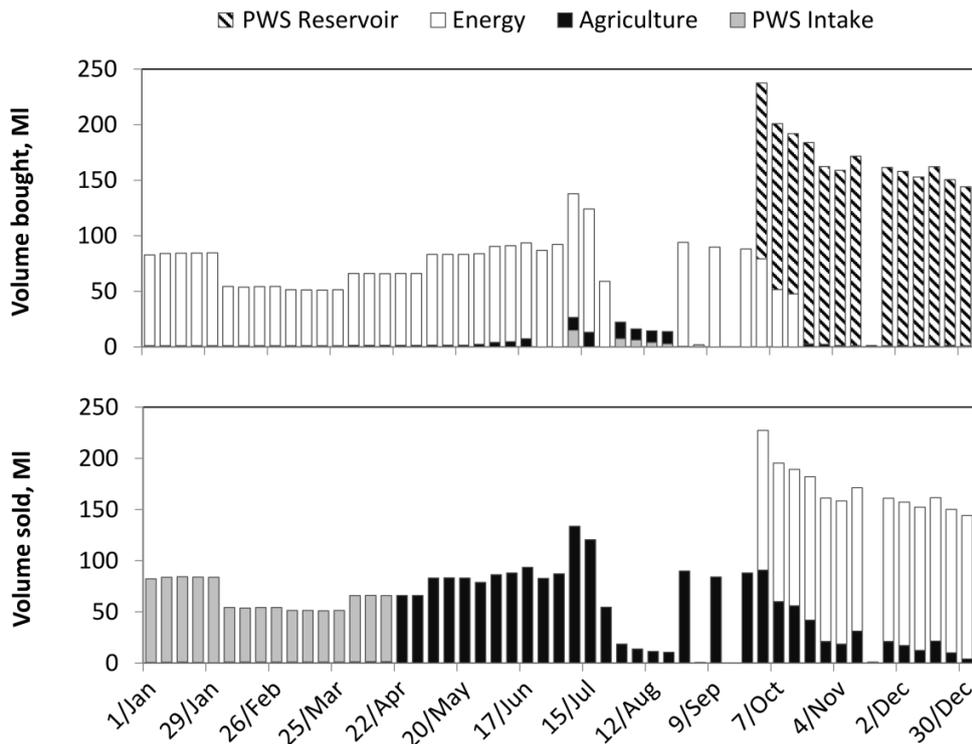
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Figure 4 PWS Reservoir storage and abstraction profiles for current (top) and proposed (bottom) licensing systems.



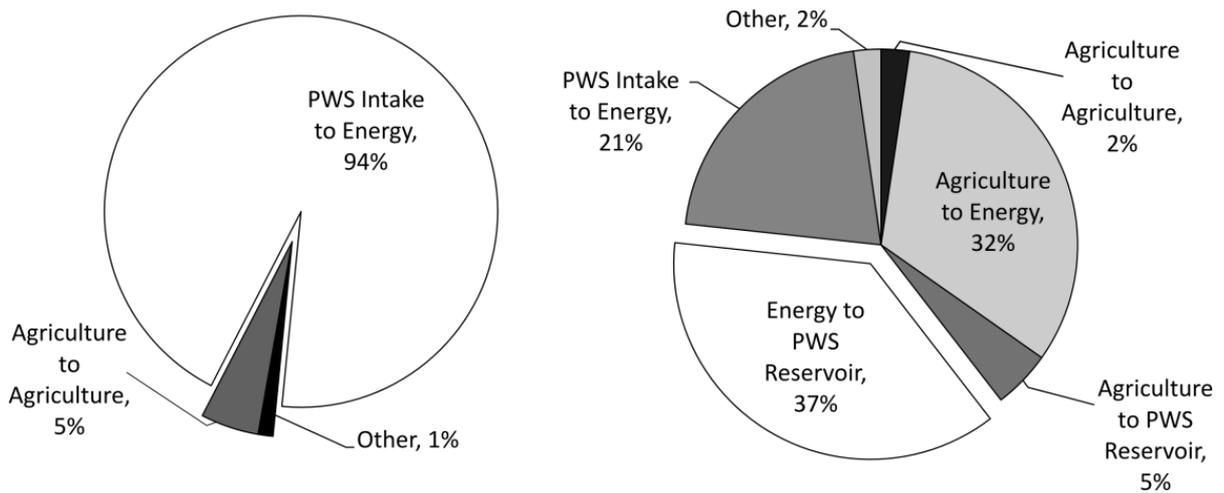
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Figure 5 Water volumes bought (top) and sold (bottom) in millions of litres per week by sector under the current licensing (volumetric) system.



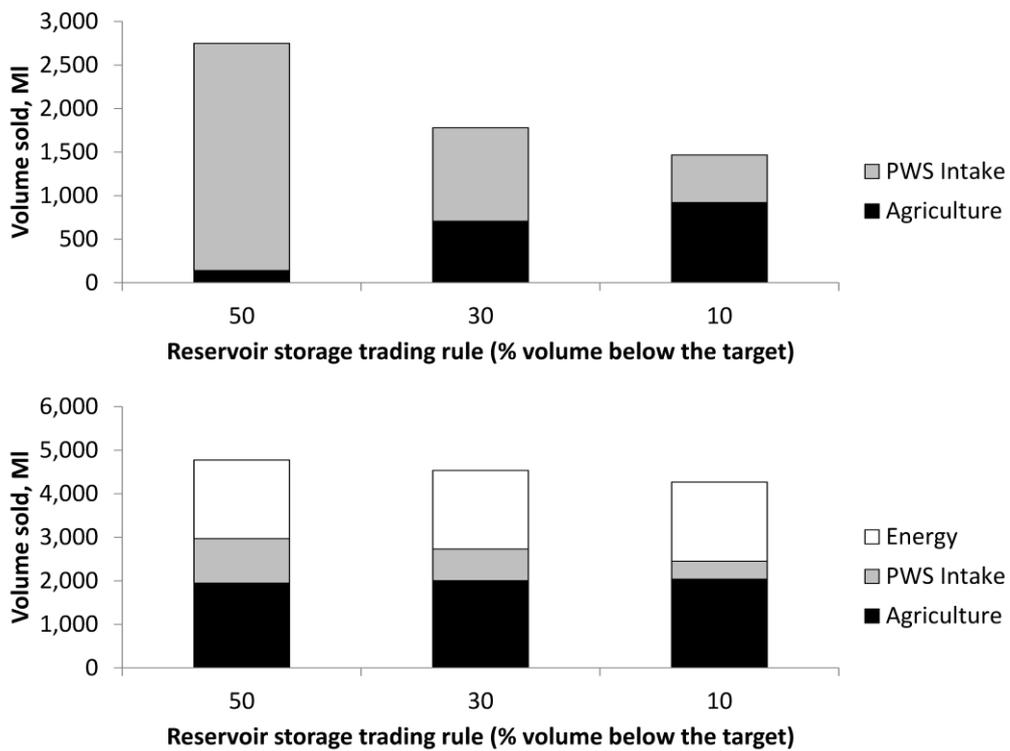
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Figure 6 Water volumes bought (top) and sold (bottom) in millions of litres per week by sector under the proposed (scalable) licensing system.



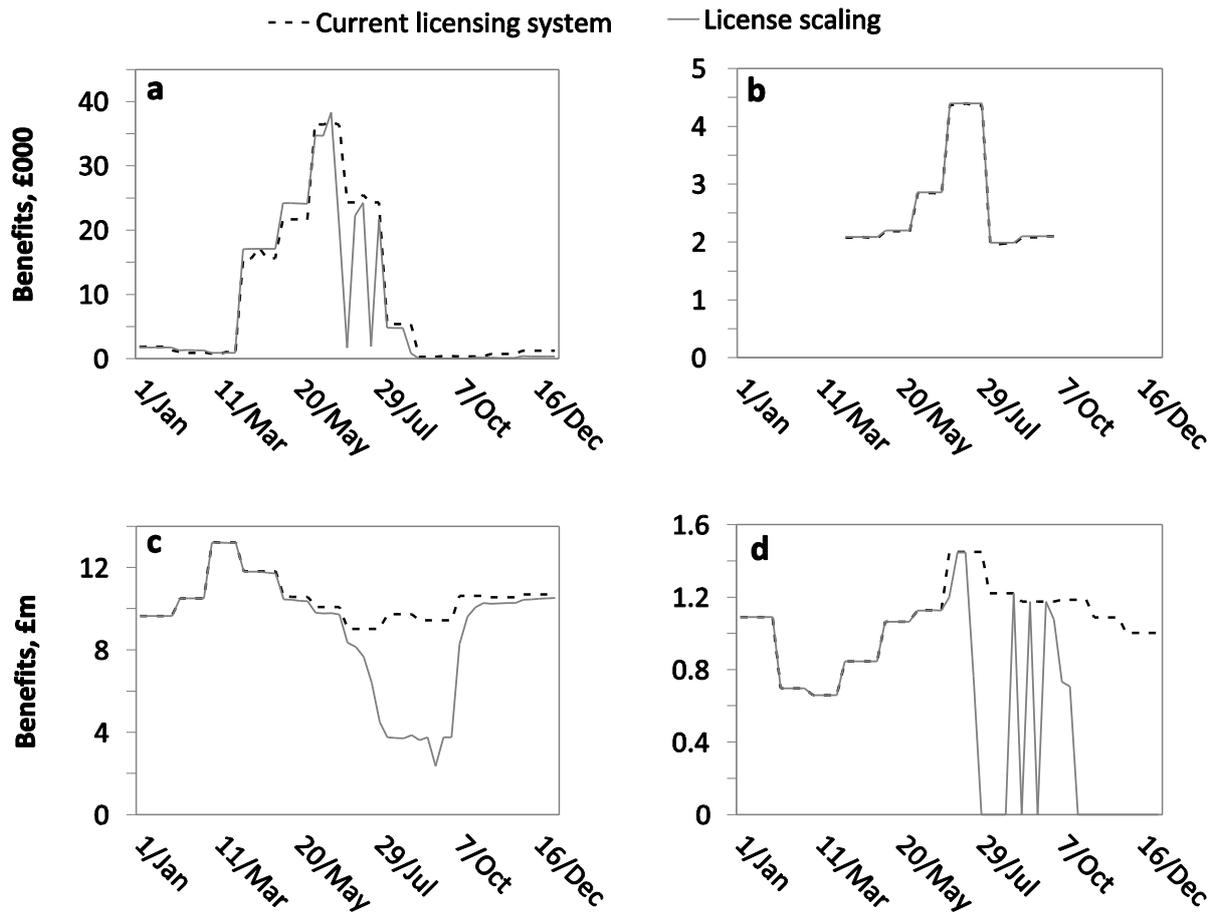
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Figure 7 Proportion of the total annual volume of trade transactions between sectors under the current (left) and proposed (right) licensing systems as simulated in a dry year.



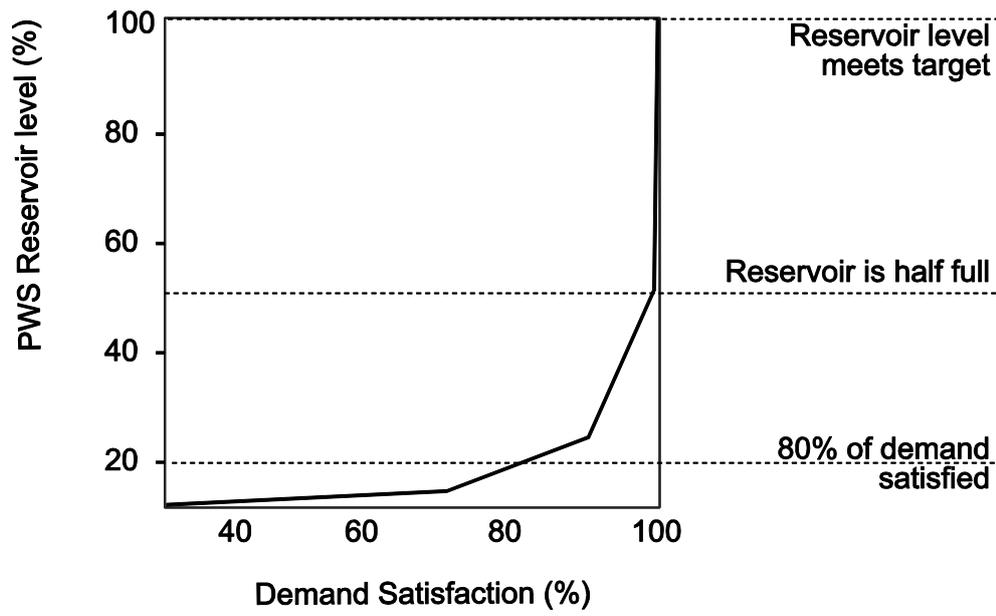
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2 **Figure 8** Effect of more conservative PWS trading rule on volumes sold under the current
 3 licensing system (top panel) and the proposed system (bottom panel). The water market under
 4 the proposed system is more active and less affected by the change in PWS trading policy.



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Figure 9 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.



1 **Figure B.1** Public Water Supply company hedging rule.