Water Markets

5

5.1 Institutional, Hydrological and Infrastructural Preconditions

5.1.1 Design of Water Markets

5.1.1.1 Design Options

Water markets are one possible institutional option to deal with water management. Currently, a few formal water markets are established in countries where water is scarce and governmental organization is fairly effective. The enforcement of basic laws and rules is essential for an effectively working formal water market, because they are needed for the registration of water rights and to specify conditions for the trading of water and water rights. Hirshleifer et al. (1969) illustrate in their reference, how water laws can promote or hinder the implementation of water markets. They focus their analysis on the riparian and appropriation rights regime in the United States.[1]

There exist a number of legal preconditions for the promotion of water markets. Based on Endo et al. (2018), these are

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[1] Under the riparian water rights regime, the water is allocated among those who possess land along the water body. All landowners whose properties adjoin a water body have the right to make reasonable use of the water source as it flows through or over their properties. However, the appropriation water rights regime originated in California, during the time of Gold Rush (Grompe and Hansjürgens 2012). The idea of this right regime is that the first person who takes the water for beneficial use is allowed to continue the water usage of this quantity for that purpose. We can differ between the senior and junior water rights, with senior rights being emitted earlier than junior rights. The water is first allocated to the senior rights owner and afterward to the junior rights owner.

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- the existence of laws and rules that allow the reallocation of water (see Grafton et al. 2012)
- the separation of water rights and landownership; (see Chong and Sunding (2006) as well as Grafton et al. (2012))
- rules for the case that water rights are non-used. Here the non-used water rights should not be canceled.
- the predictability of the available water before the irrigation periods
- public control of groundwater pumping throughout the jurisdiction

For the implementation of formal water markets the establishment of water rights are quite essential. Regarding these water rights, a number of characteristics—such as the duration, the conditions for renewing and restrictions for trading water rights—have to be determined by rules and laws:

- On the one hand, there is the duration of a water right and on the other hand, there are the conditions for renewing an expired right. These two characteristics determine the value of the water right and also affect the level of infrastructure investments in the water supply system. The higher the duration and the higher the assurance for renewing an expired water right, the higher is the incentive for investments in water (delivery) infrastructure.
- It has to be determined which party is allowed to buy a water right. It has also to be clarified whether the buyer is able to use the water in just a certain location and for just selected purposes. Furthermore, the feasibility of water rights' divisibility has to be specified, which means whether it is possible to sell just a selected proportion of the owned water right.
- It has to be specified whether a water allocation under an entitlement must be used. This may oblige a water right owner to use it for a specified time. Also, the consequences of non-using water entitlements have to be clarified. The allocated amount not used during a specified time period could either be extinguished, or may be used in later periods. The more the non-usage of water entitlements is penalized, the less is the incentive to save water for dry years.

Organizations and institutional arrangements such as water user organizations, water courts or even state courts are also important to resolve conflicts either between various water right holders or between water right holders and third parties. Here, third parties are those who may be (negatively) affected by the water trade. The best-known water markets which currently exist are in the western USA, Australia, and Chile. Evidence is mixed thus far, but one may expect that due to climate change and the resulting increase in water shortages in these countries, water markets may become more important in the future (Easter and Huang 2014b). Endo et al. (2018) analyze the countries regarding their applicability of water markets on the base of their water current laws.

Apart from the formal water markets, there also exist informal ones. Water markets are operated at a local level, for instance allowing neighboring farmers to trade water. For example, these forms of markets may make groundwater available for those farmers who cannot afford the installation of their own wells. Usually, the rules at this type of market are informal and there is no requirement for large investments in management and infrastructure capacities. Furthermore, rent-seeking issues, as well as high transaction cost, may lead to the emergence of informal markets instead of formal ones (Easter and Huang 2014b).

In addition to the distinction between formal and informal water markets, it is also possible to differentiate between markets for water rights and markets for water. Property rights are transferred to a new user (buyer) in a market for water rights, while in markets for water (which are also termed as leasing markets), water is transferred to the buyer and the seller retains the ownership of the asset (water right) (Goemans and Pritchett 2014).

5.1.1.2 Permanent Transfers: Water Right Markets

The transaction in water rights markets could either be a direct or an indirect transfer of water rights' ownership. Direct transfer means that the ownership of water rights moves during the transaction from the seller to the buyer so that the buyer obtains the right to divert water. Indirect transactions occur when a water user buys shares of a ditch company to gain water resources and the ditch company retains the right to divert. These transactions are governed by the ditch companies bylaws (Goemans and Pritchett 2014). Direct transfer of ownership becomes more complex when the location of diversion is changed or if the water is used in a different way after the transaction.

The direct transfer may involve two steps for the buyer: the purchase of the water right and the change of use. There is no fixed order in this two step-process which means that the right can be changed before selling, or the right can be sold first. Furthermore, the change in use may occur at a much later date than the selling date. This becomes especially relevant for municipal water providers which expect a high growth of water demand for the future, and thus buy water rights for covering future water demand. In the interim, the municipal water provider leases the rights back to the original water right owner (Howitt and Hansen 2005). For approving the change in use by the state administrative, in some markets it has to be demonstrated that no right owner is adversely affected by the change of use, which means that the quantity of available water must not decrease for other right owners.

5.1.1.3 Temporary Transfers: Leasing of Water Rights

For a temporary transfer of rights, the seller leases the water right to another user, but retains the ownership of the water right for future use. There exist three types of leasing water rights: water banks, single-/multi-year leases, and interruptible water supply agreements.

Water banks reallocate water on a short-term basis. They are quite often formed to fulfill a specific need, for instance, maintaining water supply during drought periods, ensuring an instream flow for habitats, or augmenting flows for future use. The water bank serves as a facilitator of exchange by matching buyers and sellers. It is a clearinghouse for transactions and it provides services to realize transactions which include the determination of the type of water right and the adherence to the regulation regime. By depositing rights into the bank, potential sellers make them available for potential buyers. The water banks differ in various categories (see Goemans and Pritchett 2014):

- the organization of the agency: it could be an organization of the federal agency, the state government, special districts or interested parties.
- the determination of prices: water banks may post a fixed price or use options to determine a market clearing price.
- contract types: there exist supplier contracts (that are used to organize specific entitlements in a bank), storage contracts (allowing the deposit of water in a physical storage), and contingent claim contracts (which permit the buyer to use water from the bank under specific circumstances such as a drought period).

While water banks are organizations where many buyers and sellers are able to exchange water rights, water leases are bilateral agreements between individuals in which the water right owner agrees to lease a specific amount of water. The bilateral negotiations make it possible to customize the contract. Typical contract stipulations include the contract term, the pricing policy (determining fixed and volume prices per unit), as well as the integration of a leaseback option, which means that the lessor has the first right to use the water if it is not needed by the lessee. A special type of water leases are the interruptible supply agreements which last for a multitude of years, but where water delivery is just made when it is needed. The interruptability could be realized by, for instance, an option agreement in which the lessee pays a baseline fee for the option to use a water right. This option does not need to be exercised each year. If the option is not exercised the lessor has the first right to use the water, while for the contrary case that the option is used the lessee pays an additional, pre-negotiated fee to exercise the option and get the water right for the year. Therefore, the lessor receives a secure revenue stream from the lessee, while the lessee in return receives the guarantee that there will be additional water supply when needed at a pre-negotiated price (Goemans and Pritchett 2014).

5.1.1.4 Limitations of Water Markets

Just as any other markets, real-world water markets are no perfect representations of theory. Rather, they are subject to transaction costs and issues of implementation (Western Governor Association 2012). Transaction costs include the search costs of a willing buyer/seller, negotiations, navigating institutional requirements (permits, water courts proceedings), and the physical expense for collecting, storing and treating of water (McCann and Easter 2004; Furubotn and Richter 2005). High transaction costs can reduce the frequency of water transfers, make it difficult to match water supplies to changing use and to limit the participants in the market. In empirical studies, transaction costs range from 3 to 70% in water markets (Garrick et al. 2013). The level of these costs mainly depends on various physical and institutional factors. A detailed overview regarding these factors is provided by McCann and Garrick (2014).

5.1.2 Transaction Costs and Institutional Factors

5.1.2.1 Physical Factors

Physical, biological, and technical factors which are subsumed under the term physical factors are important drivers for transaction and transformation costs. These physical factors are

- **Scale:** Quantity and quality issues may have to be addressed on the watershed location which means that the geographical scale of intervention is needed for resolving water market issues. This involves, for instance, the transfer of pollutants in space. If the water market issue is linked with the geographical scale, more coordination is required which results in higher transaction costs.
- **Time lags:** Time lag between a measurement and its impact, for instance, a lag between improved management and noticeable improvements in the water market.
- **Magnitude of changes:** The higher the changes in water quality standards or water consumption levels, the higher the resistance against the new policy if the change is related to an economic loss for stakeholders.
- **Heterogeneity:** Property rights are more difficult to establish if the property rights are poorly specified and fail to account for different sources of water and their hydrological interactions (Young and McColl 2009).
- **External effects:** Downstream water rights are often dependent on the return flows of upstream users. A reallocation at the upstream may affect the return flow, and therefore, lead to third-party effects for downstream water right owners.
- **Excludability:** Excluding people from consumption of a non-excludable good (e.g., groundwater) requires strict monitoring and enforcement.
- **Measurability/Observability:** Measurability and observability impact the cost for monitoring and enforcement, and determine which kind of policy is feasible.
- **Economics of scope:** Market design becomes more complex in a setting with multiple outputs, e.g., the multi-purpose design of infrastructure to optimize irrigation, flood control, hydropower, urban water use, etc.
- **Number of agents:** Transaction cost increases with the number of agents that are involved (Cacho et al. 2013). Water banks and water trading registry systems standardize policy and procedures to reduce transaction costs even for a large number of buyers and sellers.
- **Uncertainty:** Time lags, natural variability in space and time, biological diversity, heterogeneity of agents, etc., impact uncertainty. Higher uncertainty leads to incomplete contracts, and thus, increasing ex-post transaction costs (Williamson 1985).
- **Asset specificity:** Asset specificity refers to a situation in which a resource is unique to a transaction partner and cannot be easily redeployed for transactions with other partners. The design and scale of water infrastructure, as well as the heterogeneity of water rights, contribute to asset specificity and complex institutional arrangements.

5.1.2.2 Institutional Factors

Some institutional factors that affect transaction and transformation costs are

- **Culture:** Culture affects the socialization of people, their fundamental values, the level of trust within the society, notions of fairness, interest in common goods, etc. (Schmid 2004; Vatn 2005). Concerns of irrigation communities regarding the long-term effects of water trades on their economic and cultural viability have slowed down the emergence of spot markets (Howitt 2014; Bjornlund et al. 2014; Hearne and Donoso 2014).
- **Institutional environment:** The institutional environment consists of constitutions, legal systems, laws, and policies (Williamson 2000). Especially constitutional provisions related to water are quite difficult to change. This could result in a fragmented institutional framework limiting water trade (Bjornlund 2004). The legal system and the courts also affect transaction costs. The less effective the legal system is able to enforce contracts, the higher are transactions costs. The existence of conflict resolution mechanisms in water markets can avoid costly and cumbersome administrative hearings and court cases, see Ostrom (1990).
- **Physical versus administrative boundaries:** Administrative boundaries that do not coincide with environmental areas of interest make cooperation difficult (Perry and Easter 2004). Coordination costs rise with the number of agents involved in specific transactions (Laurenceau 2012).
- **Lobbying:** Transaction costs at the enactment stage may be higher than transaction costs to implement a policy (Krutilla et al. 2011).
- **Property Rights:** The exchange of property rights implies transaction costs. With changing technology and changes of preferences, the transaction cots of exchanging property rights is likely to increase (Demsetz 1967; Garrick et al. 2013; Crase et al. 2013). Also agents who do not have property rights may incur costs to change the property rights structure (Bromley 1992; Stavins 1995). Furthermore, if governments create new rights, transaction costs are incurred to allocate those rights (Krutilla et al. 2011).
- **Market structure:** A monopsony market structure may facilitate bargaining, while bilateral monopoly can impede it (McCann and Garrick 2014).
- **Sequencing and timing:** The implementation of a draconian policy may cause more transaction and transformation costs than a policy which is less restrictive (McCann and Garrick 2014). Transaction costs of multiple policies are incurred if it is required that a policy is changed subsequently. For supporting water trade, for instance Garrick et al. (2013), note the importance of multiphase sequencing of institutional transformation. This involves three phases: market emergence, market strengthening, and adjustment.
- **Intermediaries:** The use of intermediaries (e.g., brokers) may reduce transaction costs, especially for infrequent transactions that require specific knowledge (see Coggan et al. (2010)). For instance, water banks provide a clearinghouse function to decrease transaction costs of administrative reviews or price discovery for buyers and sellers.

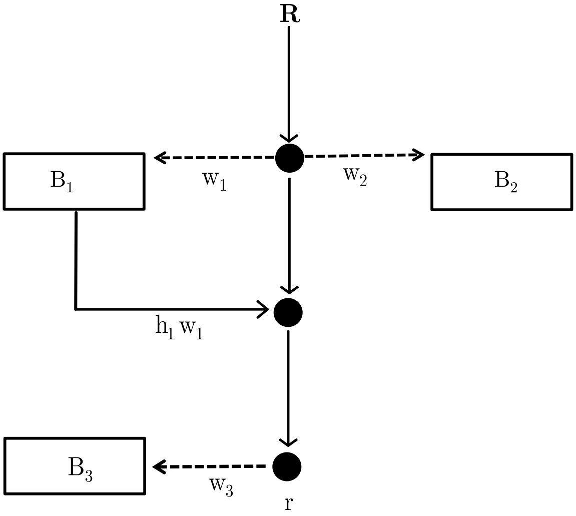

Fig. 5.1 A simple river basin model. *Source* own illustration

5.2 A Water Market Model

5.2.1 Water Markets and Return Flows

With the help of a water market model, we now derive the problems of implementing water markets. As a normative starting point we use the approach of the optimal allocation of water along a river as presented in Sect. 3.7. Figure 5.1 depicts a simple hydrological scenario.

In the river basin dealt with here, there is an inflow R and a prescribed runoff r.[2] There are three users, say farmers, who want to irrigate their plantations located along the river. Farmers 1 and 2 are located upstream. Farmer 3 is situated further below. Here we also take into account the return flows that occur in agriculture. For simplification, it is assumed that only farmer 1 has return flows.[3] The water diversion of farmer 2 and 3 is, therefore, identical to their water consumption. Regarding farmer 1 we have to distinguish between water diversion and water consumption. Diversion is captured by the variable w_1 and water consumption is $(1 - h_1)w_1$. The fraction $h_1 w_1$ returns to the river and is available for farmer 3. The reference point for an assessment is the water allocation that follows from an integrated water resource management approach. Here, we limit ourselves to the criterion of efficiency on the implicit assumption that distribution issues are solved by parallel transfer payments.

$$\max_{w_i} \left[B_1(w_1) + B_2(w_2) + B_3(w_3)\right] \tag{5.1}$$

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[2] In the following, we will assume that $r = 0$ for simplicity. All results also apply to the more general and realistic case of $r > 0$.

[3] Our results are also valid for the more general case where all three farmers have return flows.

under the constraints

$$w_1 + w_2 \leq R - r \tag{5.2}$$

$$w_3 \leq R - r - w_1 - w_2 + h_1 w_1 \tag{5.3}$$

Assuming that all farmers get a portion of the sustainable amount of available water which is $R - r$, we derive the following optimality conditions

$$B_1^{'}(w_1) - \lambda_1 - \lambda_2(1 - h_1) = 0 \tag{5.4}$$

$$B_2^{'}(w_2) - \lambda_1 - \lambda_2 = 0 \tag{5.5}$$

$$B_3^{'}(w_3) - \lambda_2 = 0 \tag{5.6}$$

From Sect. 3.7 we know that we have to distinguish two cases of optimal water allocation that depend on the farmers' marginal benefit functions and on the extent of water scarcity: In the first case, all available water is used up by farmer 1 and 2.[4] In the second case a portion of water flows to farmer 3, so that this amount and the return flow $h_1 w_1$ is available to farmer 3. In this second case we have $\lambda_1 = 0$ and the optimality conditions condense to

$$\frac{B_1^{'}(w_1)}{(1 - h_1)} = B_2^{'}(w_2) \tag{5.7}$$

$$B_2^{'}(w_2) = B_3^{'}(w_3) \tag{5.8}$$

$$w_3 = R - r - w_1 - w_2 + h_1 w_1 \tag{5.9}$$

The water allocation equates the marginal benefits of water consumption, taking farmer 1's return flows into account. The return flows increase the water productivity. Therefore, farmer 1 is assigned more of the water than in the case of no return flows.

In order to examine the problems of implementing water markets as a means of optimal water allocation in the presence of return flows, we focus on the second scenario, where Eq. (5.2) is not binding. To further simplify the algebra, we assume simple numerical values. For the marginal benefit of water we assume $B_i^{'}(w) = a - bw = 300 - w$, i.e., all farmers are identical. Further: $h_1 = 0.5$, R = 300 and $r = 0$. Inserting these parameter values into Eqs. (5.7)–(5.9) yields the optimal water allocation[5]: $\{w_1^* = 200, w_2^* = 100, w_3^* = 100\}$. Farmer 1 gets twice as much as farmer 2, so the available water R is completely allocated to them. Farmer 3 receives farmer 1's return flow. Note that the optimal allocation does not violate the constraint Eq. (5.2).

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[4] This implies that constraint Eq. (5.2) is binding and hence, $\lambda_1 > 0$.

[5] The exact calculation is presented in Exercise 5.1 in Sect. 5.4.

Now we introduce a water market in which water withdrawals are traded. The property rights to water are distributed in such a way that they protect the river basin. This implies that total water rights do not exceed $R + h_1 w_1$. Whatever the distribution of water rights between farmers, in sum they must comply to this constraint to ensure hydrological sustainability. The exact key of the distribution of water rights follows fairness criteria or is historically given.

Each farmer maximizes the net benefit

$$\max_{w_i}[B_i(w_i) - q(w_i - T_i)] \quad \Rightarrow \quad B_i^{'}(w_i) = q \tag{5.10}$$

where q is the price of, say, one m^3 of water diverted and T_i are the water rights assigned. Solving this optimization program with respect to w_i yields the individual market demand of farmer i. Taking our example we have

$$a - bw_i = q \quad \Rightarrow \quad \hat{w}_i(q) = \frac{a-q}{b} = 300 - q \tag{5.11}$$

It should be noted here that we assume a competitive market in which there is no strategic behavior. No market participant can manipulate the price of water. We, therefore, rule out collusion, monopolistic or oligopolistic behavior.

Total demand is $\hat{W} = \sum_{i=1}^{3} \hat{w}_i$. The equilibrium price q^* can be calculated by equating total demand with the given supply $R - r + h_1 w_1$. The market auctioneer has a difficult task to solve: He must not only determine the equilibrium price, but he also has to calculate the effective water supply at each price. This presupposes that he can compute the return flows of farmer 1 which is only possible if a reliable water accounting system of the river basin exists. In the following, we will assume that he is able to do so.

Since all demand functions are identical, all farmers buy the same amount of water, i.e., $\hat{W} = 3(a - q)/b$. The equilibrium price can be calculated from the market clearing condition

$$3\left[\frac{a-q}{b}\right] = R + h_1\left[\frac{a-q}{b}\right] \quad \Rightarrow \quad q^* = \left[a - \frac{bR}{3-h_1}\right] \tag{5.12}$$

Inserting the numerical values yields $q^* = 180$. If q^* is inserted in the demand functions, we obtain the market allocation $\{\hat{w}_1 = 120, \hat{w}_2 = 120, \hat{w}_3 = 120\}$. If one compares the market allocation with our reference allocation, one sees that the introduction of the market leads to a suboptimal water allocation. The water market allocates too little water to farmer 1. This is because farmer 1 does not base her demand decision on net water flows. The market refers to water diversion, not water consumption. This result is well-known in water economics and various institutional designs have been proposed to remedy this market failure. One of these proposals suggests to introduce a water market where water consumption is traded, not water diversion. Of course, if water trading is based on water consumption the return flows must be observable. In addition to the water accounting system, a hydrological model must be implemented to predict the price sensitivity of return flows.

Let us assume that this informational requirement is fulfilled. Then, our model has to be changed slightly. Farmers 2 and 3 behave as before because their water diversion is not related to return flows. Farmer 1's water demand is dependent on his water consumption. He only pays for water consumption $(1 - h_1)w_1$. Hence

$$\max_{w_1}[B_1(w_1) - q(1 - h_1)w_1 + qT_i] \quad \Rightarrow \quad B_1^{'}(w_1) = q(1 - h_1) \tag{5.13}$$

From Eq. (5.13), we can calculate the water demand of farmer 1

$$\hat{w}_1(q) = \frac{a - q(1 - h_1)}{b} = 300 - 0.5q \tag{5.14}$$

The water demand of farmer 2 and 3 remains the same. Thus, the equilibrium price of the water market follows from equating total demand to supply

$$(1 - h_1)\hat{w}_1(q) + \hat{w}_2(q) + \hat{w}_3(q) = R - r \quad \Rightarrow \quad \frac{a - q(1 - h_1)}{b} + 2\left(\frac{a - q}{b}\right) = R - r \tag{5.15}$$

Inserting the numerical values yields $q^* = 200$. Reinserting q^* into the respective demand functions leads to the final market induced water allocation $\{\hat{w}_1 = 200, \hat{w}_2 = 100, \hat{w}_3 = 100\}$. This allocation is identical to the optimal allocation derived from our IWRM approach.

5.2.2 Water Markets and Instream Constraints

Even if there were no return flows, the optimal allocation is not necessarily ensured by a single water market covering the river basin. This is the case when instream flows have to be taken into account. For various reasons a minimum of running water along the course of a river is necessary. Examples are ecological reasons, recreation of the local population, navigability, or yet other reasons. These instream flows are called environmental flows. Our model captures this inflow instream constraint by requiring that in the first flow section a flow rate $\bar{v}_1$ must not be undercut. For the second section a lower limit of $\bar{v}_2$ applies accordingly.[6] Thus, the hydrological constraints from Eqs. (5.2) and (5.3) have to be changed to[7]

$$w_1 + w_2 \leq R - \bar{v}_1 \tag{5.16}$$

$$w_3 \leq R - w_1 - w_2 - \bar{v}_2 \tag{5.17}$$

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[6] Notice, that we must have $\bar{v}_1 > \bar{v}_2$. Otherwise, upstream farmers cannot divert water from the river.

[7] Again, we assume as before that $r = 0$.

5.2.2.1 Insufficiency of a Single Market

For simplicity, let us assume that farmers are identical. In addition, we assume that the first stretch of the river is regulated, i.e., there is a minimum river flow needed, say, $\bar{v}_1 = 150$. For the second river section we assume, that $\bar{v}_2 = 0$, i.e., farmer 3 can use up all water available.

First, we calculate the optimal water allocations using the maximization program (5.1) under the new hydrological constraints. The optimal conditions consist of Eqs. (5.4)–(5.6) for $h_1 = 0$, Eqs. (5.16) and (5.17). From these conditions we can infer that the first constraint must be binding, i.e., for $\lambda_1 > 0$ this constraint was not binding and, hence, $\lambda_1 = 0$ the optimality conditions (5.4)–(5.6) would imply that $w_1^* = w_2^* = w_3^* = R/3$. But this violates constraint (5.16) since $w_1^* = w_2^* = (2/3)R = 200 > R - \bar{v}_1 = 150$. Therefore, the constraint (5.16) is binding and $w_1^* + w_2^* = R - \bar{v}_1$. Since both water allotments for farmer 1 and farmer 2 must be equal (see Eqs. (5.4) and (5.5)) we have $w_1^* = w_2^* = (R - \bar{v}_1)/2 = 75$. From Eq. (5.17) follows $w_3^* = R - w_1^* - w_2^* = 150$. The environmental instream regulation brings an advantage for farmer 3.

We now show that this allocation cannot be achieved with a single water market for the entire catchment area, although there are no return flows. If a single market is implemented, a single water price exists equilibrating total demand with supply. To secure the instream constraint in the first stretch of the river total supply is equal to $R - \bar{v}_1$ we have $\hat{w}_1 = \hat{w}_2 = \hat{w}_3 = (R - \bar{v}_1)/3 = 150/3 = 50$. This allocation does not correspond to the optimal solution. If instead total inflow R is offered, the market allocation for each farmer amounts to $R/3 = 100$. Again, this violates the hydrological constraints, since $\hat{w}_1 + \hat{w}_2 = 200 > R - \bar{v}_1 = 150$. Hence, a single market cannot provide the optimal solution.

5.2.2.2 A System of Local Markets

Therefore, a system of local markets must be introduced. We establish two markets, one for the water of the upstream section and one for the downstream section of the river. The upstream market extends from the inflow to before the lower withdrawal point of farmer 3. The lower market encompasses the flow from this withdrawal point to the end of the river. The upper stretch is regulated by the instream constraint $\bar{v}_1$, the lower section has no regulation (for simplicity). Before trade takes place, the public water authority assigns locational property rights of water withdrawal to the farmers. Upstream property rights are in total $(R - \bar{v}_1)$, guaranteeing the ecological solidity of the upper stretch. These rights are distributed to the farmers according to a given key, which we will not discuss further. Justice aspects, power structures or historically given rights can play a role here. These rights can be utilized to divert water or to sell the rights in the market. The same applies to the downstream water market. Here, total property rights cover the remaining water $\bar{v}_1$. In contrast to the upper market, there are some constraints on the part of farmer 1 and 2. Both can sell their downstream property rights, but they cannot use these rights to buy water due to the unidirectionality of the river flow.

We are now in a position to determine the demand and supply behavior of farmers in both markets. For farmer 1 and 2 we have the following net benefit functions:

$$\max_{w_i, w_{i,1}} [B_i(w_i) - q_1(w_{i1} - t_{i1}) + q_2 t_{i2}] \quad \text{s.t.} \quad w_i \leq w_{i,1} \tag{5.18}$$

where w_i is water consumption and w_{i1} is the use of water rights of farmer i in market 1. The difference $(w_{i1} - t_{i1})$ indicates the net position of farmer i. If it is positive (negative) she sells (buys) water rights in market 1. t_{i1} and t_{i2} are the respective water rights in both markets assigned to farmer i. Since both farmers cannot buy water rights to use for water consumption from market 2, they only have the option to sell their rights t_{i2}. Thus, we have included the revenue from these sales in the net benefit function. The demand function for each farmer follows from maximizing Eq. (5.18) with respect to $\{w_i, w_{i,1}\}$ subject to the constraint that water diversion cannot be more than water rights used. From the optimality conditions

$$B_i^{'}(w_i) - \lambda = 0 \tag{5.19}$$

$$-q_1 + \lambda = 0 \tag{5.20}$$

we can calculate the demand functions for the assumed specification of $B_i^{'} = a - bw_i$ which yields

$$\hat{w}_i(p_1) = \frac{a - q_1}{b} = 300 - q_1, \quad i = \{1, 2\} \tag{5.21}$$

Determining farmer 3's demand behavior is somewhat more comprehensive because farmer 3 is a buyer of water rights in both markets. She maximizes

$$[B_3(w_3) - q_1(w_{31} - t_{31}) - q_2(w_{32} - t_{32})], \quad \text{s.t.} \quad w_3 \leq w_{31} + w_{32} \tag{5.22}$$

with respect to $\{w_3, w_{31}, w_{32}\}$ where $w_{3,j}$ are water rights demanded and utilized in market j and t_{31} and t_{32} are water rights assigned in market 1 and 2 before trade takes place. Thus, we have the following assignments of water rights for all farmers and both markets.

$$t_{11} + t_{21} + t_{31} = (R - \bar{v}_1) \quad \text{and} \quad t_{12} + t_{22} + t_{32} = \bar{v}_1 \tag{5.23}$$

We assume that farmer 3 consumes water as well, i.e., $w_3 > 0$, and that he buys water rights from the second market, i.e., $w_{32} > 0$ but not from the first market.[8] The optimality conditions are

$$B_i^{'}(w_i) - \lambda = 0 \tag{5.24}$$

$$-q_1 + \lambda \leq 0 \tag{5.25}$$

$$-q_2 + \lambda = 0 \tag{5.26}$$

If the overall market equilibrium leads to water prices such that $q_1 > q_2$, then farmer 3 does not buy in the first market (Eq. (5.25) applies with strict inequality). The scenario is shown in Fig. 5.2.

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[8] Subsequently, we will show why this scenario takes place with the assumed numerical values.

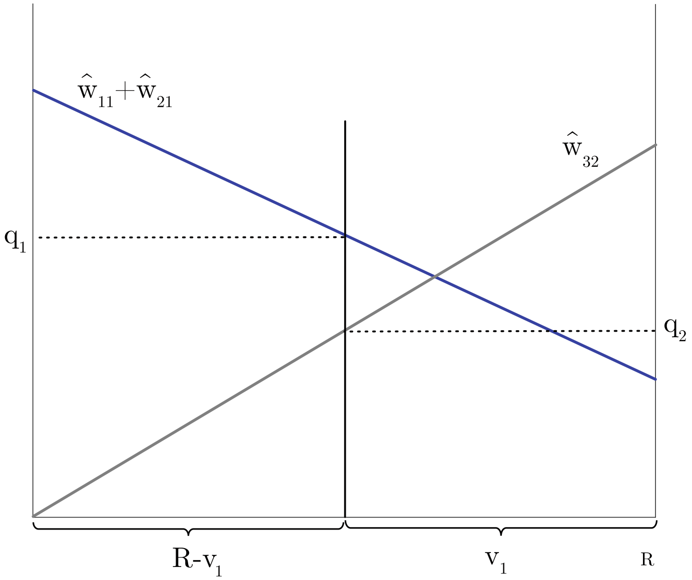

Fig. 5.2 Equilibrium of locational water markets. *Source* own illustration

Total water demand in the upper market is equal to $\hat{w}_{11}(q_1) + \hat{w}_{21}(q_1)$ since farmer 3 does not participate in this market, i.e., $w_{31} = 0$. This demand is equal to total water available in this stretch of the river, i.e., $R - \bar{v}_1 = 150$. The resulting equilibrium price is $q_1 = 225$.[9]

Similarly, the equilibrium of the second water market can be determined, i.e., $\hat{w}_{32}(q_2) = t_{12} + t_{22} + t_{32} = \bar{v}_1$. The resulting water price q_2 is lower than q_1.[10] One can see that our assumption has proven to be correct. If we insert the numerical values into the demand functions we get $\hat{w}_{11} = \hat{w}_{21} = (R - \bar{v}_1) = 150/2 = 75$ and $\hat{w}_{32} = \bar{v}_1 = 150$, which is identical to the optimal water allocation. Hence, to achieve the optimal allocation two separate markets are required.

One can see that the implementation of water markets has to be done with caution. If return flows or ecological concerns have to be taken into account, it is not enough to simply set up a water market for a catchment area. Rather, an institutionally complex system of interdependent markets must be established.

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[9] Inserting the numerical values into the market equilibrium equation $2(a - q_1)/b = R - \bar{v}_1$ gives $2(300 - q_1) = 150$.

[10] The equilibrium price can be derived from the equilibrium condition in market 2 $(a - q_2)/b = \bar{v}_1$ which yields $q_2 = 150$.

Box 5.1 Water recovery management in the Murray–Darling Basin MDB

Australia is among the first countries that have implemented water markets. In particular, the Murray–Darling Basin (MDB) has been regulated by market-oriented instruments, i.e., a cap-and-trade approach, in recent decades. This experiment is assessed very differently in the literature, and it has been criticized, amongst others, as piracy, organized theft of water, and mismanagement. The background to this debate is the history of water reforms in the MDB over the last 50 years, which became necessary due to increasing drought and severe ecological damages. The Federal Government seized power under the Water Act 2007 which, in 2012, led to a ten-year basin plan specifying so-called sustainable diversion limits (SDLs). These were based on hydrological and ecological limits. The water level of a river should not fall below 2/3 of its natural height. The necessary restriction of water abstraction, however, would have led to a substantial loss of income for the agricultural sector and would have encountered much resistance. The government, therefore, decided to buy back water entitlements and grant subsidies for technical measures to increase irrigation efficiency: 2.5 bn. dollars were earmarked for the purchase of the water entitlements and 3.5 bn. dollars. dollars for the subsidy measures.

Critics considered the unilateral granting of water rights to agribusiness as theft. There were also other remarks:

- The implementation of the water plan was intransparent. The responsibilities were unclear. This led to a high loss of confidence in government action.
- There was a serious lack of monitoring of water consumption. The National Water Commission, which was responsible for the monitoring, fulfilled the implementation requirements only partly. Just about 70% of water consumption has been metered. One of the reasons for this is that return flows are difficult to calculate.
- Subsidies for the upgrade of the irrigation infrastructure have been rather inefficient. This is not astonishing. We know from the analysis of the rebound effect that price-oriented instruments (water price) can be more efficient than fostering water saving indirectly by subsidy schemes.

The example of the Murray River shows how difficult it is to implement a management model in practice which is functional from a theoretical point of view.

Sources: Grafton and Wheeler (2018), Grafton et al. (2019)

5.3 Water Entitlements and Water Allocations

As mentioned above, some jurisdictions such as Australia and California, have established water markets based on a cap-and-trade system. In a case in Australia, the water in a catchment area is divided into a consumptive pool and water for the environment. The latter is water which must not be withdrawn from the water cycle. The consumptive pool instead defines the water that can be privately owned. A single share of this consumptive pool is called water access entitlement. It is a perpetual or ongoing entitlement to exclusive access to the water of the respective catchment area. Notice, however, that this entitlement is defined in nominal volumes and does not imply a perpetual allocation of water of this amount. The actual volume of water allocated to an entitlement depends on the scarcity of available water in a given season. The level of water allocation thus depends on the seasonal conditions of the water cycle. As a rule, due to increasing water scarcity, the total of all annual allocations is now likely to be below 100% of the consumptive pool.

Water users can use different instruments to cover their water use. They can directly use the water assigned to their entitlements (water allocations), they can buy additional water allocations or sell part or all of their allocations. Or they buy or sell entitlements. Water rights are more long-term in nature. They entitle their holders in each period (season) to a certain allocation of water. Water rights represent an asset, such as shares in a company. Trading of entitlements is, therefore, also called permanent trading. Thus, it is not surprising that empirical studies of the water market have identified a distinct dependence of the entitlement price on interest rates. Also, the price for water entitlements is higher than the price for short-term water allocations because entitlements do not expire (although their actual water claims are subject to seasonal fluctuations).

In the following, we will analyze the relationship between the market for entitlements and the market for allocations in more detail. Since water entitlements are assets with long-lasting validity, the interrelations should be examined in a dynamic model context. However, we can also investigate the essential peculiarities in a simple, quasi-dynamic model.[11]

Let us introduce a representative water user. She derives benefit (or profits) from the seasonal water use. At the same time she has to decide how much water to use and how to handle her long-term entitlements, as well as her seasonal allocations. This can be summarized in the following approach:

$$\max_{w_t, N} \sum_{t=0}^{T} \beta^t \left\{ E[B(w_t) - \tilde{p}_t(w_t - \tilde{\alpha}_t N)] \right\} - qN \tag{5.27}$$

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[11] Meant by this is a model which, although it has a multi-period planning horizon, does not apply dynamic optimization methods. The optimal demand for water allocations is determined for each period, while the demand for water rights is determined only at the beginning of the planning period (period 0).

where $E[..]$ is the expectation operator. w_t are the seasonal water allocations of the water user, $\tilde{p}_t$ is the price for allocated water in period t, N are the water entitlements that are bought at the beginning of the planning process in period 0. $\tilde{\alpha}_t N$ are the water allocations allotted in each period to the owner of entitlements. This portion is stochastic due to the seasonal weather conditions and their repercussions on the water cycle. If we define $\bar{\bar{W}}$ as the total entitlements, i.e., the size of the consumptive pool, we can define

$$\tilde{\alpha}_t = \frac{\tilde{W}_t}{\bar{\bar{W}}} \tag{5.28}$$

where $\tilde{W}_t$ is total water available in period t. Finally, we have the discount rate $\beta = 1/(1+r)$, where r is the interest rate. Discounting takes place because the water rights can be claimed in all periods.

The water user, e.g., a farmer, in the catchment area that is covered by the market system first chooses the water allocations per season she wants to buy. This leads to the usual optimality condition

$$B^{'}(w_t) = \tilde{p}_t \tag{5.29}$$

From this equation, the allocation demand $\tilde{w}_t = w_t(\tilde{p}_t)$ for each period can be derived. In our simple model, this demand does not depend on the decision with respect to water entitlements.[12] The decision on water consumption is independent of the ownership of water rights. If she needs more water than assigned to her by water allocations $\tilde{\alpha}_t N$, she buys additional water. In the reversed case, she sells part of her water allocations. The question remains as to how many water entitlements should be bought or sold. We have taken the long-term nature of this decision into account in our model by making this decision ex ante, i.e., before the realization of the actual water allocations are known. If we derive Eq. (5.27), with respect to N, we obtain

$$\Pi E[\tilde{p}_t \tilde{\alpha}_t] - q \tag{5.30}$$

where $\Pi = ((1+r)^T - 1)/(r(1+r)^T)$.[13] We see that the objective function is linear in N. This is because the participant in the water market only looks at average values. She does not assess the risk herself. Whether the volatility of allocations and prices is high or low is irrelevant for the valuation of water rights. In reality, the risk should play a role in the decision to buy or sell water entitlements, but to keep the calculations simple, we ignore it here.

If a market equilibrium exists, Eq. (5.30) must be equal to zero. Otherwise, the market participants could materialize arbitrage gains. Profits are made by either

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[12] We have assumed that the water user is risk neutral, i.e., she does not care about the riskiness of her decision.

[13] On average, each period produces the same profit. This makes it possible to write the discounting formula more compactly. The derivation can be found in any introductory textbook on financial economics $\sum_{t=0}^{T} \beta^t = ((1+r)^T - 1)/(r(1+r)^T)$. This expression is greater than 1 for all $t > 1$.

selling and buying back, or purchasing and reselling entitlements. Thus, utilizing Eq. (5.28) leads to

$$\Pi[\tilde{p}_t\tilde{\alpha}_t] - q = 0 \quad \Rightarrow \quad \frac{BE[\tilde{p}_t\tilde{W}_t]}{\bar{\bar{W}}} = q \tag{5.31}$$

For the economic interpretation it is instructive to rewrite this equation. In doing so, we make use of a simple factorization of covariances[14]

$$\Pi\left[\bar{p}\frac{\bar{W}}{\bar{\bar{W}}} + \frac{\text{cov}(\tilde{p}, \tilde{W})}{\bar{\bar{W}}}\right] = q \tag{5.32}$$

Equation (5.32) summarizes the essential relationships between the two markets in a compact way

- If one recalls the definition of Π, one sees that the relationship between the two prices depends on the interest rate r. Since $\bar{p}$, $\bar{W}$, and the covariance are determined solely in the market for allocations, i.e., are exogenous to the entitlement market, the interest rate affects q alone. Assume that the planning horizon is infinite, then $\Pi = 1/r$. It is intuitive that with rising r the price q decreases and vice versa. This is exactly what empirical studies have shown and it is rather plausible. We know that this inverse relationship is observable in the stock market. High interest rates decrease the value of shares and vice versa.
- When comparing the time series of both prices, it becomes evident that q is greater than p. This is because the water entitlements are assets, while the water allocation is only valid for one period.
- Without discounting, the average allocation price $\bar{p}$ would be higher than q. This can be seen from the expression in square brackets in Eq. (5.32). First of all, $\bar{W}/\bar{\bar{W}}$ is less than 1 because the average seasonal allocation is less than the consumption pool. Also, the covariance is negative because the price and the seasonal supply of allocations are negatively related. If the allocation is high, the price is low and vice versa. Therefore, for B = 1 it holds that $\bar{p} > q$. That is plausible. The average supply of water allocations is less than the amount of water entitlements ($\bar{W} < \bar{\bar{W}}$). On average, water rights cannot be converted 100% into water allocations due to water scarcity.
- It is also interesting to note that the price difference between q and $\bar{p}$ decreases with increasing variability (covariance) in the allocation market because the variability leads to a devaluation of water entitlements. This is not due to the valuation of the risk (we have assumed risk neutrality), but due to the fact that with higher volatility of $\tilde{W}$ the ownership of water rights must be worthless. If the negative

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[14] The covariance of two stochastic variables $\tilde{x}$ and $\tilde{y}$ is defined as $\text{cov}(\tilde{x}, \tilde{y}) = E[(\tilde{x} - \bar{x})(\tilde{y} - \bar{y})]$ where $\bar{x} = E[\tilde{x}]$ and $\bar{y} = E[\tilde{y}]$ are the respective means. Multiplying yields $\text{cov}(\tilde{x}, \tilde{y}) = E[\tilde{x}\tilde{y}] - \bar{x}\bar{y}$.

correlation between the water allocations and prices increases in absolute value, an increase in allocations ($\tilde{\alpha}$) is countervailed by a sharp price decrease ($\tilde{p}$) and vice versa.

5.4 Exercises

Exercise 5.1 Optimal water allocation for the simple river basin model
We have chosen parameter values such that the unidirectionality of the river does not play a role, i.e., the allocation of water to farmer 1 and 2 is not constrained by Eq. (5.2). Thus, we can take the optimality conditions Eqs. (5.7)–(5.9) to calculate the optimal values and check whether they violate the constraint (5.2). Inserting $B_i^{'} = 300 - w_i$ and the numerical values $R = 300$ and $h = 0.5$ it follows from Eq. (5.7) that

$$(300 - w_1)/(1 - 0.5) = 300 - w_2 \tag{5.33}$$

From Eq. (5.8), we have $w_2 = w_3$ such that Eq. (5.9), can be written as

$$2w_2 = 300 - (1 - 0.5)w_1 \tag{5.34}$$

From Eqs. (5.33) and (5.34), it follows that $\{w_1^* = 200, w_2^* = 100\}$. If we insert these values in Eq. (5.2) we have $w_1^* + w_2^* = 300 \leq R = 300$. The optimal values do not violate the constraint. Hence, our assumption that $\lambda_1 = 0$ was plausible. Finally, we can calculate the optimal allocation for farmer 3 which is simply the return flow $0.5w_1^* = 100$.

Exercise 5.2 NGO intervention in the water market
There are some initiatives in the European carbon market to buy up CO_2 certificates and then cancel their validity. Of course, this strategy assumes that NGOs are allowed to participate in trading or have an accredited trader who makes purchases on their behalf in the market. We want to transfer this idea to a water market. We assume that a water market has been implemented in a water catchment area. The water authorities provide a fixed amount of water rights for purchase (water supply) that can be bought by the local economy (farmers, industry, municipalities). The members of a local NGO find that too many water rights have been emitted and decide to buy and cancel water rights on the basis of donations in the market.

We want to derive the water demand of the local economy from the usual approach of benefit maximization.

$$\max_w [B(w) - pw] \quad \Rightarrow \quad B'(w) = p \tag{5.35}$$

As in Sect. 5.3, we assume a quadratic benefit function. The demand function is, therefore, linear (see Eq. (5.11)).

$$w = (a - p)/b \tag{5.36}$$

From the NGO's point of view, the assessment of water use leads to environmental damage, which can be expressed by a damage function. From the NGO's point of view, the damage lies in the fact that the abstraction of water for economic and consumption purposes damages the local ecosystem. We summarize this assessment by a quadratic damage function, from which the demand for water rights can also be derived. We assume that the purchases are covered by donations.

$$\min_{v}[(D/2)(\bar{W} - v)^2 + pv] \quad \Rightarrow \quad D(\bar{W} - v) = p \tag{5.37}$$

where $D > 0$ is a constant, $\bar{W}$ the amount of water entitlements issued by the local water authority and v the water demand of the NGO. From Eq. (5.37), the water demand function of the NGO follows:

$$v = \bar{W} - p/D \tag{5.38}$$

Adding both demand functions to total demand and equating to the regulated water supply allows the calculation of the equilibrium price

$$\frac{a-p}{b} + \left[\bar{W} - p/D\right] = \bar{W} \quad \Rightarrow p^* = \frac{Da}{(D+b)} \tag{5.39}$$

The intervention of NGOs in the water market apparently leads to the fact that the water price is independent of the regulated supply of water rights. The NGOs react to every change in the water supply with compensatory purchases. This can be seen from Eq. (5.38). Thus, if NGOs are allowed access to the water market, they take over the political control of the water supply displacing the local authorities. This may be a problem from a democratic point of view. However, note that our model's result is only valid as long as the financing of the purchases is secured by donations. If their budgets are limited, the effective purchases might be less than v.

Exercise 5.3 Markets for entitlements and allocations

This problem is about calculating the prices for the market for water entitlements and for the market for water allocations. We assume that two identical farmers have water rights corresponding to the full amount of the water pool, say $\bar{\bar{W}} = 60$. The benefit function of both farmers is identical and quadratic, so the first derivative is linear, $B_i^{'}(w_i) = a - bw_i$, whereby by assumption $a = 615$ and $b = 1$. From Eq. (5.29), the demand function follows

$$w(\tilde{p}) = 615 - \tilde{p} \tag{5.40}$$

The equilibrium price can be determined by setting total demand equal to the seasonal water supply $\tilde{W}$

$$2w(\tilde{p}) = 2(615 - \tilde{p}) = \tilde{W} \quad \Rightarrow \quad \tilde{p} = 615 - \frac{1}{2}\tilde{W} \tag{5.41}$$

The average price is calculated by taking the expectation of both sides, yielding

$$\bar{p} = E[\tilde{p}] = 615 - \frac{1}{2}\bar{W} \tag{5.42}$$

where $\bar{W} = E[\tilde{W}]$. Let us assume that $\tilde{W}$ is independent and identically distributed, i.e., the probability density is identical for all $\tilde{W}$ and independent across all periods supported by a finite interval $I = [0, \bar{\bar{W}}]$, where $\bar{\bar{W}} = 60$. From statistics textbooks we know

$$\bar{W} = \frac{\bar{\bar{W}}}{2} \quad \text{and} \quad \mathrm{Var}[\tilde{W}] = \frac{\bar{\bar{W}}^2}{12} \tag{5.43}$$

where $Var[\tilde{W}]$ is the variance of the periodical water supply. Due to our assumption, the mean water allocation to both farmers is half of total entitlements leading to $\bar{\alpha} = (1/2)$ (See Eq. (5.28)).

Now we are able to calculate the average price for water allocations. From Eq. (5.42), it follows

$$\bar{p} = 615 - \frac{\bar{W}}{2} = 615 - \frac{\bar{\bar{W}}}{4} = 615 - 15 = 600 \tag{5.44}$$

In order to calculate the price for water rights, we have to determine the covariance in Eq. (5.32). Utilizing Eqs. (5.41) and (5.42), we have

$$\mathrm{cov}[\tilde{p}, \tilde{W}] = E\left[\left(615 - \frac{\tilde{W}}{2} - 615 + \frac{\bar{W}}{2}\right)(\tilde{W} - \bar{W})\right] = -\frac{1}{2}E[(\tilde{W} - \bar{W})^2] = -\frac{1}{2}\mathrm{Var}[\tilde{W}] \tag{5.45}$$

Inserting the numerical values yields $\mathrm{cov}[\tilde{p}, \tilde{W}] = -(1/2)60^2/12 = -3600/24 = -150$.

Assuming that the horizon T is infinite, we know that $\Pi = 1/r$. Taking $r = 0.1$ it is straightforward to calculate the entitlement price q. Simply insert the numerical values in Eq. (5.32). This yields

$$q = (1/0.1)[(1/2)\bar{p} - 150] = 10(600 \times (1/2) - 150) = 1500. \tag{5.46}$$

Due to the discount factor and the infinite planning horizon the price for water entitlements is much higher than the price for the seasonal water allocations.

5.5 Further Reading

The economic analysis of water markets started quite early at a time when water allocation did not follow economic criteria but was determined solely by ownership structures. Certainly, the increasing scarcity of water in many regions of the world has led to an increased focus on economic efficiency criteria in water allocation.

Olmstead and Stavins (2009) provides an overview in which the welfare effects of price-oriented allocations are compared to those of quantity allocations based on rights. The functioning of water markets is subject to certain conditions, which Endo et al. (2018) further specify. In establishing these conditions, they examine in which countries of the world markets could be introduced in principle. Some examples are presented in the volume (Easter and Huang 2014a). Australia provides the first experience with water markets, and Turral et al. (2005) and Grafton and Wheeler (2018) provide an overview about the evolution of the case of the Murray–Darling Basin. They also analyze the effects of a policy mix (water market, subsidies). Grafton and Wheeler (2018) and Grafton et al. (2019) examine further management approaches in Mexico, Tanzania, USA, and Vietnam.

In water markets, specific hydrological relationships must be taken into account. Griffin and Hsu (1993) have examined these interrelationships in detail within the framework of a market model. Return flows, in particular, are taken into account here. Ansink and Houba (2012) deal with competition problems. How do water markets allocate scarce water when the water supply along a river is monopolized? Finally, Wheeler et al. (2008) empirically investigate the determinants that explain the price difference between water allocations and water entitlements.

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