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Evaluating the Feasibility of Water Sharing as a Drought Risk Management Tool for Irrigated Agriculture

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Abstract: Droughts can exert significant pressure on regional water resources resulting in abstraction constraints for irrigated agriculture with consequences for productivity and revenue. While water trading can support more efficient water allocation, high transactional costs and delays in approvals often restrict its wider uptake among users. Collaborative water sharing is an alternative approach to formal water trading that has received much less regulatory and industry attention. This study assessed how the potential benefits of water sharing to reduce water resources risks in agriculture are affected by both drought severity and the spatial scale of water-sharing agreements. The research focused on an intensively farmed lowland catchment in Eastern England, a known hot-spot for irrigation intensity and recurrent abstraction pressures. The benefits of water sharing were modelled at four spatial scales: (i) individual licence (with no water sharing), (ii) tributary water sharing among small farmer groups (iii) sub-catchment and (iv) catchment scale. The benefits of water sharing were evaluated based on the modelled reductions in the probability of an irrigation deficit occurring (reducing drought risks) and reduced licensed 'headroom' (spare capacity redeployed for more equitable allocation). The potential benefits of water sharing were found to increase with scale, but its impact was limited at high levels of drought severity due to regulatory drought management controls. The broader implications for water sharing to mitigate drought impacts, the barriers to wider uptake and the environmental consequences are discussed.

Keywords: catchment; farm management; modelling; irrigation deficit; water resources

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1. Introduction

Droughts occur in most regions of the world and have affected more people globally than any other natural hazard over the last 40 years [1]. The IPCC's Fifth Assessment report [2] had low confidence in a global-scale observed trend in drought or dryness (lack of rainfall) since the mid-20th century, although it considered it likely that there have been changes in drought frequency and intensity in some regions. However, the challenges of drought and water scarcity are expected to become more severe in many regions over the coming decades [3], due to increasing sectoral competition between water supply, environment and agriculture for water resources [4,5] and increasing climate variability and climate change [6–8].

The agricultural sector is the largest global user of freshwater, mostly for irrigation, and is particularly exposed and vulnerable to both increases in drought and water scarcity [9]. In order to limit environmental impacts, such as the depletion of aquifers, low flows in rivers and degradation of aquatic habitats [10,11] associated with uncontrolled and inefficient abstraction, many countries have abstraction regimes with licences or permitting systems [12–20]. These usually specify a fixed annual allocation of water but tend to be awarded on a 'first come—first served' basis leading to a sub-optimal and over-allocation of water. This is increasingly leading to pressure for more efficient water allocation that moves agricultural irrigation allocations to uses with higher economic value, in particular cities [5,21].

However, agricultural irrigation is not confined to arid and semi-arid regions, but is also increasingly important in humid temperate regions such as the UK [22–25], where supplementary irrigation supports the production of high quality and high-value fruit and vegetables [26,27] and generates high net financial benefits, particularly in drought years [28]. However, agricultural irrigation is often given the lowest use priority under drought conditions, in order to protect drinking water supplies and reduce the risks of environmental degradation, which can lead to widespread regional economic damage [28] (e.g., Anglian Water, University of Cambridge [29]) and along the value chain (e.g., Newton et al. [30]).

Such existing sub-optimal water allocation regimes typically lack the flexibility to address emerging challenges such as drought, which has led to attempts to improve their performance through the use of economic instruments. Water trading, allowing those with a greater allocation than their need to trade water (either permanently or seasonally) to other agricultural or non-agricultural water users [31], is one such approach [32,33]. However, there are concerns over water trading, ranging from its high transactional costs, delays in approvals and water allocations being permanently traded out and lost from agriculture [33,34] that have restricted its use and uptake.

There is thus increasing interest in collaborative water sharing or co-management approaches to water allocations [35–39] to address some of these shortcomings. Collaborative water sharing can be implemented either informally or through water abstractor groups but has received much less regulatory and industry attention to date. The desire for water sharing is likely to be greatest when irrigation demands are high, water availability is low and the risk of drought-related abstraction restrictions [18,40] is high. Consequently, the actual benefits of water sharing in reducing on-farm drought risk and improving short-term water allocation are unclear.

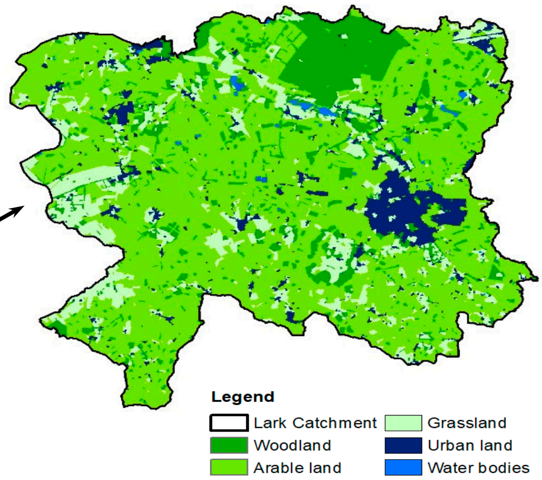
The aim of this paper was to evaluate how the benefits of water sharing for drought risk management are affected by the likelihood of abstraction restrictions and the spatial scale of water-sharing agreements. These effects have been analysed using a novel probabilistic or risk-based approach to the calculation of irrigation deficit and unused licensed ‘headroom’ for individual businesses or water-sharing groups that integrate irrigation needs, water availability and environmental protection. It uses a case study in Eastern England where 60% of the UK’s total irrigated area is concentrated [25] and where most catchments have been classified as either over-abstracted and/or over-licensed [41,42]. Increasing water scarcity is likely to compound the drought challenges faced by irrigated agriculture in this region [43]. This research focused on the River Lark catchment, an intensively farmed lowland rural catchment that is an irrigation hotspot with recurrent abstraction pressures, but with a highly engaged water abstractor group. The methodology and approaches developed are transferable to other regions internationally where similar water pressures exist.

2. Materials and Methods

2.1. Case Study Description

The River Lark catchment in Eastern England (Figure 1a) covers approximatively 460 km^2 of low-lying intensively farmed land with an elevation range of 7–125 m.a.s.l [44]. Eastern England is the driest region of the UK, with an annual average rainfall (1900–2014) in the Lark catchment of 618 mm/year [45]. Drought, as indicated by a Standardised Precipitation Index (SPI) of below −1.5 is a regular feature of the regional climate, with notable droughts in 1976/77, 1990, 1996, 2011 and 2018 (Figure 1c). Daily river flows are measured by the water regulatory authority (Environment Agency, EA) at three gauging stations along the main channel, at the outlet at Isleham (local station number 33004) and upstream at Temple (33014) and Fornham St Martin (33070). There are four main tributaries: Tuddenham Stream, River Linnet, Cavenham stream and Culford stream. The mean daily flow at the catchment outlet is 1.803 m^3/s, and the river has a relatively high base flow index of 0.64 due to groundwater inflows from the underlying major chalk aquifer [46].

(**a**)



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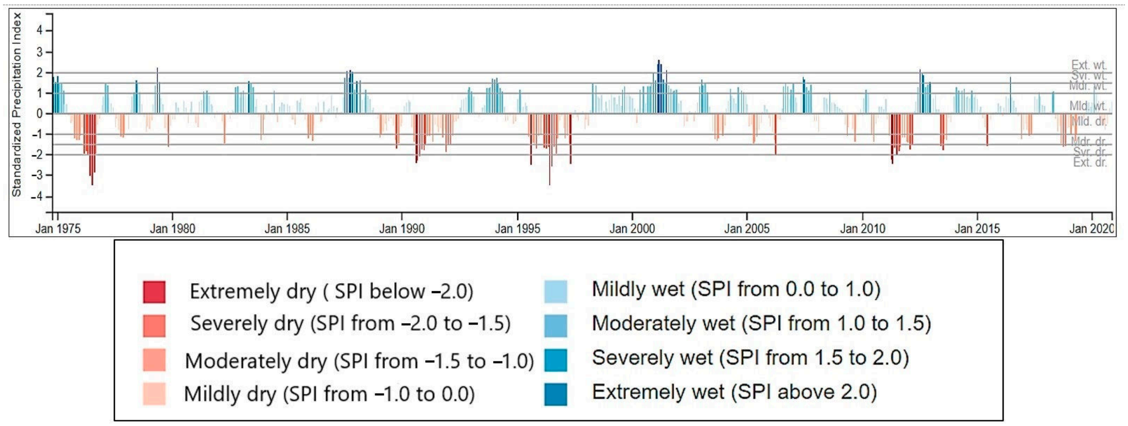

(**c**)

Figure 1. General overview of the study area including national location (**a**), land cover map of Lark catchment for 2015 [47] (**b**) and Standardised Precipitation Index (SPI) period of 6 months from the UK Drought Portal (**c**).

Land use in the catchment (Figure 1b) is dominated by arable (62.4%) and grassland (18.0%) with minor areas of woodland (12.8%) and urban (6.42%). Due to the catchment's freely draining sandy and loamy soils [48], horticultural crops are commonly grown within the arable rotations—in particular maincrop potatoes, carrots, onions and parsnips. To achieve required crop quality standards, irrigation is used to supplement rainfall with Figure 2 showing that the main period of irrigation in most years is between May and July.

All water abstractors are required to have an abstraction licence or permit, issued by the EA, which imposes annual and daily volumetric abstraction limits. These licences can also be subject to restrictions during extended dry periods or droughts, due to either stipulated river flow thresholds (termed hands-off flows or HOFs) below which surface water abstraction must cease or mandatory drought management restrictions under Section 57 (S57) of the Water Resources Act (1991) to protect the public water supply and the environment [40]. Consequently, some farming businesses cannot fully meet their irrigation water needs in dry years due to a combination of their business' volumetric licence limits and/or low river flows triggering HOF or S57 restrictions. The Lark catchment is part of the larger Cam and Ely Ouse catchment, which has been designated as a 'Priority Catchment' for developing and testing innovative solutions to achieve greater access to water and address unsustainable abstraction [49].

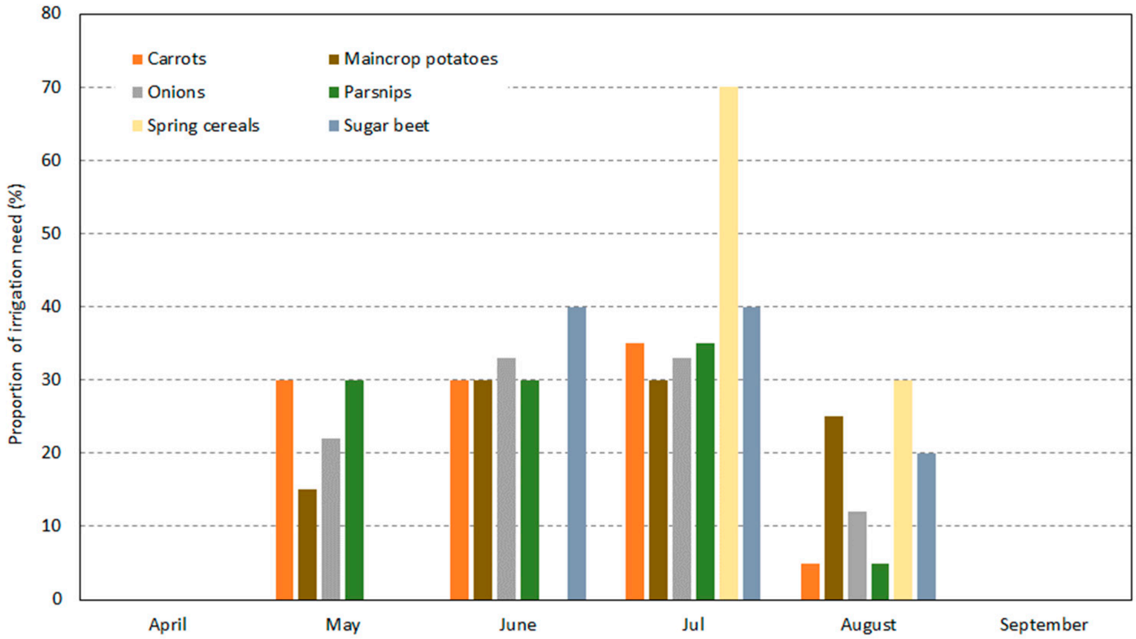

Figure 2. Typical monthly distribution of annual supplemental irrigation need (%) of major irrigated crops in the study area (based on Morris et al. [50]).

2.2. Methodology

Nine farm businesses belonging to the Lark Abstractors Group (LAG) and with surface water abstraction points and who had previously expressed an interest in water sharing and other forms of collaborative water management were the focus of this study. The businesses each have single or multiple abstraction licences for one or more surface and/or groundwater abstraction points in the catchment. Irrigation abstraction licences are specified for either 'direct' abstraction (typically limited to between April and September) where the abstracted water is directly applied to the crop or for 'storage' (typically limited to between October and March) where the abstracted water is stored in an on-farm reservoir for later use. To preserve business confidentiality, an anonymised overview of the selected businesses is given in Table 1. Each farm's typical irrigated cropping is a complex function of each crop's design-dry year irrigation need (crop types, areas and soil types); volumetric licence limits; available on-farm reservoir storage; and the expected abstraction reliability considering the licence-specific HOF and catchment-wide S57 mandatory abstraction restrictions.

The methodology had two discrete stages:

1. Analysis of each farm business's actual abstraction in a recent drought year;
2. Probabilistic analysis of drought risk associated with different scales of water sharing using the modified D-Risk webtool to evaluate the benefits of water sharing.

2.2.1. Analysis of Actual Abstraction in a Recent Drought Year

Monthly abstraction records for each licence were collated from the businesses to understand their actual water use in the recent drought year of 2018 [51] and to highlight which licenses and businesses might have spare water available for water sharing, and, conversely, those who would be keen to secure additional water. The total abstracted volumes between January and December 2018 were used for direct licences; whereas the total abstracted volumes from April 2018 to March 2019 were used for storage licences to include the on-farm reservoir re-filling period.

Table 1. Data collected and used to run drought impact simulations for different water-sharing groups.

Business No.	Irrigated Crop Type	Soil AWC *	Planting Month	Irrigated Area (ha)	Licence No.	Tributary Group	Sub-Catchment Group	Source/ Purpose **	Annual Licensed Volume (m^3)	Daily Limit (m^3)	Abstraction Period	Eq. HOF (L/Sec)	Reservoir Storage ($\times 10^3$ m^3)
1	Maincrop potatoes Onions Parsnips	Low Low Low	April March Feb	68 50 68	L1 L2	River Lark Tuddenham	Isleham Isleham	SW-S GW-D	231,285 295,545	2569 6818	1/11–31/3 1/3–31/10	510 -	350
2	Maincrop potatoes Maincrop potatoes Onions Carrots Parsnips	Low Med Low Low Med	March March March May April	364 156 516 252 149	L1 L2 L3	River Lark River Lark River Lark	Temple Temple Isleham	SW-D GW-S GW-S	90,922 945,600 1,432,000	1592 872 622,616	1/4–31/8 1/4–31/3 1/4–31/3	- - -	740
3	Onions Parsnips Maincrop potatoes	Low Low Low	March April March	72 78 54	L1	River Lark	Temple	SW-S	340,950	2851	1/11–31/3	490	330
4	Maincrop potatoes Onions Sugar beet	Med Med Med	March March April	80 45 15	L1 L2 L3	Culford River Lark River Lark	Temple Fornham Temple	SW-S SW-S GW-D	154,54 6154,54 6230,000	4000 2592 3637	1/11–31/3 1/11–31/03 1/04–31/03	- 120 -	150
5	Spring cereals Spring cereals Sugar beet Onions Carrots Maincrop potatoes	Med Med Med Med Med Low	March Sept March April April April	38 92 78 21 72 92	L1 L2 L3 L4	Tuddenham Tuddenham Tuddenham Tuddenham	Isleham Isleham Isleham Isleham	SW-S SW-S GW-D GW-D	230,000 127,200 80,000 33,000	3264 3437 1137 941	1/11–31/3 1/4–31/10 1/4–31/10 1/4–31/10	821 1917 - -	409.15
6	Sugar beet Maincrop potatoes Maincrop potatoes	Med Med Low	March April April	26 24 10	L1 L2	Cavenham River Linnet	Temple Fornham	SW-S SW-S	90,909 90,909	1300 1300	1/11–31/3 1/11–31/3	404 -	91
7	Maincrop potatoes Sugar beet	Low Low	April March	23 81	L1	Culford	Temple	SW-S	113,636	880	1/11–31/3	1510	93
8	Maincrop potatoes	Low	March	9	L1	Culford	Temple	SW-D	55,598	982	1/4–30/9	-	0
9	Maincrop potatoes	Low	March	62	L1	Culford	Temple	SW-D	45,500	955	1/5–30/9		0

* Available Water Capacity ** SW-D: Surface water direct, SW-S: Surface water storage, GW-D: Groundwater: direct, GW-S: Groundwater storage.

2.2.2. Probabilistic Analysis of Drought Risk Using the Modified D-Risk Webtool

The analysis of the benefits of water sharing at different spatial scales was completed using a modified version of the D-Risk webtool that is available at www.d-risk.eu. The development of D-Risk is given in Haro-Monteagudo et al. [52] but briefly described below.

The D-Risk webtool uses a gridded weather time series dataset called the "MaRIUS event set" [53,54] to derive a probabilistic assessment for any irrigated enterprise of their likelihood of having an irrigation deficit and unused licence allocation (headroom), to support drought risk planning at the individual (business) level [52]. This gridded weather dataset is composed of 100 member ensembles of 30-year time-series of daily rainfall and potential evapotranspiration [53,54]. For each ensemble member, D-Risk uses a daily water balance between the rainfall and potential evapotranspiration to calculate the annual maximum potential soil moisture deficit (PSMDmax). Using the irrigated cropping and soils data for each business or water-sharing group and the annual PSMDmax time series, the D-Risk tool was used to calculate the theoretical annual irrigation needs (depths applied, mm) for each crop-soil combination using previously derived regression equations [55] that are used by the EA in setting irrigation licence volumetric limits [56]. The irrigation needs were then combined with the irrigated areas (ha) for each business or water-sharing group to estimate total volumetric annual irrigation demand (m^3).

A monthly time-step water balance model was then used to calculate whether the irrigation demands could be met, considering the daily and annual licensed abstraction limits and the specified start and end months of each licence and any available on-farm storage. It was assumed that licenses dependent on surface water are used before licensed groundwater sources due to their greater vulnerability to abstraction restrictions and that direct abstraction was preferred before storage.

From the water balance modelling, the annual irrigation deficit representing the proportion of annual irrigation demand that was not met and the licensed abstraction 'headroom' defined as the proportion of the total licensed volume that is not abstracted in a given year were calculated.

However, the current D-Risk webtool does not incorporate local river flow conditions and associated HOF and S57 abstraction constraints, assuming that abstraction is unconstrained on all days within a given month, which may not fully reflect reality during a drought. It may, therefore, under-estimate the volume of any unused licence during a drought and attendant drought risks. Hence, in this study, the HOF and S57 abstraction restriction rules applied to daily river flows were incorporated into the D-Risk algorithms to reflect more typical local river management practices under drought conditions.

The daily river flows were simulated using the DECIPHeR hydrologic model [57]. DECIPHeR is a flexible hydrological modelling framework that can simulate flows across multiple catchments with different hydrological characteristics. It has previously been applied to 1366 gauges across Great Britain and shown to perform well for four different evaluation metrics across a wide range of catchments [57]. Daily 1 km^2 gridded rainfall and potential evapotranspiration data for 1961–2015 were obtained from the UKCEH 'Gridded Estimates of Areal Rainfall' dataset (CEH-GEAR) [45,58] and climate hydrology and ecology research support system potential evapotranspiration dataset for Great Britain (CHESS-PE) [59]. The model was calibrated and validated against observed daily streamflow data for the Lark at Temple gauging station obtained from the National River Flow Archive (www.nrfa.ceh.ac.uk). Once calibrated and validated using observed data, DECIPHeR was used to simulated daily river flows using the precipitation and potential evapotranspiration data of the MaRIUS event set ensembles. For each surface water licence, the equivalent number of days each month in which abstraction was constrained due to simulated river flows being below the licence-specific HOF or in which abstraction was under different levels of mandatory S57 restrictions (i.e., Level 1 = 50% reduction; Level 2 = 75% reduction; Level 3 = 100% reduction) according to Salmoral et al. [40] were calculated. From this, the potential number of days per month in which surface water abstraction was allowed were incorporated into the D-Risk monthly time-step water balance model.

The modified D-Risk algorithms were then applied to derive aggregate irrigation deficit and headroom profiles for the following:

1. Licence groups (9): in which all businesses operate independently with no water sharing between businesses;
2. Tributary groups (5): businesses with licences with water abstraction points along the same tributary or main channel reach;
3. Sub-catchment groups (3): businesses with licences with abstraction points within common sub-catchments determined by the gauging station;
4. Catchment group (1): representing all licences and businesses.

The abstraction points for each business and their grouping at different spatial scales of water-sharing groups are summarised in Figure 3. D-Risk was run for each sharing group separately, representing a total of 18 simulations. For each simulation, the relevant input data were extracted from Table 1. Where a business's abstraction licences spanned more than one water-sharing group, the business' irrigated crop areas were split and subdivided according to the proportion of the licence's total abstraction volume of each business. For licences which had HOF conditions at ungauged locations, these were converted to an equivalent HOF condition at the Temple gauging station based on the proportional catchment area.

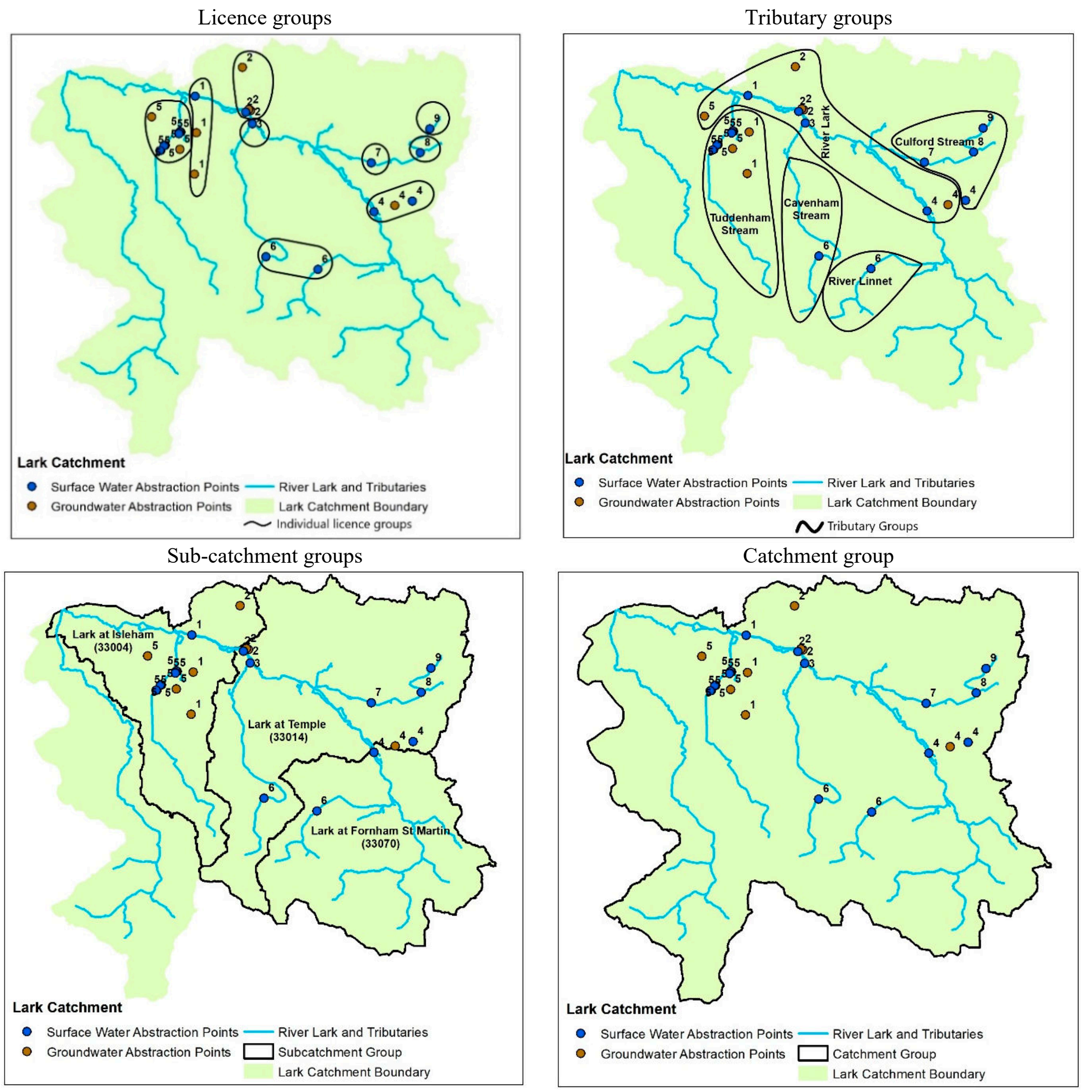

Figure 3. Water-sharing groups at different spatial scales with abstraction locations for each business.

The individual D-Risk drought risk profiles for each water-sharing group at a given spatial scale were converted to aggregated profiles to evaluate the potential benefits of water sharing, especially during drought years. The 80th percentile values of the profiles (corresponding to 20% probability of exceedance for irrigation deficit and 80% probability of exceedance for headroom) represents the scenario for a drought year. In addition, gridded matrices of the estimated irrigation deficits (expressed as a proportion of the licence volume) and headroom for each business within the different scales of water sharing were also generated based on results for the typical 'design' dry year (80th percentile probability of non-exceedance). Finally, the total volume of water abstracted with each scale of water sharing was calculated to understand any potential increased risk of abstraction-induced ecological impacts due to water sharing.

3. Results

3.1. Comparison of Total Licenced Volume and Actual Abstraction for a Drought Year

The annual licensed volume and reported actual abstractions for 2018 for each farm business ranked by their total licensed volume (Figure 4) showed that most (though not all) of the businesses had significant unused allocation. This unused licensed volume, which reflects the difference between the annual licensed volume and actual abstraction in a given year, and defined as 'headroom' arises through a combination of (1) being unable to abstract water because of HOF restrictions during and after the drought (recognising that S57 restrictions were not imposed in 2018); (2) a mismatch between the magnitude of peak irrigation demand and daily abstraction limits (3) modifications to their irrigation plans (e.g., irrigating their full area to a reduced irrigation schedule or irrigating a reduced area to their full irrigation schedule—[25]) to avoid running out of water during the drought due to the uncertainty in the drought duration; and (4) reduced irrigated cropped areas in 2018 due to rotational restrictions. This 'unused' water in 2018 shows the potential for water sharing to improve the efficiency of water allocation and thus increase the quality and quantity of crop production locally.

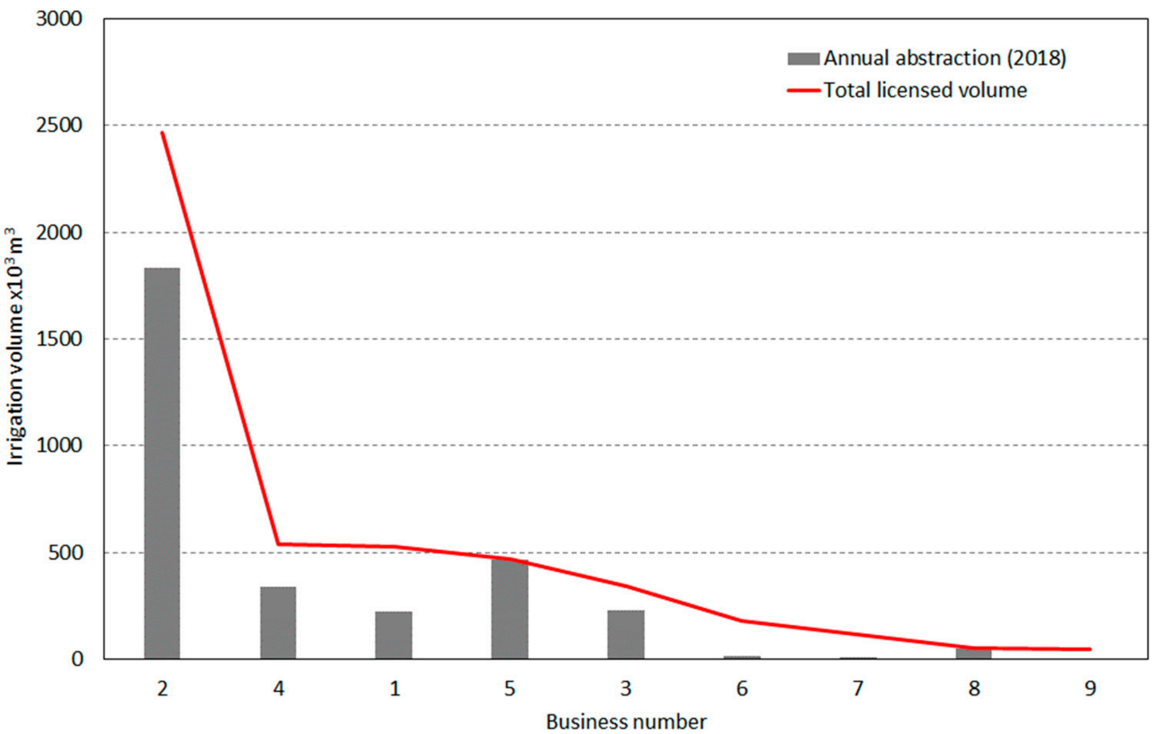

Figure 4. Ranked licensed annual abstraction volume ($\times 10^3$ m^3) compared to actual 2018 abstraction across the nine farm businesses in the Lark catchment.

3.2. Benefits of Water Sharing within the Catchment

Figure 5 shows the derived profiles of annual exceedance probabilities of the aggregate irrigation deficits for each different scale of water sharing. With no water sharing, the nine businesses have a combined annual irrigation deficit of around 1,000,000 m^3 in a design dry year (20th percentile probability of exceedance across the 100 × 30 simulated years), although this ranges between 350–200,000 m^3 across individual ensemble members (shaded uncertainty zone in Figure 5). Around 65,000 m^3 of this deficit is caused by the simulated river flow-based restrictions on surface water abstraction. This aggregate risk profile derives from three distinct typologies of risk profile of individual businesses: those that have zero irrigation deficit and significant headroom (e.g., business 8 in Figure S1a,b) and those that have a significant irrigation deficit despite abstracting their annual volumetric limit (e.g., business 2 and 3 in Figure S1a,b). For this latter group, the irrigation deficit mainly arises because their daily licensed volumetric limit is insufficient to meet their peak daily irrigation demand, although their annual volumetric licence limit meets the annual irrigation demand.

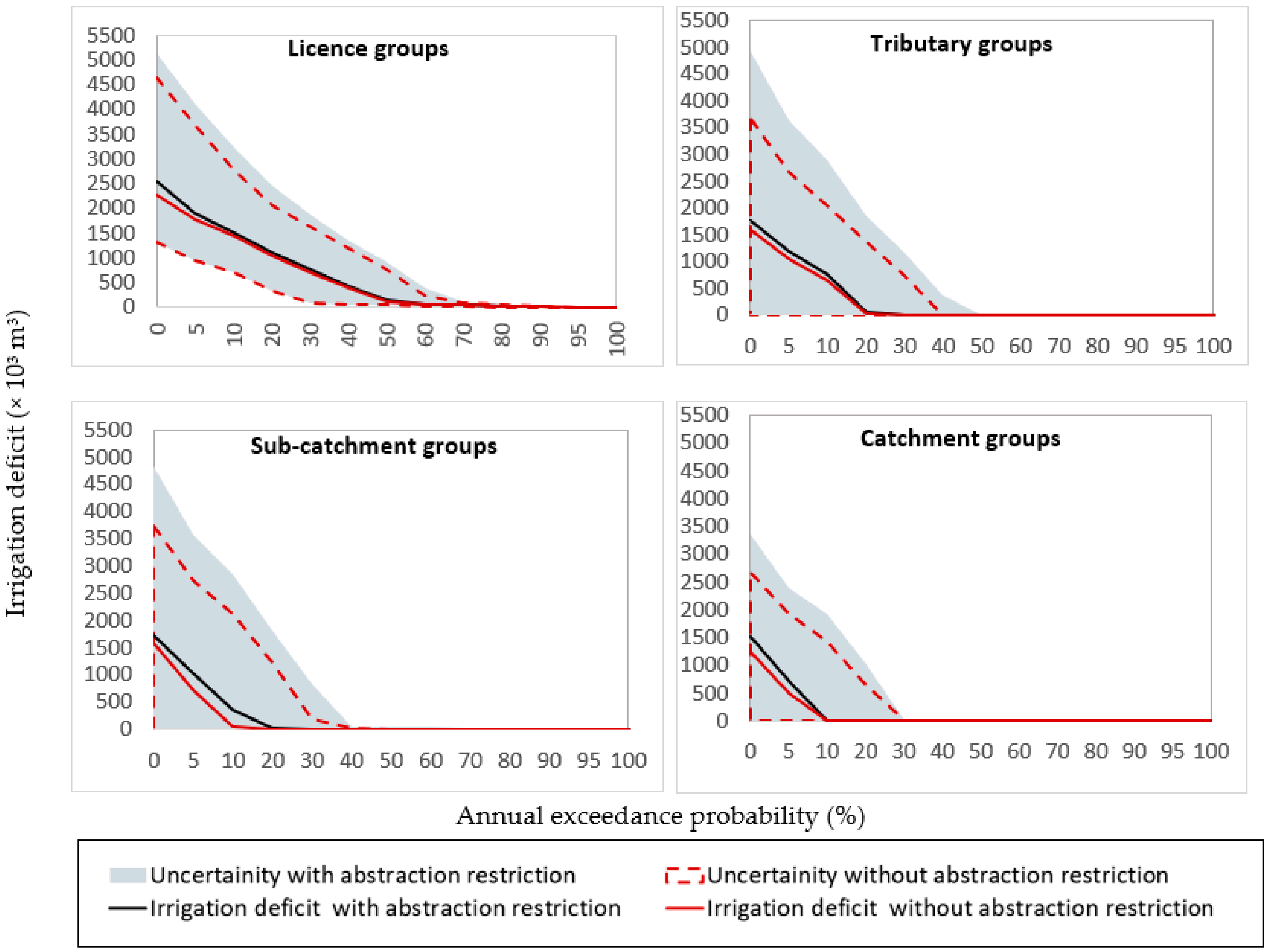

Figure 5. Annual probability distribution of aggregated irrigation deficits 'with' and 'without' simulated river-flow based abstraction restrictions for different scale of water-sharing groups within the Lark catchment.

The benefits of water sharing in decreasing the annual probability or risk of an aggregate irrigation deficit (and uncertainty range) increase with an increasing spatial scale (Figure 5). Water sharing within tributary groups reduces the irrigation deficit with a 20th annual probability of exceedance from around 1,000,000 m^3 to only 47,000 m^3, although all of this deficit occurs in the River Lark main channel group (Figure S2a) who have zero headroom (Figure S2b). Water sharing at the sub-catchment and catchment scales further reduces the annual risk of a significant annual deficit to 10% or less, with irrigation deficits of 100–250,000 m^3 in both the Isleham and Temple sub-catchments (Figure S3). Similarly, as the scale of water sharing increases, the flow-based abstraction restrictions generally become less important due to the increasing ability to conjunctively utilise both surface water licences with different flow-based restrictions (Table 1) and groundwater licences that are not subject to drought restrictions according to river flow levels. Consequently, at the catchment-scale, the abstraction restrictions only affect the overall irrigation deficit in extreme drought years.

The gridded matrix in Table 2 showing the relationship between the annual volumetric irrigation deficit (expressed as a percentage of annual licensed volume) and headroom for each business in the design dry-year clearly demonstrates the risk reduction benefits to businesses associated with water sharing. Risk levels are highlighted using the colours ranging from red with the highest risk to green with the lowest risk. As the scale of water-sharing increases, fewer businesses are expected to experience an irrigation deficit while the heterogeneity in licensed headroom reduces, showing a more even utilisation of licensed water.

Table 2. Gridded matrix of the relationship between the irrigation deficit and headroom for individual businesses in a 'design' dry year and for different scales of water sharing. Colour of the cells indicates the risk levels from highest (dark red) to lowest (dark green) risk.

Water Sharing Category	Zero Deficit	Low Deficit (0–25%)	Medium Deficit (25–50%)	High Deficit (>50%)
Licence groups				
High headroom (50–100%)	8			
Medium headroom (25–50%)	4	6	2	7
Low headroom (0–25%)	1,5			3,9
Tributary groups				
High headroom (50–100%)				
Medium headroom (25–50%)		6		
Low headroom (0–25%)	1,2,3,4,5	7,8,9		
Sub-catchment groups				
High headroom (50–100%)				
Medium headroom (25–50%)		4,6		
Low headroom (0–25%)	1,2,3,5,7,8,9			
Catchment groups				
High headroom (50–100%)				
Medium headroom (25–50%)				
Low headroom (0–25%)	1,2,3,4,5,6,7,8,9			

Finally, to assess the potential effect that water sharing might have on the environment, Figure 6 shows the annual exceedance probability for total annual abstraction across the nine businesses for each scale of water sharing. As expected, the total annual volume abstracted increases with an increasing scale of water sharing as the efficiency of utilisation of the licensed water increases. However, the increased annual abstraction enabled by water sharing is generally less than 400,000 m^3 or 10% of the total licensed volume.

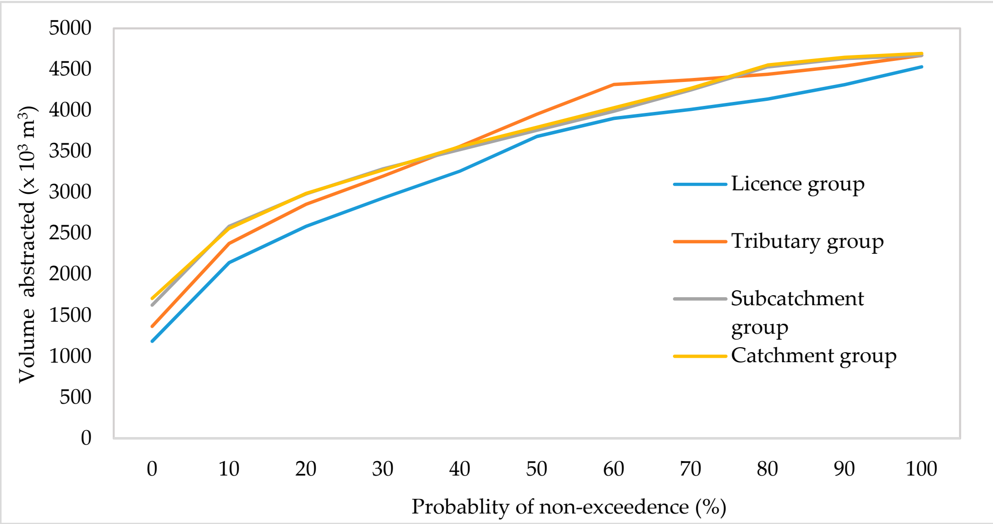

Figure 6. Variations in the volume of abstraction for different water-sharing groups.

4. Discussion

The allocation of water for agricultural irrigation in many regions or countries is accepted as economically sub-optimal. In many cases, a lack of regulatory flexibility to overcome the limitations in the original allocation process (for example, first come, first served basis) means that allocated water remains unused, even in drought years. Economic or market-based instruments, including water trading, have been introduced successfully in other countries and river basins, such as the Murray–Darling in Australia [60,61]. However, in humid countries with high climatic variability, water trading has not been popular due to the bureaucratic assessment procedures, high transactional costs and time lags, which mean that trades cannot be approved sufficiently quickly to meet the short-term need during drought years. Although contract options [62,63] that provide the licence holder with the right (but not obligation) to buy or sell water at a point in the future help to overcomes some of these drawbacks, the usual payment of the option premium for the future right to purchase the water [62] entails a financial cost that will not be justified in most (non-drought) years. This study aimed to assess whether the benefits of informal water sharing between local agricultural abstractors to address the desire to increase the efficiency of water allocation and, therefore, the economic benefit and associated increased productivity could be realised given existing regulatory constraints to prevent environmental harm.

Our analysis showed that water sharing at any scale tends to reduce the exposure of businesses to the risk of an irrigation deficit, especially in drought years. Furthermore, the potential benefits of water sharing increase with scale. This potential drought risk–benefit is, however, associated with a generally increased aggregate annual abstraction, thereby posing a potential threat to the condition of the aquatic ecology [64].

River flow reductions can affect the drift behaviour of stream invertebrates [65] and macrophyte communities [64]. The analysis by Poff and Zimmerman [66] supported the inference that flow alteration is associated with ecological change and that the risk of ecological change increases with an increasing magnitude of flow alteration. However, most studies have focused on the impacts of long-term changes in river flow (e.g., [66–68]) rather than the consequences of short-term (seasonal) increases in abstraction. In their systematic review of fish and invertebrate responses to droughts in Europe, research [69] reported statistical evidence for a decrease of invertebrate richness/abundance and fish density immediately following drought, but no significant effect of event severity. Furthermore, this research did not consider recovery [70] to assess the longer-term implications of short-term stress, although this can take from a year (higher plants: Wright et al. [71]; macroinvertebrates: Wood and Petts [72]) to 5+ years (fish: Elliott [73]).

By taking into account the current regulatory and drought management restrictions on irrigation abstraction, our analysis showed that water sharing does not completely remove drought risk due to the combination of water resources management constraints that are embedded in the volumetric licence limits to ensure sustainable abstraction and drought management protections such as abstraction restrictions at low river flows (e.g., licence-specific HOF and Sec 57). Nevertheless, there remains considerable uncertainty regarding the optimum scale of water sharing to maximise the economic benefits of more efficient water allocation while maintaining appropriate environmental protection. While water sharing at larger scales provides the greatest flexibility and the potential to avoid concentrated periods of abstraction, significant up-river shifts in the distribution of abstraction towards small sub-catchments and headwater tributaries could cause significant impacts on flow and ecology. Similarly, water sharing at too small a scale may also lead to detrimental local increases in abstraction. This complexity suggests that the successful adoption of informal water sharing requires clearly articulated, managed and regulated allocation rules and temporary reallocation procedures during drought conditions [39] must provide clarity, trust and environmental protection. Such requirements will require the continued role of the regulator [38] and the co-ordination of a collective water user body, whether this be a legal entity (e.g., Rouillard, J.; Rinaudo [39]) or water abstractor group [74]. Water sharing that combines careful abstraction management and adequate allocation safeguards has the potential to provide wider benefits to the socio-economic-environmental integrity of a region, but further work is required between the regulator and the farming communities to understand how best to operationalise the approach.

5. Conclusions

This research explored the benefits of water sharing between irrigators to reduce drought risks in a humid climate. Although the study focused on an intensively farmed lowland catchment in the UK with its particular irrigated agriculture and water governance; it has wider relevance to agricultural abstraction management in other regions where consideration of water sharing within a risk-based approach to irrigation management that takes account of water resource availability and environmental protection may deliver improved outcomes, especially in dry years. The study showed that the water sharing benefits from a socio-economic perspective increase with the spatial scale of water-sharing agreements, but also lead to higher levels of abstraction. The importance of regulatory and drought management restrictions on irrigation abstraction in preventing increased environmental harm is demonstrated by the water sharing not completely removing drought risk despite unused water allocations during drought years. Nevertheless, understanding how to operationalise water sharing to deliver the economic benefits of improved agricultural water allocation while maintaining ecological quality requires an ongoing dialogue between the regulator and the farming communities.

Supplementary Materials: The following are available online at https://www.mdpi.com/2071-1050/13/3/1456/s1, Figure S1: Probability of (**a**) Irrigation deficit and (**b**) Headroom as percentage of licence for individual licence groups; Figure S2: Probability of (**a**) Irrigation deficit and (**b**) Headroom as percentage of licence for tributary groups; Figure S3: Probability of (**a**) Irrigation deficit and (**b**) Headroom as percentage of licence for sub catchment groups.

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Data Availability Statement: All input data supporting this study and required to run the d-risk.eu webtool are provided in the Methods section of this paper.

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