Jeffery D. Connor, Brad Franklin, Adam Loch, Mac Kirby, Sarah Ann Wheeler
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Trading water to improve environmental flow outcomes

Jeffery D. Connor,[1] Brad Franklin,[2] Adam Loch,[3] Mac Kirby,[4] and Sarah Ann Wheeler[3]

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[1] As consumptive extractions and water scarcity pressures brought about by climate change increase in many world river basins, so do the risks to water-dependent ecological assets. In response, public or not for profit environmental water holders (EWHs) have been established in many areas and bestowed with endowments of water and mandates to manage water for ecological outcomes. Water scarcity has also increasingly spawned water trade arrangements in many river basins, and in many instances, EWHs are now operating in water markets. A number of EWHs, especially in Australia, begin with an endowment of permanent water entitlements purchased from irrigators. Such water entitlements typically have relatively constant interannual supply profiles that often do not match ecological water demand involving flood pulses and periods of drying. This article develops a hydrologic-economic simulation model of the Murrumbidgee catchment within the Murray-Darling Basin to assess the scope of possibilities to improve environmental outcomes through EWH trading on an annual water lease market. We find that there are some modest opportunities for EWHs to improve environmental outcomes through water trade. The best opportunities occur in periods of drought and for ecological outcomes that benefit from moderately large floods. We also assess the extent to which EWH trading in annual water leases may create pecuniary externalities via bidding up or down the water lease prices faced by irrigators. Environmental water trading is found to have relatively small impacts on water market price outcomes. Overall our results suggest that the benefits of developing EWH trading may well justify the costs.

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1. Introduction

[2] Economists have long advocated water trading as a means to allow dynamic and efficient reallocation of water to higher-value uses as diverse water use values evolve and change [*Easter et al*., 1999; *Howe et al*., 1986]. Recent decades have seen the increasing emergence of water markets in a number of middle-income developing countries (e.g., Chile and Mexico), as well as for higher-income developed countries (e.g., the western U.S. and Australia) [*Grafton et al*., 2011; *Svendsen and Meinzen-Dick*, 1997]. Water trade commonly involves annual leases of irrigation water amongst irrigators [*Michelsen and Young*, 1993; *Quiggin*, 2006]. For example, in-season water transfers via simple market and redistribution arrangements have helped New Zealand irrigators to avoid supply shortfall during drought [*Hayward*, 2006], while Australian irrigators now commonly use formal and informal water leasing (referred to as water allocation trading in the local vernacular) to manage risk positions within and across seasons [*Bjornlund*, 2004; *Connor and Kaczan*, 2013]. Similarly, irrigators in the western US [*Hansen et al*., 2008] and Chile [*Bauer*, 2004] tend to favor water leasing over permanent transfers as the former is possible under simple institutional arrangements. Annual water leases from irrigators to governments or water utilities are also common, especially during times of drought to meet municipal industrial water supply deficits. Such transactions occur, for example, in the U.S. of California [*Howitt*, 1994] and Georgia [*Cummings et al*., 2004] and in parts of Spain [*Pulido-Velazquez et al*., 2008].

[3] Government and nonprofit entities also operate in many river basins to achieve environmental objectives [*Garrick et al*., 2011; *Hadjigeorgalis*, 2010]. In the western US, environmental water recovery projects date back to the late 1980s, with significant volumes of water leasing for environmental flow purposes being documented. For example, *Scarborough and Lund* [2007] identify 7400 GL of environmental transfers between 1998 and 2005, while *Garrick et al*. [2012] catalog 24 programs totaling 3000 GL of environmental transfers; mainly through lease or spot-market transactions.

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[1] CSIRO Ecosystem Science, Adelaide, South Australia, Australia.

[2] Department of Environmental Sciences, University of California, Riverside, California, USA.

[3] Centre for Regulation and Market Analysis, School of Commerce, University of South Australia, Adelaide, South Australia, Australia.

[4] CSIRO Land & Water, Canberra, Australian Capital Territory, ACT, Australia.

Corresponding author: J. Connor, CSIRO Ecosystem Science, Adelaide, South Australia, Australia. (jeff.connor@csiro.au)

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[4] A challenge arises for environmental water managers who acquire permanent water entitlements from irrigators because the temporal profile of releases from entitlements developed for irrigation are unlikely to provide a flow regime consistent with realizing environment goals. Irrigation water entitlements are typically developed through use of dams and release rules to smooth flow variation across seasons and provide relatively constant supply to irrigators across irrigation seasons [*Dreverman*, 2013]. In contrast, ecologically desirable flow regimes generally mimic natural flow patterns, with episodic large floods followed by periods of drying [*Overton et al*., 2009].

[5] If an environmental water holder (EWH) can participate in an annual water lease market, they should be able to lease in water to increase environmental water supply when greater flow is ecologically desirable and lease out water when drying is helpful in realizing riverine and riparian ecological health objectives [*Kirby et al*., 2006]. This is a possibility in the Australian Murray-Darling Basin (MDB), where since 2004 the Commonwealth, states, and various organizations have acquired a significant volume of permanent water entitlements through purchases from willing sellers and investments in efficiency improvements to reallocate water from irrigation uses [*Wheeler and Cheesman*, 2013; *Lane-Miller et al*., 2013]. The water bought by the Commonwealth since 2007–2008 will be managed by an entity known as the Commonwealth Environmental Water Holder (CEWH). Enabling legislation allows the CEWH to lease part of its permanent water right when environmental demand is less (for example, a year after a large flood) and save the proceeds to lease water from irrigators in years when this is environmentally beneficial [*Commonwealth Environmental Water Holder* (*CEWH*), 2011].

[6] In considering the implementation of an EWH trade scheme, some deductions are obvious and do not require empirical assessment. For example, economic logic and water market experience suggests that allowing those managing permanent water entitlements for the environment the flexibility to participate in an annual water lease market should facilitate some possibilities to improve environmental outcomes. This logic holds as long as reallocation between seasons can be helpful ecologically, and transactions costs in annual water lease markets are small [*Wheeler et al*., 2013]. It can also be concluded a priori that irrigators will only trade on water lease markets if this improves their welfare. Still, there can be significant concerns that are not easily understood without empirical modeling of the magnitudes of environmental flow responses and water market effects.

[7] One significant concern, voiced by some in the MDB is that the magnitude of potential environmental benefit may be too small to justify the costs of developing trading strategies and transacting in annual water lease markets [*CEWH*, 2011]. Others are more optimistic and suggest that allowing annual EWH leasing could achieve desired environmental objectives with a smaller endowment of permanent water entitlements [*Peterson et al*., 2005; *Tisdell*, 2010; *Wheeler et al*., 2013]. However, such leasing activity may mean that irrigators who are not direct parties to EWH trade may be impacted through pecuniary externalities. A relatively large EWH market participant, who will hold at least 20% of all permanent water entitlements in the MDB, could bid up the market price. Irrigators wishing to lease in more water could face increased costs when the EWH also stands to benefit from leasing in water. Likewise, irrigators wishing to lease their water out in the same years as the EWH could experience lower prices than they would otherwise. To the extent that water markets are unconstrained, no loss of efficiency would be expected through pecuniary externalities; still they may be of concern to some as they will tend to redistribute any surplus amongst water buyers and sellers.

[8] To understand the magnitude of potential environmental benefits for EWH trading in an annual water lease market and the scale of potential pecuniary externalities for irrigators, we develop an integrated hydrologic, economic, and environmental model where the EWH has acquired irrigator water entitlements. These water entitlements have a temporal profile of release that is distributed relatively evenly over years, consistent with irrigators' preferences, but not well matched to environmental demand. In one scenario, the EWH can only supply environmental water in the temporal profile associated with the water entitlements it has acquired from irrigators. In a second scenario, the EWH participates on an annual water lease market to better meet environmental watering objectives.

2. Murrumbidgee Catchment

[9] Our case study in the MDB is the Murrumbidgee catchment in southern New South Wales (Figure 1). The headwaters for the river are located in the slopes of the Great Dividing Range, and the river runs westward until it joins with the Lachlan River and then the Murray River near Balranald. Reliable stocks of water are provided by the Eucumbene and Tantangara Dam in the Snowy Mountains and the Burrinjuck and Blowering Dams near Canberra. Covering 900 km, the Murrumbidgee has an annual average flow of approximately 4400 GL and provides water supply for the towns of Wagga Wagga, Gundagai, Hay, and Griffith. It also provides irrigation water to the Murrumbidgee Irrigation Area (MIA) and Coleambally Irrigation Area, as well as some smaller irrigation schemes. The area supplied represents approximately one quarter of the total MDB-irrigated area. Common crops in the MIA include rice, wheat, grapes, citrus, and vegetables. The majority of MIA's crops are annual and of lower commodity value, which is one of the reasons it has been a net exporter of water allocations to Victoria and South Australia through water trade from 1998 to 2010 [*Kirby et al*., 2012; *National Water Commission* (*NWC*), 2011].

[10] Water extractions in the MDB grew over time such that withdrawals are now estimated to average 53% of available water for the MDB as a whole [*CSIRO*, 2008]. This extraction level and the most severe drought on record (the 1998/1999 to 2009/2010 Millennium drought) led to significant environmental issues for the Murrumbidgee River system. These issues included poor floodplain Redgum and Blackbox forest conditions, and pressure on water-bird and native fish stocks dependent on healthy wetland and floodplain habitats. Although the region's floodplain forests can survive droughts to some extent through mechanisms such as reliance on stored water and reduced transpiration, beyond a certain "return interval" threshold between inundations, trees will begin to die off. Rates of

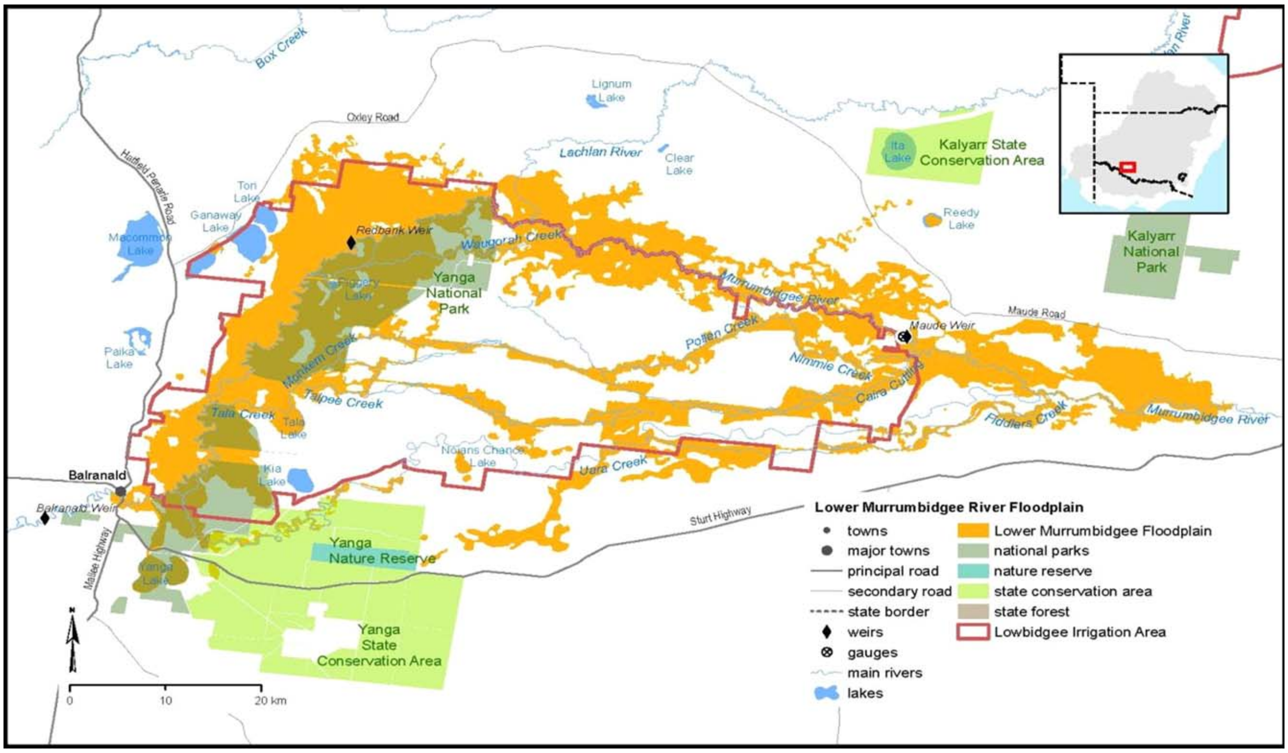

Figure 1. Murrumbidgee River Catchment (source: *Murray-Darling Basin Authority* (*MDBA*) [2012a]).

die off will increase in concert with the return interval length. Review of recent evidence [*Overton and Doody*, 2013] suggests that floodplain forests die off rates increase at an increasing rate when the interval between return flows exceeds approximately three times the predevelopment inundation interval.

[11] During the Millennium drought, when environmental flows creating inundations at sufficient intervals were absent, environmental assets such as the mid-Murrumbidgee Wetlands, the Lowbidgee Floodplain, and the Fivebough and Tuckerbil Swamp Ramsar listed sites suffered significant degradation [*CSIRO*, 2008].

3. Methodology

[12] To simulate the above context, an integrated model was developed for the Murrumbidgee River catchment area with submodels representing the hydrologic system, the ecological response to water flows, and the economic aspects of managing environmental water flows including the dynamics of annual water lease prices. The water balance base case mimics conditions that prevailed prior to any environmental water reallocation with release and storage decisions designed primarily to meet irrigation water demand. Environmental water reallocation scenarios involve reallocation of a fraction of permanent irrigation water entitlements with and without EWH annual lease market trade. Environmental damages are represented functionally as an exponential loss increasing in time following floods of defined magnitudes. This captures the fact that ecosystems suffer damage at an increasing rate the longer they experience drought beyond the duration to which they are adapted.

[13] Simply reallocating water without EWH trade can benefit some parts of the floodplain by providing moderate floods at increased intervals. However, other parts of the floodplain that require larger floods continue to suffer longer intervals between inundation than what they are adapted to and hence experience exponential damage. By participating in the annual water lease market, the EWH has the opportunity to lease water to irrigators in years when there has been a recent inundation, and therefore, little damage results from reducing seasonal environmental flow. This activity allows fundraising to finance leasing from irrigators in future years in order to create larger floods when the return interval between floods is longer. The motivation is that this can avoid exponentially rising environmental damage.

[14] The strategy of selling soon after floods and buying when longer, more damaging intervals of drought can be avoided is challenging because, while conditions in a given year can be observed, future year flows must be anticipated on the basis of imperfect expectations. We represent this limited foresight with an objective function for the EWH that involves minimizing the sum of current period known environmental outcomes of alternate leasing decisions, as well as the expected values of future flow and environmental outcomes. Annual lease water price dynamics are important because they determine costs and returns to EWH leasing decisions and also because they are a potential source of pecuniary externalities inflicted on irrigators. We determine current period and expected future water lease prices using a regression simulation approach: the

past water price is regressed on past seasonal allocations and the resultant relationship is used to simulate prices resulting from further additions or subtractions to annual lease market supply by a trading EWH.

3.1. Hydrology Submodel

[15] The hydrologic water balance model includes water inflows, dam stocks and flows, diversions, and losses. It is an extract from a MDB-wide water balance model, described in more detail in *Kirby et al*. [2012]. In the extract, we represent the Murrumbidgee catchment alone with five spatial elements: a headwaters region, the Snowy Mountains, which produces annually varying inflows into all dams in the catchment; the dams, represented as a single dam with a 3600 GL capacity; a single river reach downstream of the dam; an irrigation diversion point on the downstream reach, representing all irrigation in the catchment; and an environmental asset at the end of the downstream reach, comprising the Lower Murrumbidgee Swamps. For modeling simplicity, water inflows to the single dam ($I_{t,r}$) are treated as exogenous and predetermined for the historic climate sequence. The predetermined inflows are calculated from the biophysical relationships between rainfall, pan evaporation, runoff, and evaporative losses and basin inflows, and calibrated against river flow records from *Kirby et al*. [2012].

[16] The sum of total annual releases for irrigation (iw_t) and all purposes other than irrigation (cw_t) that were a feature of water allocation policy prior to environmental flow reallocation represent our modeling base case. These base case releases are simulated assuming current level of irrigation development and current allocation rules governing releases with historical climate time series inflows for the 113 year period from 1896 to 2008. In the base case, all historic permanent irrigation water entitlements with annually varying release patterns over years (iw_t) are assumed to be available for irrigators, with none available for the EWH.

[17] To model the EWH with permanent water entitlements acquired from irrigators, we assume that 20% of all historic irrigation permanent water entitlements have been reallocated to the EWH who therefore has access to the associated annual releases, ew_t. Prior to any EWH annual leasing activity, the EWH water holdings have the same interannual variability as historic annual irrigation releases, iw_t. The assumed 20% reallocation level was chosen because it is generally consistent with lower-bound target recovery figures of 2400 GL expressed in Murray-Darling Basin Authority (MDBA) plans.

[18] The water balance equations for the dam are

$$S'_t = S_{t-1,r=river} + I_{t,r=headwater} - iw_t - ew_t - et_t - cw_t - l_{t,r=dam}. \tag{1}$$

$$sp_t = max\left[0,\ S'_t - S_{Max}\right]. \tag{2}$$

$$S_{t,r=river} = S'_t - \quad sp_t. \tag{3}$$

where

[19] t is an index of years; r is an index of geographic element equal to "headwaters" for the element upstream of the dam, "dam", and "river" for the river element downstream of the dam. This index is used for components of flow that occur in more than one type of geographic element; S'_t is a temporary dam water accounting variable equal to the value of initial dam storage plus all inflows minus all outflows and losses, but before spills are accounted for; sp_t is dam spill which is zero if the sum of initial storage ($S_{t-1,r=dam}$) plus net inflow is less than the maximum dam storage capacity (S_{Max}) and is equal to inflow plus initial storage in excess of maximum storage otherwise; $S_{t,r}$ is the dam or river reach storage level at time t and is equal to initial storage (S_{t-1}) plus net inflows up to the capacity of the dam or river reach to hold stored water (S_{Max}); $I_{t,r}$ is the inflows to geographic element r, which for the dam is an exogenous time series calculated by the hydrology model; $l_{t,r}$ is losses at time t from the inflows to element r, calculated as a fixed proportion of inflows that varies by element; iw_t is irrigation water released from the dam at time t that, in the base case (i.e., with no environmental water), is given as an exogenous time series calculated by the hydrology model or, in the cases with environmental water, is given as the exogenous input less (ew_t) plus or minus any environmental water traded (et_t); ew_t is the environmental water release from the dam prior to any environmental water trade; and cw_t is conveyance water release representing all other water releases.

[20] The outflows from the dam are the sum of the negative quantities on the right hand side of equation (1) and spills. In principle, they can exceed the sum of initial dam storage plus inflows ($S_{t-1,r=dam} + I_{t,r=headwater}$) which implies that the dam storage ($S_{t,r=dam}$) would become negative. To prevent this, in any time step in which equation (1) would result in a negative storage, the outflows are adjusted downward such that $S_t = 0$ (and any adjustments are handled in the downstream river reach, as described later). Thus outflow from the dam are described by equation (4).

$$\begin{aligned} O_{t,r=dam} \ &= min[(iw_t + \ ew_t + \ et_t + \ cw_t + l_{t,r=dam}) + sp_t, \\ &(S_{t-1,r=dam} + I_{t,r=headwater})]. \end{aligned} \tag{4}$$

[21] The outflows from the dam, with the additional of runoff within the river reach ($ro_{t,r}$) form the inflows into the river reach.

$$I_{t,r=river} = O_{t,r=dam} + ro_{t,r}. \tag{5}$$

[22] The irrigation supply is diverted from the river reach, and the reach also incurs losses (from evaporation and seepage), so the outflow from the river equals the inflows less losses, irrigation diversions, and any change in river channel storage as seen below:

$$O_{t,r=river} \ = I_{t,r=river} - \ iw_t - l_{t,r=river} - \ \left(S_{t,r=river} - S_{t-1,r=river}\right). \tag{6}$$

[23] The river reach has a storage capacity (in the river channel itself, in irrigation canals, in on-farm and off-farm storages, in backwaters, etc.). For simplicity, we consider this to be a single element treated similarly to dam storage in equations (1)–(3). This storage capacity has the incidental consequence of providing an adjustment mechanism to resolve the possibility of outflows in excess of inflows plus

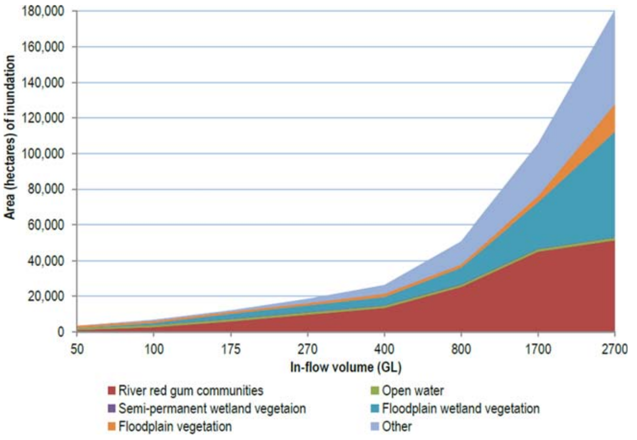

Figure 2. Ecological habitat and inundation zone frequencies (source: *MDBA* [2012a]).

storage in equation (4): irrigation and environmental flow demands are still satisfied (from storage) despite the shortfall in outflows from the large headwater dam through changes in river reach storage.

[24] The outflows at the end of the river reach $\left(O_{t,r=river}\right)$ represent the flow into the Lower Murrumbidgee Swamps. This is influenced by environmental releases (ew_t) but also by EWH water trading. The traded water (et_t) can be positive or negative according to whether environmental water is purchased or sold. It is subtracted from water released from the dam for the environment and added to water available for irrigation (if environmental water is leased to irrigators et_t is negative) or added to environmental water release and subtracted from irrigation supply (if environmental water is leased from irrigators et_t is positive).

3.2. Ecological Response Model

[25] The environmental value function used in this analysis relates to the idea of a threshold interval between inundations as discussed earlier. The Murray-Darling Basin Authority (MDBA) in its determination of the ecological responses to flow in the Murrumbidgee distinguishes between six inundation zones; each different in predominant ecological composition because of the frequency of inundation that would have occurred prior to significant extractions. For each zone, the MDBA developed estimates of the frequency of inundation that would be required to achieve ecological targets for the zone with a high probability. These frequencies with the area impacted and ecological habitat by inundation zone are shown in Figure 2 and Table 1 [*Murray-Darling Basin Authority* (*MDBA*), 2012a].

[26] The salient point is that flora, fish, and bird habitat and populations can be expected to remain healthy if the inundation frequency is less than or equal to the frequency recommended for each zone (EF_i) in Table 1. When the period since inundation frequency grows beyond the recommended inundation return frequency threshold levels, ecological damage increases at an increasing rate. This is represented with an environmental damage function that grows exponentially with an increasing number of years above the threshold level in equation (7) (Figure 3).

[27] Damage is summed over zones with a weight for each zone (w_j) proportional to the area in the zone (see last column of Table 1 for relevant areas):

$$\sum_{j,t=t,\ t+n} w_j\ exp\left[\left(\frac{eh_{j,t}-EF_j}{EF_j}\right)\right]. \tag{7}$$

[28] The index j denotes the inundation zones in Table 1, where $ei_{j,t}$ is a binary variable, with a value of 1 indicating that flow greater than or equal to the flow level EF_j required to inundate zone j is provided in year t; and $eh_{j,t}$ is a count of years since flow exceeded EF_j.

[29] The variables ($ei_{j,t}$, $eh_{j,t}$) are updated iteratively on an annual time step with equations (8) and (9):

$$ei_{j,t}=0,\quad \ldots if \ldots O_{t,r=river}\geq EF_j. \tag{8}$$

$$eh_{j,t}=ei_{j,t}{}^{*}\left(eh_{j,t-1}+ei_{i,t}\right). \tag{9}$$

[30] Equation (8) compares flow to inundation threshold level for each zone (EF_j) if flow exceeds the threshold for a zone, the binary indicator $\left(ei_{j,t}\right)$ set to zero and is otherwise set to 1, indicating insufficient flow to inundate the zone occurred that year. Equation (9) counts years since an inundation for each zone and resets the count to zero when an inundation occurs.

3.3. Environmental Water Holder Submodel

[31] The EWH has an objective of delivering water in a pattern that minimizes damages from increasing return time since inundation beyond the threshold frequencies in Table 1 associated with a high probability of maintaining good ecological health. The ability to achieve the environmental objective is limited by water available to the EWH. However, the EWH can influence inundation frequencies (EF_j) by trading on the annual lease market. The control variable (et_t) is the level of water leased to or from irrigators, which can take positive or negative values.

Table 1. Murrumbidgee Environmental Flow Objectives

Flow in GL/year to Lower Murrumbidgee Swamps (ER_i)	Desired Return Interval—Years Between Flow Events of This Size (EF_i)	Average Frequency-Proportion of Years That Met Required Ecological Target (%)	Proportion of Years That Flow-Event Occurred Under Baseline Conditions (%)	Impacted Area in hectares
170 GL	1.33	72.5	68	11,718
270 GL	1.4	65	57	6,340
400 GL	1.67	57.5	52	8,164
800 GL	2	45	39	24,401
1,700 GL	4	22.5	18	57,334
2,700 GL	6.67	12.5	9	78,046

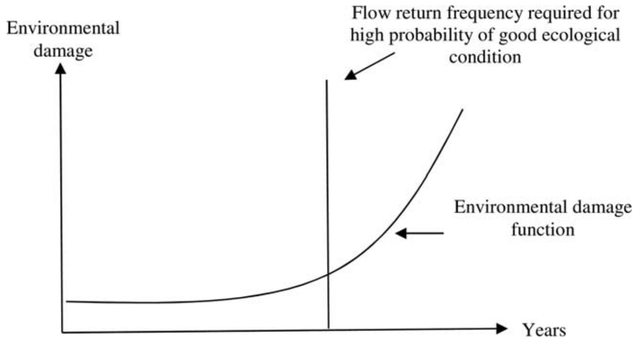

Figure 3. Conceptual representation of environmental damage function.

[32] The EWH begins with an exogenously determined annually varying river outflow ($O_{t,r=river}$) available to the environment as inflow, as explained in equation (6). The EWH then has the ability to lease et_t GL of water to or from irrigators with a maximum lease to irrigators equal to the EWH's available water for that year ($ew_{t.}$). However, the possibility to lease water from irrigators is also constrained by a budget limit, as described later. The EWH's objective is to minimize the exponent of the area weighted sum of differences between actual environmental flow return intervals (eh_i) and the target return intervals, EF_i (equations (11) and (12)). This objective is also mapped over the time horizon to $t + n$ years, where t is the starting year and n is the length in years of the planning interval. The problem takes the form of a dynamic optimization model employing a running horizon algorithm. Running or rolling horizon algorithms have long been used in the operations research literature to model dynamic problems in which agents have imperfect forecasts of future events. *Baker and Peterson* [1979, p. 341] define the algorithm as when "[a] rolling schedule is formed by solving a multiperiod problem and implementing only the first period's decisions; one period later the multiperiod model is updated and the process repeated." See *Chen et al*. [2011] for a recent application in the agricultural economics literature.

[33] Because the model involves discontinuities and nonlinearity, the optimization problem is hard to solve reliably with standard packaged solvers. To overcome this, the key model decision (variable quantity of water to lease to or from irrigators) is discretized and represented as a set of fractional values. These fractional values represent 5% intervals of the full amount of water available for both irrigation and environmental allocation in each year. The multiple-period environmental outcome space (the possible values of the objective function expressed in equation (10)) is fully enumerated for all possible discrete combinations of leasing decisions in $T = 3$ periods. As all possible decisions and outcomes are computed prior to solution, the problem is then one of choosing an optimized combination of possible leasing activities in T periods that achieves the minimum possible value of equation (10). This reduces the model to a simple convex archetype that solves reliably. In the discretization of the model, the index: c {1 ... 20} represents the fraction of total water allocation released to the environment, expressed in discrete 5% increments (i.e., 0.00, 0.05, 0.10, ..., 0.95); i {1, 2 ... 6} indicates the zones targeted for environmental water flows from Table 1; t {1, ..., T} is the year in the hydrological time series where T = 113 in the current simulation; and τ {0, 1, 2} is the index of the 3 year planning horizon.

[34] Note that the τ index is used in combination with the t index, effectively giving a rolling planning horizon of $\tau + t = t,\ t + 1,\ t + 2$. That is, for a given year t, the planning horizon includes the current year and the following 2 years. The outcome of the EWH decision in the current year is deterministic given that allocation levels are announced at the beginning of the period and flows are known when the EWH decides how much to lease to or from irrigators. However, the decision is chosen based on future expectations about allocations and flows for the following 2 years, which are stochastic. It is assumed that the EWH knows the probability distribution of the whole hydrological time series and uses the expected value of the time series for all expected future water flows. Note that this expected value assumption could be updated to allow for a learning algorithm based on an auto-correlation prediction of the time series in future research. We comment on this further in the discussion. The objective function of the EWH is then:

$$min \sum_{t=1}^{T}\sum_{c=1}^{20} ed_{c,t}. \tag{10}$$

where environmental damages ($ed_{c,t}$) are defined as

$$ed_{c,t} = E_t\left[\sum_{\tau=0}^{2}\sum_{i} a_{c,\ t+\tau}\ w_j\ exp\left\{\frac{eh_{i,j,c,t+\tau} - EF_j}{Ej_i}\right\}\ \middle|\ eh_{j,c,t-1}, \mathrm{ew}_{\mathrm{t}}\right]. \tag{11}$$

[35] In this model formulation, the term $a_{c,\ t+\tau}$, a binary choice variable indicating the level of environmental water released in each year of the planning horizon. The EWH must choose one unique environmental water level in each period of the planning horizon:

$$\sum_{c} a_{c,\ t+\tau} = 1. \tag{12}$$

[36] The actions of the EWH are constrained by financial requirements. This means that the EWH must plan to be self-funded over the planning horizon (equation (13)), and any trading profits accumulated over time must not grow too large (in a sense, formalized in equation (14)):

$$\pi_t^e = E_t\left[\sum_{\tau=0}^{2}\sum_{c} a_{c,\ t+\tau}\ WP_{c,t+\tau} * et_{c,\ t+\tau}\ \middle|\ \mathrm{ew}_{\mathrm{t}}\right] \geq 0 \tag{13}$$

where $WP_{c,t+\tau}$ is the expected future water allocation price, and E_t is the period t expectations operator. Equation (13) controls for the requirement that expected profit over the planning horizon must be non-negative, given expected water allocations. The upper bound on accumulated profits is

$$\sum_{n=1}^{t}(1 + int)^{t-1}\pi_n \leq \pi^{Max} \tag{14}$$

where the index $n = 1, \ldots, t$ allows us to sum over the whole history up to time t; *int* equals 0.05 is the interest rate; and π^{Max} equals \$120 million is the maximum revenue accumulation allowable. We choose this level as it allows accumulation of revenues sufficient to make large purchases of 30% to 40% of all available case study catchment allocations. In application, this constrains the EWH from accumulating more than an average annual profit of approximately \$106 million over the 113 year hydrological time series. The realized profit in each year is given by

$$\pi_t = \sum_c a_{c,\ t}\ WP_{c,t}{}^{*}et_{c,\ t+\tau}. \qquad (15)$$

[37] Note that in the above equation, profit realized in any given year is equal to the profit from the first period of the planning horizon ($\tau = 0$) in the expected profit equation (13). The expectation drops out of the equation because the EWH's allocation (ew_t) is known, and hence there is no uncertainty.

3.4. Water Price Model

[38] Water price impacts are modeled with the inverse supply relationship derived from regressing past price on level of allocation in the Murrumbidgee:

$$WP_t = \beta_0 + \beta_1 (iw_t - ew_t - et_t) \qquad (16)$$

where WP_t equates to the historic average annual water allocation price in the Murrumbidgee.

[39] In the regression prediction using equation (16), ew_t and et_t is taken away from irrigation allocation (iw_t) such that greater reallocations to the environment decrease irrigation supply and result in a higher market equilibrium water price. The expected water price over time—and probable future allocation state (p)—is then computed over 10 future allocation states with equal probabilities Pr(p) = 0.1, as follows:

$$E_t[WP_{t+\tau}] = \beta_0 + \beta_1 \left(\sum_{p=1}^{10} \Pr(p) \left(iw_{t+\tau,p} - \left(ew_{t+\tau,p} \; - \; et_{t+\tau,p} \right) \right) \right)$$

$$\forall \tau = 1, 2 \quad (17)$$

where $E_t\,[WP_{t+\tau}]$ is the mathematical expectation of water price in future periods. β_0 and β_1 are 7.092 and −0.0012, respectively, and equate to the coefficients obtained from regressing historical allocation level on water allocation prices for the period 1999 to 2008. The regression multiple *r*-square is 0.85 and the results, including predicted annual water allocation prices from the regression, are presented graphically (Figure 4). While, this econometric water price model is very simple, it is used because our tests of alternative specifications, for example including rainfall terms, did not provide greater explanatory power.

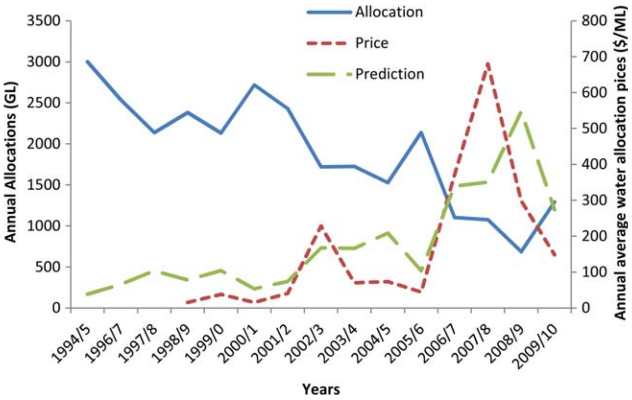

Figure 4. Murrumbidgee water allocation price/allocation levels regression predictions 1999–2008.

4. Results and Discussion

4.1. The Ecological Impact of More Environmental Water Without Trade

[40] Consider first reallocating 20% of irrigation entitlement to the EWH, without allowing them to trade water. The frames in Figure 5 show desired environmental flow return intervals, that is, the number of years since the area experienced flows at the desired level, as solid lines. The three left hand side frames show the base case prior to reallocation of any irrigation water for environmental flows. The three right hand side frames show the modeled return interval when 20% of irrigation entitlements have been reallocated to the EWH. For both the base case and the 20% reallocation case without trade, modeled return intervals for 800 GL, 1700 GL and 2700 GL flow volumes are then shown as dashed lines. Where the modeled environmental flow return interval (dashed line) rises above the ecological interval/flow goal (solid line), this indicates periods when environmental interval/flow goals would have been less than the level required to maintain ecological health objectives for the Lower Murrumbidgee floodplain. In those instances, the probability of ecological damage increases.

[41] The results show that improvement in ecological outcomes, dependent primarily on flows of less than 800 GL, can be achieved simply through water reallocation. That is, no additional EWH trade is necessary to create inundations on intervals consistent with the EWH objectives for the 800 GL inundation zone. This is evident in the top right hand side frame of Figure 4 where it can be seen that, with a 20% reallocation of water to the environment and no trade, the desired return intervals of 2 years or less for floods of less than 800 GL is never exceeded. This result suggests that the flexibility to trade could allow achievement of inundation goals for this inundation zone with less permanent water allocation; although this possibility is not analyzed in detail. In contrast, the base case shows a significant period at the end of the time series where no floods >800 GL occur for 5 years, which is significantly greater than the desired maximum return interval of 2 years.

[42] As can be seen in the bottom two frames of Figure 5, for the base case there are several periods where the intervals between moderately large (i.e., > 1700 GL) and very large (i.e., > 2700 GL) floods exceed the recommended return interval periods. This is most notable for the Millennium drought at the very end of the modeled hydrology time series, and the Federation drought at the very beginning of the time series (as circled in Figures 5 and 6).

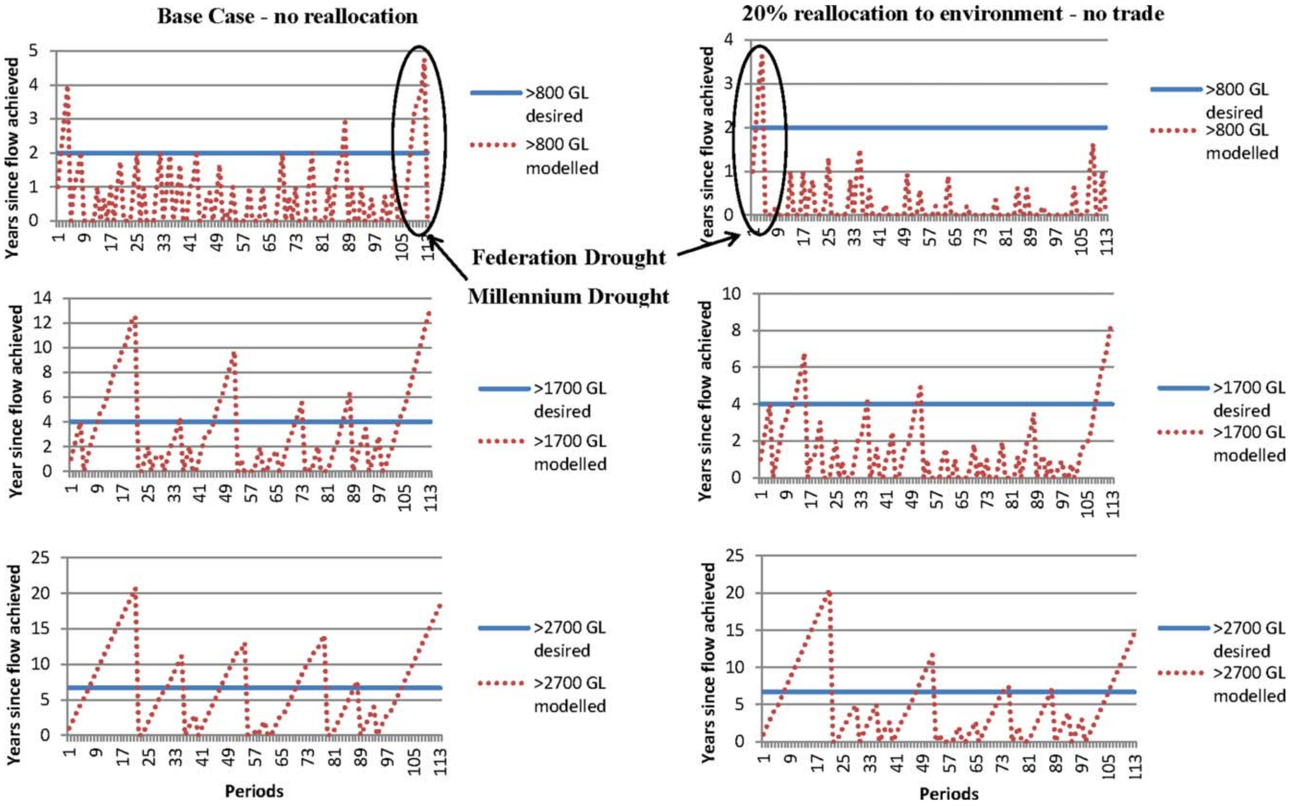

Figure 5. Modeled return period between flows of 800, 1700, and 2700 GL for base case and 20% reallocation of irrigation entitlements to the environment, no trade.

[43] In both frames, the return interval for moderate floods ($\geq$1700 GL) exceeds 12 years. This compares poorly with the 4 year minimum recommended return flow/interval requirement for $\geq$1700 GL flooding necessary to maintain ecosystem health [*MDBA*, 2012a]. Similarly in the base case, modeled intervals between very large flooding events ($\geq$2700 GL) during both the Millennium and Federation droughts are around 20 years. This also compares poorly to the recommended return interval of 6.67 years (Table 1). The impact of a 20% reallocation of water from irrigation to the EWH on frequency of moderately large and very large floods can be seen by comparing the right

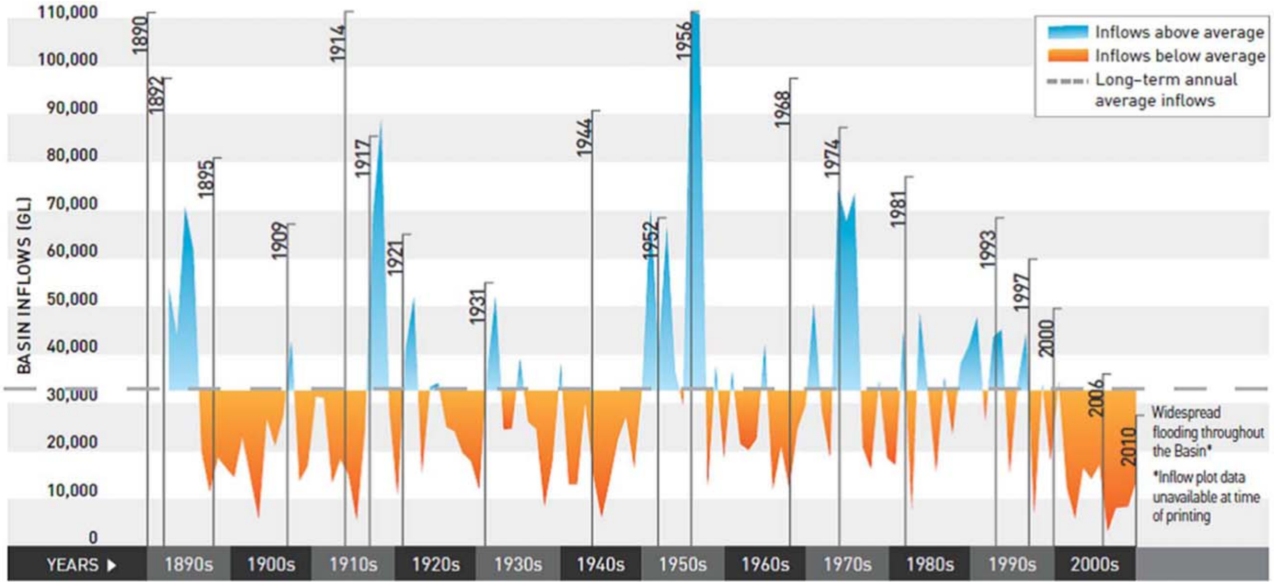

Figure 6. MDB significant flooding and drought events (source: *MDBA* [2012b]).

hand and left hand sides of the plots in Figure 5. Notably, there are fewer of periods of return intervals less than recommended for larger floods. Further, the duration between moderately large and very large flows is reduced when 20% of irrigation entitlements have been reallocated to the EWH. That said, with a 20% reallocation there are several instances of large and moderately large flood return intervals that exceed what would support a high probability of maintaining floodplain ecological health.

[44] We therefore conclude that returning 20% of irrigation allocations to the environment can provide floods of magnitude >800 GL at a frequency sufficient to maintain the ecological health of 18% of the Lower Murrumbidgee Flood and about 47% of Lower Murrumbidgee Floodplain River Redgum area [*MDBA*, 2012a]. However, this action alone does not provide floods >1700 GL with sufficient frequency to maintain habitat reliant on such floods in good ecological health. The most notable periods of return flow intervals in excess of that required for large and very large floods are the Millennium drought at the end of the time series and the Federation drought at the beginning of the series.

4.2. The Benefits of EWH Trade

[45] The results above illustrate that simply reallocating some water to the environment from irrigation is sufficient to meet ecologically desirable flood return interval objectives for smaller and moderate flows ≤800 GL. However, simply reallocating 20% of irrigation entitlement was not estimated to be sufficient to meet recommended return intervals for moderately large and very large floods. Our modeling results provide some evidence that EWH annual water lease trading can improve the frequency of moderately large floods ≥1700 GL (Figure 7).

[46] Under an assumed 20% reallocation of water entitlements to the environment, the top two frames in Figure 7 show how estimated time intervals between floods of this magnitude change when the possibility of EWH trade is introduced. Comparing the top left (without trade) and top right (with trade) frames in Figure 7, it is evident that allowing the EWH to trade can reduce or shorten the incidence of return intervals in excess of the ecologically desirable return period for moderately large floods (i.e., ≥ 1700 GL). The ability to avoid longer than ecologically desirable intervals between moderately large floods, once EWH trade is introduced, is most notable during the Federation drought period at the beginning of the modeled hydrology sequence. Comparing the top left and right frames in Figure 7 shows that the return interval of over 6 years in the 20% reallocation without trade scenario can be reduced below the ecologically recommended interval objective of 4 years. Additionally, a slightly longer than ecologically recommended drought in the mid-1940s is entirely avoided. Finally, the length of time between flows ≥ 1700 GL is reduced by more than 1 year during the Millennium drought from greater than eight to less than 7 years following the introduction of EWH trade.

[47] On the other hand, the introduction of EWH trade appears to offer little opportunity to reduce return intervals between very large floods (i.e., ≥2700 GL). This is evident in Figure 7, where in the bottom left (without trade) and bottom right (with trade) frames the periods of time since a flood ≥2700 GL are nearly identical. Essentially, this indicates that floods of very large magnitude are rare and primarily weather-driven events, not easily manipulated by river management and/or water trade actions available to the EWH. We experimented with the level of reallocation from irrigation to the EWH necessary to achieve floods of

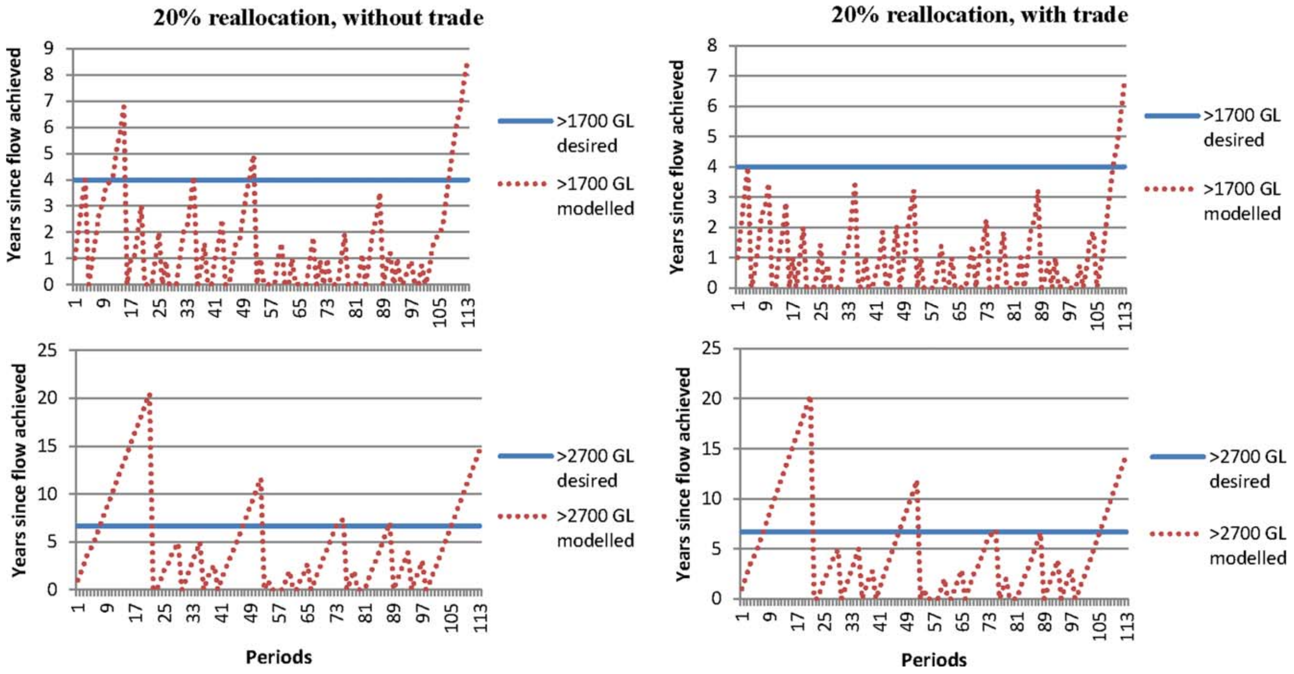

Figure 7. Modeled return period between flows of 1700 and 2700 GL for 20% reallocation of irrigation entitlements to the environment; with and without trade.

magnitude greater than >2700 GL on the frequency required for a high likelihood of good ecological health for habitat dependent on such large flood events and found that achieving these large flood return intervals was only possible with a reallocation of greater than 70% of irrigation water entitlements to the EWH.

[48] It is possible that altering some of the parameters in our modeling specification could improve prospects of achieving very large magnitude floods through EWH trading. Currently, the ability to achieve very large floods is limited in two ways: one is the fund accumulation limit which currently does not allow accumulation of enough money to buy more than about one third of total allocations in any given year; another potential limitation is the 3 year time horizon. A longer time horizon and a higher limit on fund accumulation may allow accumulation of sufficient funds for the kinds of very large water purchases that would be required to facilitate more frequent very large floods. Given that such accumulation would require forfeiting opportunities for smaller floods, trading to achieve more frequent very large floods may also require a greater weighting of larger less frequent floods in the EWH objective.

4.3. EWH Trading Dynamics and Water Price Impacts

[49] Dynamic EWH buying and selling behavior is driven by the model objective function and budget constraints. These, in turn, mimic the incentives and constraints faced by the EWH. As explained in equation (10) and shown in Figure 3, the objective is to minimize environmental damage (expressed as an increasing function of the difference between actual and desirable return intervals between flows of various volumes). As the intervals between floods increase, the incentive to buy water to supplement flows and avoid longer return intervals also increases. On the other hand, funds to buy water must be earned from water sales. Consequently, there is an incentive to sell just after a flood when expected environmental damage from reduced environmental water is minimal, because the probability of exceeding the desired return interval in the near term is relatively low [*Costello*, 2012]. A third motivation for EWH behavior is the non-negative revenue constraint. This, along with the environmental objective, provides an incentive for the EWH to sell at higher prices and buy at lower prices, where possible. Finally, in some years, the EWH must buy water simply to comply with the maximum revenue accumulation constraint, regardless of other environmental or cost considerations.

[50] The potential water price impacts of these somewhat complex EWH trade incentives and constraints is of central interest to irrigators, as it may impact upon water prices and costs of production. Figures 8 and 9 provide a summary of water leasing and water allocation price outcomes. Figure 8 illustrates how additional demand or supply from EWH leasing influences water allocation price. EWH leasing from irrigators drives up the price, while EWH leasing to irrigators drives the price downward in accord with the endogenous water allocation price relation included in the model as outlined by equation (16). It can be seen that, while in some years the impact results in higher water allocation prices, in other years it is lower. Overall a pattern of correlation between price impact direction and water scarcity (e.g., a tendency to bid up price in water scarce years) is not clearly evident.

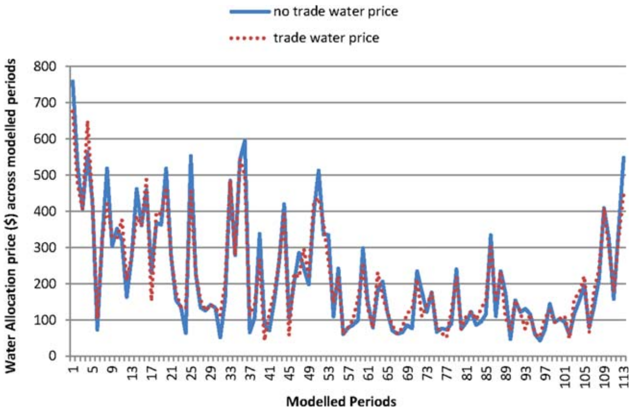

Figure 8. Expected water allocation price with and without environmental water trade.

[51] On average, we estimate a negligibly lower price for water allocations across years in the with trade scenario ($217.70) than in the without trade scenario ($218.30).We conclude that, at least for the modeled conditions, EWH trading behavior may have little influence on water allocation price on average. That is, we find essentially symmetric bidding up and bidding down effects from EWH supply and demand decisions (Figure 9). Despite little influence on average price, EWH trading appears to have potential to moderate water price volatility somewhat; estimated variance in water price in the trading scenario was about 20% less than in the no trade scenario. The model does predict a significant water allocation price rise from $153/ML to $218/ML on average as a result of relative scarcity induced by a 20% water reallocation from irrigators to the environment.

[52] An additional summary of modeled EWH trade outcomes is provided in Figure 10. The chart illustrates that yearly leasing from irrigators occurs more frequently than yearly leasing to irrigators. Notably, the average price for

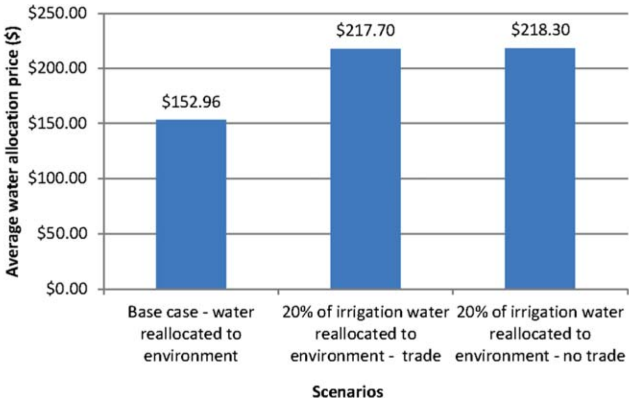

Figure 9. Average water allocation price impact of 20% reallocation and EWH trade.

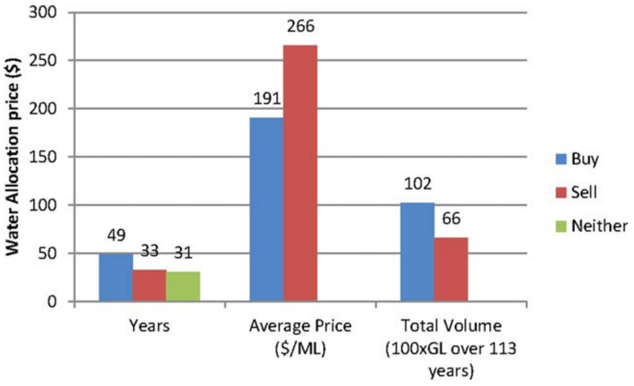

Figure 10. Summary of EWH water trading outcomes.

leasing to irrigators ($266/ML) is somewhat higher than the average price for leasing from irrigators ($191/ML), and the total volume leased from irrigators over the entire hydrology sequence somewhat exceeds the total volume leased to irrigators. This result, essentially demonstrates some tendency to "buy low and sell high." The result is somewhat consistent with *Kirby et al*. [2006], suggesting such behavior could be an advantageous strategy to improve the cost-effectiveness of achieving environmental watering objectives. However, the extent of opportunity for such an approach appears to be more limited with this model specification than was the case in the *Kirby et al.* [2006] model. This may be a result of: the endogenous price impacts included here, but not in their study; somewhat more explicit and temporally dependent environmental objectives included in the current model specification; and greater geographic scope or opportunity for carryover included in their analysis.

4.4. Caveats to the Study Findings

[53] Before concluding this section, it should be noted that there are several limitations and opportunities to extend the analysis presented here. First, results are for a single catchment, and the conditions in other catchments may afford more or less opportunity for ecological benefit from EWH trading.

[54] Second, we have not considered the opportunity for irrigators to learn about EWH trading behavior, nor the impact within a water season of EWH trading behavior. Evidence from the water market suggests that irrigators quickly learn about, and take advantage of strategic opportunities to benefit from trade. For example, the recent introduction of more advantageous carryover provisions in some states appears to have led to large trade into Victoria to hold water where more carryover is possible [*NWC*, 2012]. Irrigators may also learn about EWH trade objectives and identify opportunities to command higher prices. This could reduce the potential ecological benefits of environmental water trading [*Iftekhar et al.,* 2013]. Third, in addition to trade, the CEWH will have some opportunity to carryover water. Regulating legislation essentially requires prioritization of carryover ahead of trade. This may provide some ecological benefit with an approach that reduces additional benefits from trade. Finally, we have not explored opportunities to sell permanent water entitlements or lease out water annually in one catchment where it is less essential for ecological outcomes with an objective of financing purchase or lease of more entitlement in locations where it is more critical to meeting or maintaining environmental health.

5. Conclusions

[55] This study models possible ecological and economic impacts of returning water from irrigation to an EWH. Additionally, we model the possible impacts of providing an EWH the flexibility to trade water allocations on an annual basis. Specification of the EWH's objectives and constraints were chosen to reflect actual conditions faced by Australia's MDB CEWH, who is tasked with using MDB held environmental water for maintaining and improving environmental outcomes. We modeled one catchment, the Murrumbidgee, and a 20% reallocation of water from irrigation to the environmental water holder. For the conditions and location considered, we found that desired frequencies of relatively small floods ($\leq$800 GL), as expressed in the latest MDBA assessment of desired ecological flow regimes for the Lower Murrumbidgee Floodplains, could be achieved simply by a 20% water reallocation from irrigation to the EWH; whether or not opportunity for EWH trade exists. We also found negligibly opportunities to influence frequency of very large floods ($\geq$2700 GL) by allowing EWH trade. Massive and infrequent flooding events are essentially "acts of God," and of such large volumes that they overwhelm storages and opportunities for environmental water holder manipulation.

[56] In contrast, we found that allowing EWH to trade water annually may provide some opportunity to reduce the time between floods of moderately large magnitude (i.e., $\geq$1700 GL for the Murrumbidgee). More specifically, in the case of a 20% reallocation without the capacity to trade, we estimated that two significant drought events with significantly greater than the desired return interval for such floods would occur. Introducing the possibility for EWH water trade provided an opportunity to eliminate one of these events. Such action could have positive ecological impacts for significant River Redgum communities in the moderate to higher elevation Lower Murrumbidgee Floodplains.

[57] A concern for some irrigators may be that a trading EWH, as the single largest water holder in the MDB, may create pecuniary externalities, for example, by bidding up water allocation prices faced by irrigators also seeking to lease in additional water in times of scarcity. Results did show that those who do not trade with the EWH but wish to lease from other irrigators in the same years as the EWH chooses to trade, can face higher water lease costs than they would otherwise. However, the magnitude of such pecuniary externalities arising from trading consistent with provisions in the legislation regulating the CEWH were found to be small on average and were as likely to influence irrigators' returns positively as negatively.

[58] In summary, we find that there are opportunities for significant environmental benefits, and that pecuniary externalities are unlikely to create efficiency losses or even very large redistribution impacts; we conclude that the benefits of developing EWH trading may well justify the costs.

[59] **Acknowledgments.** This research was funded by the CSIRO Water for a Healthy Country research initiative, and a National Climate Change Adaptation Research Facility grant SD 116.

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