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Article

Water Trading: Locational Water Rights, Economic Efficiency, and Third-Party Effect

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Abstract: Rivers flow downstream and unidirectionally. However, this fact has not yet been utilized in the institutional design for water trading. By utilizing this characteristic, we first designed a water trading system of "locational water rights." This new system is able to mitigate the return flow-related and instream flow-related third-party effects of volumetric reliability from water transfers. We provided mathematical proof of its economic efficiency. We then applied this water trading system to the case of the Choushui River basin in Taiwan. In this area, agriculture is highly developed while domestic and industrial water demands have increased rapidly. Using an agent-based model simulation, we estimated the potential economic benefits of implementing the system of locational water rights in the Choushui River basin.

Keywords: water market; locational water right; economic efficiency; third-party effect; return flows

1. Introduction

Associated with population growth and economic activities, difficulties in developing new water supplies, as well as increasing uncertainties regarding hydrology and water disasters due to climate change, water has become increasingly scarce and more essential than ever in almost every country. Several countries, such as the United States (western part), Australia, Chile, and South Africa, have adopted the water market as an alternative to various methods of water allocation (see e.g., the review of Hadjigeorgalis [1]).

Water trading has great potential to increase the efficiency of water use and help water users to cope with a drier and more unstable climate (see e.g., [1–4]). Successful water trading needs the following three conditions: (i) a monitorable and enforceable quantity cap that is placed on the market that limits the amount of resource used in a defined area; (ii) entitlements are defined and distributed among the users; and (iii) a market is created to enable trading of entitlements [2]. However, even when these conditions are met, they are not sufficient to achieve social optimality. Other factors such as increasing uncertainties from climate change and institutional constraints may make water trading perform unexpectedly. Most importantly, water trading usually fails to take into account third-party effects, that is, the effects of water transfers on parties that are not directly involved in the transaction (also called externalities) (see e.g., p. 2 in Hartman and Seastone [5] and p.5 in Scheierling [6]). There are several kinds of third-party effects that result from water trade such as volumetric reliability, delivery reliability, timeliness of delivery, water quality, and rural development effects [7,8]. Based on the water reform experiences in Australia's Murray-Darling Basin and Chilean water markets, some recent papers examine the social, economic, environmental, and institutional limitations and externalities that restrict the success of water trading (see e.g., [2,3,9,10]).

The first purpose of this article is to reduce the third-party effects associated with water transfers by designing a system of "locational water rights" for a spot water market. This trading system exploits the specific characteristic that water flows downstream unidirectionally. Among the various externalities, we focus on the third-party effects of volumetric reliability related to return flow and instream flow [11,12]. For example, water transferred from downstream to upstream users might reduce intermediate instream flows and flows to intermediate users. The changes in return flows might also result in insufficient water for diversion to downstream users. To internalize the externalities that affect other water users, most studies propose that the water rights should be defined on the basis of consumptive use (see e.g., [13–15]). When flow constraints are not binding, this type of water rights implements the optimal solution. When flow constraints are binding, however, a two-party upstream transfer can result in impairment even when consumptive use is the measure of water right [13,16]. Moreover, consumptive use transfers may not prevent damage to instream flows [17]. Therefore, requiring a review and approval of transactions by a public agency and/or establishing a fund to compensate third parties for damages incurred in trading are the usual methods used to deal with the externalities [18]. However, a court system might result in a litigious environment and increase transaction costs substantially [19].

For the system of locational water rights proposed in this article, the initial cap of consumption rights allowed for each location is calculated from upstream to downstream with consideration of the requirement of minimum instream flows. Each consumption right is labeled by location and defined as

a locational water right. This special design aims to be consistent with the characteristic of water, namely, it always flows downstream unidirectionally, and also meets the requirement of minimum instream flows. To our knowledge, it is the first time this characteristic of water has been used in designing water rights (for effluent trading, this characteristic has been applied in Hung and Shaw [20]). By so doing the system can ensure no third-party effects will be caused on the instream flows since the caps of locational water rights meet the requirements. It should be noted that the locational water rights can be distributed suitably to water users in other locations so that there is no conflict with the existing water using institution. In combination with the traditional trading of consumption and return-flow rights, the system of locational water rights can achieve economic efficiency even when flow constraints are binding. In addition, by restricting only downstream transfers of locational water rights, no negative externalities will result to other water users. Transfers can be made bilaterally and are not restricted to being simultaneous, adjacent or approved *ex ante* (regardless of the import/export of water or non-adjacent transfers). Transaction costs can therefore be largely reduced. Theoretically, this locational water right system improves the way in which the third-party effects of volumetric reliability related to return flow and instream flow are handled [21].

The second purpose of this article is to apply the system of locational water rights to study the economic efficiency of a potential water market for the case of the Choushui River basin in Taiwan. In this area, agriculture is highly developed and the local irrigation associations own most of the registered water rights. However, because the water demand of industrial and domestic uses increase rapidly and the uncertainty and unevenness of water supply rise, conflicts and problems among water users have been increasing. Agricultural irrigation water is arbitrated by the government for regular reallocation to industrial and domestic uses. The existing water transfers do not adequately address the third-party effects, return flows, and ecological and environmental problems, however. It is therefore very important to deal with the third-party effects to water users and the environment and to improve the economic efficiency of water usage by a well-designed water market in this area [22,23]. By using an agent-based model, we have simulated the water trading scenarios in this area with the proposed trading system of locational water rights.

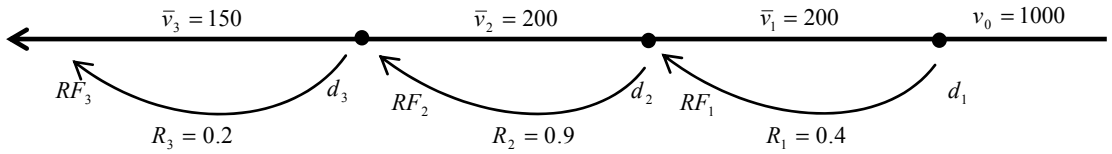
The remainder of this article is organized as follows. In Section 2, the basic environment of a river system is first described. We introduce the system of locational water rights and prove that water transfers under this institutional design can achieve economic efficiency. We also propose a simple example to illustrate the third-party effect with and without the design of locational water rights. In Section 3, the system of locational water rights is applied to the Choushui River basin in Taiwan. In this area, the promotion of water use efficiency is very important and imperative. The last section offers a conclusion.

2. Locational Water Rights, Economic Efficiency, and Third-Party Effect

In this section, we first describe the basic environment of a river system where there are no branches feeding into the system. The return flow of a diversion returns back to the river before the next diversion point (see Table 1). This is a common scenario setting in the literature (see e.g., [13,24,25]). The simplified river system facilitates the analysis but is not necessary, however [26]. We then introduce the design of locational water rights and its advantages. A simple illustration follows to explain the

differences between the system of locational water rights and other water right systems and to discuss the third-party effect. Lastly, the economic efficiency of water transfers under the system of locational water rights is proved.

Table 1. Schematic diagram of a simplified river system.



	Scenario	v_0	d_1 (c_1)	v_1	RF_1	d_2 (c_2)	v_2	RF_2	d_3 (c_3)	v_3	RF_3
(0)	Status quo	1000	−500 (300)	500	+200	−500 (50)	200	+450	−500 (400)	150	+100
(1)	Diversion trading	1000	−1000 (600)	**0**	+400	**−400 (40)**	**0**	+360	−0 (0)	**360**	+0
(2)	Consumption trading	1000	−900 (540)	**100**	+360	**−460 (46)**	**0**	+414	−0 (0)	**414**	+0
(3)	Locational water right	1000	−500 (300)	500	+200	−500 (50)	200	+450	−500 (400)	150	+100
(4)	Environmental flows	1000	−300 (180)	**700**	+120	−500 (50)	**320**	+450	−500 (400)	**270**	+100

Notes: [1] In the table, v_i represents streamflow in section i, RF is return flow, and minus (plus) sign indicates the reduction (increase) of streamflow; [2] Row (3) indicates the allocation of locational water rights to water users according to the status quo distribution.

2.1. Basic River System and Optimal Water Allocation

Suppose that there is a set of water users located along a river and numbered as $i = 1, \ldots, n$ from upstream to downstream. Water flow at the source is denoted by v_0. The requirement of minimum instream flow at location i is denoted by $\bar{v}_i$. A minimum flow which aims to provide a certain level of protection for the aquatic environment describes the amount of water flow required to preserve aquatic life, habitat, water quality, navigation, recreation, or aesthetic beauty (see e.g., [27–29]). If we designate user i's diversion and consumption of water by d_i and c_i, respectively, then

$$c_i = (1 - R_i)d_i \tag{1}$$

In this equation, R_i (≥ 0) is a net return flow parameter which indicates the percentage of diversion water returning to the river after a specific water use of user i. The evaporation, seepage, and infiltration have been deducted. This parameter is usually assumed exogenous in the literature because water use habits, irrigation technologies, land uses, or natural conditions do not change in the short run. In the long run, the introduction of water trade would create incentives for water users to modify their practices of water use so as to maximize the benefits of both consumptive use and return flows. The authority could update the return flow parameters periodically. In addition, because the calculation of this parameter case-by-case is complicated in practice, R_i is often determined by the particular water uses (e.g., agricultural, domestic, or industrial use) and geographic conditions.

To satisfy the requirement of minimum instream flows, the following constraints for diversions must be satisfied:

$$v_0 - (\sum_{j=1}^{i-1}(1-R_j)d_j + d_i) \geq \overline{v}_i, \quad i = 1,\ldots,n \tag{2}$$

Equivalently,

$$\sum_{j=1}^{i-1}(1-R_j)d_j + d_i \leq v_0 - \overline{v}_i, \quad i = 1,\ldots,n \tag{3}$$

That is, at a particular location, the total amount of water consumed upstream and the immediate diversion must be less than the total available amount of water. According to Equation (1), the above constraints for diversions can be rearranged as constraints for water consumption:

$$(1-R_i)\sum_{j=1}^{i-1}c_j + c_i \leq (1-R_i)(v_0 - \overline{v}_i), \quad i = 1,\ldots,n \tag{4}$$

Assuming that water user i's benefit depends only on the amount of water he consumes, his benefit function can be written as $B_i = B_i(c_i)$, where $B_c > 0$ and $B_{cc} < 0$. The regulator maximizes the total benefits by solving the optimization problem

$$\underset{c_i}{Max} \quad \sum_{i=1}^{n} B_i(c_i) \tag{5}$$

$$s.t. \quad (1-R_i)\sum_{j=1}^{i-1}c_j + c_i \leq (1-R_i)(v_0 - \overline{v}_i), \quad i = 1,\ldots,n \tag{6}$$

$$\mathbf{c} = (c_1,\ldots,c_n) \geq 0 \tag{7}$$

The necessary condition for an interior solution with strictly positive consumption is

$$B_i' = \lambda_i + \sum_{j=i+1}^{n}(1-R_j)\lambda_j, \quad i = 1,\ldots,n \tag{8}$$

where B_i' is the marginal benefit of water user i and λ is the shadow price of water consumption.

2.2. Locational Water Right

One of the very specific characteristics of water is that it always flows downstream unidirectionally. By using this important feature, we propose an institutional design of locational water right which allocates the initial cap of consumption rights for each location from upstream to downstream subject to the requirement of minimum instream flows. Note that the locational water right is defined on the basis of consumptive use. Mathematically, this allocation design is represented as:

$$T_i^0 = (1-R_i)(v_0 - \overline{v}_i) - (1-R_i)\sum_{j=1}^{i-1}T_j^0, i = 1,\cdots,n \tag{9}$$

where T^0 is the initial amount of water rights for each location [30]. Water users can freely trade these water rights. Owning one unit of local locational water rights, a water user can increase one unit of water consumption. Owning one unit of upstream (downstream) water rights, a water user can increase one (no) unit of water diversion.

It should be noted that the above analysis is based on a scenario with certainty. In regions with high hydroclimatic variability or areas that are susceptible to major shifts in water availability, it is very difficult to robustly quantify the amount of minimum instream flows [2]. Under such uncertainty, the government or organizations can buy water rights for the environment to protect instream uses; other consumptive water users can also react to changes through water trading. In addition, due to increasing variable environment in the world, e.g., the prolonged "Big Dry" in Australia from 1997 to 2009, there might be not enough water in the system to meet the requirement of minimum instream flows. In this kind of extreme case, the protection level of environmental flows might need to be traded off with other consumptive uses. However, the market mechanism for water transfers can help improve water use efficiency especially when water is such a scarce resource. NWC [31], which studied Australia's prolonged drought, demonstrated that water markets and trading made a major contribution to the achievement of optimizing the economic, social, and environmental value of water.

The advantages derived from the locational water rights are as follows. First, the allocation Equation (9) is essentially derived from the constraints of the minimum instream flows (Equation (4)) by substituting T^0 for c. This water consumption cap, T^0, for each location will therefore protect the minimum instream flows not being violated due to water transfers. Second, this upstream to downstream allocation method "exploits all the available water allowed by the instream constraint" for each location "from upstream to downstream." In one aspect, because return flows can be used downstream, this upstream to downstream allocation can assure the possibility of water being used most efficiently to achieve economic efficiency. In the other aspect, since all available and allowed water has been allocated to the upstream locations, only downstream transfers of locational water rights will be needed subsequently. If, however, locational water rights are transferred upstream, more water (higher than the allowed quantity of water) will be used upstream and reduce intermediate instream flows and flows to intermediate users. Conversely, downstream transfers of locational water rights will keep water in the river until it is consumed downstream. These kind of transfers will therefore not result in negative externalities to other users and instream uses. The authority does not need to review and approve every trade in advance. Transaction costs are largely reduced.

It should be noted that the locational water rights are defined by location, not by water users. The rights of location i are not necessarily distributed to water users located at i. They can be allocated to users at other places at the beginning to meet the existent status of water right distribution. In the next subsection, a simple example is used to illustrate the differences between the system of locational water rights and other water right systems under different scenarios.

2.3. A Simple Illustration

Suppose there are three water users (i = 1,2,3) located along a river from upstream to downstream as shown in Table 1. Water flow at the source (v_0) is 1000 acre-feet (af hereafter). The requirement of minimum instream flow ($\bar{v}_i$) after diversion at Sections 1 and 2 are both 200 af and 150 af for Section 3. The return flow parameters R_1, R_2, and R_3 are 0.4, 0.9, and 0.2, respectively. The *status quo* is that water users 1–3 all have rights to divert 500 af of water (see Row (0) in Table 1). Note that the flow constraints are binding at the *status quo* because the water quantity allowed by the requirements of minimum instream flow is all consumed.

Let us consider some trading scenarios. First, if the water rights are defined on the basis of diversions, negative externalities might occur after trading. See Row (1) in Table 1. When user 3 sells 500 af to user 1, the instream flow requirement at Section 1 is violated where the streamflow $v_1 = 0 < \bar{v}_1 = 200$. Meanwhile, user 2 is affected by this trade. The available water for user 2 to divert is now only 400 af which is less than the amount of water allowed by his diversion rights (500 af). The instream flow requirement at Section 2 is also violated ($v_2 = 0 < \bar{v}_2 = 200$). Second, suppose that water rights are defined on the basis of consumptive use as suggested by some literature to avoid negative externalities. If user 3 sells consumption rights of 400 af (a corresponding reduction in diversion of 500 af) to user 1 and lets user 1 increase his diversion of 400 af, the instream flow requirement at Section 1 is still violated (see Row (2), $v_1 = 100 < \bar{v}_1 = 200$). User 2 is affected and has only 460 af of water to divert. The instream flow requirement at Section 2 is again violated ($v_2 = 0 < \bar{v}_2 = 200$). In addition, the flow constraint at Section 3 in both cases is not binding. This implies that water can be used more efficiently to increase benefits. In sum, the possible negative externalities resulting from the transfers of water diversion or consumption make trades should be reviewed and approved *ex ante*. The derived substantial transaction costs will defer the development of the water market.

Third, when the design of locational water rights is applied, the initial allocations of water rights for locations 1–3 are 480, 32, and 270.4 af, respectively, according to Equation (9). Note that this initial allocation is consistent with the instream requirements and the unidirection flow characteristic of rivers. Therefore, none of the instream requirements will be violated.

These locational water rights can be distributed to water users to be consistent with the existent situation of water right distribution at the beginning. In this case, the government distributes 300 and 180 af of location 1's water rights to users 1 and 2, respectively. By so doing, initially, all users can divert their water at the *status quo* levels (see Row (3)). That is, $d_1^0 = (480 - 180)/(1 - 0.4) = 500$; $d_2^0 = 180 + 32/(1 - 0.9) = 500$; and $d_3^0 = (180 \times 0.9) + (270.4/(1 - 0.2)) = 500$ (the first parenthesis in d_3^0 is the derived return flow from the transfer of location 1's water rights to user 2).

Now, if the marginal benefit from water consumption of user 1 is higher than that of user 2, user 1 can buy location 1's water rights from user 2 to improve economic efficiency. It should be noted that the downstream transfer is a constraint to locational water rights. It does not mean that the upstream water user cannot buy upstream locational water rights from downstream water users. Since the amount of locational water rights at each location is a constant cap consistent with the instream flow requirement and there are only downstream transfers of locational water rights, no negative externalities of_volumetric reliability related to return flow or instream flow will occur after trades. Thus no *ex ante* reviews by the government are needed.

In addition, the government or environmental parties can participate in the market and purchase water for environmental benefit. For example (following the scenario of locational water rights meeting the *status quo*), the government can purchase 120 af of location 1's water rights from user 1 (a corresponding reduction in a diversion of 200 ($= 120/(1 - 0.4)$) af to increase instream flows for all downstream sections (see Row (4)). Or, if the government just wants to increase the instream flows at Section 1, it can sell the rights to user 2.

2.4. Market Equilibrium and Efficiency

As shown above, due to the design of locational water rights and downstream transfers of rights, no third-party effect will be caused on in-stream flows or other water users. However, to achieve economic efficiency of water uses, return flows derived from water transfers should be used. It is therefore in addition to locational water rights, that a right of return flows should be considered as well. The return-flow rights, S_i, are generated when the water rights bought by water user i are used and new return flows occur. A downstream water user can buy the upstream return-flow rights to increase his diversion. One unit of the return-flow right bought can be used to increase the diversion of the buyer by one unit.

We assume that the market is perfectly competitive so that there is no strategic behavior among water users. Faced with choosing a non-negative level of water consumption and quantity of rights transferred, the objective of a water user is to maximize his net benefit which is composed of the benefit from water consumption and net revenue from water rights. Water user i's problem can be characterized as:

$$\underset{c_i,\, T_{ij},\, T_{ji},\, S_{ij},\, S_{ji}}{Max} \quad B_i(c_i) + P_i \sum_{j=i+1}^{n} (T_{ij} + S_{ij}) - \sum_{j=1}^{i-1} P_j (T_{ji} + S_{ji}) \tag{10}$$

$$s.t. \qquad c_i + \sum_{j=i+1}^{n} T_{ij} - (1 - R_i)[\sum_{j=1}^{i-1} T_{ji} + \sum_{j=2}^{i-1} S_{ji}] \le T_i^0 \tag{11}$$

$$\sum_{j=i+1}^{n} S_{ij} \le R_i[\sum_{j=1}^{i-1} T_{ji} + \sum_{j=2}^{i-1} S_{ji}] \tag{12}$$

where Equation (10) is the objective function, P_i is the price of the water rights that prevails at location i, T_{ij} and S_{ij} are location i's water rights and return-flow rights that user i sells, and T_{ji} and S_{ji} are the location j's water rights and return-flow rights that user i buys.

Equations (11) and (12) are the transfer constraints under the institution design of locational water right system. Equation (11) means that, for water user i, his actual consumption of water must not be greater than the total effective amount of water rights he owns. On the left-hand side, the first term is water user i's actual water consumption, the second term is the location i's water rights that user i sold, and the third term, $(1 - R_i)\left[\sum_{j=1}^{i-1} T_{ji} + \sum_{j=2}^{i-1} S_{ji}\right]$, refers to the increasable amount of water consumption by the rights user i bought. The term on the right-hand side is the initial amount of location i's water rights that user i owns. Equation (12) requires that the amount of return-flow rights user i sells must not be greater than the amount of return-flow rights he owns.

The necessary conditions for interior solutions with strictly positive water consumption and right transfers are

$$B_i' = P_i, \; i = 1, \ldots, n-1 \tag{13}$$

$$P_1 = P_2 = \ldots = P_{n-1} = (1 - R_n) B_n^{'} \tag{14}$$

Equation (13) means that, in equilibrium, the marginal benefit of water consumption should equal the price of the water right. Equation (14) indicates that the prices of the water rights at each location (except the most downstream location) are the same in equilibrium. This is because locational water rights can be traded and used across locations. If different prices exist for different locational rights, the supply (demand) of the higher-priced locational rights will increase (decrease), which forces the price to decrease. Conversely, the supply (demand) of the lower-priced locational rights will decrease (increase), which forces the price to increase. Finally, the prices of different locational water rights will be the same in equilibrium. The shadow price for the water rights of the most downstream location is equal to $B_n^{'}$. Because the buying of one unit of an upstream water right by user n can increase water consumption by $(1-R_n)$ units, $P_i = (1-R_n)B_n^{'}$ $(i < n)$.

In the following, we take two steps to prove that the above market equilibrium can achieve the efficiency of water use. First, we prove that if a social planner who maximizes the total benefits by applying the trading rule of Equations (11) and (12), the social planner will implement the optimal solution to Equations (5)–(7). Then, we use this result to prove that the market equilibrium solution is socially optimal. Since the mathematical proof is complex and lengthy, we present it in the appendix.

Proposition 1. The market equilibrium solution under the system of locational water rights is socially optimal.

Proof. See Appendix 1.

3. Case Study: Water Transfers in the Choushui River Basin

In this section, we apply the design of locational water rights to the southern part of the Choushui River basin located in central-western Taiwan. We first introduce the basic environment and water using situation in this area and then use an agent-based model to simulate various scenarios of water trading.

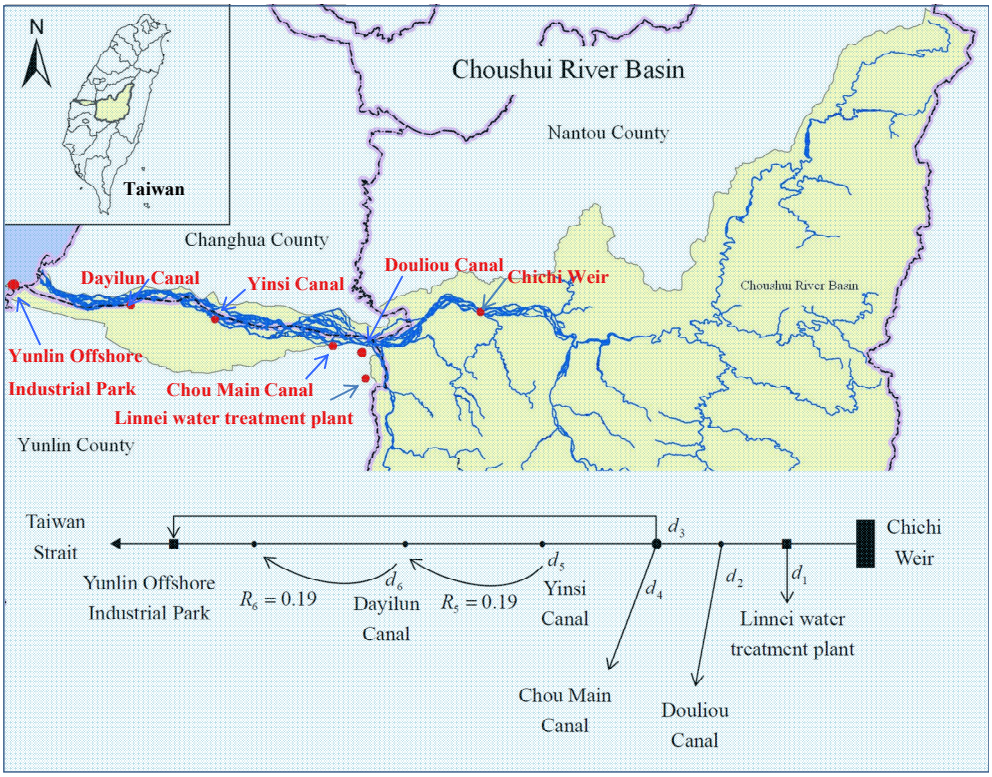
3.1. Background and Existing Registered Water Rights

The Choushui River is 187 km in length and is the longest river in Taiwan. The rainfall pattern here is seasonal. Over 70% rainfall in a year happens in the wet season (from June to October). In the southern part of the Choushui River basin, there are different water uses including irrigative, domestic, and industrial water demands. Agriculture in the Choushui River basin is highly developed and the irrigation associations own most of the registered water rights. Paddy rice is the primary crop and is irrigated mainly by surface water with a flooding method. However, the water demands for industrial and domestic uses have increased rapidly. The shortage of water and loose enforcement of a water right system create the very common problem of an illegal overdraft of groundwater which has resulted in serious ecological damage and environmental problems of seawater intrusion and land subsidence. Facing the problems of water shortages and environmental damage, the government constructed the Chichi Diversion Weir in 2001 to integrate water uses.

The schematic diagram of the Choushui River basin is illustrated in Figure 1. We focus on its southern part in the simulation. Along the Choushui River, the main water users are: the Linnei water treatment plant (for domestic water demand, indexed by 1), Douliou Canal (for agricultural irrigation,

indexed by 2), Yunlin Offshore Industrial Park (for industrial water demand, indexed by 3), Chou Main Canal (for agricultural irrigation, indexed by 4), Yinsi Canal (for agricultural irrigation, indexed by 5), and the Dayilun Canal (for agricultural irrigation, indexed by 6). Although the Yunlin Offshore Industrial Park is located farthest downstream, its water demand is diverted from a more upstream point and transported through a specific pipe for industrial water use only. In addition, the No. 6 Naphtha Cracking Project (No. 6 NCP) of the Formosa Petrochemical Corporation (FPC) is the major industrial water user in this industrial area. It should be mentioned that in the simulation, the complex geography and water using situation practically is largely simplified; therefore, not all water users are included.

Figure 1. Schematic diagram of the Choushui River basin.



The registered rights to divert water for different water uses are promulgated in the "Directions on Chichi Diversion Weir Operation" (Directions hereafter). The amounts vary among months and users. In particular, the amounts of registered water rights for industrial use are zero in the dry season (from February to May). Since the climatic conditions differ largely between the dry and the wet seasons, these two seasons should be defined as two distinct trading periods. In this case study, we consider the period of the dry season. It is also the period when the first crop grows. According to the Directions, existing water rights for different water users in the dry season are calculated as 12, 16, 0, 96, 38, and 36 million cubic meters (mcm hereafter) for water users 1 to 6, respectively. Note that the agricultural water rights belong to the Yunlin Irrigation Association. We calculate existing water rights for different canals by their individual share of the total irrigated area. In addition, the requirement of minimum instream flow is 3.1 cm anywhere to maintain the downstream ecology of the river based on the Water Resources Agency [32].

The return flow parameter of agricultural use for the first crop is 0.19 in the studied area according to the Water Resources Agency [33]. The return flows of agricultural water users 2 and 4, however, do

not go back to the Choushui River. In general, the agricultural return flows can be reused by the downstream farms and industry (at least as water for cooling). The return flows derived from industrial and domestic uses are specified as zero. This is because the Yunlin Offshore Industrial Park is located farthest downstream and there is no well-constructed infrastructure for domestic water reclamation in this area. All effluent should meet the water quality requirement promulgated by the government. In sum, the parameter vector of return flows for users 1–6 is R = (0, 0, 0, 0, 0.19, 0.19). Currently, the return flows in the Choushui River basin are not used. However, because of the high water demand in this area, central and local governments and scholars have begun to bring attention to this issue and give a value to return flows.

The total amount of source water of the Chichi Weir deducted from the minimum instream flows is assumed to be equal to the summation of existing registered water diversions because the water in this area is not abundant. It is 198 mcm. Empirical benefit functions specifically estimated for water uses in the Choushui River basin are not available. The benefit transfer method is thus applied. The inverse water demand functions for individual water user are obtained from Hung and Chie [34], Chiueh and Chen [35], and Wu [36] and are listed as follows:

$$\text{Domestic water user 1: } p = 37002550/(c - 11844426) \quad (15)$$

$$\text{Agricultural water user 2: } p = 28.593453 - 0.00000208c \quad (16)$$

$$\text{Industrial water user 3: } \ln p = 18.36231 - 0.93406 \ln c \quad (17)$$

$$\text{Agricultural water user 4: } p = 28.746093 - 0.000000348c \quad (18)$$

$$\text{Agricultural water user 5: } p = 28.916009 - 0.000000885c \quad (19)$$

$$\text{Agricultural water user 6: } p = 28.568181 - 0.000000992c \quad (20)$$

In Equations (15)–(20), p is the price of water (unit: NT\$/m^3; the average exchange rate for the year 2013 is 29.77 NT\$ = 1 U.S. dollar according to the Central Bank of Taiwan) and c is the water consumption (unit: m^3) [37].

3.2. Application of the System of Locational Water Rights

If the system of locational water rights is applied, the initial allocations of locational water rights are consistent with the instream flow constraints. For the case of the Choushui River basin, they are 198 mcm for location one, and 0 for other locations according to Equation (9) (note that the minimum instream flows have been deducted as mentioned in the background description). There are two important things that should be noted again. First, the locational water rights are defined by "location," not by water users. The rights of location i are not necessarily distributed to water users located at i. They can be allocated to users at other places at the beginning to meet the existent status of water right distribution. In this case study, the government should initially distribute location 1's water rights to every user except for user 3 to meet the *status quo*. That is, user 1–6 has 12, 16, 0, 96, 38, and 36 units of location 1's water rights to divert water, respectively (here we assume that one unit water right is equal to one mcm water; note also that at the *status quo*, return flows are not considered). The corresponding quantities of consumption are 12, 16, 0, 96, 30.78, and 29.16 mcm for user 1–6, respectively.

Second, the downstream transfer is a constraint to locational water rights rather than to users. This means that the upstream water users can buy upstream locational water rights from downstream water users. For example, if the marginal benefit from water consumption of user 1 is higher than that of user 4, user 1 can pay money to buy location 1's water rights from user 4 to increase water consumption; user 4 sells location 1's water rights and earns money.

3.3. Simulation and Discussion

In this section, we use an agent-based model to simulate the implementation of *status quo* water consumption and water trading based on the system of locational water rights (a simple explanation for the agent-based water rights trading is provided in Appendix 2). We define a water user as an agent. The above-mentioned water demand functions (Equations (15)–(20)) are used to calibrate the behavior of individual agents. Theoretically, locational water rights and return-flow rights are traded with perfect information in a market. In practice, information is limited. We therefore separate the market into two parts. First the locational water rights are traded; thereafter the return-flow rights are traded. It is expected that the equilibrium price of the return-flow rights will be lower than that for locational water rights because the qualified buyers of return-flow rights are more restricted and the willingness to pay for additional water is decreasing.

The first simulation scenario is the present situation in the Choushui River basin. The return flows are not considered. As mentioned above, d_i = 12, 16, 0, 96, 38, and 36 mcm for water users 1–6, respectively, according to the Directions. Their corresponding quantities of consumption are 12, 16, 0, 96, 30.78, and 29.16 mcm, respectively. For this *status quo*, the total benefit (the summation of the areas under the individual demand function corresponding to its water consumption) is NT$ 2,664,532,902 [38]. Table 2 lists all the individual water consumptions and the corresponding total benefit under different scenarios.

Table 2. Individual water consumption and total benefit.

Water user *i*	*Status quo* Diversion (mcm)	*Status quo* consumption (mcm)	LWR_NORF[a] consumption (mcm)	LWR_RF[a] consumption (mcm)
1	12	12	18.2	18.2
2	16	16	11	11
3	0	0	52.1	61.2 (+9.1)[b]
4	96	96	65.9	65.9
5	38	30.78	21.1	21.1
6	36	29.16	20	20.5 (+0.5)[b]
Total benefit (NT$)		2,664,532,902	3,439,845,867	3,491,961,946

Notes: [a] LWR_NORF and LWR_RF indicate the scenarios applying the system of locational water rights without and with considering return flows, respectively; [b] Figures in parentheses are the consumption increases resulting from the quantities of return-flow rights bought.

The second simulation scenario is the application of the system of locational water rights which meets the *status quo*. Under this scenario, the government distributes location 1's water rights to every user except for user 3 to reconcile the *status quo* at the beginning. In addition, return flows are not considered. After trading, the final consumptions are listed in column LWR_NORF. It is shown that the domestic

and industrial water users 1 and 3 increase their water consumptions by paying money to buy location 1's water rights from agricultural water users (users 2, 4, 5, and 6). Agricultural water users sell location 1's water rights and earn money. The industrial user 3 in particular sees a large increases in water consumption. The total benefit is NT$ 3,439,845,867 which is higher than that under the *status quo*.

The equilibrium price of water rights is 5.84 NT$/m^3 and the quantity transferred to the industrial user is 52.1 mcm. These figures are higher than the present compensation and quantity of water transfers from agricultural to industrial uses. According to the news report regarding contracts signed among the irrigation associations, the No. 6 NCP, and the Industrial Development Bureau, the annual compensation to irrigation associations is NT$ 240 million if the water transfer is around 300,000 m^3 per day (2.1918 NT$/m^3 on average) and the No. 6 NCP should pay 5.6467 (4.1559) NT$/m^3 if the water transfer is larger (not larger) than 300,000 m^3 per day. The quantity of water transfer is around 300,000–350,000 m^3 per day. The higher equilibrium price indicates that the present water price might be under-priced and does not reveal the true value of water in this area. The higher equilibrium quantity indicates that the marginal benefit of industrial water using is far higher than that from agriculture and industry might like to buy more water if the quantity was not capped. Presently, the market mechanism for water transfers does not work. On the one hand, because the industry does not have any registered water rights in the dry season, the large regular transfer of water is controversial and has been considered a possible cause of the problem of land subsidence since it reduces the available water for agricultural and domestic uses and thus results in the overdraft of groundwater. On the other hand, the government is criticized for favoring industry at the expense of agriculture. Farmers do not receive sufficient compensation. In our simulation of the water market, industrial and domestic water users can buy more water and agriculture obtains a higher compensation, which might be a win-win solution and increases the economic efficiency of water use.

The third simulation scenario is the application of the system of locational water rights which takes return flows into account (see column LWR_RF in Table 2). Since a downstream water user can buy the upstream return-flow rights to increase water diversion, the simulated results show that the industry user 3 (located at the most downstream) buys the return flows from users 5 and 6; and user 6 from user 5. The equilibrium price of return-flow right is NT$ 5.02 and the increase in total benefit resulting from the use of return flows is NT$ 52,116,079.

There are very few studies in Taiwan which focus on the demand-side management for water use in comparison to the abundant research for the supply side. To the best of our knowledge, this article is the first simulation for a potential water market for the case of Taiwan. There are three caveats to this simulation that should be noted. First, because of the unavailability of the water demand functions specifically estimated for the Choushui River basin, a benefit transfer method is applied. Since related studies are rare in Taiwan, the water demand functions for agricultural and industrial users are old and the raw water demand for the domestic user is substituted by the demand for higher quality tap water. To obtain a precise estimation, demand functions should be estimated specifically for the studied area. Second, we take only six main water users among others in the Choushui River basin to simulate water trading. The complicated situations regarding return flows and infrastructures are also simplified. More thorough consideration of water users involved and rigorous design of a topographic map should be studied in the future. It is expected that the more users participating in the market, the higher the total benefit will be achieved. Third, for such a potential water trading market to work in practice, property

rights should be well-defined and enforced. Related water laws would therefore need to be amended or stipulated. This will cause substantial transaction costs preventing the application of a free market. However, as the well-known Demsetz hypothesis indicated, property rights develop to internalize externalities as the gains of internalization become larger than the cost of internalization [39]. Therefore, when the problems of water shortage, land subsidence, and ecological damage become even worse, the possibility of obtaining additional water by constructing new dams or reservoirs becomes less, negative externalities to third parties of water users and instream flows are addressed, and the economic efficiency of water use is promoted, then the water trading market will be a promising mechanism for demand-side management.

4. Conclusions

By exploiting the characteristic that water flows downstream unidirectionally, this article proposes a system of locational water rights. Under this system, the initial cap of water rights at each location is calculated from upstream to downstream according to the requirement of minimum instream flows in order to protect the instream uses and to efficiently use all available water. These locational water rights could then be distributed to water users to meet the *status quo* of water use. Based on its trading rules, economic efficiency of water use can be achieved and no third-party effects of volumetric reliability related to return flow and instream flow arise. To be practical, however, it is of course the case that information and experience are very important. A procedure of learning by doing is inevitable. Measures such as a transparent and real-time information system, separating the trading period into marketing and implementation stages, and testing the system of locational water rights by means of laboratory experiments, *etc.*, could help the application of this system in practice. In addition, under an uncertain environment, the requirement of minimum instream flows might not be met. Buying water for environmental flows may be an effective way to protect instream uses.

For the simulation of a potential water trading market in the Choushui River basin, the higher equilibrium price indicates that the present water price does not reveal the true value of water. In fact, an under-priced situation has resulted in the *status quo* of water shortage, stress among water users, overdraft of groundwater, as well as ecological and environmental damage in this area. The simulation shows a substantial economic benefit from water trading. The industrial and domestic water users are the buyers while the agricultural water users are the sellers of the water rights. In addition, the equilibrium price of return-flow right provides a reference for the value of return flows which has not yet been used in this area.

As previously mentioned, there are several kinds of third-party effects from water trade such as volumetric reliability, delivery reliability, timeliness of delivery, water quality, and rural development effects, which will result in market failure. A lot of methods like taxation, compensation, or the one proposed in this paper have been studied to cope with some of the effects. However, there is still room for improvement and further research is needed. In particular, the impacts on social and environmental aspects have been examined less than the economic aspect. Kiem [2] indicated water trading reallocates a resource to high-value users who may be high greenhouse gas emitters. These kinds of trades will worsen the environment. Therefore, not only should the externalities in the water market *per se* be internalized, other external costs like pollution should also be internalized (this makes the polluters pay

and reduce the artificial high-value uses) to ensure resource allocation is efficient and fair. Finally, a complete design of a water transfer system for conjunctive use of surface water and groundwater is important. The usage and concerns regarding the return flow parameters under the locational water right system might be expanded to consider the complicated hydrological conditions of groundwater and surface water. In addition, derivatives such as forwards, options, and futures should be developed for water users to hedge under an increasingly stochastic environment associated with climate change.

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Appendix 1. Proof of Proposition 1

Step 1. Prove that a social planner who maximizes the total benefits by applying the trading rule of Equations (11) and (12) (that is, the following Equations (A2) and (A3)) will implement the solution to Equations (5)–(7).

The optimization problem of the social planner is as follows:

$$\underset{\mathbf{c},T,S}{Max} \sum_{i=1}^{n} B_i(c_i) \tag{A1}$$

$$s.t.\ c_i + \sum_{j=i+1}^{n} T_{ij} - (1-R_i)\left[\sum_{j=1}^{i-1} T_{ji} + \sum_{j=2}^{i-1} S_{ji}\right] \le T_i^0, i = 1,\ldots,n \tag{A2}$$

$$\sum_{j=i+1}^{n} S_{ij} \le R_i\left[\sum_{j=1}^{i-1} T_{ji} + \sum_{j=2}^{i-1} S_{ji}\right], i = 2,\ldots,n \tag{A3}$$

$$T_{ij} \ge 0,\ i,j = 1,\ldots,n, i < j \tag{A4}$$

$$S_{ij} \ge 0,\ i,j = 2,\ldots,n, i < j \tag{A5}$$

$$\mathbf{c} = (c_1,\ldots,c_n) \ge 0 \tag{A6}$$

Let us denote the set of water consumptions that satisfies the constraints of Equations (A2)–(A6) as Ω^{LWR}, and the set of water consumptions that satisfies the constraints of Equations (6) and (7) as Ω.

Step 1.1: Prove $\Omega^{LWR} \subseteq \Omega$

Here we first show that constraints (A2)–(A5) imply that constraint (6) is satisfied.

For any $\mathbf{c} \in \Omega^{LWR}$, $c_i + \sum_{j=i+1}^{n} T_{ij} - (1-R_i)\left[\sum_{j=1}^{i-1} T_{ji} + \sum_{j=2}^{i-1} S_{ji}\right] \le T_i^0, i = 1,\ldots,n$. (Equation (A2)).

By using the initial allocation rule (Equation (9)), the above equation can be rearranged as:

$$c_i + \sum_{j=i+1}^{n} T_{ij} + (1-R_i)\left[\sum_{j=1}^{i-1} T_j^0 - \sum_{j=1}^{i-1} T_{ji} - \sum_{j=2}^{i-1} S_{ji}\right] \le (1-R_i)(v_0 - \bar{v}_i), i = 1,\ldots,n.$$

Because $\sum_{j=i+1}^{n} T_{ij} \ge 0$ and $c_j + \sum_{k=j+1}^{n} T_{jk} - (1-R_j)\left[\sum_{k=1}^{j-1} T_{kj} + \sum_{k=2}^{j-1} S_{kj}\right] \le T_j^0$ (by Equation (A2)), we have:

$$c_i + (1-R_i)\left\{\sum_{j=1}^{i-1}\left[c_j + \sum_{k=j+1}^{n} T_{jk} - (1-R_j)\left[\sum_{k=1}^{j-1} T_{kj} + \sum_{k=2}^{j-1} S_{kj}\right]\right] - \sum_{j=1}^{i-1} T_{ji} - \sum_{j=2}^{i-1} S_{ji}\right\} \le (1-R_i)(v_0 - \bar{v}_i)$$

Equivalently,

$$c_i + (1-R_i)\sum_{j=1}^{i-1} c_j + (1-R_i)\left\{\begin{array}{l}\sum_{j=1}^{i-1}\left[\begin{array}{l}(\sum_{k=j+1}^{i-1} T_{jk} + T_{ji} + \sum_{k=i+1}^{n} T_{jk}) - (\sum_{k=1}^{j-1} T_{kj} + \sum_{k=2}^{j-1} S_{kj}) \\ + R_j(\sum_{k=1}^{j-1} T_{kj} + \sum_{k=2}^{j-1} S_{kj})\end{array}\right] \\ - \sum_{j=1}^{i-1} T_{ji} - \sum_{j=2}^{i-1} S_{ji}\end{array}\right\} \le (1-R_i)(v_0 - \bar{v}_i)$$

That is,

$$c_i + (1-R_i)\sum_{j=1}^{i-1} c_j + (1-R_i)\sum_{j=1}^{i-1}\sum_{k=i+1}^{n} T_{jk} + (1-R_i)\left\{\sum_{j=1}^{i-1} R_j(\sum_{k=1}^{j-1} T_{kj} + \sum_{k=2}^{j-1} S_{kj}) - (\sum_{j=1}^{i-1}\sum_{k=2}^{j-1} S_{kj} + \sum_{j=2}^{i-1} S_{ji})\right\} \le (1-R_i)(v_0 - \bar{v}_i) \quad \text{(A7)}$$

Let us define the terms in the above brace as W.

Based on the constraint (A3), we have $\sum_{j=1}^{i-1}(\sum_{k=j+1}^{n} S_{jk}) \le \sum_{j=1}^{i-1} R_j\left[\sum_{k=1}^{j-1} T_{kj} + \sum_{k=2}^{j-1} S_{kj}\right]$.

Because $\sum_{j=1}^{i-1}(\sum_{k=j+1}^{i} S_{jk}) \le \sum_{j=1}^{i-1}(\sum_{k=j+1}^{n} S_{jk})$, we have $\sum_{j=1}^{i-1}(\sum_{k=j+1}^{i} S_{jk}) = \sum_{j=1}^{i-1}(\sum_{k=j+1}^{i-1} S_{jk} + S_{ji}) \le \sum_{j=1}^{i-1} R_j\left[\sum_{k=1}^{j-1} T_{kj} + \sum_{k=2}^{j-1} S_{kj}\right]$.

Then:

$$\sum_{j=1}^{i-1} R_j\left[\sum_{k=1}^{j-1} T_{kj} + \sum_{k=2}^{j-1} S_{kj}\right] - \sum_{j=1}^{i-1}(\sum_{k=j+1}^{i-1} S_{jk} + S_{ji}) \ge 0 \quad \text{(A8)}$$

The left-hand side of Equation (A8) is just the terms in the brace (W) in Equation (A7).

Now because $\sum_{j=1}^{i-1}\sum_{k=i+1}^{n} T_{jk} \ge 0$ and $W \ge 0$, by Equation (A7),

$$c_i + (1-R_i)\sum_{j=1}^{i-1} c_j \le (1-R_i)(v_0 - \bar{v}_i), i = 1,...,n \quad \text{(A9)}$$

This equation is exactly the requirement of minimum instream flows (Equation (6)). In addition, constraint (A6) is the same as constraint (7). Therefore, for any $\mathbf{c} \in \Omega^{LWR}$, we have $\mathbf{c} \in \Omega$. We have shown that $\Omega^{LWR} \subseteq \Omega$.

Step 1.2: Prove $\Omega \subseteq \Omega^{LWR}$

Here we show that, given constraint (6), we can find at least a set of ***T*** and ***S*** satisfying constraints (A3)–(A5) that imply that constraint (A2) is satisfied.

For any $\mathbf{c} \in \Omega$, $(1-R_i)\sum_{j=1}^{i-1} c_j + c_i \le (1-R_i)(v_0 - \bar{v}_i), i = 1,\ldots,n$. (Equation (6))

There exists a set of ***T*** and ***S***:

$$T_{i(i+1)} \equiv (1-R_i)(v_0 - \bar{v}_i) - (1-R_i)\sum_{j=1}^{i-1} c_j - c_i \ge 0, i = 1,\ldots,n \text{ (by Equation (6))} \quad \text{(A10)}$$

$$T_{n(n+1)} \equiv 0 \geq 0 \tag{A11}$$

$$T_{ij}\Big|_{j=i+2,\ldots,n} \equiv 0 \geq 0, i = 1,\ldots, n \tag{A12}$$

$$S_{ij}\Big|_{j=i+2,\ldots,n} \equiv 0 \geq 0, i = 2,\ldots, n \tag{A13}$$

$$\begin{aligned} S_{i(i+1)} \equiv R_i\left(\sum_{j=1}^{i-1} T_{ji} + \sum_{j=2}^{i-1} S_{ji}\right) &\leq R_i\left(\sum_{j=1}^{i-1} T_{ji} + \sum_{j=2}^{i-1} S_{ji}\right) \\ &\geq 0,\ i = 2,\ldots,n \text{ (by equations (A10-A13))} \end{aligned} \tag{A14}$$

such that constraints (A3)–(A5) are satisfied and Equation (6) becomes

$$(1-R_i)\sum_{j=1}^{i-1} c_j + c_i + T_{i(i+1)} = (1-R_i)(v_0 - \bar{v}_i) \leq (1-R_i)(v_0 - \bar{v}_i), i = 1,\ldots,n \tag{A15}$$

Because $(1-R_i)(v_0 - \bar{v}_i) = T_i^0 + (1-R_i)\sum_{j=1}^{i-1} T_j^0$ (by Equation (9)), we rearrange Equation (A15) as

$$c_i + T_{i(i+1)} - (1-R_i)\sum_{j=1}^{i-1}(T_j^0 - c_j) \leq T_i^0, i = 1,\ldots,n \tag{A16}$$

Expand T_j^0 by using Equation (9) and adding $\left(-(1-R_j)\sum_{k=1}^{j-1} c_k + (1-R_j)\sum_{k=1}^{j-1} c_k\right)$ in the following brackets, we have: $c_i + T_{i(i+1)} - (1-R_i)\sum_{j=1}^{i-1}\left[(1-R_j)(v_0 - \bar{v}_j) - (1-R_j)\sum_{k=1}^{j-1} T_k^0 - c_j - (1-R_j)\sum_{k=1}^{j-1} c_k + (1-R_j)\sum_{k=1}^{j-1} c_k\right] \leq T_i^0$.

Therefore, $c_i + T_{i(i+1)} - (1-R_i)\sum_{j=1}^{i-1}\left[T_{j(j+1)} - (1-R_j)\sum_{k=1}^{j-1}(T_k^0 - c_k)\right] \leq T_i^0$.

By continuing to expand T^0 on the LHS and performing the same rearrangement procedure as in the previous equation, we have

$$c_i + T_{i(i+1)} - (1-R_i)\sum_{j=1}^{i-1}\left[T_{j(j+1)} - (1-R_j)\left[\sum_{k=1}^{j-1}(T_{k(k+1)} - (1-R_k)\left[\sum_{m=1}^{k-1} T_{m(m+1)} - \cdots - (1-R_2)\left[T_1^0 - c_1\right]\right]\right)\right]\right] \leq T_i^0 \tag{A17}$$

Equivalently,

$$c_i + T_{i(i+1)} - (1-R_i)\left[T_{(i-1)i} + R_{i-1}\left[T_{(i-2)(i-1)} + R_{i-2}\left[T_{(i-3)(i-2)} + \cdots + R_3\left[T_{23} + R_2(T_{12})\right]\right]\right]\right] \leq T_i^0 \tag{A18}$$

By using Equations (A12)–(A14), we can rearrange Equation (A18) as $c_i + T_{i(i+1)} - (1-R_i)\left[T_{(i-1)i} + S_{(i-1)i}\right] \leq T_i^0$.

By adding $\sum_{j=i+2}^{n} T_{ij} = 0$, $\sum_{j=1}^{i-2} T_{ji} = 0$, and $\sum_{j=2}^{i-2} S_{ji} = 0$ to the LHS of the above equation, we have:

$$c_i + T_{i(i+1)} + \sum_{j=i+2}^{n} T_{ij} - (1-R_i)\left[T_{(i-1)i} + \sum_{j=1}^{i-2} T_{ji} + S_{(i-1)i} + \sum_{j=2}^{i-2} S_{ji}\right] \leq T_i^0$$

.

That is,

$$c_i + \sum_{j=i+1}^{n} T_{ij} - (1-R_i)\left[\sum_{j=1}^{i-1} T_{ji} + \sum_{j=2}^{i-1} S_{ji}\right] \leq T_i^0 \ (i = 1,\ldots,n) \tag{A19}$$

This equation is the exact constraint on water right transfers (Equation (A2)). In addition, constraint (7) is the same as constraint (A6). Thus, for any $\mathbf{c} \in \Omega$, we have $\mathbf{c} \in \Omega^{LWR}$. We have shown that $\Omega \subseteq \Omega^{LWR}$.

Since $\Omega^{LWR} \subseteq \Omega$ (*Step 1.1*) and $\Omega \subseteq \Omega^{LWR}$ (*Step 1.2*), we have $\Omega^{LWR} = \Omega$.

Because the objective functions and constraints of Equations (A1)–(A6) and Equations (5)–(7) are the same, the solution under the scenario of the social planner who applies the locational water right system, $\mathbf{c}^{SP}$, is the same as the solution to Equations (5)–(7), $\mathbf{c}^{*}$.

Step 2. Prove that the market equilibrium solution is socially optimal.

Based on Step 1, $\mathbf{c}^{SP}$ is the same as $\mathbf{c}^{*}$. Then, if the market equilibrium solution, $\mathbf{c}^{ME}$, is $\mathbf{c}^{SP}$, the market equilibrium solution is efficient.

Both $\mathbf{c}^{ME}$ and $\mathbf{c}^{SP}$ are feasible under the locational water right system. Supposing that $\mathbf{c}^{ME} \neq \mathbf{c}^{SP}$, then $\sum_{i=1}^{n} B_i(c_i^{ME}) < \sum_{i=1}^{n} B_i(c_i^{SP})$.

Because ($\mathbf{c}^{ME}$, $\boldsymbol{T}^{ME}$, $\boldsymbol{S}^{ME}$, $\boldsymbol{P}$) is the market equilibrium,

$B_i(c_i^{ME}) + P_i \sum_{j=i+1}^{n}(T_{ij}^{ME} + S_{ij}^{ME}) - \sum_{j=1}^{i-1} P_j(T_{ji}^{ME} + S_{ji}^{ME}) > B_i(c_i^{SP}) + P_i \sum_{j=i+1}^{n}(T_{ij}^{SP} + S_{ij}^{SP}) - \sum_{j=1}^{i-1} P_j(T_{ji}^{SP} + S_{ji}^{SP})$ for $i = 1,\ldots,n$. Summing over $i = 1,\ldots,n$, we have $\sum_{i=1}^{n} B_i(c_i^{ME}) > \sum_{i=1}^{n} B_i(c_i^{SP})$, which is a contradiction. Therefore, $\mathbf{c}^{ME} = \mathbf{c}^{SP} = \mathbf{c}^{*}$, *i.e.*, the market equilibrium solution is efficient. Q.E.D.

Appendix 2. The Agent-based Water Rights Trading

We define a water user as an agent. The water demand functions (Equations (15)–(20)) are used to calibrate the behavior of individual agents. Assume that agent *i*'s willingness to pay (WTP) for an additional unit of water rights is represented by:

$$BID_i(q_0 + 1) = D_i^{-1}(q_0 + 1) \tag{A20}$$

where BID_i is the "bid price" function of agent *i*, q_0 is the status-quo water rights, and D_i^{-1} is the inverse water demand function. In the same manner, agent *i*'s willingness to accept (WTA) for giving up one unit of water rights is:

$$ASK_i(q_0) = D_i^{-1}(q_0) \tag{A21}$$

where ASK_i is agent *i*'s "asking price" function.

The trading mechanism follows Chicago Board of Trade (CBOT) matching rule. A locational water right is like a financial asset (e.g., stock). In the water right market, only orders from qualified traders are accepted. That is, a water user can just buy non-downstream locational water rights to increase water diversion. The orders are taken on a continuous basis. The matching is based on the principle of first come first served. However, if more than one buy or sell orders are received for the same locational water right at the same time, the order with a better price will be matched as a priority, resembling current bids and offers of a stock market. A transaction is made when one of the following criteria is met, (i) the bid price is higher than the outstanding (lowest) asking price or (ii) the asking

price is lower than the outstanding (highest) bid price. Under the CBOT mechanism, the transaction price for location *l*'s water right (P_l) will be carried out by the mean of its bid price and asking price, which can be represented by

$$P_l = (ASK_i + BID_j)/2 \tag{A22}$$

where $i \neq j$.

Traders will submit their orders to the locational water rights with the best affordable offer. For a potential buyer (seller), the best offer will be his or her reachable lowest asking (highest bid) price for a locational water right. Let's give a simple illustration in Table A1. Suppose there are two agents (*k* and *m*) located at location 3, both own some location 3's water rights, and $R_k = R_m = 0$. Currently, agent *k*'s WTA is $ASK_k = 30.7$ and WTP is $BID_k = 30.5$. Since Agent *k*'s WTA is higher than the outstanding asking price for location 3's water right, he will not place an order for selling water right. On the other hand, he is a qualified buyer for water rights of locations 1 to 3. Then, his best choice is to place a buy order for location 1's water right, where the outstanding asking price is the lowest. Column "Location 1" shows the current market status after taking agent *k*'s buy order. The latest transaction price of location 1 will be updated to (30.5 + 9.0)/2 = 19.8. For agent *m*, his WTP is $BID_m = 4.7$ and WTA is $ASK_m = 8.2$. Since Agent *m*'s WTP is lower than the outstanding bid prices for location 1 to 3's water rights, he will not place an order for buying a water right. On the other hand, his WTA is lower than outstanding asking price for location 3's water rights, he will place a sell order there. Column "Location 3" shows the current market status after taking agent *m*'s sell order. The latest transaction price of Location 3's water right is then updated to (12.2 + 8.2)/2 = 10.2. The market clearing will be achieved until no agent has a motive to submit orders to the market.

Table A1. Illustration of market transaction.

Water right	Location 1		Location 2		Location 3		Location 4		Location 5	
	bid	ask	bid	ask	bid	ask	bid	ask	bid	Ask
Current market status										
Outstanding	5.3	9.0	10.1	10.5	12.2	13.5	11.2	13.3	6.3	7.1
Next	5.2	9.1	10.0	10.6	12.1	13.6	11.1	13.4	6.2	7.2
Transaction price	8.5		10.4		12.6		12.0		6.9	
Current market status after taking agent *k*'s and agent *m*'s orders										
Outstanding	30.5	9.0	10.1	10.5	12.2	8.2	11.2	13.3	6.3	7.1
Next	5.3	9.1	10.0	10.6	12.1	13.5	11.1	13.4	6.2	7.2
Transaction price	8.5		10.4		12.6		12.0		6.9	
Current market status after matching agent *k*'s and agent *m*'s orders										
Outstanding	5.3	9.1	10.1	10.5	12.1	13.5	11.2	13.3	6.3	7.1
Next	5.2	9.2	10.0	10.6	12.0	13.6	11.1	13.4	6.2	7.2
Transaction price	19.8		10.4		10.2		12.0		6.9	

Conflicts of Interest

The authors declare no conflict of interest.

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30. Note that if $T_i^0 < 0$ according to Equation (9), location *i* is called a critical location. $\bar{v}_i$ then becomes the binding constraint for its immediate upstream location, i.e., the regulator should set $T_i^0 = 0$ and reset $T_{i-1}^0 = (v_0 - \bar{v}_i) - \sum_{j=1}^{i-2} T_j^0$ by expanding and rearranging Equation (9).
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37. In fact, there is very little research studying demand functions of water consumption in Taiwan which might be due to the regulation and small variation of water price. After considering the compatibility with this simulation, we applied demand functions estimated for other cases in Taiwan. First, the domestic water demand function was drawn from Hung and Chie [34] who studied the case of Taipei City. We adjusted the function by using the 2011 household data in the Choushui River basin for variables in the equation; Second, the agricultural water demand function was obtained from Chiueh and Chen [35] who studied the case of water demand for the first crop in the Kaohsiung area. We adjusted the function according to the coverage of irrigated area in 2011 for each canal in our case; Third, the industrial water demand function is acquired from Wu [36] who studied the water demand of the chemical materials industry. Because the No. 6 NCP of FPC is the dominant and largest user in the Yunlin Offshore Industrial Park, we applied the water demand of the chemical materials industry with the adjustment of using 2011 data of the No. 6 NCP for variables in the equation. Finally, the time span of water demand for all these demand functions was transformed to four months to be consistent with the length of dry season.
38. It should be mentioned that the inverse demand functions for agricultural users are linear, while those for domestic and industrial users are nonlinear. As the water consumption approaches zero, the marginal benefits of agricultural water are no larger than 29 NT\$/m^3 while the marginal benefits for domestic and agricultural water approach infinity. This will result in an unrealistic high value of the estimated total benefit for water using. Because the agricultural user will sell water if the bid for water is higher than 29 NT\$/m^3, we assume that the maximal WTP for water of domestic and industrial users is 30 NT\$/m^3 (a little higher than 29 NT\$/m^3) to calculate the total benefit.
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