

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

3

4 T. Erfani*^{1,2}, O. Binions*², J.J. Harou^{1,2}

5 [1] School of Mechanical, Aerospace and Civil Engineering, University of Manchester,
6 Manchester, UK, M13 9PL

7 [2] Department of Civil, Environmental and Geomatic Engineering, University College
8 London, Chadwick Building, Gower Street, London, UK, WC1E 6BT

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

10 *Authors contributed equally

11

12 **Abstract**

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

1 licensing system protects river flows more effectively than the current static minimum flow
2 requirements during a dry historical year, but that the total opportunity cost to water
3 abstractors of the environmental 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.,
8 1996;Postel, 1998). Current water diversion practices lead to degradation of river
9 environments in some areas, resulting in regional water scarcity and conflicts (Smakhtin et
10 al., 2004).

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

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

29 The objectives of water resource allocation systems is to regulate access to water resources,
30 ensuring flexibility, security of access, predictability, and fairness, and to reflect public
31 values and opportunity costs (Howe et al., 1986). More recently environmental protection has
32 been added to those goals. One of the methods used to preserve adequate river flows is to set

1 a minimum flow below which water abstraction must reduce or cease (Acreman, 2005).
2 These static threshold or minimum flow methods of maintaining river flows often do not
3 achieve ecologically or economically efficient results (Arthington et al., 2006;Katz, 2011).
4 The aquatic environment relies on a natural hydrological cycle, but human water abstractions
5 alter the natural flow variability which is important to sustaining riverine species, and
6 minimum flow regimes do not support natural flow regimes (Poff et al., 1997). Hence, fixed
7 volumetric allowances have evolved into allowances with reference to river flow conditions
8 such as ‘per cent of flow’ regime, with abstractions limited to a sustainable share of the
9 natural river flows (Richter et al., 2012). Environmental flow methods are used to determine
10 the sustainable levels of abstractions. Over 200 environmental flow approaches have been
11 developed to provide the policy-makers with tools to re-design water allocation systems
12 ensuring that river ecology is protected, whilst taking into account human water needs
13 (Acreman and Dunbar, 2004). Environmental flow methodologies have been developed and
14 applied in 44 countries, spanning 6 world regions with the United States the most active
15 proponent of the approach (Tharme, 2003).

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

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

1 This paper extends the generic water market simulation model proposed by Erfani et al.
2 (2014) to assess possible outcomes of water trading under a share-based licensing system
3 where allocations (water rights) are updated according to current flow conditions and
4 dynamically updated environmental flows (EA, 2013;Young and McColl, 2005). The new
5 model is applied to a case-study basin in Eastern England. The performance of the proposed
6 licensing system is compared to the currently used licensing system which uses static
7 minimum environmental flows and volumetric licenses. The current system allocates fixed
8 water volumes whilst the proposed system scales weekly licensed volumes proportionally to
9 each abstractors' shares depending on flow conditions. The contribution of this paper is to
10 represent a novel modern water management licensing system within a hydro-economic
11 water market simulator to assess the hydrological and economic impacts of the new policies
12 on a real-world complex multi-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
16 discussion 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
20 al. (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
27 incorporate plausible trading behaviours. The model formulation described in Section 2.1 and
28 Appendix B summarise previous work by (Erfani et al., 2014). In this paper model extensions
29 to model dynamic environmental flows and scalable water licenses are presented in Sections
30 2.2 and 2.3.

31 **2.1. Pair-wise trading model**

1 The Erfani et al. (2014) model (see appendix B for equations) uses economic optimisation
 2 subject to constraints to simulate a short-term (spot) market for water. The river network is
 3 modelled as a network of nodes (e.g. demands, storage reservoirs, junctions where flow links
 4 converge or diverge) and conveyance links (e.g. river ‘reaches’, i.e., segments) and water
 5 balance is ensured at each junction or storage node (see e.g. Loucks et al., 1981, Loucks and
 6 Van Beek, 2005). Economic benefit functions that quantify the economic gains from water
 7 diverted must be provided for each demand node at each time step. The maximized objective
 8 function is the sum of economic benefits from water use across all users in each individual
 9 time step, net of transaction costs. This objective functions identifies trades that make
 10 economic sense whilst meeting constraints that ensure regulations are followed and plausible
 11 agent behaviours are considered. For example it includes a penalty function for deviating
 12 from the target level of reservoir storage. Water user nodes consume some water using their
 13 own license or by buying from other license holders, and can sell the rest to others. Since
 14 most abstractors’ water use is not fully consumptive, some water is returned to the river as
 15 return flow. The sum of volumes of water abstracted and sold by the users cannot exceed
 16 both their annual and weekly licensed allocation.

17 **2.2. Dynamic environmental flows**

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

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

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

29 **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.

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

4
 5 $\forall i \in User, k \in river$ (2)

6 where

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

7
 8 In the above equation, $nFlGA_j - MinFlow_j$ is the water available for abstraction for license
 9 holders upstream of gauge j .

10

11 3. Case study

12 3.1. Water management in England and Wales

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

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

1 use and there are institutional barriers to water trading (Defra, 2011). The current licensing
2 system in many areas results in over-abstraction and environmental damage: 18% of river
3 catchments are classed as over-licensed, and a further 15% - over-abstracted (EA, December
4 2008). In around a quarter of water bodies in England and 7% of water bodies in Wales new
5 consumptive abstractions cannot be provided with reliable water supply (EA, 2011).
6 Nationally, over a third of licenses are not utilized and kept as a reserve in case of a drought,
7 making 20% of the licensed volume unused, but which could have otherwise been licensed to
8 new uses requiring water (EA and Ofwat, 2012). Water trading could provide flexibility in
9 regional water resource management and is being considered in individual water resource
10 management zones (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
13 changes in water availability and regulators to better guarantee environmental flows (EA and
14 Ofwat, 2012). The new regime is due to be implemented by the mid- to late-2020s. In the
15 meantime, the EA has been assessing sensitivity of rivers to abstractions through the
16 Restoring Sustainable Abstraction program, and making changes to licenses on a case-by-
17 case basis to help prevent 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
22 river management approach that takes into consideration human water needs (Acreman and
23 Dunbar, 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,
28 the 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

1 part and flood plains and meadows in the lower part. Average annual rainfall varies from
2 540mm 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
5 are shown in Figure 1. Around 95% of yearly surface water abstractions are appropriated by
6 the 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
18 implemented to model the fixed volumetric water management system only. This is
19 represented in the model by constraints on license usage. When the river flows are below the
20 threshold limit defined by the hands-off-flow (HoF), the license is temporarily suspended,
21 prohibiting abstractions or trading of this license. The rule specified in Section 57 of the 1991
22 Water Resources Act reduces spray irrigation water diversions when river flow reaches low
23 levels. In our model a 50% rationing is imposed on farmers when river flows are below the
24 flow historically exceeded 95% of the time at the downstream gauges (see appendix B for
25 equations).

26 To model PWS Reservoir operation rules, the following set of instructions is employed for
27 both the fixed and dynamic water management licensing regimes. If reservoir storage is
28 below the minimum volume, withdrawals from the reservoir stop. Storage target seeking
29 behaviour by utilities is modelled by penalizing storage target deviations in the objective
30 function. As the reservoir levels get progressively lower, the more water-saving initiatives are
31 implemented, and the lower proportion of the demand is satisfied, resulting in lower benefits

1 from water use for the water company and the consumers. This loss of benefits is reflected in
2 the reservoir deviation penalty factor α (y-axis in Figure 2 (left)):

3

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

4

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

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

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

14

15 **3.3.2. Water trading**

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

28

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 figure 3). Using the Environmental Flow Indicator (EFI) method discussed in Section 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). Please see Klaar et al. (2014) for further information on the EFI approach.

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 Section 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 (Figure 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.

4.2. Water diversions

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

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

14 **4.3. License trading results**

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

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

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

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

23

24 **5. Discussion**

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

30 Gross economic benefits from water use are estimated for each abstraction license holder
31 using their economic water demand functions (see Erfani et al. (2014) for details). For each
32 week, the benefits generated from water use by each abstractor were aggregated into sectoral

1 benefits. Figure 8 compares the economic benefits by sector generated from water use for the
2 two licensing systems in conjunction with the modelled water market. The energy sector sees
3 the largest decrease in benefits due to the increased environmental protection of the proposed
4 licensing system mostly due to the sector's inability to buy water from public water under
5 drought. The water company also incurs significant summer losses as it introduces
6 restrictions. English policy-makers are currently discussing the possible 'grandfathering' of
7 the current system priorities in the new licensing system; this would result in a multi-tiered
8 scaling systems where certain sectors have priority over others. As the details of such a
9 system were not yet established, these have not been modelled, but if PWS were given
10 priority within the scaled system, its loss of benefits would likely decrease.

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

18 These opportunity costs for improving environmental flows may appear large. Our analysis
19 uses catchment inflows from one of the driest years on record so this cost can be considered
20 an upper-bound on potential costs imposed on water users for enhanced environmental
21 performance. Also, if the power station had an alternative supply to its surface water licence,
22 its opportunity costs would decrease. To put the value in perspective, a survey by NERA
23 (2007) estimated the present value of improvements in water environment of all water bodies
24 in the UK to be between £18bn and £29bn (benefits incurred for an indefinite period), or
25 between £618 and £1020 million per year. Garrod and Willis (1996) estimated the annual
26 value of alleviating low flows for River Darent (river catchment area is 14% of the Great
27 Ouse) at around £37 million (£2011).

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

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

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

27

28 **6. Conclusions**

29 This paper uses a hydro-economic model to assess the performance of two water licensing
30 regimes in conjunction with surface water markets. The first regime is the minimum-flow-
31 based system with fixed volumetric licenses currently used in England and Wales. The
32 second one is a proposed licensing system based on scalable licenses where shares are

1 translated into actual permissible allocation volumes depending on minimum environmental
 2 flows that are set dynamically to adapt to naturalised flow conditions. The model was applied
 3 to the Great Ouse River basin in East England over a historically dry year.

4 Results suggest the proposed dynamic environmental flow with scalable licensing system is
 5 better able to prevent very low flows during droughts than the current abstraction regime
 6 based on volumetric licensing. Flows under the proposed system don't reduce below
 7 680Ml/week whereas under current licensing flows reduce down to nearly zero for over 4
 8 months of the year. With more water left to the environment, less water is available to satisfy
 9 human water demands leading to a more active water market. The number of trades under the
 10 scalable licenses system is more than double the number under current system and the
 11 volume traded is 77% greater. Still the more active water market is not able to compensate
 12 for the loss of abstraction (increases in environmental flows); the opportunity cost of the
 13 increased environmental quality in the dry year is a loss of about 15% compared to the
 14 current licensing system with a water market, or 10% when compared to current system
 15 without a market (the current situation).

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

26

27 **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
$flGA_j$	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
3 convenience. Section headers specify which section of the current paper the equation relates
4 to.

5

6 **Section 2.1.**

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

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

10 subject to the following mass balance constraints:

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

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

11

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

12

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

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

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

13

$$ReturnFlow_{ij} = \sum_{k \in Owner} (1 - consFactor_i) WaterAbstracted_i^k$$

$$\forall i \in User, \quad DW_{ij} = 1 \quad (B6)$$

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

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:

$$(flGA_j \leq AlGA_j) \rightarrow (WaterAbstracted_i^{k \in river} + Trade_i^{k \in river} = 0)$$

$$\forall i \in user, j \in Gauge, \quad RuGA_{ij} = 1 \quad (B8)$$

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

$$(flGA_j \leq Q95GA_j) \rightarrow (WaterAbstracted_i^{k \in river} + Trade_i^{k \in river} \leq 0.5 \times WkLi_i)$$

$$\forall i \in Agriculture, j \in Gauge, \quad UpGA_{ij} = 1 \quad (B9)$$

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:

$$WaterAbstracted_i^j = F\left(\sum_{k \in Owner} Res_j^k\right),$$

$$\forall i \in user, j \in Reservoir, CO_{li} = 1 \quad (B11)$$

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

1 **References**

- 2 Acreman, M.: Linking science and decision-making: features and experience from environmental
3 river flow setting, *Environmental Modelling & Software*, 20, 99-109,
4 <http://dx.doi.org/10.1016/j.envsoft.2003.08.019>, 2005.
5
- 6 Acreman, M. C., and Dunbar, M. J.: Defining environmental river flow requirements - a review,
7 *Hydrology and Earth System Sciences*, 8, 861-876, 2004.
8
- 9 Acreman, M. C., and Ferguson, A. J. D.: Environmental flows and the European Water Framework
10 Directive, *Freshwater Biology*, 55, 32-48, 10.1111/j.1365-2427.2009.02181.x, 2010.
11
- 12 Arthington, A. H., Bunn, S. E., Poff, N. L., and Naiman, R. J.: The challenge of providing environmental
13 flow rules to sustain river ecosystems, *Ecological Applications*, 16, 1311-1318, 2006.
14
- 15 Bjornlund, H.: Efficient water market mechanism to cope with water scarcity, *International Journal*
16 *of Water Resources Development*, 19, 553-567, 2003.
17
- 18 Brewer, J., Glennon, R., Ker, A., and Libecap, G.: 2006 Presidential Address Water Markets in the
19 West: Prices, Trading, and Contractual Forms, *Economic Inquiry*, 46, 91-112, 2008.
20
- 21 Britz, W., Ferris, M., and Kuhn, A.: Modeling water allocating institutions based on Multiple
22 Optimization Problems with Equilibrium Constraints, *Environmental Modelling & Software*, 46, 196-
23 207, <http://dx.doi.org/10.1016/j.envsoft.2013.03.010>, 2013.
24
- 25 Cheng, W.-C., Hsu, N.-S., Cheng, W.-M., and Yeh, W. W. G.: A flow path model for regional water
26 distribution optimization, *Water Resources Research*, 45, W09411, 10.1029/2009WR007826, 2009.
27 Defra: Water for life, 2011.
28
- 29 Draper, A., Jenkins, M., Kirby, K., Lund, J., and Howitt, R.: Economic-Engineering Optimization for
30 California Water Management, *Journal of Water Resources Planning and Management*, 129, 155-
31 164, doi:10.1061/(ASCE)0733-9496(2003)129:3(155), 2003.
32
- 33 EA, and Ofwat: Review of barriers to water rights trading, 2008.
34
- 35 EA: The case for change - current and future water availability, 2011.
36
- 37 EA, and Ofwat: The case for change: Reforming water abstraction management in England, 2012.
38
- 39 EA: Environmental Flow Indicator, edited by: Agency, E., 2013.
40
- 41 EA: Water resources in England and Wales - current state and future pressures, Environment
42 Agency, December 2008.
43
- 44 EA: The Upper Ouse and Bedford Ouse Catchment Abstraction Management Strategy, Environment
45 Agency, March 2005.
46
- 47 Erfani, T., Huskova, I., and Harou, J. J. Tracking trade transactions in water resource systems: A node-
48 arc optimization formulation, *Water Resour. Res.*, 49, 3038–3043, doi:10.1002/wrcr.20211, 2013.
49

1 Erfani, T., Binions, O., and Harou, J. J., Simulating water markets with transaction costs, *Water*
2 *Resour. Res.*, 50, 4726–4745, doi:10.1002/2013WR014493, 2014.

3

4 Garrod, G. D., and Willis, K. G.: Estimating the Benefits of Environmental Enhancement: A Case Study
5 of the River Darent, *Journal of Environmental Planning and Management*, 39, 189-203, 1996.

6

7 Gleick, P.: *The World's Water, Volume 7. The Biennial Report on Freshwater Resources*, 2011.

8

9 Grafton, R. Q., Libecap, G., McGlennon, S., Landry, C., and O'Brien, B.: An integrated assessment of
10 water markets: a cross-country comparison, *Review of Environmental Economics and Policy*, 5, 219-
11 239, 2011.

12

13 Harou, J. J., Pulido-Velazquez, M., Rosenberg, D. E., Medellín-Azuara, J., Lund, J. R., and Howitt, R. E.:
14 Hydro-economic models: Concepts, design, applications, and future prospects, *Journal of Hydrology*,
15 375, 627-643, <http://dx.doi.org/10.1016/j.jhydrol.2009.06.037>, 2009.

16

17 Hodgson, S.: *Modern water rights: Theory and practice*, Food and Agriculture Organization of the
18 United Nations, Rome, 2006.

19

20 Howe, C. W., Schurmeier, D. R., and Shaw, W. D.: Innovative Approaches to Water Allocation: The
21 Potential for Water Markets, *Water Resources Research*, 22, 439-445, 10.1029/WR022i004p00439,
22 1986.

23

24 Katz, D.: Water markets and environmental flows in theory and in practice, *Ecological Applications*,
25 12, 1247-1260, 2011.

26

27 Klaar, M. J., Dunbar, M. J., Warren, M., and Soley, R.: Developing hydroecological models to inform
28 environmental flow standards: a case study from England, *Wiley Interdisciplinary Reviews: Water*, 1,
29 207-217, 10.1002/wat2.1012, 2014.

30

31 Libecap, G., Grafton, R. Q., Landry, C., O'Brien, R. J., and Edwards, E. C.: *Water Scarcity and Water*
32 *Markets: A Comparison of Institutions and Practices in the Murray-Darling Basin of Australia and the*
33 *Western US*, ICER Working Paper No. 28/2010, 2010.

34

35 Loucks, D. P., Stedinger, J. R., & Haith, D. A. *Water resources systems planning and analysis*.
36 Englewood Cliffs, N.J.: Prentice-Hal, 1981.

37

38 Loucks, D. P., E. van Beek. *Water Resources Systems Planning and Management - An Introduction to*
39 *Methods, Models and Applications*. Paris: UNESCO, 2006.

40

41 NERA: *The Benefits of Water Framework Directive Programmes of Measures in England and Wales. A*
42 *Final Report to DEFRA re CRP Project 4b/c*, 2007.

43

44 Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegard, K. L., Richter, B. D., Sparks, R. E., and
45 Stromberg, J. C.: The Natural Flow Regime, *BioScience*, 47, 769-784, 10.2307/1313099, 1997.

46

47 Postel, S. L., Daily, G. C., and Ehrlich, P. R.: Human appropriation of renewable fresh water, *Science-*
48 *AAAS-Weekly Paper Edition*, 271, 785-787, 1996.

49

50 Postel, S. L.: Water for Food Production: Will There Be Enough in 2025?, *BioScience*, 48, 629-637,
51 10.2307/1313422, 1998.

1
2 Richter, B. D., Davis, M. M., Apse, C., and Konrad, C.: A PRESUMPTIVE STANDARD FOR
3 ENVIRONMENTAL FLOW PROTECTION, *River Research and Applications*, 28, 1312-1321,
4 10.1002/rra.1511, 2012.
5
6 Smakhtin, V. U., Revenga, C., and Döll, P.: Taking into account environmental water requirements in
7 global-scale water resources assessments, *Comprehensive Assessment Secretariat, Colombo, Sri*
8 *Lanka*, 2004.
9
10 Stern, J.: *Water Rights and Water Trading in England and Wales*, The Foundation for Law, Justice and
11 *Society*, 2013.
12
13 Syme, G. J., Nancarrow, B. E., and McCreddin, J. A.: Defining the components of fairness in the
14 allocation of water to environmental and human uses, *J. Environ. Manage.*, 57, 51-70,
15 <http://dx.doi.org/10.1006/jema.1999.0282>, 1999.
16
17 Tharme, R. E.: A global perspective on environmental flow assessment: emerging trends in the
18 development and application of environmental flow methodologies for rivers, *River Research and*
19 *Applications*, 19, 397-441, 10.1002/rra.736, 2003.
20
21 Thobani, M.: Formal Water Markets: Why, When, and How to Introduce Tradable Water Rights, *The*
22 *World Bank Research Observer*, 12, 161-179, 10.1093/wbro/12.2.161, 1997.
23
24 Ward, F., Booker, J., and Michelsen, A.: Integrated Economic, Hydrologic, and Institutional Analysis
25 of Policy Responses to Mitigate Drought Impacts in Rio Grande Basin, *Journal of Water Resources*
26 *Planning and Management*, 132, 488-502, doi:10.1061/(ASCE)0733-9496(2006)132:6(488), 2006.
27
28 Wheeler, S., Garrick, D., Loch, A., and Bjornlund, H.: Evaluating water market products to acquire
29 water for the environment in Australia, *Land Use Policy*, 30, 427-436,
30 <http://dx.doi.org/10.1016/j.landusepol.2012.04.004>, 2013.
31
32 Wilkinson, M.: Farmers won't go with flow, in: *Sydney Morning Herald*, Sydney, 2008.
33
34 Young, M., and McColl, J.: Defining Tradable Water Entitlements and Allocations: A Robust System,
35 *Canadian Water Resources Journal*, 30, 65-72, 10.4296/cwrj300165, 2005.
36
37 Young, M.: *Towards a Generic Framework for the Abstraction and Utilisation of Water in England*
38 *and Wales*, UCL Environment Institute Report 2012.

39
40
41
42

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

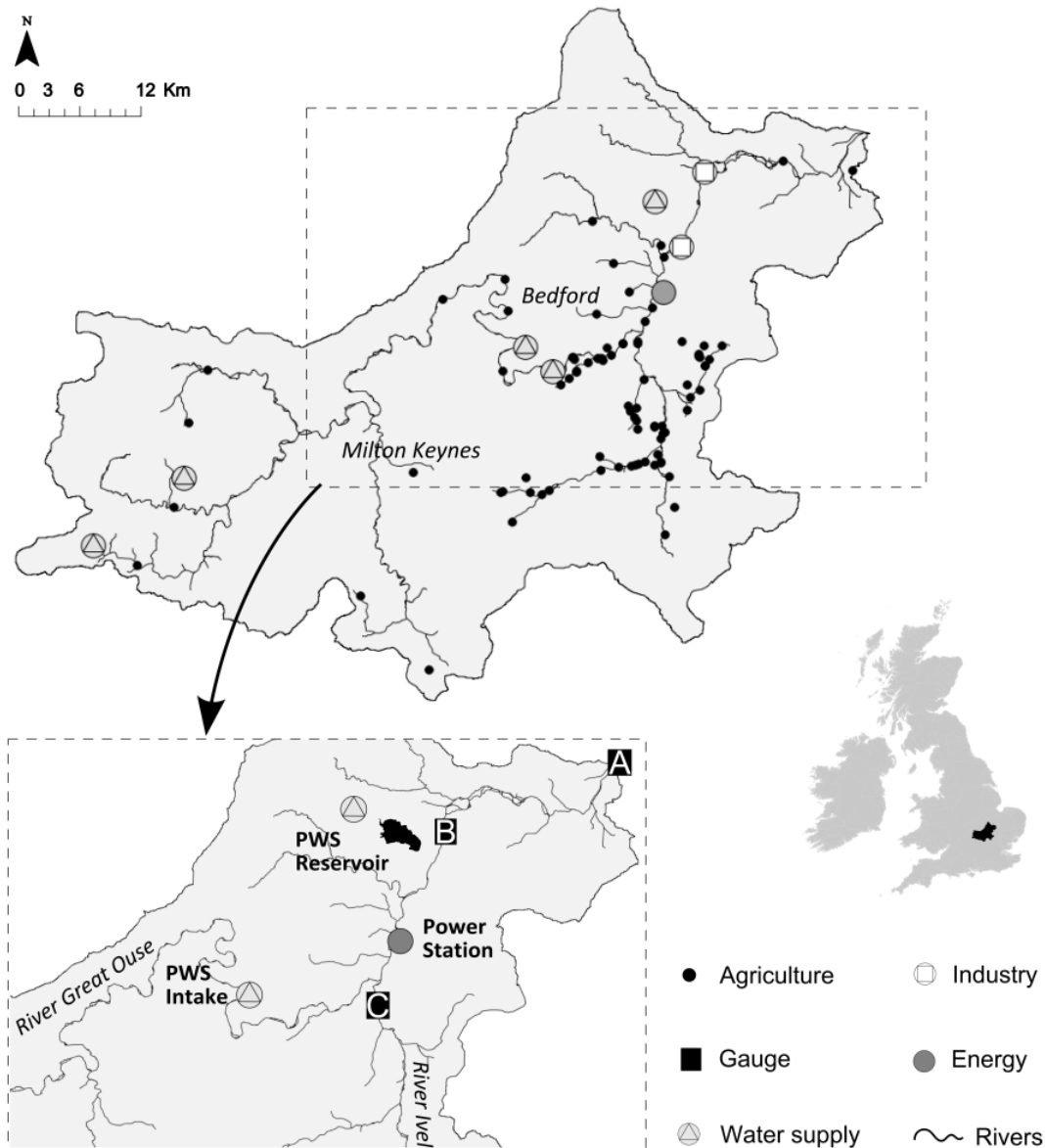
Percentile natural flow at downstream gauge of the sub-catchment	Q30	Q50	Q70	Q95
Percentage of naturalised flow allowed for abstraction (%)	26	24	20	15

3
4
5
6
7
8
9

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.

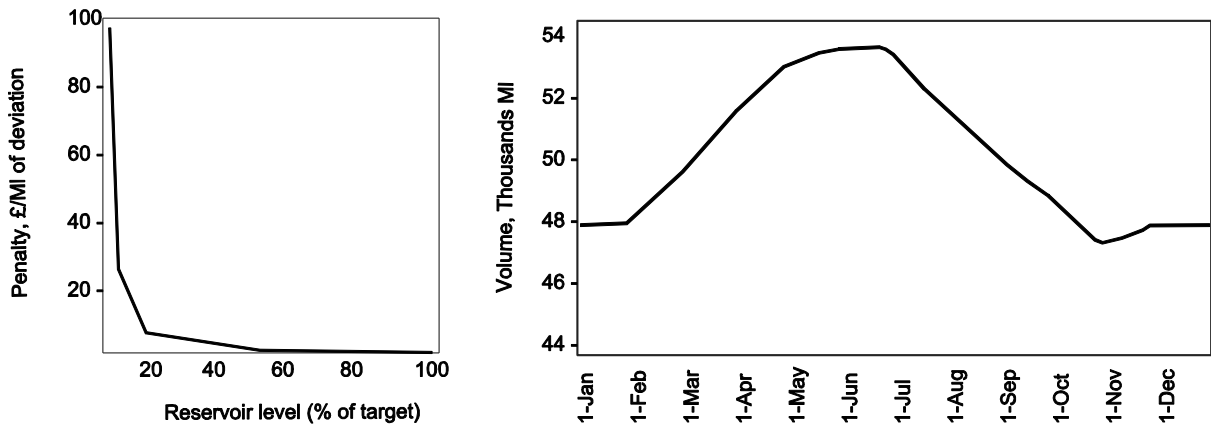
	Volumetric licenses	Sharing system
Number of trades	299	678
Sellers	48	90
Buyers	19	32
Total volumes traded, MI	2750	4860

12
13
14
15
16



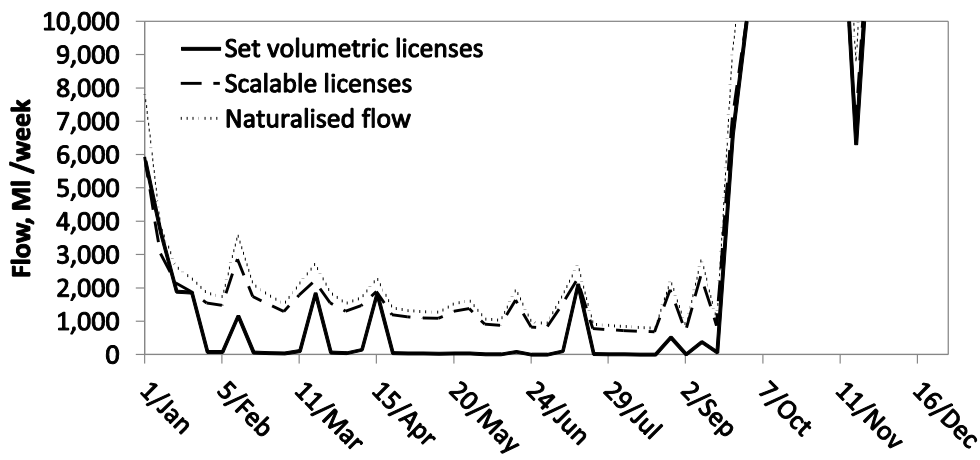
1

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



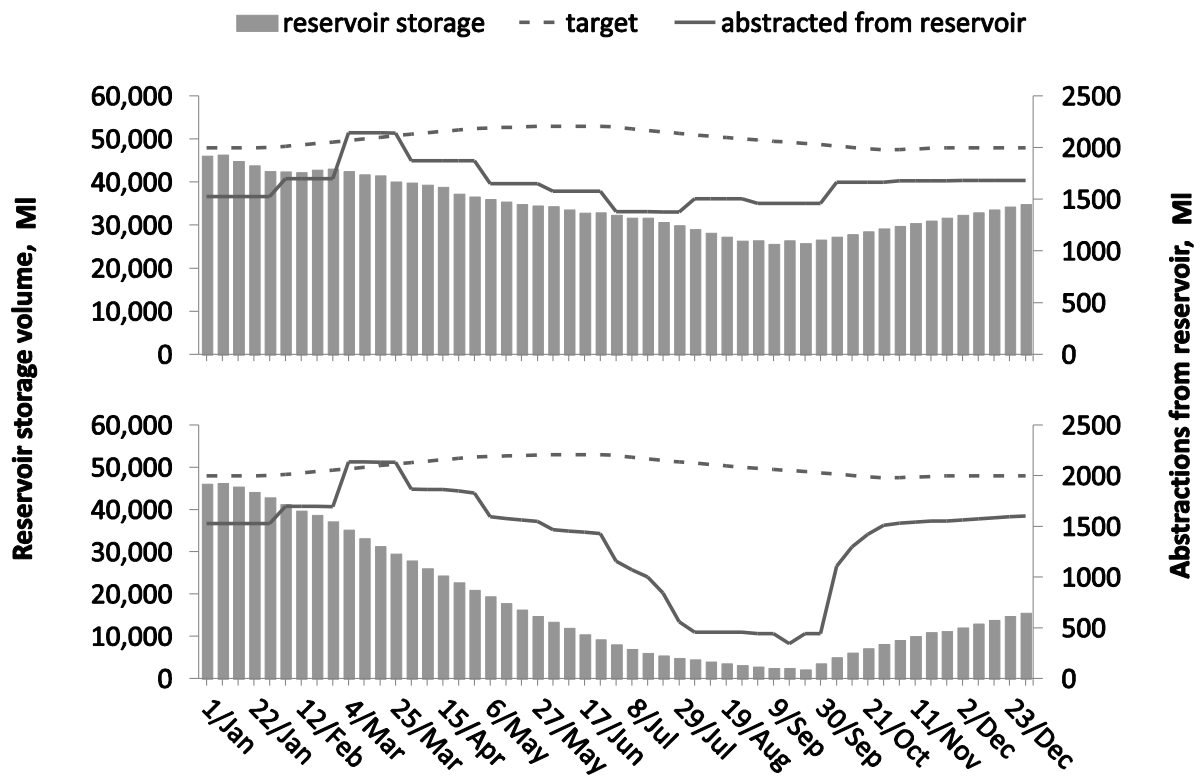
1
2
3
4
5
6
7
8

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



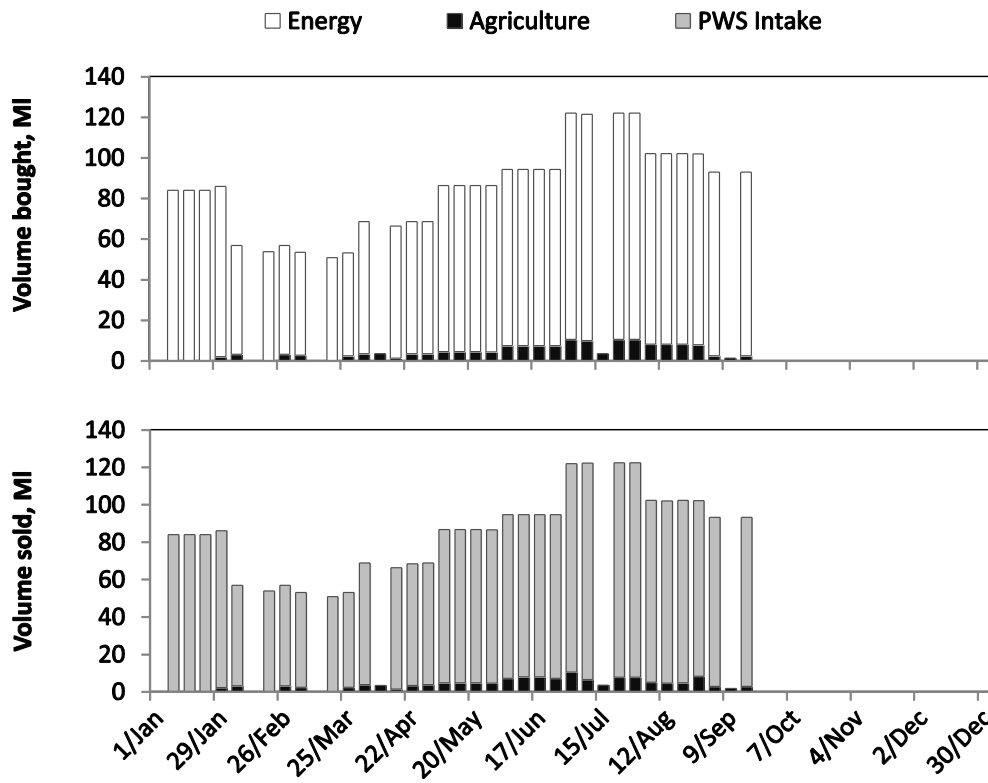
9

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



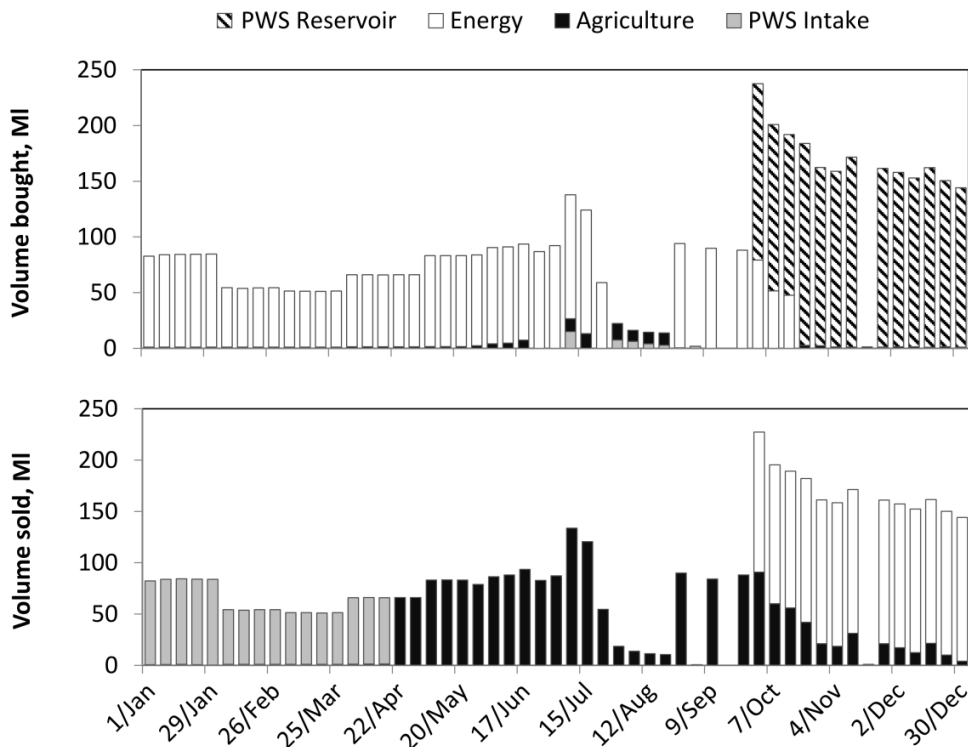
1
2
3
4
5

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



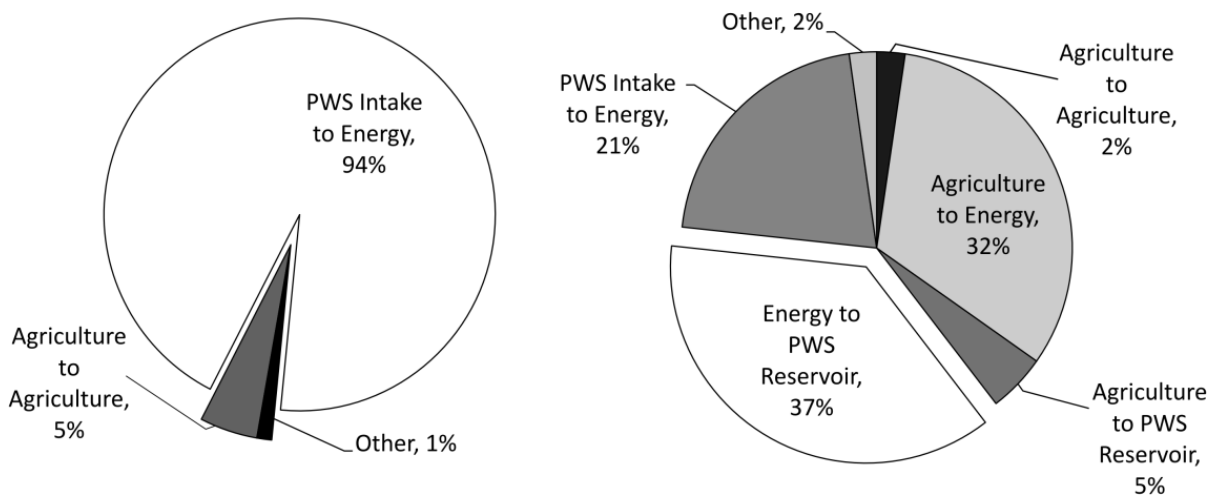
1
2
3
4

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



1
2
3
4
5
6

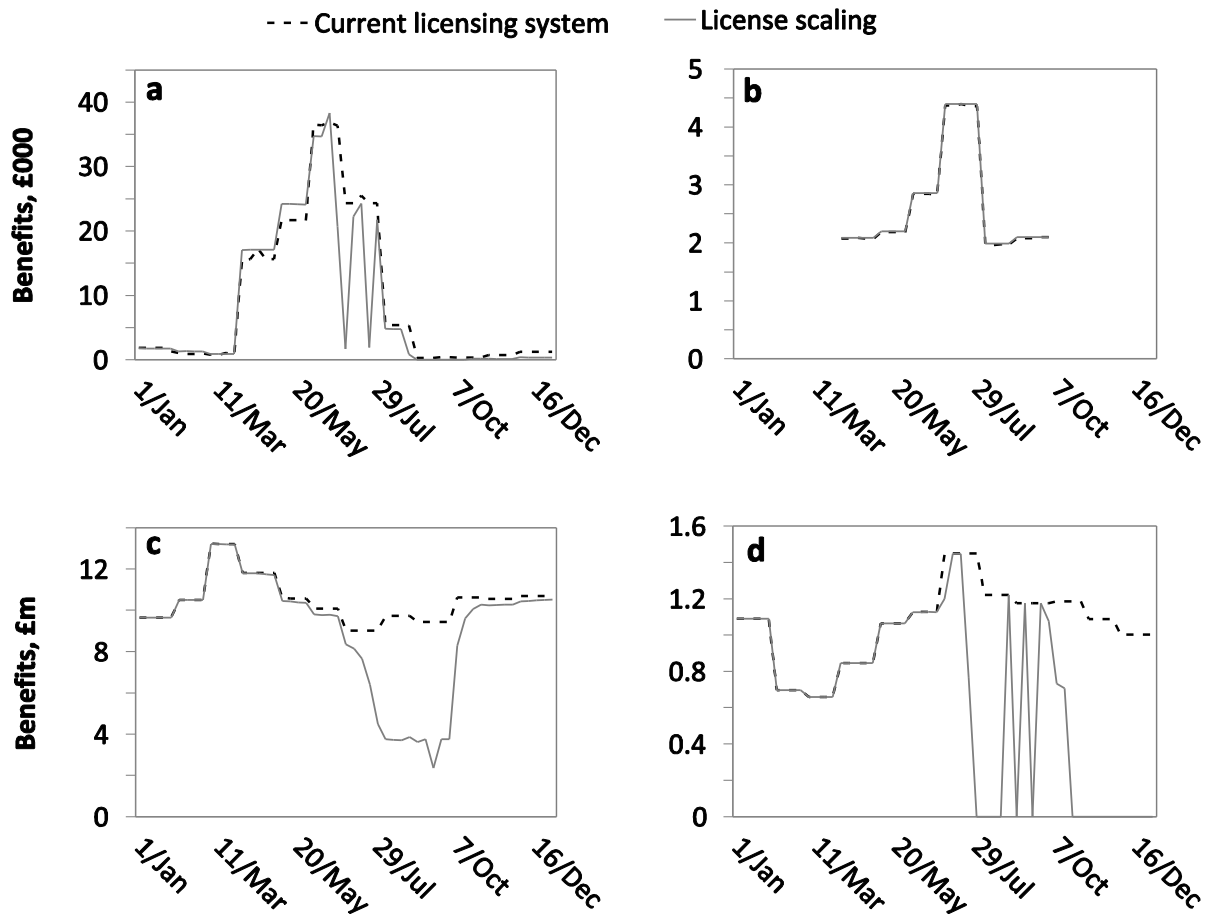
Figure 6 Water volumes bought (top) and sold (bottom) in millions of litres per week by sector under the proposed (scalable) licensing system.



7
8
9
10

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.

1

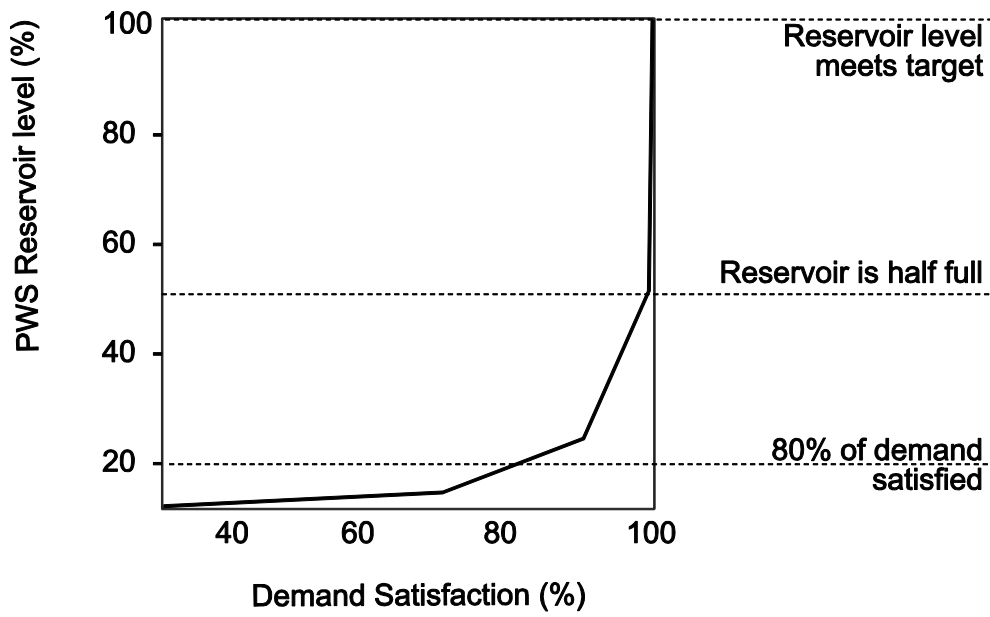


2

3 **Figure 8** Comparison of gross economic benefits by sector from water use under the current
4 and proposed licensing systems acting in conjunction with a short-term water market. The
5 results are aggregated by sector: a) Agriculture; b) Industry; c) Water Supply; d) Energy. The
6 top panels show benefits in thousands of pounds and the bottom one in millions.

7

8



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