Water Permit Trading for reservoir water under competing demands and downstream flows

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Abstract: The design of effective market institutions for allocation of water among competing uses remains an economic challenge both at a theoretical and practical level. The public good characteristic of instream flows adds another layer of externality which complicates transfers between consumptive and environmental water users, leading to the slow evolution of this market in many parts of the world including western United States. Utilizing a unique case study of reservoir management in northeast Oklahoma, this research explicitly ties the third-party impacts of binding stream flow constraints with the opportunity costs of water transfers, paving the way for a centralized market mechanism for water transfers among consumptive and non-consumptive users over time. The study aims to enhance the evolving research around environmental water markets and offer a possible solution to a long-standing debate among local stakeholders on a suitable allocation of water for environmental purposes.

Keywords: *instream flows, market, flow constraints, opportunity costs*

JEL classification: *Q00, Q25*

1. Introduction

The evolution of water markets to allocate water in an economically efficient manner has been well established for almost four decades with the most successful markets operating in Australia, western United States, Chile, Spain and to some extent in South Africa. Markets include but are not limited to permanent trades, short term of multiyear leases, dry year options, water banks, buy backs etc. and trading has taken place in accordance with the necessity of water for the sector or region and how well market-based principles could be adopted for water allocation. However, markets do suffer from several limitations such as high transaction costs, ill-defined property rights, third party externalities, lack of competition (Young, 1986; Colby, 1990; Chong and Sunding, 2006; Libecap, 2005; Garrick et al., 2013; Borghesi, 2013) and so there has been some reluctance in translating economic principles to cases where such limitations pose high externality costs. A prominent example is the use of markets for environmental flows, an often-debated topic from an academic as well as from a policy standpoint. Environmental or instream flows has public good characteristics and so prone to free riding and other externalities leading to undervaluation when traded within markets. Thus, water for environmental use particularly for recreational purposes has been valued through nonmarket valuation techniques like contingent valuation, conjoint analysis, travel cost method or hedonic pricing. Over the last two decades though, market-based transfers of environmental water have gained popularity particularly in western United States and in Australia, with such transfers in the form of permanent trades and leases accounting for 7% of the annual value of current water traded in US (Westwater Research, 2020). Loomis et al. (2003) concluded that prices paid for market-based acquisitions of water for environmental purposes in western United States closely match the non-market-based willingness to pay measures, illustrating the growing importance of environmental water transactions. In Australia where water markets are one of the most developed in the world, there has been an extensive research on the role of economic instruments for acquiring environmental water and how they best align the solutions to address water scarcity with economic incentives for environmental water trades like water buyback programs from voluntary sellers (Quereshi et al, 2007; Quereshi et al., 2010; Wheeler et al., 2013; Grafton and Wheeler, 2018).

The importance of instream flows as part of environmental resources is acknowledged for its non-use and bequest values and several studies have looked at optimal allocation of water when instream flow constraints are binding (Johnson et al., 1981; Griffin and Hsu, 1993; Weber, 2001). The demand and valuation for such flows has been mostly limited to its use for recreational purposes where nonmarket valuation techniques as mentioned above have been utilized to measure economic benefits (Loomis, 2012; Loomis and McTernan, 2014, Debnath et al, 2015). The main reason is the absence of an actual priority right and beneficial use clause associated with this kind of water, since it is used for non-consumptive purposes and considered part of the downstream flow when all other rights have been fully allocated. As a public good, instream flows are non-excludable, an additional layer of externality which complicates the management of surface water flows even with the property right being defined as a consumptive use water right. (Weber, 2001). Thus, even though instream flows are an integral part of discussions centered on third party impacts of water transfers, there remains a gap in practice of including environmental users into an effective market mechanism contributing to the slow evolution of instream flow markets in western US. In fact, the idea of marketing instream or environmental flows has not been accepted in all western states and even if transferable rights exist in several states, most of these rights are owned by federal and state agencies and a few environmental NGOs and water trusts (Hadjigeorgalis, 2010; Rehreing, 2019). It has been noted in a recent report that over 90% of the volume of water purchased for environmental flows are part of state or Federal regulatory programs (Westwater Research, 2020). This is notable since cap and trade mechanism has been advocated by many as a promising market mechanism to transfer water to sustainable uses when formal water rights do not exist (Ward and PulidoValezquez, 2012).

Economic studies analyzing environmental water transfers are often motivated by the role of externalities and transaction costs embedded in these trades, since markets may not efficiently allocate a resource that has public good properties. Prominent studies on water markets in western US have focused upon the determinants of market prices and price efficiency, the trends in market activity over time, the importance of water leases, the inter sectoral direction of trades, dry year options and groundwater banking in recent years, the problem of transaction costs in water transfers (Brookshire et al., 2004; Brown, 2006; Brewer et al., 2008; Jones and Colby 2010; Payne and Smith, 2013; Payne et al., 2014)**.** Some studies focus specifically on the institutional transaction costs of water transfers including those for environmental water allocations (Colby, 1990; Garrick and Alyward, 2012; Garrick et al., 2013; Skurray and Pannell, 2013; McCann and Garrick, 2014; Colby and Isaaks, 2019; Colby, 2020). Innovative theories to explain organization and costs of environmental water trade like the Punctuated Equilibrium theory (PET) and the Social Ecological Economics of Water have been applied recently (Colby, 2020; Colby and Isaaks, 2019). A vast majority of these studies have employed regression techniques to estimate the effect on sales or lease prices including environmental leases.

A second economic approach has applied optimization methods to derive efficient outcomes over status quo like no allocation for environmental flows. In two recent studies dealing with the Murray Darling Basin in Australia (regarded as one the most active water markets in the world), Qureshi et al. (2007, 2010) show how Government purchases of water from irrigators or buyback programs resulted in greater return flows to the environment, compared to alternative policies like allocating water to the environment or subsidizing irrigators for infrastructure options to reduce conveyance losses and improve on farm irrigation. In fact, Qureshi et al (2007) conclude that interregional trading raises net revenues as compared to a policy of environmental water allocation in various scenarios like allocating more water in wet years and transferring water from low valued regions.

Another set of economic literature that has evolved in the last decade has exploited experimental techniques to understand how far externalities may be mitigated when the environmental trader is considered as part of the simulated market setting. Compared to research on water markets within experimental settings, there has been limited attention given to market efficiency when instream flows are considered as part of the trading mechanism. The seminal work by Murphy et al. (2006) exploiting the smart market model for water trading aimed to address the third party impacts of voluntary water transfers. They simulated two policy scenarios where one allowed water rights holders to participate in market transactions if they were to experience third party impacts from voluntary trades. Both policies resulted in high transaction costs. In an extension to these findings, Murphy et al. (2009) proposed three institutional settings: having markets with minimum instream flow constraints, an environmental agent (Instream Flow District) that contributed to downstream flow provisions and tradeable rights for instream flows. They concluded that the first setting does achieve competitive equilibrium unlike the last two and that strategic behavior was revealed when the IFD had tradeable rights. Cummings et al. (2004) tested an auction mechanism for environmental water during low flows while Tisdell (2010) considered an environmental trader in the market and found that public information about the trader influenced average bid prices and supply of water during trading. In contrast to studies which analyze the growth and current legal and socioeconomic challenges for environmental water markets or markets for instream flows, the studies mentioned above directly simulate a water market and derive results based on the role of the environmental trader in the market. Such experimental settings illustrate the dynamic nature of such trades and how externalities (strategic and environmental) that correlate with public goods affect allocative efficiency within a competitive market model.

Our study attempts to complement the last two approaches by introducing a common pool framework where an external market manager takes on the role of mediating the transactions thus lowering transaction costs. Utilizing a centralized market, the study explicitly ties the third-party impacts of binding stream flow constraints with the opportunity costs of water transfers. In addition, the paper utilizes a unique case of reservoir management in northeast Oklahoma to illustrate how marginal cost price paid by participants effectively internalize some of the third-party impacts of water transfers across consumptive and non-consumptive users. The marginal cost price reflects each user's impact upon water availability for all other users. Thus, many of the third-party externalities are reduced in this system because potential damages to downstream water use are compensated through appropriate pricing mechanisms.

We also try to deviate from studies looking specially at the trends in environmental water marketing and factors that affect voluntary sales of water to Federal, state and environmental agencies. Instead, the study attempts to devise a market mechanism with flows for environmental water explicitly included in the design, following the work of Murphy et al. (2006, 2009). The empirical model is built based on data for the study region, where water markets and instream flow valuation have been largely unexplored to date and water rights are fully allocated

One final contribution of the current paper is an attempt to develop an institutional design that can be made operational for the allocation of reservoir water with competing uses from both consumptive and non-consumptive users. Debnath (2014) and Debnath et al. (2015) have examined the optimal allocation of reservoir water for Lake Tenkiller in detail, with a focus upon the economic tradeoffs in hydropower versus recreational benefits. McKenzie (2003) examined the reservoir management practices for Broken Bow Lake located in southeastern Oklahoma. Ward and Lynch (1996) used an integrated optimal control model designed to optimize the net benefits of water resource management for reservoirs in the Rio Chama River basin in New Mexico. The studies cited have the stated objective to identify the optimal allocation of reservoir water among the different uses. However, none of these studies address the problem of designing an institutional structure that could be implemented to achieve the allocation of reservoir water resources they identify in their respective research studies. The mechanism for water allocation developed in this paper is closely aligned to the "smart market" model for water resources as suggested by Raffensperger and Milke (2017) and utilized for modeling tradeable emissions discharge permits in Willett et al. (2014). Although development of an actual smart water market is beyond the scope of our research, the study draws in particular features in the design of the market that is applicable to water allocation in the study region.

2. Conceptual Model

The basic structure of our market will have some features that are similar to the emission discharge permit trading market developed by Willett et al. (2014). The pricing mechanism and institutional structure used for pricing and distributing water rights is called a common pool permit market. Here, each market participant determines a bid or offer schedule for water rights for a range of possible prices by solving its own version of a microeconomic decision problem. A key component of this market institution design is the market manager. This individual or agency provides the market with a range of prices for water rights and each decision maker responds by giving the market manager a quantity of water rights to buy or sell at each possible price. The market manager issues a final call for bids and the makes an announcement that the market bidding has closed, and no more bids are accepted at that point. The market manager then puts the bid-offer functions into a mathematical programming model which is then solved to determine those prices and water rights allocations that maximize the gains from trade subject to an appropriately defined constraint set. All trading in this system is through the common pool and bilateral or one-to-one trades between market participants are not allowed. Trading within a common pool is a key characteristic of our institutional design and offers the potential to significantly reduce the transaction costs associated with this type of market.

The model outlined in this section utilizes the basic framework of the above market with some structural differences. The common pool refers to the possibility of multilateral transfers among all consumptive and non-consumptive water users. The user specific demand for water is represented as continuous demand functions instead of as discrete steps where quantities demanded are revealed through a bidding process at each market price. This reduces the computational burden on the model and makes it more flexible for use within a nonlinear optimization framework. The market manager in our model is the responsible state or local Government agency which issues permits for water use and which can oversee the transfer process. The solution to the mathematical programming model determines those prices and water use and allocations that maximize net benefits for the users (market participants) subject to an appropriately defined constraint set.

All consumptive and non-consumptive water users own water rights permits which are considered transferable permits in this modeling structure. To avoid complexity, we assume that permits are held by the hydroelectric wholesale distributor or the power company, residential users (water companies which serve the residential water needs), nonresidential users (commercial and industrial water users) at an aggregated level. This implies that all users represent a group with no heterogeneity in the individual water use such that trading takes place between the residential users, nonresidential users and hydroelectric users based on their water use and allocation. Currently, recreational use and instream flows do not own property rights to the water for the study region but are recognized as important for lake recreation and fishing and for regional economic development. So, we consider minimum lake level for recreational purposes and the downstream flow needs are modeled as minimum instream flow requirements. The market framework is thus represented as:

$$Max \sum_{t=0}^{T} \left\{ \sum_{r=1}^{I} \int_{0}^{R_{rt}} P_{rt}(x_{rt}) dx_{rt} + \sum_{n=1}^{J} \int_{0}^{N_{nt}} P_{nt}(y_{nt}) dy_{nt} + \int_{0}^{H_t} B_{Ht}(e_{Ht}) de_{Ht} \right\} \quad (1)$$

Subject to

$$R_{rt} \leq \bar{R}_{rt} \;\; (\psi_{rt}) \quad (2)$$

$$(r = 1, \dots, I)$$

$$(t = 0, \dots, T)$$

$$N_{nt} \leq \bar{N}_{nt} \ \ (\psi_t) \tag{3}$$
$$(n = 1, \dots, J)$$
$$(t = 0, \dots, T)$$

$$H_t \leq \bar{H}_t \ \ (\psi_t) \tag{4}$$
$$(t = 0, \dots, T)$$

$$V_{t+1} = V_t - \sum_{r=1}^{I} R_{rt} - \sum_{n=1}^{J} N_{nt} - H_t \ + Inflows_t - Outflows_t(\lambda_{t+1}) \tag{5}$$
$$(t = 0, \dots, T)$$

$$V_t \leq \bar{K}_t \ \ (\Lambda_t) \tag{6}$$
$$(t = 1, \dots . T)$$

$$\tilde{V}_t \leq V_t \ \ (\Gamma_t) \tag{7}$$
$$(t = 0, \dots, T)$$

$$H_t \geq \bar{Q}_t \ (\Delta_t) \tag{8}$$
$$(t = 0, \dots, T)$$

$$\sum_{r=1}^{I} R_{rt} + \sum_{n=1}^{J} N_{nt} + H_t \leq \bar{W}_t \ \ (\Psi_t) \tag{9}$$
$$(t = 0, \dots, T)$$

The terms in parentheses are Lagrangean multipliers or shadow prices.

Equation (1) is the objective function representing the net benefit from market-based water allocations and is subject to the following economic and physical constraints. Equations (2)-(4) represent capacity constraints reflecting exogenous bounds on how much water can potentially be allocated and transferred for residential use (R_{rt}), nonresidential use (N_{nt}) and hydropower use (H_t). The volume of water available in each period is described by Equation (5) which is a state equation showing that at any time period, the stock of remaining water is given by the initial stock and the exogenous inflows minus the outflows and water withdrawals for consumptive and non-consumptive purposes. The outflows are endogenously determined as a function of the power releases. The constraint (6) represents the reservoir capacity constraint for water available for direct withdrawals from the reservoir along with releases, while constraint (7) defines the minimum amount of water that must remain in the reservoir each time period to meet a predetermined level of recreational demand.

The minimum instream or downstream flow constraint is represented by equation (8) which states that the water allocated for hydropower should satisfy at a minimum the required downstream flows. Finally, equation (9) states that the number of water rights used in each period from the reservoir cannot exceed the number of water rights issued by the market manager in each period. This constraint is included in the model to prevent the optimal number of permits used or traded to exceed the initial number of permits allocated in each time period.

Derivation of the shadow prices for permit trade

The shadow price representing the storage value of the stock of water in the reservoir is given as.:

$$\lambda_{t+1} = -\sum_{\tau=t+1}^{T} (\Lambda_\tau + \Gamma_\tau) \tag{10}$$

The shadow price Λ_t is associated with the reservoir capacity constraint (6) while the shadow price Γ_t is associated with the minimum reservoir constraint (7). Realistically speaking, these two constraints cannot be binding simultaneously. In general, λ_{t+1} should be viewed as the marginal value of reservoir water in storage. In the current model formulation, if neither of these two constraints are binding, it is concluded that λ_{t+1} is zero for all periods.

The discussions now turn to the marginal opportunity cost pricing rules that the common pool market model provides when an optimal market solution is achieved. First, it is assumed in the following discussions that none of the water transfer systems constraints are binding in all of the cases discussed. The marginal opportunity cost price for residential user r in period t is as follows:

$$P_{rt}(R_{rt}) = \psi_t + \lambda_{t+1} \tag{11}$$

$$(r = 1, \dots, I)$$
$$(t = 1, \dots, T)$$

The term on the right-hand side of equation (11) is the price on the rth residential user's demand schedule for direct water withdrawals from the reservoir in time period t. The right-hand side of this equation represents the marginal opportunity costs of the direct water withdrawals from the reservoir and consists of two components. As discussed previously, the shadow price λ_{t+1} is the marginal opportunity cost of stored water in the reservoir while the shadow price $\psi_t$is associated with the water permit allocation constraint (9) which limits the number of permits that could be used or traded in the market.

The second category of direct withdrawal of water from the reservoir is for nonresidential use. The marginal opportunity cost pricing rule for nonresidential user n in period t is the following:

$$P_{nt}(N_{nt}) = \psi_t + \lambda_{t+1} \tag{12}$$

$$(n = 1, \dots, J)$$
$$(t = 1, \dots, T)$$

The term on the left-hand side of equation (12) is a point on the demand schedule of the nth nonresidential water user for period t and is the price that this user is willing and able to pay for a unit of water directly taken from the reservoir. The right-hand side of equation (12) represents the marginal opportunity cost of taking a unit of water directly from the reservoir and is the same as shown in equation (11).

The following pricing relationship is for water that is released from the reservoir for hydropower generation.

$$B_{Ht}(H_t) = \psi_t + \Delta_t + \lambda_{t+1} \tag{13}$$

$$(t = 1, \dots, T)$$

The term on the left-hand side of equation (B.13) is the price for the hydropower generator is willing and able to pay for a unit of water released from the reservoir for hydropower generation and is a point on the demand schedule for hydropower water releases.

Finally, we examine the relationship between the prices of water rights for the direct withdrawal of water from the reservoir for residential and nonresidential use versus the price of water releases for hydropower generation. Equations (B.11) -(B.13) can be combined to derive the following two sets of pricing relationships:

$$B_{Ht}(H_t) = P_{rt}(R_{rt}) + \Delta_t \quad (14)$$

$$B_{Ht}(H_t) = P_{nt}(N_{nt}) + \Delta_t \quad (15)$$

These equations show the pricing relationships that evolve when the minimum instream flows for the downstream fishery/environmental requirement become binding. The hydropower users pay an amount equal to residential/nonresidential users and also bear the opportunity costs of binding instream flows. If the minimum instream flows are nonbinding during most of the year, then our model suggests that hydropower will pay almost the same price as the other users. The model may have more realistic implications if hydropower does pay different prices during different months depending upon when instream flows are binding.

3. Empirical Methodology

The previous section delineates the basic optimization framework for derivation of the prices for market-based transfers, along with underlying physical and economic constraints. However, it is necessary to describe the empirical specification used in the study for deriving the demand functions for residential, nonresidential, and hydroelectric water use. These functions are the basis of the net benefits from water use from each sector as shown in objective function (equation (1)) of the previous section. Note that the time period (t) for the empirical modeling is at the monthly level.

Hydropower

The empirical model for hydropower generation from reservoir water is based upon the work by ReVelle (1999), Ward and Lynch (1996) and Young and Loomis (2014). According to these engineering studies, hydropower demand (generation) is assumed to be a function of the effective head, the power releases from the reservoir and a parameter indicating generator efficiency. In addition, Young includes another constant for conversion of the water generated in acre feet to Kwh, similar to Lynch and Ward's specification. So, the monthly model for hydropower generation may be expressed as:

$$Hydropower_m = EH_m * releases_m * geneff_m * C \qquad (16)$$

where, $releases_m$ indicates monthly power releases, EH_m represents the effective head of the turbine (defined below) which varies with monthly power releases, $geneff$ stands for generator efficiency which ranges from 0.85-0.90 (USACE data, Young and Loomis, 2014), and the value of C equals 1.024 (Young and Loomis, 2014). The above has to be constrained by maximum turbine capacity for power releases and maximum generator capacity as:

$$releases_m \leq \max turbine\ cap\,acity$$

$$Hydropower_m \leq \max gen\ capacity$$

Also, the following equations relate the amount of hydropower generated monthly to the lake level, height of the turbine (head) and the volume of water in the reservoir. The head of the turbine is defined as the difference between the level of water in the reservoir and the height of the generating turbine. The effective head is used in the model to minimize the impact of large power releases on changes in the head and is defined as the average of the heads in months m and (m+1) (Lynch and Ward, 1996). In addition, the average volume constraint is added to ensure the optimal feasibility of the monthly water demand model and along with the state equation (5), renders sustainability to water flows over time.

$$Level_{\ m} = F(Vol_m)$$

$$Head_m = Level_{\ m} - height\ of\ turbine$$

$$EH_m(effective\ head) = \frac{Head_m + Head_{m+1}}{2}$$

$$Averagevol = \frac{Vol_m + Vol_{m+1}}{2}$$

The level of water in the reservoir is a function of the volume of water and is estimated in the empirical model using data from the United States Army Corps of Engineer's Office (USACE), Tulsa District.

$$Level_{\ m} = 567.49 + 0.0001194 * Vol_m - 3.26e^{-11} * {Vol_m}^2$$

Finally, the hydropower economic benefit function is expressed as

$$Hydropowerben_m = P_m * Hydropower_m \qquad (17)$$

Where, P_m denotes the monthly price of electricity expressed in \$/MWh. It should be noted that net benefits from hydropower is assumed to the same as above, since the fixed costs of plant capacity and investment are not likely to affect marginal hydropower releases and monthly generation of hydroelectricity from the reservoir.

The above specification utilizes the engineering studies used in previous works by Ward and Lynch (1996), ReVelle (1999) and Young and Loomis (2014) among many others. Debnath (2009, 2014) and McKenzie (2005) used an estimated demand function for hydropower with head and power releases as the independent variables and historical observations on hydropower generation data as the dependent variable. The reason for not selecting an econometric demand function for the current study are twofold. One, historical observations for hydropower generation although available[1], are not well-defined for several days in each month and shows wide variation between months leading to unreliable observations for estimation purposes. This is because, there are time periods during the year when low releases account for inaccurate hydropower estimation with a few observations from 1995-2000 (which are publicly available through USACE, Tulsa District Office) showing negative hydropower generation. Secondly, econometric estimation of hydropower generation is a way to empirically estimate the value of $(geneff_m * C)$, which are borrowed from existing literature and from USACE data for the current study.

Residential and nonresidential water demand

The study uses the point expansion method illustrated in Griffin (2006) and Young and Loomis (2014) for determining the demand and the net benefits from residential and non-residential water use. According to Griffin (2006), the point expansion methodology is capable of estimating demand functions in potentially all sectors provided an elasticity of demand is available from an external source. The point expansion methodology with a mathematical programming model has been widely used in studies on municipal water demand (James and Lee, 1971; Griffin, 2006). It relies on a given elasticity estimate for urban residential/ non-residential use and a point estimate on the marginal benefit function (observed value of a quantity of water and its corresponding marginal value or price) for a baseline year.

[1] The availability of current data (2000 onwards) was subject to signing a Freedom of Information Act with USACE and is not available publicly through the Tulsa District website.

Suppose water demand in each sector "i" is represented by a linear marginal benefit function having the following form:

$$\hat{p_i} = \hat{a_i} - \hat{b_i} w_i$$

where, $\hat{p_i}$ and w_i denote the sectoral level price of water and water use respectively and $\hat{a_i}$ and $\hat{b_i}$ represent the intercept and the slope parameters (refer to the Appendix for derivation of $\hat{a_i}$ and $\hat{b}$ when an elasticity of demand for residential and nonresidential water use is available)

A linear marginal benefit schedule implies a nonlinear quadratic total benefit function for water use for each of the residential and non-residential sectors as follows:

$$TB_I\,(w_i) = \int (\hat{a_i} + \hat{b}_i w_i) dw$$

The net benefit from water use in each sector is then expressed as the joint maximization of the consumer and producer surplus (total benefits) after subtracting the total costs of water delivery for each sector in each region.

Recreational water demand

The conventional practice has been to estimate recreational demand models using non-market valuation methods like the travel cost or contingent valuation methods (Boyer et al., 2008; Reilley, 2011; Loomis, 2012; Loomis and McTernan; 2014), with at least one study (Prado, 2006) employing the travel cost method to determine the economic value of trout fishery in the Lower Illinois River. Although lake level and volume of water in the reservoir influence people's willingness to pay for recreational visits, some studies have explicitly tied the number of visits with the level of water in the reservoir and then obtained an estimate of recreational benefits by multiplying the value of a single day visit with the total number of visits (Boyer et al., 2008; Debnath, 2014, 2015). Since the purpose of the current study is to determine an institutional mechanism for allocation of water among the various competing uses — consumptive and non-consumptive (like recreational and environmental uses) — recreational water demand is considered as part of the minimum capacity of water in the reservoir. In other words, reservoir water allocation is tied to the minimum level or volume of water that the reservoir should have in order to support recreational water demand. Equation (7) in the conceptual model captures this constraint. Utilizing a minimum reservoir storage/volume constraint allows us to preserve the tractability of the dynamic model as well as follow the movement of the shadow prices over months, when a non-consumptive use like recreation directly competes with hydropower, preservation of instream flows and other consumptive uses.

Instream flow demand

The demand for environmental water though closely related to recreational demand for water, instream flows is a necessity to preserve wildlife and the ecosystem which not only benefits the environment but also brings in millions of dollars in revenue from tourism and recreation to the region. The economic challenge lies in the absence of an estimated value to flows since in most parts of western United states and in many other countries, flow rights are not assigned and so institutional allocation of water may not benefit and in fact, can hinder the valuation of instream flows. This issue has been noted in the background to the current study which is set in a state in western United States, where instream flow rights are not legally defined (Rehreing, 2019; Boyer et al., 2015).[2] A number of previous studies have employed a quadratic or a Cobb Douglas benefit function to estimate recreational benefits from instream flows using lake volume or the actual streamflow as the independent variable (Ward and Lynch, 1996, McKenzie, 2005). However, the applicability of such a benefit function is limited by data to estimate the stream flows in real time to determine how flow change affects environmental water use at each point of time. For instance, Ward and Lynch (1996) used a regional simulation model (RIOFISH) to determine recreational benefits from both reservoir and instream flows. Since the dynamic model considered in this study does not include many of the spatiotemporal interdependencies in the functional relationships, a benefit function dependent on flows is not estimated. A second reason for not considering an estimated benefit function is data constraint—instream flow methodology with physical flow levels has been recently completed for the Illinois River Basin (Rehreing, 2019). Instead, the approach taken in this study is to use minimum instream flows as a constraint in the model to assess the opportunity cost of the minimum flows being binding at any time period within a year. This approach has been applied in the Rio Grande basin studies by Ward and Pulido Velazquez (2008, 2009) and by Ward and Booker (2006) and conforms to some of the ongoing debates around minimum flows implementation in the Illinois River. The minimum flow constraint in each month is described by Equation (8) in the previous section.

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[2] Oklahoma and ND are the only two states of western US where instream flows are not recognized directly.

Apart from the specific consumptive and non-consumptive water use benefits, a number of physical and economic constraints like minimum and maximum lake levels, maximum storage capacity, and permits for water use are also incorporated in the empirical model. The model is solved in GAMS, using the CONOPT nonlinear optimization solver.

4. Study region and Data

The historic Illinois River in northeast Oklahoma stretching 145 miles between OK and AR is considered as one of the scenic rivers of the state of Oklahoma. While the Tenkiller Dam serves hydropower to the regional economy, the Lower Illinois river is home to one of Oklahoma's year-round trout fishery. Apart from serving the water supply needs for hydropower and municipal and industrial needs, the recreational value from the Illinois River including trout fishing has been estimated at $14.3 million- $17.1 million a year (USDOI, 2012), with Lake Tenkiller itself estimated to have a recreational value of $300 million for a 50-year time period. (Debnath et al., 2015).

Currently, the water rights in the reservoir are shared by hydropower, municipal and rural water companies and industrial and commercial users. 93% of water storage rights are owned by Southwestern Power Administration (SWPA, an agency of USDOE) while 7% rights are allocated to the other consumptive users. The Oklahoma Department of Water Conservation has regular permit for trout fishing in the Lower Illinois which replaced the temporary 90-day permit for stocking trout, though the permit is contingent upon sufficient water available for upstream consumptive uses. Trout fishing also depended upon a leak in the Tenkiller Dam that provided water for fish survival until that leak was fixed in 2018. Thus, under the current circumstances, instream flows to preserve the environmental and recreational values from fishing and other forms of recreation is a significant topic of study and research in this region.

Data for monthly hydropower releases, lake level (elevation) and lake volume or storage are obtained for Jan 2008-Dec 2019 from the United States Army Corps of Engineer's Office (USACE), Tulsa district. The power releases data are available in dfs and are converted to acre feet/ month. The USCAE also has publicly available data on monthly evaporation, rainfall and inflows for the Tenkiller Dam used for this study. As noted in the previous section on empirical methodology, the hydroelectric power coefficients like generator efficiency are borrowed from published studies (USACE, Young and Loomis, 2014) while generator capacity and turbine capacity are obtained from daily generation schedule data published by Southwestern Power Administration. [3]Finally, the monthly price of electricity per MWh is obtained from the Oklahoma Municipal Utility Costs 2017-2018 report published by the Oklahoma Municipal League. These numbers are close to the rates published by the Oklahoma Electric Cooperative which purchases power from SWPA.

However, it was not so straightforward to obtain data for monthly residential and nonresidential water use and prices. Residential water use consists of municipal water and water served by the rural water companies while nonresidential water use refers to commercial water use. The first task is to identify the set of rural water districts and the municipal water providers in the cities, towns and rural areas which use water from Lake Tenkiller. An overview of the studies done by Debnath (2009) and Debnath et al. (2015) and the Safe Drinking Water Information Systems database, revealed 21 cities, towns, water associations and rural water districts that provide residential water needs to communities (residential water users) and around 6 commercial (non-residential) water users. All these users are listed in Table A1 in the Appendix. Once the different water entities are identified, data on population served and size of household are obtained from the American Community Survey (US Census) and from SDWIS website. Data on residential and nonresidential water use are obtained from USGS state level water surveys conducted every five years. The reason for using USGS annual data instead of monthly data was the unavailability of monthly water use data for all the regional towns, cities and rural water districts that use water from the Lake. [4]Data is gathered for the years 2000, 2005 and 2015 for the three counties of Muskogee, Cherokee and Sequoyah where majority of water comes from Lake Tenkiller and consist of domestic water use and commercial and industrial use. It is assumed that water use should vary by season and not necessarily by months at a more aggregated level, so varying the price elasticity of demand for water over summer and winter months is considered a realistic option. The elasticities for summer and winter months for residential water use are obtained from Davis et al. (1987) while the same for non-residential

[3] The numbers are cross checked with Teresa Flood, USCACE, through a telephone conversation
[4] OWRB and ODEQ both have links to USGS data on water use.

water use are obtained from Renzetti (1992, 2002). [5] Residential and non-residential water rates vary widely and so prices are obtained from data published on water rates by municipal providers like the Tahlequah Public Works Authority, the Town of Gore, the Sequoyah County Water Association and the Cherokee County Rural Water Districts. The rate of water per 1000 gallons is converted to price per acre feet for residential and non-residential water use. The above data for water use, prices, elasticities and population served are utilized for generating the intercept and slope parameters for demand functions for residential and nonresidential water use. In addition, we use the marginal cost of water delivery from Debnath (2014) in the full-scale optimization model for maximizing the net benefits from residential and nonresidential water use.

The hydrological or physical parameters like monthly inflows, monthly storage volumes or reservoir capacity and exogenous outflows are obtained from USACE. For the minimum instream flows, the most recent work completed by OWRB for the Upper Illinois River is used for representing base flows at a monthly level (Rehreing, 2019)[6]. These flows are varied to denote maximum flows for each month in a separate sensitivity analysis. The allocation of permits is assumed to follow the current ownership of storage rights by SWPA and the residential and nonresidential units. According to Oklahoma Department of Wildlife Conservation (ODWC), SWPA owns 93% of the water storage rights in the reservoir, while 7% of the rights are allocated to water companies and rural water districts providing water to the municipal and commercial water users. It is assumed that 7% of the storage rights are distributed equally among municipal and commercial water use. Also, as water storage capacity varies monthly, the water availability to the various user groups varies although their initial allocation remains the same.

Table A.2 in the Appendix describes the data sources for all economic and physical parameters for the model.

5. Results and Discussions

[5] It should be noted here that it is difficult to find elasticities of demand for water for commercial and industrial use since it is hard to separate the source as treated water or self-supplied through industrial treatment and reuse. Renzetti (1992,2002) provide some of the best-known elasticities value for industrial water use.

[6] Note that this is the most recent study to determine physical flows in the Illinois River Basin and the work is completed for the Upper Illinois River.

The results from the full-scale optimization mode for water allocation with minimum instream flows constraint are shown in Tables A. 3-A. 5 in the appendix. Table A. 3 illustrate the monthly lake levels and head, volume, releases and outflows from the reservoir, while A. 4 describes the monthly water use for hydropower, residential and nonresidential uses. As expected, residential and nonresidential water use peak during the summer months while prices do not vary much over months for both uses.

[*Insert Tables A.3 and A.4 here*]

Results from the optimization model reveal some interesting pattern in water use particularly for hydropower. The monthly power releases and the hydropower generation are depicted in Tables A. 3 and A.4 in the appendix. Although the optimal levels of power releases correspond to monthly releases observed from data from USACE, the hydropower generation shows up as 23100 MW every month except for November. We could consider this as an upper bound on the generation capacity constraint. The power releases contribute to the shadow prices observed in Table A.5 which correspond to the maximum capacity constraints for the reservoir, the state equation illustrating the mass balance constraint and the minimum flows constraint corresponding to the base streamflow (the negative signs for the shadow prices in the minimum flows constraint is due to the greater than equal sign on that constraint in the empirical model). It may be noted that these shadow prices reflect the marginal cost prices if municipal or hydropower users were to purchase additional water in an actual market. As was shown in Section 2, they denote the prices for water permits for the various users provided that the above constraints are binding. So, for instance, if water was transferable across users, hydropower user (SWPA) would have to pay $ 38.22 /acre foot for September to holders of environmental water permits. This number comes from two constraints—the mass balance constraint and the capacity constraint, which are both binding in September. In October and November, the water balance constraint become binding leading to water use satisfying the minimum streamflow and so the permit prices vary over these months. Interestingly, these are the same prices that municipal water users will have to pay if they want to purchase any additional water during this time period. However, since hydropower effectively uses more water during September (power releases lead to satisfying the maximum capacity constraint for the reservoir), hydropower ends up paying more than residential and nonresidential water users. It is noteworthy that even though municipal water demand is higher in most summer months, the prices that affect additional water sales or purchase are determined through the releases from the reservoir that contribute to minimum flows. This is because, the amount of water released through the turbines is dependent upon the total water use in this multiperiod optimization modeling, making some of the capacity constraint for the reservoir binding in certain months. In order to check whether higher water demand from residential users affect the results, the monthly household water use is increased. Apart from raising the quantity demanded every month for residential users, this has limited impact on the earlier results.

[*Insert Table A.5*]

The next step in our analysis was increasing the minimum flows to 1000 cfs per month which is slightly below the maximum flow range or 1200 cfs, for public safety and recreation (Rehreing, 2019). As shown in table A.6, the balance constraints become binding for every month from June to November indicating that satisfying the increased flows will result in paying higher prices at the margin for very additional water use during these months. Since none of the capacity constraints are binding, all users pay a range from $38.9-$17/acre foot of water if they want any water transferred from the reservoir. This shows that current debates around what should be the minimum flows based upon recreational as well as instream or environmental flow criteria are an important aspect of instream flow methodology to be adopted in this region. If a market transfer mechanism exists, it will require a marginal cost price for binding flow constraint that is absent from current water rates established for municipal use or for other consumptive purposes. This is evident from Table A.7, which compares the residential and non-residential water prices for the two scenarios— one when the flow constraints correspond to the base flows and two, when the required minimum flows are raised to 1000 cfs. Although the prices do not vary for the two user types, there seems to an increase in prices in the summer months by 13.8-15% when the minimum flows are binding at 1000cfs. This price change compared to base flows, reflects the higher opportunity costs of municipal water used during the summer months, the source of which is water allocated from the reservoir. More water uses results in higher prices if downstream flows are binding in certain months.

[*Insert Tables A.6 and A.7 here*]

The above discussions suggest that a market framework for water allocation where permit prices include the marginal costs of water allocation across consumptive and non-consumptive uses, can internalize some of the externalities imposed on downstream flows or environmental water use. These prices are generated through an optimization framework which solves for market clearing prices and quantities for each period. The three main participants in this optimal water allocation are hydropower, residential and nonresidential water users, who may face different prices for water use depending on binding flow and capacity constraints. These results do not include an actual trading exercise between the market participants when instream flows are binding and only explain the different prices for water transfers that form the empirical basis for the common pool trading.

A separate trading simulation involving a central market manager who settles all transactions for the trade is the next step in this paper. The central manager could be the state water agency or any local environmental agency (Trout Unlimited in OK) or a water trust which could determine the initial allocation of the permits and help with the market mechanism to work. The common pool would be a regional pool where water rights could be either stored or storage credits could be purchased by competing users. Although the theoretical basis of the model shown here is inspired by the wholesale electricity prices market, a spot market for water trading may not be the most feasible option for this model. The water permits allocated and traded and the respective prices can be generated through an annual or seasonal market-based transfer mediated by the market manager. The monthly variation in flows is likely to change some of these prices but long-term contracts with consumptive users may alleviate some of this problem.

6. Conclusions

Market based water transfers have gained popularity around the world, yet externalities and transaction costs associated with transfers have dominated gains from trading in most circumstances. Hence, design of effective market institutions for allocation of water among consumptive and non-consumptive use remains an economic challenge both at a theoretical and practical level. The public good characteristic of instream flows adds another layer of externality which complicates transfers between consumptive and environmental water users, leading to the slow evolution of this market in western United States. This paper contributes to the existing work by offering a centralized market-based transfers that could explicitly tie the third-party impacts of binding stream flow constraints with the opportunity costs of water allocation among users.

The study region in northeast Oklahoma offers a unique case study with water allocated for reservoir often affecting downstream flows that contributes to recreation and other environmental purposes like trout fishery, bringing in millions of dollars in revenue every year. An optimal model for reservoir management with constraints on downstream flows provides the water uses for municipal and hydropower as well as the shadow prices or opportunity costs of binding flow constraints. These flow constraints are minimum streamflow for preserving habitats and for recreation and hence a positive price with a binding constraint, reflects the price that other users may need to pay for incremental water use under a market-based allocation of water. Although a central manager's role is not shown in the model, a state or local agency can mediate the transactions in such transfers with prices changing seasonally or annually based on flow constraints.

A simulated trading exercise among consumptive and non-consumptive water users is the next step in this research, something which is not presented here. The water rights awarded to the various users along with the shadow prices, could form the basis of an initial allocation and prices for water transfers in this region. The study aims to enhance the evolving research around environmental water markets and offer a possible solution to a long-standing debate among local stakeholders on a suitable allocation of water for environmental purposes.

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Appendix

Let i $(i = 1, 2)$ denote the category or sector of water use (residential or nonresidential), w_i the quantity of water used in sector i, and $MB_i(w_i)$ the marginal benefit function for water use, in sector i. We assume that the marginal benefit function or the inverse demand for water is linear, so that

$$MB_i(w_i) = a_i + b_i w_i \qquad (A1)$$

This marginal benefit function in the residential sector is affected by population and household size while in the non-residential sector, it may be influenced by growth in industrial and commercial activities. We also note that

$$\frac{dMB_i(w_i)}{dw_i} = b_i \qquad (A2)$$

Let the price elasticity of demand for water coefficient be denoted as ε_i. This elasticity coefficient is defined as

$$\varepsilon_i = \frac{dw_i}{dMB_i(w_i)} \frac{MB_i(w_i)}{w_i} \qquad (A3)$$

Using equation (A2) to rewrite equation (A3), we obtain the following:

$$\varepsilon_i = \frac{1}{b_i} \frac{MB_i(w_i)}{w_i} \qquad (A4)$$

The parameters a_i and b_i may now be determined by the point expansion process. First, we can solve equation (A4) for b_i:, which is the slope of the sectoral water demand function

$$b_i = \frac{1}{\varepsilon_i} \frac{MB_i(w_i)}{w_i} \qquad (A5)$$

Let the exogenously determined value for the elasticity coefficient be denoted as $\bar{\varepsilon}_i$, the known value for w_i be denoted as $\overline{w}_i$ and the corresponding marginal benefit of water be $MB_i(\overline{w}_i)$. We can substitute these values into equation (A5) to compute the slope parameter, $\hat{b}_i$. The value of the intercept (a_i) can then be obtained by substituting the value of b_i into equation (A1) as follows:

$$\hat{a}_i = MB_I(\overline{w}_i) - \hat{b}_i \overline{w}_i \qquad \text{(A6)}$$

Once these slope and intercept parameters are calibrated using actual data for water demand, prices or rates per unit of water delivered and costs of water distribution/ delivery, they are inserted back into equation (A1). Finally, the total benefit function is determined by the area under the marginal benefit function corresponding to the quantity of water consumed in sector i. Let $TB_i(w_i)$ represent total benefits of water consumption for sector i. Integrating the marginal benefit function (A1), generates a quadratic total benefit function for water use in sector i as follows:

$$TB_I(w_i) = \int_0^{w_i^*} \left(\hat{a}_i + \hat{b}_i w_i\right) dw \qquad (A7)$$

Table A.1: Residential and nonresidential water users and population served

Cities/towns/ rural water districts	population served	household size
Tahlequah (TPWA)	16667	3
Gore	958	3
Vian	1282	3
Sequoyah County Water Assoc	13460	N/A
Cherokee County RWD#1	710	N/A
Cherokee County RWD#2	1493	N/A
Cherokee County RWD#3	2300	N/A
Cherokee County RWD#7	418	N/A
Cherokee County RWD#8	413	N/A
Cherokee County RWD#13	1640	N/A
Muskogee County RWD#4	783	N/A
Muskogee County RWD#7	1710	N/A
Sequoyah County RWD #7	2948	N/A
Tenkiller Utility co	860	N/A
Sequoyah CDP	957	3
Park Hill CDP	4001	3
Fort Gibson	4021	2
Muldrow	3270	3
Sallisaw	8571	3
Paradise Hills	71	3
Hulbert	627	3
Fin and Feather Resort	150	
Paradise Hills	270	
Tenkiller Aqua Park	150	
Tenkiller State Park	115	
Greenleaf Nursery Co	650	
Burnt Cabin	118	

Source: US Census ACS and SDWIS

Table A.2: Data sources for the main variables and the parameters used

Variable/ Parameter	Data source
Lake level	USACE
Hydropower release	USACE
Volume or storage	USACE
Monthly inflows	USACE
Base flows	OWRB, Upper Illinois River Pilot Study
Permits allocated	ODWC
Generator capacity	SWPA
Turbine capacity	SWPA
Generator efficiency	USACE
Monthly price of electricity	Oklahoma Municipal League Report (2017-2018)
Population and household size	SDWIS, US Census American Community Survey
Per capita residential water use	USGS
Per capita nonresidential water use	USGS
Price elasticity of demand	Davis et al, 1987; Renzetti (2002)
Water prices or rates	Municipal water providers

Table A.3 Monthly lake level, volume, releases and outflows from optimal model

Months	Lake level (feet)	Head (feet)	Volume (acre feet)	Releases (acre feet)	Outflows (acre feet)
Jan	638.40	136.40	745730.00	59322.66	50000.00
Feb	635.69	133.69	708120.00	60524.33	52000.00
Mar	634.78	132.79	695810.00	65955.92	80000.00
Apr	635.75	133.75	708930.00	63247.55	150990.00
May	637.23	135.23	729310.00	62556.21	78409.24
June	645.00	143.00	843360.00	57842.55	52156.93
July	645.00	143.00	843360.00	59837.12	78282.15
Aug	640.49	138.49	775640.00	60397.99	34967.95
Sep	637.03	135.03	726500.00	62649.84	20000.00
Oct	635.09	133.09	699980.00	62845.89	28000.00
Nov	635.07	133.07	699700.00	70029.53	45000.00
Dec	632.00	130.00	658780.00	114530.00	672750.00

Table A.4 Monthly water uses and hydropower generation

Months	Residential water use (acre feet)	Nonresidential water use (acre feet)	Total municipal water use (acre feet)	Hydropower generation (MWh)
Jan	461.99	364.95	826.94	23100.00
Feb	461.99	364.95	826.94	23100.00
Mar	461.99	364.95	826.94	23100.00
Apr	461.99	364.95	826.94	23100.00
May	539.34	424.90	964.24	23100.00
June	539.34	424.90	964.24	23100.00
July	539.34	424.90	964.24	23100.00
Aug	539.34	424.90	964.24	23100.00
Sep	537.90	423.72	961.62	23100.00
Oct	461.77	364.21	825.98	23100.00
Nov	461.77	364.22	825.99	14458.73
Dec	461.99	364.39	826.38	23100.00

Table A.5 Shadow prices with minimum flows restricted to base flows

Months	Max Capacity constraint ($/acre foot)	Mass balance constraint ($/acre foot)	Min flows constraint ($/acre foot)
Jan			
Feb			
Mar			
Apr			
May			
June			
July			
Aug			
Sep	19.43	18.79	-18.79
Oct		18.17	-18.17
Nov		17.49	-17.49
Dec			

Table A.6	**Shadow prices with minimum flows of 1000 cfs per month**		
Months	**Max Capacity constraint** ($/acre foot)	**Mass balance constraint** ($/acre foot)	**Min flows constraint** ($/acre foot)
Jan			
Feb			
Mar			
Apr			
May			
June		38.83	-38.83
July		37.98	-37.98
Aug		36.92	-36.92
Sep		35.72	-35.72
Oct		30.41	-30.41
Nov		17.08	-17.08
Dec			

Table A.7	**Minimum flows correspond to baseflows**		**Minimum flows correspond to 1000 cfs**	
Months	**Price of residential water** ($/acre foot)	**Price of nonresidential water** ($/acre foot)	**Price of residential water** ($/acre foot)	**Price of nonresidential water** ($/acre foot)
Jan	257.64	257.64	257.64	257.64
Feb	257.64	257.64	257.64	257.64
Mar	257.64	257.64	257.64	257.64
Apr	257.64	257.64	257.64	257.64
May	257.64	257.64	257.64	257.64
June	257.64	257.64	296.47	296.47
July	257.64	257.64	295.62	295.62
Aug	257.64	257.64	294.56	294.56
Sep	276.44	276.44	293.36	293.36
Oct	275.81	275.81	288.05	288.05
Nov	275.13	275.13	274.72	274.72
Dec	257.64	257.64	257.64	257.64