Response to Referees

Protecting environmental flows through enhanced water licensing and water markets

T. Erfani, O. Binions and J.J. Harou

Referee #1

Referee: This manuscript addresses an interesting topic related to the impacts of institutional change to water allocation approaches in the UK. At the heart of this manuscript is an analysis of the differences between an allocation policy with rights/licenses subject to a constant minimum flow constraint, and one in which the quantity that the license entitles the owner to "scales" as streamflow declines. Results suggest that the scaled approach protects environmental flows more effectively, but at the sacrifice of some economic benefits.

I found the paper to be interesting, and the modeling approach sound, but kept asking what the nature of the contribution might be. The results are useful (i.e. scaled approach improves environmental flows), in particular to the basin in question, but surely the outcome could have been largely predicted before the analysis was undertaken. Is identifying the magnitude of the effect alone enough to constitute a novel addition to the literature? I'm not sure. The fact that this manuscript appears to be the third of three papers in a similar vein also gives rise to questions about what differentiates this work from the earlier submissions (both in review). It would be nice to see the authors take a bit more time to make an academic case for the novelty of the work. Presuming that the authors can provide a reasonable rationale, this work is likely to be interesting to some portion of the HESS readership.

Authors' response:

The authors thank Referee #1 for their comments and we appreciate this opportunity to further specify the paper's research contribution, both here and in the manuscript. First we will explain how this paper relates to the two related 2013, 2014 Erfani et al. papers (now published in Water Resources Research) by the same authors, and secondly we describe further the paper's academic and water management contribution.

1. Erfani et al. (2013) described a modification of a conventional network flow optimisation model formulation that enables such a model to track transactions in water resource networks. Erfani et al. (2014) used the innovative optimisation formulation published in 2013 to propose a generic optimisation-driven simulation model of a water market that can incorporate transaction costs, i.e., the cost incurred when water users interact in a water resource system with market transactions. This model was applied to the Ouse basin, comparing results with and without a market. In summary these two WRR papers are modelling papers; they build a new model type (Erfani et al 2013), and they use it build a generic model of a water market (Erfani et al 2014).

2. The submitted paper is a different type of paper. It is not primarily a modelling methods paper; this is a water management paper designed to simulate and evaluate specific English water management policy proposals. In England policy makers are considering some radical water management proposals to react to increasing water scarcity (many basins are over-extracted) and policy realities (e.g. EU water framework directive). Currently, this had led to 3 policy proposals:

1. Current volumetric licenses will be replaced by water 'shares', where abstractors get a percentage of the environmentally available water rather than a fixed volume.
2. Environmental minimum flows should vary as a function of environmental conditions (as manifested by hydrological flows), rather than being fixed.
3. Water markets should be enabled by legislation such that when abstraction is restricted, high economic value water users can obtain water on a spot market (i.e. enact short-term water leases with other water rights holders).

This leads to the following policy question: how would the system perform (hydrologically and economically) if the proposals were enacted?

This policy question had never been posed before, a model did not exist to address it, and no case-study had been implemented to investigate it with a real-world system. We do all three in the submitted paper and that is the paper's unique contribution. In this light, the paper is, in our opinion, a fully original and significant specific contribution to the literature and is not incremental. Results of the study are significant and of direct interest to the current policy-maker decision: should we enact these reforms? The paper reveals that in a historical dry year, the annual total catchment societal lost economic benefits due to the new policies (what economists call the 'opportunity cost') would be £58 million (a 10% loss) compared to the existing system. It is now up to policy-makers to decide whether this cost is appropriate and justified given the increases environmental quality linked to higher flows during dry periods.

To answer the policy question we extended a state-of-the-art hydro-economic agent water market simulation model such that it represents the three policy proposals. Our existing water market simulation model, published in WRR in 2014, covers policy question 3. In this submitted paper we modified the model such that it represents policy proposals 1 and 2 which involved embedding new equations into the optimisation model constraint set. These are significant modelling innovations beyond the WRR paper.

The modelling is innovative and state of the art, but the most noteworthy aspect of the paper is the novelty and ambition of the paper's questions and the policy relevance of its results. We have answered a current policy question in a rigorous and comprehensive way using state-of-the-art hydro-social analysis. Results are directly relevant to the UK and to other countries considering changing their water abstraction policies to improve the ecological health of river systems. Because of the success of the Australian shares-based licensing system in helping Australia survive its recent unprecedented decade long drought with minimal economic scarcity costs, there is currently significant international interest in their innovative 'shares' licensing system. Such a system is used in no other country. England is currently considering it; this is a significant development in water management science. This paper represents the first quantified assessment of its potential hydrological and economic impacts on a real UK water system. Results were enabled by a customised policy relevant model which uses the latest in hydro-economic modelling methods.

It was our assessment that such a contribution would be highly regarded in a hydrological system science journal, considering that humans play an influential role in terrestrial hydrology in many areas. Human water abstraction is an essential component of the hydrological system in England. This paper was funded by government and has been presented several times to different groups in the Environment Agency, DEFRA, and to water company regulation managers. It has been met with very substantial interest; this sort of policy modelling is not typically practiced in England. In our group we consider this paper to be perhaps the most significant work we have produced in recent years. New models appear every day, but models built for and with the participation of government officials to answer current sophisticated policy questions, this is truly of scientific and practical value we believe. As water management academics, this is what we most strive for.

To better specify the nature of the research contribution, we have edited the end of the introduction, the new text is as follows:

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

Based on the above, we believe this paper is a state-of-the-art research contribution in water markets and associated water management policy design. We've presented this work at several UK water management meetings and international academic conferences; in both cases the work, because of the modelling and its implications, has received a positive response and led to interesting discussions on future water management.

Referee: With regard to specific questions, most of mine revolve around the role of Public Water Supplies (PWSs) in this work. Do I understand correctly that PWS usage (read: urban) comprises 95% of basin demand? If so, does that make this problem less interesting in general?

Authors' response: PWS abstraction in the case-study basin constitute 95% of total yearly historical abstractions. However, PWS water abstracted is not all used within the basin (the largest proportion is stored in the reservoir also feeds surrounding population centres). Generally the UK has higher relative PWS consumption than many other countries using or considering water markets. In many areas with markets, market activity is somewhat predictable: farmers sell to cities during dry spells. In this case, because of the high volume of high-value usage (PWS, energy cooling) in the basin, results are different than in many water market studies; we see this as strength of the case-study. In particular, the study allows investigating for example how reservoirs could be used in markets and how large well-funded actors could potentially interact with a multitude of smaller actors (e.g. farmers) with lower valued water uses, in a context where there is high value placed on environmental quality. This is an interesting topic for the future, bringing up human-environment interaction issues relevant to precisely the special issue to which this paper was submitted. This topic also brings up human equity issues of general interest to water managers and water market specialists.

Referee: In most water scarce regions the transfers move irrigation-to-urban uses, but here it is urban-to-power. In the regions I am familiar with, an urban supplier would never transfer water to another user under conditions of scarcity out of concern (however unjustified) that the urban supplier might "run out" of water.

Authors' response: Thank you, this is of course a good and fair point. The paper does consider concerns over selling water that a public water supply company would certainly have. This concern is reflected in a trading rule described on last paragraph of Section 3.3.1. The PWS has 2 surface water sources, one being the reservoir. When a drought alert is activated (when the reservoir is some % below the target storage), PWS stops selling water. The percentage can be changed to investigate different levels of conservatism by PWS managers. We used 50% as an example. This is perhaps on the low side, but we wanted to investigate how a relatively active market would work, so we chose this number. Further studies could complete a large sensitivity analysis, where the behaviours of different agents could be varied systematically to assess impacts on other sectors.

Referee: In this case, it appears that the PWSs enjoy some sort of favored status under drought, however, and are not subject to reductions in their supply. If true, is that the reason that they feel comfortable in selling water to energy producers during drought (i.e. they have so much that it doesn't matter). And, if that is the case, it would seem that the PWSs are set up to collect substantial economic rents from this arrangement. Some more discussion of this would assist in an understanding of Figures 5 & 6. This point might also have bearing on the transferability of the results to other water scarce regions, especially if the magnitude of the economic losses imposed by a move to scalable allocations in the point of the paper (this value is likely to be substantially higher than in the more common scenario involving irrigator-to-urban transfers in a market where urban users receive no such protection).

Authors' response: Thank you for this interesting comment. We have added text to the discussion section (see below) about Figures 5 and 6 to respond to the comment above.

Under the current licensing system, both of the PWS licenses are not restricted by 'hands-off flow' (HoF) rules (please see Section 4.2) although they still have maximum weekly and yearly allowances. The PWS Intake abstracts the amount demanded, and sells the rest to other users (mostly the Power station). As noted in the previous response, the PWS agent only sells water if the reservoir is sufficiently full. Regulators are definitely concerned about rent seeking behaviour of privatised water companies. Under license scaling, as modelled, PWS loses its priority status (because the lack of HoF conditions on the PWS license is replaced by severe restrictions imposed on all abstractors by the new environment flows regime). This means reservoir storage reduces rapidly and PWS is unable to sell water from end of April. In fact, in the shares-based system, PWS has to buy allocations from other users in June-September, so the irrigator-to-urban transfers are presented. A variety of other attitudes to trading could be represented in the model, but we consider this more behavioural work is beyond the scope of this paper.

The following text was added at the beginning of results section 4.3:

"Figure 5 shows that because of PWS's lack of HoF conditions, they are able to sell water to the energy sector throughout the year. Under the proposed system as modelled (Figure 6), where sectors are on equal footing, these rents are not available and PWS stops selling water at the end of April, at which point the energy sector begins buying from farmers (with higher transaction costs due to the larger number of transactions involved)."

Referee #2

Referee: Main part of the method adopted in this manuscript is very similar to the one used in another paper published by the authors (Erfani et al., 2014, Water Research). I would suggest the author try to revise their manuscript greatly and specify the main innovations compared with their previous works.

Author response:

Thank you for this comment. We have included here a response that was also provided to the other referee to specify the exact nature of the academic research contribution.

The authors thank Referee #2 for their comments and we appreciate this opportunity to further specify the paper's research contribution, both here and in the manuscript. First we will explain how this paper relates to the two related 2013, 2014 Erfani et al. papers (now published in Water Resources Research) by the same authors, and secondly we describe further the paper's academic and water management contribution.

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The modelling is innovative and state of the art, but the most noteworthy aspect of the paper is the novelty and ambition of the paper's questions and the policy relevance of its results. We have answered a current policy question in a rigorous and comprehensive way using state-of-the-art hydro-social analysis. Results are directly relevant to the UK and to other countries considering changing their water abstraction policies to improve the ecological health of river systems. Because of the success of the Australian shares-based licensing system in helping Australia survive its recent unprecedented decade long drought with minimal economic scarcity costs, there is currently significant international interest in their innovative 'shares' licensing system. Such a system is used in no other country. England is currently considering it; this is a significant development in water management science. This paper represents the first quantified assessment of its potential hydrological and economic impacts on a real UK water system. Results were enabled by a customised policy relevant model which uses the latest in hydro-economic modelling methods.

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Referee:

Detailed comments for authors:

1. In 2.1, the core model is similar with the author's previous paper. The further extended models, described in the sections 2.2 and 2.3, are regarded as two more constraints compared with the authors' previous work,

Authors' response: As detailed in the previous author response, this paper builds on the Erfani et al. (2014) paper. The equations presented in sections 2.2 and 2.3 are new. Also, the way in which the shares system is modelled is new and distinct from Erfani et al. (2014). Firstly, the river basin is broken down into sub-catchments delineated by gauging stations. Each sub-catchment's abstraction volumes are determined as a percentage of the environmental flow. Secondly, within each sub-catchment, each water abstraction license is translated into a share of the available resource.

As discussed in the comment above, this is not primarily a modelling paper, although the modelling innvotations are significant. This is a water management policy investigation. A country with 80 million inhabitants is considering to completely change their water rights regime. We have tested the hydrological and economic implications of this for a complex real-world system. Such a study has never been conducted before. This work was funded by government and extneisvely checked, interrogated and reviewed by various government and water company regulators and managers. The strength of the paper is the way the model was extended to address two pertinent policy questions, and the in-depth way this policy question is addressed (hydrological, allocation, and economic impacts of new regulations). The policy question: how pro-environment regulation would impact water users when paired with a water market is a novel hydro-economic modelling and policy questions and it is answered using state-of-the-art customised modelling approach. The results will be of interest to water managers world-wide who are considering to switch to an Australian style 'shares-based' water allocation system.

Referee:

2. In 2.2 and 3.4, more explanation and comparison of MinFlowj with other similar research should be added,

Authors' response:

Thank you for this comment. Dynamic environmental flows are now being considered in many regions. This is not our invention; we follow the English 'EFI' (Environmental Indicator) approach which has been adopted by England's Environment agency. In response to the request we have now added, in addition to the explanations on EFI in section 3.1, the following reference to section 3.4 which will further clarify the background behind the EFI dynamic flow approach:

"Please see Klaar et al. (2014) for further information on the EFI approach."

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

Referee:

3. The case study in the section 3.2 is the same with the one in section 3 of the authors' previous work (Erfani et al., 2014),

Authors' response: Thank you for this comment. We have given a short review of the case-study basin so that readers don't have to download other papers to understand this paper. Although the case study river basin is the same, the abstraction regulation setting is different: the 2014 paper concerns only the current existing regulation framework. The proposed paper represents a very different "shares-based" licensing system with dynamic environmental flows and compares this to the current system. There are several series of papers in the literature that have been published on a single basin. This is only the second paper published on the Ouse basin and we think this valuable data-rich case-study will support further studies (e.g. we're now working on a paper about how investment in small reservoirs by farmers is encouraged or discouraged by water markets and water management policy innovations).

Referee:

4. The relationship among "junction", "gauge", "node", "junction node", and "river" should be explained in details (e.g., with the employment of a figure).

Authors' response:

Thank you for this comment. We have now added the following text in section 2.1 to further specify what is meant by these terms.

"The river network is modelled as a network of nodes (e.g. demands, storage reservoirs, junctions where flow links converge or diverge) and conveyance links (e.g. river 'reaches', i.e., segments) and water balance is ensured at each junction or storage node (see e.g. Loucks et al., 1981; Loucks and Van Beek, 2005)."

Because we already have many figures (8 in addition to tables), we prefer not to include a figure on this as these are standard terms used to refer to water resource network models. We have included a reference where readers unfamiliar with these terms can get more information. We hope this is acceptable to the reviewer. If not, and if the editors accept to make the apper longer, we can add more information on this point.

We are grateful for the review which has allowed us to improve the paper substantially.

Protecting environmental flows through enhanced water licensing and water markets

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Abstract

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

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

1. Introduction

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

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

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

The objectives of water resource allocation systems is to regulate access to water resources, ensuring flexibility, security of access, predictability, and fairness, and to reflect public values and opportunity costs (Howe et al., 1986). More recently environmental protection has been added to those goals. One of the methods used to preserve adequate river flows is to set a minimum flow below which water abstraction must reduce or cease (Acreman, 2005). These static threshold or minimum flow methods of maintaining river flows often do not achieve ecologically or economically efficient results (Arthington et al., 2006;Katz, 2011). The aquatic environment relies on a natural hydrological cycle, but human water abstractions alter the natural flow variability which is important to sustaining riverine species, and minimum flow regimes do not support natural flow regimes (Poff et al., 1997). Hence, fixed volumetric allowances have evolved into allowances with reference to river flow conditions such as 'per cent of flow' regime, with abstractions limited to a sustainable share of the natural river flows (Richter et al., 2012). Environmental flow methods are used to determine the sustainable levels of abstractions. Over 200 environmental flow approaches have been developed to provide the policy-makers with tools to re-design water allocation systems ensuring that river ecology is protected, whilst taking into account human water needs (Acreman and Dunbar, 2004). Environmental flow methodologies have been developed and applied in 44 countries, spanning 6 world regions with the United States the most active proponent of the approach (Tharme, 2003).

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

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

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

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

2. Methods

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

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2.1. Pair-wise trading model

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

2.2. Dynamic environmental flows

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

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

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

2.3. License scaling

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

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

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

where

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

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

3. Case study

3.1. Water management in England and Wales

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

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

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

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

3.2. Modelling the Great Ouse river basin

To investigate the outcomes of potential license reform options, we apply the proposed model to the 3000 km^2 Great Ouse River basin in eastern England (Figure 1). The largest towns are Milton Keynes and Bedford. The basin is characterized by gently rolling land in the upper

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

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

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3.3. Case study-specific constraints

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

3.3.1. Current license restrictions

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

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

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

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, water sales by PWS the following week are prohibited, until the level recovers.

3.3.2. Water trading

Agricultural users require water for the irrigation season and will in many instances be unwilling to sell their license before it. To represent varying degrees of water market participation, a limit on volumes sold by agricultural users was set in both the fixed and dynamic water management system modelling. For this a constraint (Appendix 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

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.

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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

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

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

4.3. License trading results

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

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

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

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

5. Discussion

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

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

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

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

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

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

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

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

6. Conclusions

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

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

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

Appendix A: Nomenclature

$Junction$	No-demand and non-storage nodes which join 2 or more links in the network
$User$	The set of all licensed river abstractors including Agriculture,

	Industry, Water supply and Energy
Owner	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*

Appendix B. Formulation details

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

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Section 2.1.

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

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

subject to the following mass balance constraints:

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

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

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

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

$$\forall i \in User, k \in Owner \qquad \text{(B4)}$$

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

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

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

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

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:

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

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

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

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

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

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

$$2627 \le \textstyle\sum_{k \in Owner} Res_j^k \le 55450 \qquad \forall j \in Reservoir. \qquad \text{(B10)}$$

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

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

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

where *F(.)* 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.

Section 3.3.2.

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

$$Trade_i^{k \in river} \quad \leq \quad \max\{0, sL_i^t\} \qquad \forall i \in user \qquad \text{(B12)}$$

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

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

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

$$sL_i^0 = YrLi_i - c_i \times EWN_i \qquad \text{(B14)}$$

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

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

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

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

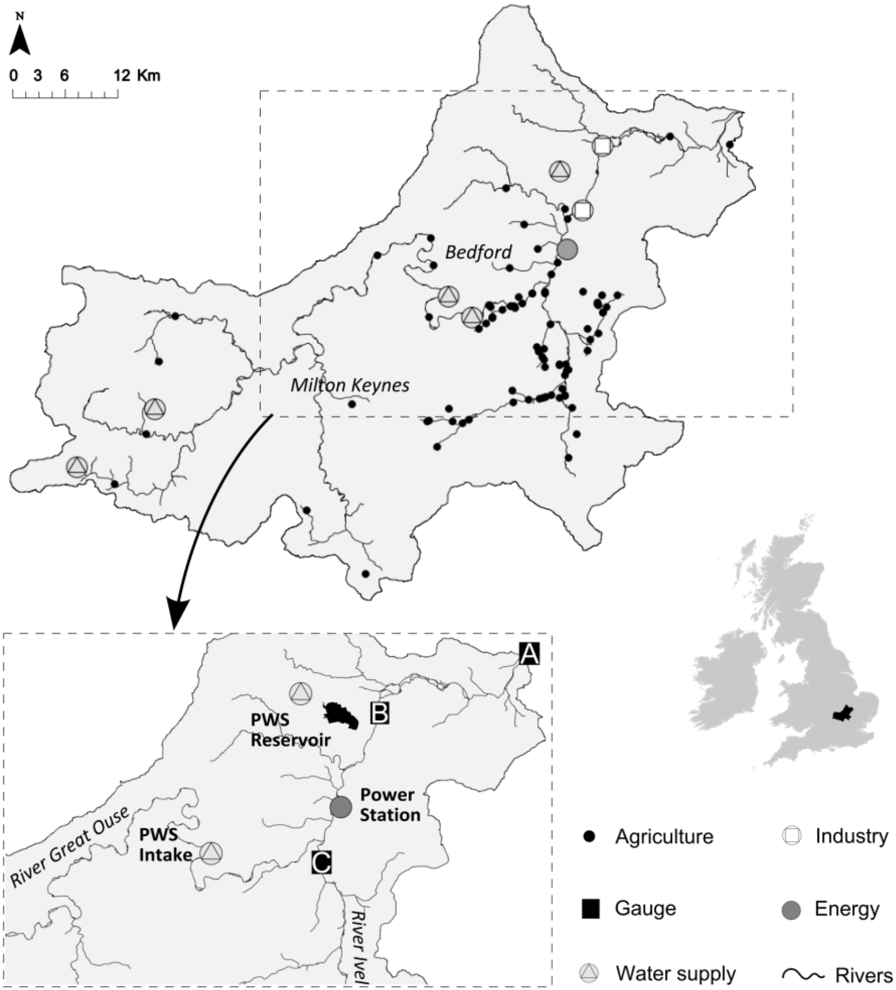

Figure 1 Map of the Great Ouse River basin showing approximate locations of water users and main river flow gauging stations: A – last flow gauge in the basin (sink), B – Offord gauge defining license scaling for PWS Reservoir and Power station, C – gauge defining license scaling for agricultural users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

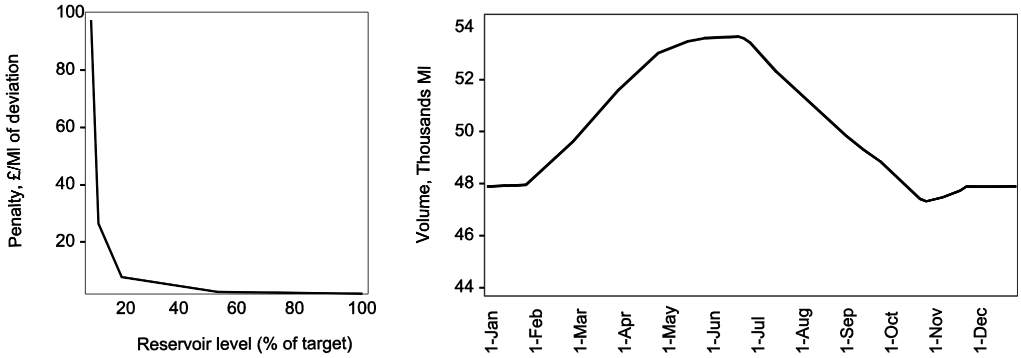

Figure 2 Reservoir storage deviation penalty (left), PWS Reservoir storage targets (right)

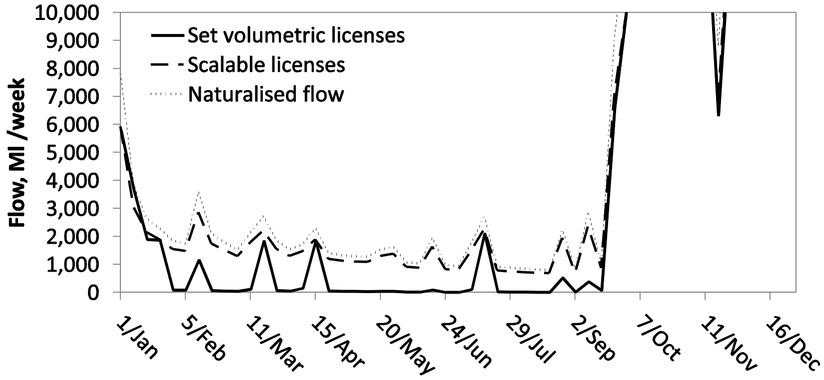

Figure 3 River flow at the last gauge in the basin (marked A in Figure 1).

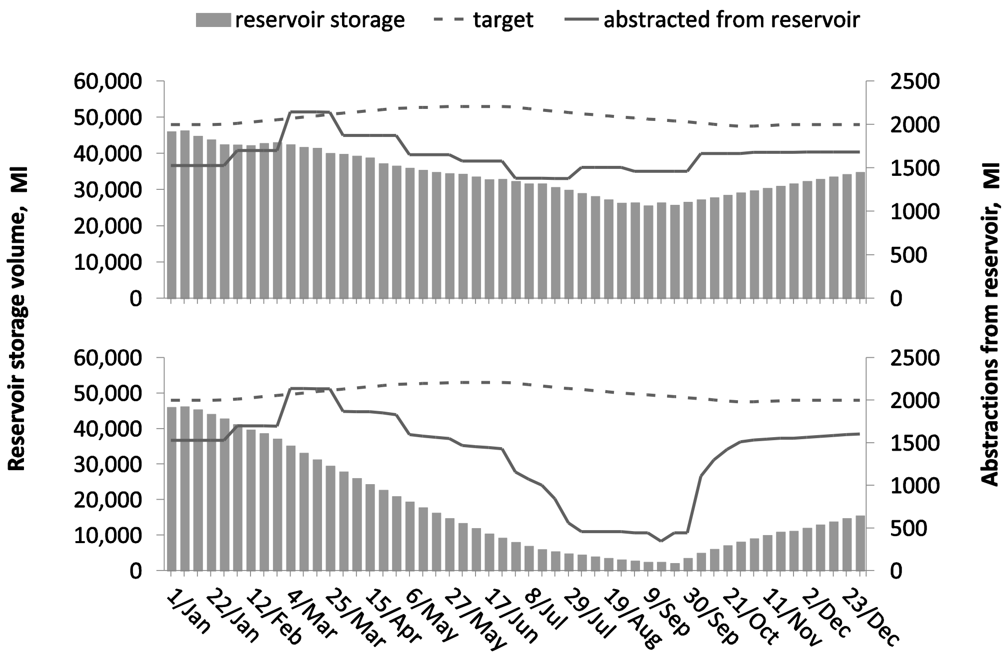

Figure 4 PWS Reservoir storage and abstraction profiles for current (top) and proposed (bottom) licensing systems.

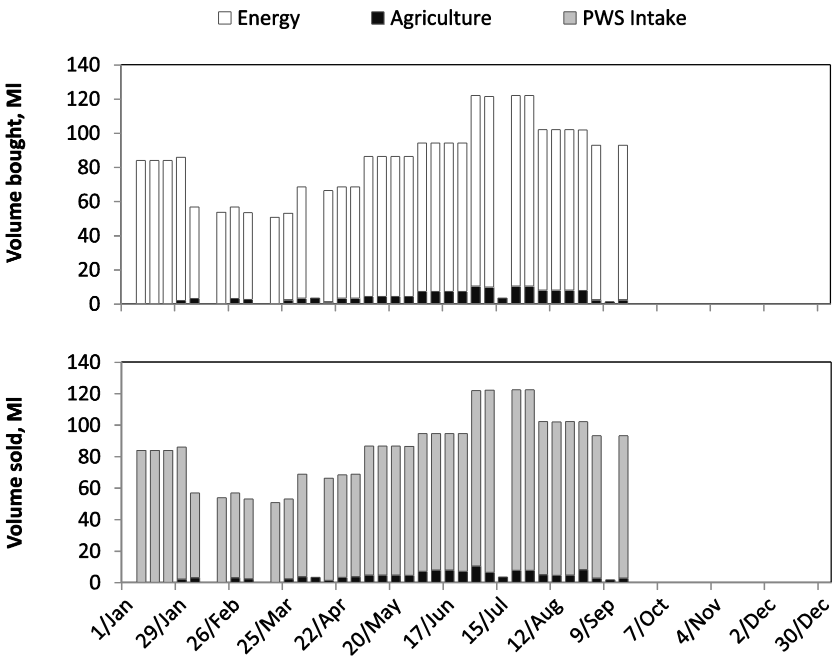

Figure 5 Water volumes bought (top) and sold (bottom) in millions of litres per week by sector under the current licensing (volumetric) system.

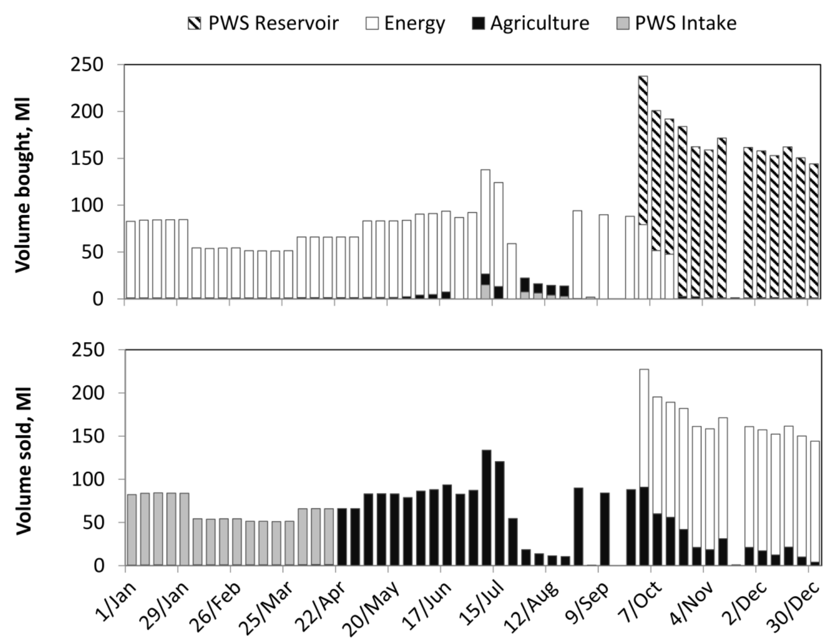

Figure 6 Water volumes bought (top) and sold (bottom) in millions of litres per week by sector under the proposed (scalable) licensing system.

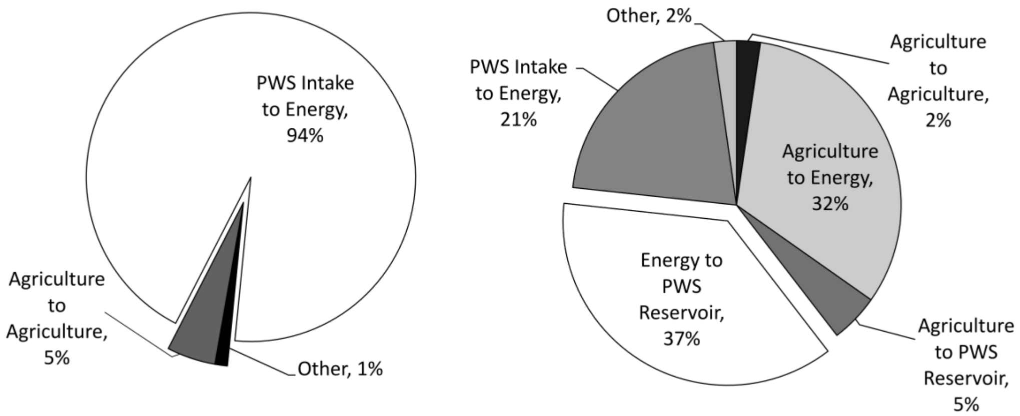

Figure 7 Proportion of the total annual volume of trade transactions between sectors under the current (left) and proposed (right) licensing systems as simulated in a dry year.

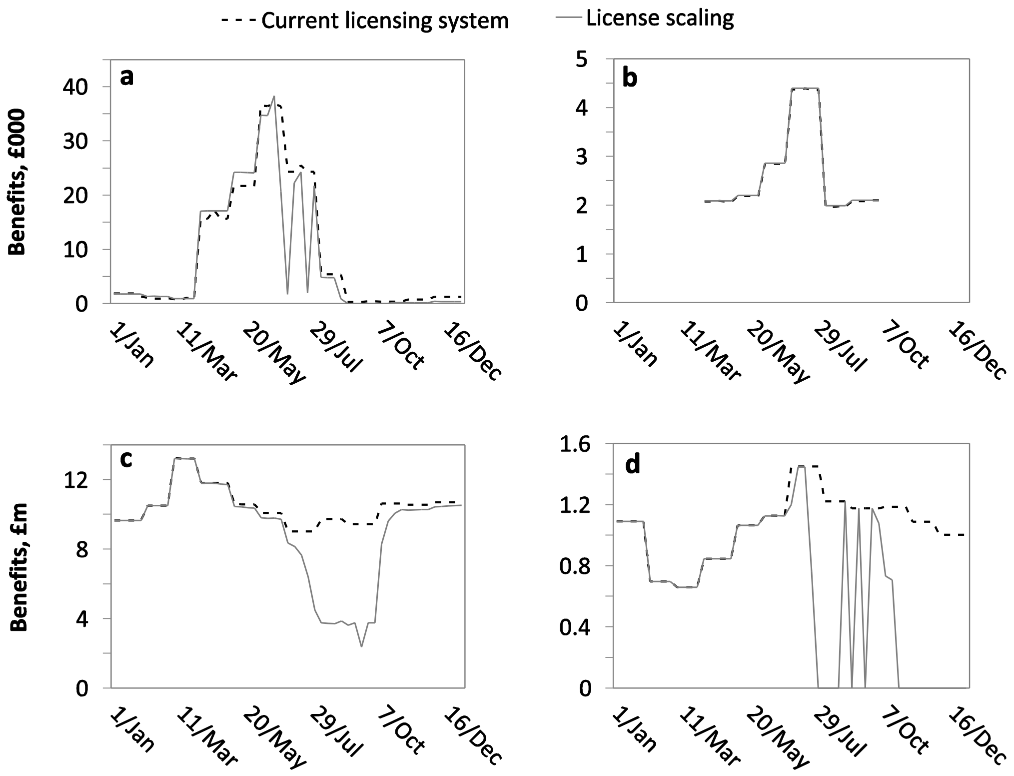

Figure 8 Comparison of gross economic benefits by sector from water use under the current and proposed licensing systems acting in conjunction with a short-term water market. The results are aggregated by sector: a) Agriculture; b) Industry; c) Water Supply; d) Energy. The top panels show benefits in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

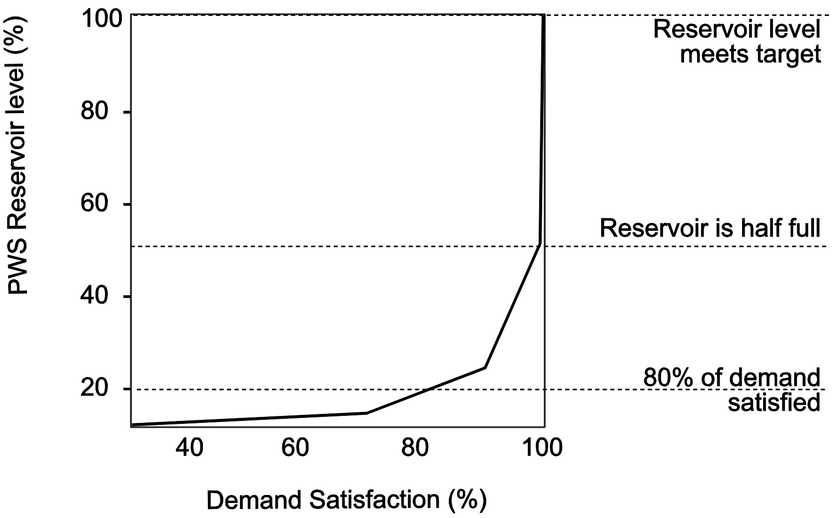

Figure B.1 Public Water Supply company hedging rule.