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Possible negative feedbacks from 'gold-plating' irrigation infrastructure

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ABSTRACT

For an irrigator, investments in on-farm water infrastructure that increase the marginal productivity of water may improve use efficiency. However, increasing on-farm water use efficiency invariably diminishes return flows, compromising the ability to maintain sufficient water flows in streams to support natural environmental values, particularly in dry states of nature. As climate change can increase the probability of dry states, modelling that does not incorporate state-contingent treatments of uncertainty may misrepresent the benefits of public investment on irrigation infrastructure improvements to recover environmental water flows. This paper uses a state-contingent modelling approach to review an extended farm capital investment policy in Australia's Murray–Darling Basin. We examine technical efficiency gain implications for irrigation and environmental water managers under alternative states of inflow variability and the role that increasing climatic uncertainty has on policy objectives. Results suggest that the incentives provided to recover environment water via on-farm capital investments could have two principal negative feedbacks given future uncertainties. First, farm capital investments may encourage inflexible production systems that fail to respond to future water scarcity, exposing that investment to increased risk. Second, technical efficiency gains may reduce return flows, creating perverse policy outcomes aligned with meeting environmental objectives. Highlighting these ulterior policy outcomes provides irrigators and policy makers the capacity to adapt and develop flexible arrangements, robust policy, and management solutions that help negate future uncertainty.

1. Introduction

By 2050, up to 3.9 billion people globally are expected to reside within river basins affected by severe water stress and supply scarcity (OECD, 2012). Scarcity drives change, and consequently agricultural water within many of these basins has been targeted for reallocation to achieve multiple water use objectives (Saleth et al., 2011). Sustainable water use that maintains both agricultural production and the biophysical environment involves a complex trade-off between economic, social-cultural and ecological systems (Chiesura and de Groot, 2003). One such example of complex economic, social and ecological water demand trade-offs can be found in Australia's Murray–Darling Basin (MDB) (Fig. 1). This trade-off relationship has motivated an implementation of costly and contentious intervention strategies to reallocate water from economic (e.g. irrigated agriculture) to ecological (e.g. basin river flow) and social uses. Major MDB intervention approaches involve: (i) market purchase of agricultural water rights through an AUD$3.1 billion programme known as *Restoring the Balance (RtB)*; and (ii) off-farm storage/delivery infrastructure upgrades and on-farm irrigation technical efficiency improvements through an AUD$5.8 billion programme known as *Sustainable Rural Water Use and Infrastructure (SRWUI)* (Crase and O'Keefe, 2009).[1] A target reallocation figure of 2750 GL from these intervention programmes by 2019 was established through a Basin-wide Plan, inclusive of a minimum 650 GL/pa total flow to the River Murray mouth at the Coorong (MDBA, 2012).[2] Recently, a further AUD$1.7 billion was committed to purchasing additional water rights and addressing water delivery constraints in the MDB (DSEWPC, 2013). Consequently, reallocation targets for environmental outcomes have increased by 450–3200 GL and the completion timeframe by five years to 2024.

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[1] For the purposes of this paper, we apply a definition of water use efficiency consistent with Perry (2011), which differentiates between total water use efficiency (i.e. production yield per unit of *total* water used) and irrigation water use efficiency (i.e. production yield per *unit* of irrigation water applied). Herein, the concept of technical efficiency is consistent with the total water use efficiency definition above.

[2] The Coorong, located near the mouth of the River Murray in South Australia, is an iconic National Park and wetland environmental area which has been identified as a key bird-breeding and species habitat management site in the Basin Plan.

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Fig. 1. The Murray–Darling Basin and its hydrological catchments.

These intervention programmes constitute a transfer of public funds to purchase water from irrigators and subsidized capital payments to upgrade infrastructure owned by both on-farm and off-farm operators. Of the two intervention programmes, *SRWUI* represents the larger proportion of funding commitment (68%). However, water reallocation from this programme may be limited to 40% of the 3200 GL target if historic MDB water saving outcomes can be maintained.[3] As previous policy has divided water savings equally between irrigation and environmental uses, the total water reallocation from infrastructure projects may be as low as 20% of environmental needs. Further, climate change is predicted to reduce MDB surface water availability between 9% (northern MDB) and 13% (southern MDB) under the median 2030 scenario (CSIRO, 2008). If accurate, this has important implications for future water saving outcomes from any executed *SRWUI* projects between now and 2024. Finally, the MDB experiences high seasonal variability in surface water runoff into storage and delivery systems (Connor et al., 2012), which must factor into environmental managers' capacity to deliver environmental objectives across a temporal scale. The uncertainties related to the *SRWUI* program include water returned from capital works, future climate change impacts and MDB seasonal inflow variability; all of which require flexible water management arrangements to achieve the Basin Plan objectives. The Basin Plan environmental flow objectives include providing habitat refugia or rejuvenation, sediment or nutrient flushing from the system, and ephemeral connections between spatially diverse species populations while maintaining low levels of salinity (Connor et al., 2013). Investing in fixed capital projects across the MDB may therefore be inconsistent with a flexible management approach to counter the inherent variability and uncertainty associated with future flow patterns.

The size of the budget allocated to the Basin Plan requires careful scrutiny to ensure value from such public expenditure, and to prevent the intervention being perceived as a public to private wealth transfer. To examine this issue, this paper reviews the *SRWUI* program objectives and models technical efficiency gain implications for agricultural water users and the environment under

[3] The Living Murray (TLM) programme invested AUD$1 billion in market purchase and (predominantly) infrastructure upgrade projects between 2004 and 2009 to generate 225 GL of water savings from technical efficiency improvements (MDBA, 2009). These savings were divided equally between agricultural, environmental and urban uses (Quiggin, 2011). With no discount factor—an unlikely outcome given an expected diminishing availability of suitable infrastructure investment projects over time (Crase and O'Keefe, 2009)—a further AUD$6 billion investment could generate $\sim 6 \times 225 = 1350$ GL water savings; or 40% of the reallocation objective. Water recovered via TLM does not contribute in any way towards meeting the current Basin Plan targets.

assumptions of increasing future water supply uncertainty. The technical efficiency gain implications are demonstrated using a modified version of the state-contingent MDB model developed by Adamson et al. (2009), which highlights differences between variability and climate change within the basin and allows for proactive water user responses to environmental stimuli. Qureshi et al. (2010) provide a useful base examination of the interaction between MDB intervention approaches and return flow outcomes. This paper expands that study in three ways. First, a full-Basin model is optimized rather than focusing on a single-catchment example. Second, while the two studies share similar state of nature constraints this study considers future risk and adaptation to both climate change and extended drought conditions. Third, where Qureshi et al. concentrate on return flow impacts from intervention this paper assesses capital works contributions towards achieving MDB Plan objectives (environmental, social and economic) to determine the net economic return from incentivized capital investments. Results suggest that increasing farm technical efficiency via capital investment may encourage production systems with reduced adaptive capacity to future water scarcity, thus exposing prevailing irrigation capital to unacceptable risk. Further, the modelling suggests that rather than freeing water for environmental use, the proposed technical efficiency investment creates second-best options for the MDB environment if changes to return flow are ignored. Finally, during climate change or drought-induced water scarcity this approach results in significant reductions in the water supply available to achieve environmental, social and economic outcomes across the MDB.

The remainder of this paper outlines: general issues associated with technical efficiency improvement in the MDB; the modified state-contingent MDB model and its application in this context; results from the modelling process; and implications for water managers. We conclude that federal basin water managers at multiple governance scales should avoid reallocation policy options that reduce the flexibility of managers to respond to the inherent variability and uncertainty associated with their systems.

2. Technical efficiency issues

The reallocation of water resources to the environment via investment in on-farm capital is based on an assumption of technical efficiency gains. In this paper, technical efficiency is expressed as both a reduction in the total volume of water required to produce (at least) similar original technology outputs, and a reduction in the rate of return flows (Cummins and Watson, 2012). Irrigation water is applied to support plant growth and yield. The difference between applied water and plant uptake (return flow) contributes water to the hydrological system from irrigation runoff, seepage or evaporation, and provide a basis for a variety of downstream water rights (Nieuwoudt and Armitage, 2004). Thus, more efficient water use may result in reduced irrigation water use as well as less 'excess' water availability as return flows to the hydrological system (Grafton and Hussey, 2007; Wu et al., 2014). Negative impacts from reduced return flows include less surface water runoff and groundwater recharge (Young, 2010), water quality impacts from increased pollutants (e.g. salt or phosphate) or turbidity (Grafton and Hussey, 2007), and magnified consumptive irrigation use (Connell and Grafton, 2008) reducing total water for the environment. Extended drought, drainage collection improvements and altered on-farm water use practices have reduced MDB return flows since the early 1990s (URS Australia Pty Ltd., 2010). Return flow reductions from changed water use practices to manage variable water supply conditions under climate change are also reported by Connor et al. (2012).

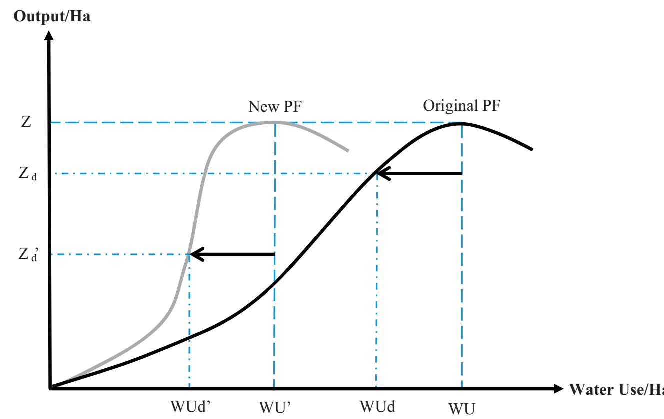

Fig. 2. Capital transformation and inflexibility.

The technical efficiency impacts explored herein are best highlighted through example. Fig. 2 illustrates expected perennial crop water use changes following subsidized capital investments. The original production function generated an output per hectare (Z) from water use WU. With farm capital investment the new production function generates the same Z from a reduced water volume (WU'). For simplicity, input quantities are held fixed. Under drought (climate change) conditions the available water will decrease proportionally for each production function to WUd/WUd' such that the reduction is equivalent ($WU - WUd = WU' - WUd'$). Farm output also falls from Z to Zd/Zd', where $Zd' < Zd$.

During drought supply conditions we assume all saved water from capital transformation has been applied to higher value perennial horticulture production, resulting in an increased capital level exposure to risk than in the original production function context. Further, where the capital transformation has not increased water supply security, or where the water savings are not used to improve flexibility in farm risk management, then subsequent droughts will result in additional negative capital returns (e.g. the perennial crop asset may be lost). Young et al. (2002) suggest that, over 20 years, water efficiency savings following capital transformation could reduce net (return) flows by as much as 723 GL per annum—or 23% of reallocation objectives under the 3200 GL target. Climate change could further impact on return flows in the southern MDB. Quantifying the impacts of changes to land and water use, and the subsequent return flow implications under inherent basin water supply uncertainties, motivates our application of a modified state-contingent model.

3. Model methodology and data

Thorough decision making needs to consider how risk and uncertainty impact on choices. The MDB water resource allocation literature abounds with modelling studies (e.g. Grafton et al., 2011; Qureshi et al., 2010) where risk and uncertainty is encapsulated within an expected value framework using error terms to provide a stochastic representation of outcomes. This approach dominates the literature despite its recognized ability to provide "inefficient and biased results" (Just and Pope, 1978, pg. 67), as the decision-maker is modelled to be passive towards environmental signals and always engages in the same response. The state-contingent approach tackles the allocation of resources differently. By representing uncertain outcomes as a set of mutually exclusive states of nature (i.e. droughts, floods and normal) with a probability of occurrence, uncertainty can then be treated in a manner similar to certainty. Further, in the state-contingent approach decision makers are modelled to adapt their responses to environmental signals by allocating resources between alternative management responses (Chambers and Quiggin, 2000).

This paper utilizes an adapted and updated version the Risk and Sustainable Management Group MDB Model (RSMG model), which applies the state-contingent approach to risk and uncertainty. The model is described in Adamson et al. (2007, 2009) and the assumption and datasets used are documented in RSMG (2010). This model provided analysis during the development of the Murray–Darling Basin Plan (Adamson et al., 2011; Mallawaarachchi et al., 2010), and its use in this analysis allows for comparison with other public documentation. The model documentation also notes limitations to the state-contingent modelling approach. The RSMG model is a bio-economic representation that tracks the interaction of conjunctive water, its use and salinity outcomes along the entire basin. The model optimizes resource allocation subject to stipulated settings including, but not limited to: climate change impacts on water supply; total conjunctive water use; trade rules; salinity mitigation schemes; flow rules; water price; environmental and salinity targets; and alternative irrigation technology settings.

The following sections describe how the RSMG model has been modified to examine the implications from subsidizing capital via the *SRWUI* and the impacts that increased water efficiency may have on achieving identified ecological and social goals from the new water use settings. This paper evaluates the effectiveness of the *SRWUI* program to achieve its goals by comparing it to the Base solution. The Base solution assumes that water use is constrained to the sustainable diversion limits (SDL) defined in the Basin Plan (see Table 1). To simplify the discussion further, no compensation is paid to obtain this water. The impact that a changing climate may have on the *SRWUI* is examined in two contrasting approaches discussed below. Complete data sets and results applicable to this paper can be obtained from the corresponding author.

First, the RSMG Base solution model was adapted to incorporate the *SRWUI* programme. For this paper the model is solved from the national good perspective, where a single individual can allocate all resources throughout the Basin to achieve a maximum possible return (Eq. (1)) subject to a set of constraints (Eqs. (5)–(10)) (Table 2).

$$MaxE[Y] = \sum_{K}\sum_{s\in\Omega}\pi_s(R_{s,k} - C_{s,k}) \quad (1)$$

Where:

$$\text{Revenue}: \quad r_{s,k} = z_{s,k}p_{s,k} \quad (2)$$

$$\text{Costs} \quad c_{s,k} = a'_{s,k}x_{s,k} \quad (3)$$

$$\text{Output} \quad z_{s,k} = f(x_k) \quad (4)$$

Subject to:

$$b_{s,k}x_{s,k} \le B_{s,k} \quad (5)$$

$$x_s \ge 0 \quad (6)$$

$$w_{s,k} \le wf_{s,k} \quad (7)$$

Table 1
Net reduction in extractions, by trade zone.

K	Catchment (*k*) Name	Surface diversion limits		Water already returned	Water from capital investment
		Current	Proposed		
1	Condamine	586.8	526.8	16.8	
2	Border Rivers QLD	404.0	396.0	5.0	
3	Warrego Paroo	168.9	159.9	9.0	
4	Namoi	508.0	498.0	10.0	
5	Central West	734.0	669.0	65.0	
6	Maranoa Balonne	391.2	351.2	11.2	
7	Border Rivers Gwydir	753.0	704.0	5.0	
8	Western	198.0	192.0	0.0	
9	Lachlan	618.0	553.0	*65.0*	
10	Murrumbidgee	2553.5	2233.5	173.0	
11	North East	329.9	297.0	32.9	
12	Murray 1	54.4	46.5	7.9	
13	Goulburn Broken	1915.7	1546.4	369.3	
14	Murray 2	906.0	775.0	131.0	
15	North Central	1441.6	1247.1	194.5	
16	Murray 3	815.4	697.5	117.9	
17	Mallee	204.8	174.5	30.4	
18	Lower Murray Darling	96.7	83.5	13.2	
19	SA MDB	459.0	358.0	101.0	
20	Adelaide	206.0	206.0		
21	Coorong				
	Total	13344.9	11714.9	1358.0	
Reduction in surface extractions (*A*)			1630.0		
Other adjustments zone					
Northern (*k* = 1–8)			143.0		
Southern VIC (k = 11, 13, 15, 17)			425.3		425.3
Southern NSW (inc ACT) (*k* = 10, 12, 14, 16, 18)			462.9		462.9
Southern SA (*k* = 19)			82.8		82.8
All Southern (k = 10–19)			450.0		450.0
Total shared reduction (*B*)			1564.0		1421.0
TOTAL reduction in surface flows (*A* + *B*)			3194.0		

Notes differences to Basin Plan are due to:
- Reduction in the SDL to Basin Plan is due to the Wimmera not being modelled.
- Lachlan's propped SDL reduction is 48 GL but already 65 GL has been returned

Source: (MDBA, 2012)

Table 2
Equation symbol definitions (1).

Symbol:	Definition:
$E[Y]$	Expected [Income]
K	Catchments in the Basin (K = 1, . . ., 21)
S	States of nature (S = 1, . . ., 3)
π	Probability of state occurrence
R	Revenue
C	Costs
Z	Output
P	Price per unit of output
x	Vector of activities
a	Vector of input prices (land, fixed costs, variable costs, water)
b	Vector of input requirements (land (l), fixed costs, variable costs, water)
B	Input constraints (land (L), water)
w	Volume of water used derived from $b_{s,k}x_{s,k}$
wf	Volume of water flowing in the catchment
SDL	The total constraint on the water use set by the Basin Plan
σ	Salinity level in EC units

$$\sum_k W\pi_s \leq SDL \tag{8}$$

$$wf_{s,21} \geq 650\,\text{GL} \tag{9}$$

$$\frac{\sigma_{s,20}}{0.64} \leq 800\,EC \tag{10}$$

To represent the *SRWUI* programme the RSMG model had to be modified to examine the policy signals of reducing the cost of capital, the change in water use and associated variable costs, and the impacts of increasing water use efficiency by manipulating the volume of water returning to the river system after irrigation use. The following assumptions have been made for the *SRWUI* programme. Only 50% of the water efficiency gained from capital expenditure is transferred to the environment. A total budget of AUD$7.6 billion exists (MDBA, 2012) to recover 971 GL and the programme only occurs in the southern Basin.[4] This then provides an annuity per ML of AUD$367 at 7% over a 20 year period. By assuming that capital is subsidized by the total volume of water returned to the environment per hectare the reduced capital by commodity by catchment is determined. The reduction in variable costs is determined by the total water efficiency gain multiplied by the price of water.

3.1. Production systems

The model has 23 state-contingent production systems. These include: 21 choices in irrigated production activities; a dryland production activity; and water to be diverted for Adelaide, as illustrated by the first column in Table 3. These production systems are derived from a set of commodities (M = 1, . . ., 17). The transformation of commodities to state-contingent production systems occurs by mixing and matching commodities, transitioning commodities between dryland and irrigated activities, altering inputs and outputs, and switching between two technology settings (low and high). Low technology can be illustrated by furrow or overhead irrigation production systems. High technology may comprise drip or trickle-tape irrigated production systems. Columns 2, 3 and 4 illustrate how managers can alter commodity selection by states of nature. As illustrated, once a perennial crop (e.g. grapes) is selected, that commodity must always be produced in each state of nature.

The manager's response for perennials in alternative states is to alter inputs b to produce alternative outputs Z. For modelling the *SRWUI* program, x increases to 30 commodities by modifying production systems (x = 1, . . ., 7) to illustrate changes to vectors a and b (as per Table 4).

Due to a lack of data it was assumed that the new capital intensive horticultural crops would experience a net reduction in water use of 20–30% depending on their existing technology settings. Importantly, some state-contingent annual cropping systems include multiple crop rotations and limits on output consistent with production systems.

The total land L constraint in B is derived by increasing the area reported as irrigated in 2001 (ABS, 2004). This version of the model allows for total area to increase by 50%, with the exception of *k1*, *k6* and *k11* where the total area dedicated to irrigation has been allowed to increase by 150%, 200% and 100% respectively to bring data into line with known capacities. To prevent unrealistic expansion of horticultural commodities (x = 1, . . ., 7) in the Base model, the area reported to be under horticulture in the above data set is constrained to only increase by 50%. This then prevents horticulture dominating the landscape in the Base model in accord with assumed capital constraints. This separation also allows for the model to treat the expansion in perennial and broad acre production separately. Any land not allocated to an irrigation activity then transitions to R_{23} (i.e. dryland production). However, this constraint was relaxed in the *SRWUI* runs to deliberately illustrate perverse policy outcomes where subsidized capital could alter investment patterns.

Unlike the previous model versions, the constraints concerning operator labour have been relaxed on the assumption that labour would enter the market to take advantage of opportunities. This then helps illustrate the story of horticultural expansion in the southern Basin.

3.2. Interaction between water and salinity

The Basin is modelled as a directed flow network across 21 catchments. Conjunctive exogenous water resources θ include surface flows, groundwater extractions and net inter-basin transfers. However, due to complexities with the Basin Plan, groundwater resources are not examined in this model. The states of nature are defined by a proportional change to the normal state's θ, where the drought state is 0.6θ and the wet state is 1.2θ. The model assumes that the probability of a drought, normal and wet states is 0.2, 0.5, and 0.3 respectively. The flow leaving each catchment $wf_{k,s}$ is derived from Eq. (11). Here, the flow is determined by the impact that conveyance losses wc have on water resources and include the net water used from irrigation less the water return flows wr from its use

$$wf_{k,s} = (\theta_{k,s} \cdot wc_{k,s}) - (w_{ks} - wr_{k,s}) \tag{11}$$

For each production system $x_{k,s}$, a defined water use and reflow variable by technology option exists. This provides the capacity to model the *SRWUI* and the impacts of the spatial location of investment. Water quality is simplified to reflect salinity σ (see Eq. (12)) as it is a binding policy constraint to ensure that the Basin Plan's requirement for the City of Adelaide's water quality is achieved (Eq. (10)). Herein, σ is a ratio of the salt load G and f where:

$$\sigma_{k,s} = \frac{G_{k,s}}{wf_{k,s}} \tag{12}$$

$G_{k,s}$ is a combination of the naturally mobilized exogenous tonnes of salt that enters with θ_{ks}, less the exogenous tonnes of salt removed via the salinity mitigation programme, plus the endogenous salt transported with reflow determined by $\theta_s w_{ks}$. Lacking a detailed environmental management approach in the Basin Plan,

[4] The 971 GL figure is based on the volume of water to be sourced from the southern trading zones (New South Wales, Victoria and South Australia) as detailed in Table 1. Other options in regards to the total volume to be obtained from the *SRWUI* were examined, but they violated key constraints and thus have not been reported.

Table 3
The state contingent production system.

x	Production system name	State contingent crop		
		Drought	Normal	Wet
1	Citrus-H	Citrus-H	Citrus-H	Citrus-H
2	Citrus-L	Citrus-L	Citrus-L	Citrus-L
3	Grapes	Grapes	Grapes	Grapes
4	Stone Fruit-H	Stone Fruit-H	Stone Fruit-H	Stone Fruit-H
5	Stone Fruit-L	Stone Fruit-L	Stone Fruit-L	Stone Fruit-L
6	Pome Fruit	Pome Fruit	Pome Fruit	Pome Fruit
7	Vegetables	Melons	Vegetables	Fresh Tomatoes
8	Cotton Flex	Dryland Cotton	Cotton Flex	Cotton Flex
9	Cotton Fixed	Cotton Fixed	Cotton Fixed	Cotton Fixed
10	Cotton/Chickpea	Chickpea	Cotton Flex	Cotton Flex
11	Cotton Wet	Dryland Cotton	Dryland Cotton	Cotton Flex
12	Rice PSN	Rice PSD	Rice PSN	Rice PSW
13	Rice Flex	Dryland Wheat	Rice PSN	Rice PSW
14	Rice Wet	Dryland Wheat	Dryland Wheat	Rice PSW
15	Wheat	Wheat	Wheat	Wheat
16	Wheat Legume	Wheat Legume Dry	Wheat Legume	Wheat Legume Wet
17	Sorghum	Sorghum	Sorghum	Sorghum
18	Oilseeds	Oilseeds	Oilseeds	Oilseeds
19	Sheep Wheat	Sheep Wheat Dry	Sheep Wheat	Sheep Wheat Wet
20	Dairy-H	Dairy-H	Dairy-H	Dairy-H
21	Dairy-L	Dairy-L	Dairy-L	Dairy-L
22	Dryland	Dryland	Dryland	Dryland
23	Adelaide Water	Urban Water	Urban Water	Urban Water

Table 4
How capital investment has been modelled to influence water use, return flow rates and subsidized capital expenditure in the Murrumbidgee only.

x	Production system name	Reduction water requirements			Return flow rates			Reduction in capital
		Drought	Normal	Wet	Drought	Normal	Wet	
24	Citrus-H	2.3	2.3	2.7	0.05	0.15	0.15	\$828
25	Citrus-L	2.0	2.0	2.4	0.05	0.15	0.15	\$736
26	Grapes	1.8	1.8	2.2	0.05	0.15	0.15	\$677
27	Stone Fruit-H	0.9	0.9	1.1	0.05	0.15	0.15	\$331
28	Stone Fruit-L	1.3	1.3	1.5	0.05	0.15	0.15	\$474
29	Pome Fruit	2.1	2.1	2.5	0.05	0.15	0.15	\$773
30	Vegetables	0.0	2.5	1.8	0.05	0.15	0.15	\$904

Note: Half of the water reduction is estimated to go to the environment by state of nature
The reduction in water costs is reflected in the changes to variable costs under constant \$/ML

Eq. (9) provides the only environmental target for this model.[5] This ensures that 650 GL of water arrives to the Coorong in all states of nature.

3.3. *The Basin Plan and capital infrastructure*

Water used for irrigation is constrained by $wf_{k,s}$ (Eq. (7)) and the Basin Plan's exogenous sustainable diversion limits (Eq. (8)). However, to model the Basin Plan, Eq. (8) has to be transformed into Eqs. (13)–(17). The Plan stipulates both a reduction by k and a defined volume to be sourced from within interconnected or state-based trading regions (Table 1). Of the two unconnected systems, only the Lachlan ($k=9$) is included within our modified model. Within the identified trading zones the Base model assumes free trade to obtain water at least-cost for the environment. The model assumes that all water diverted for irrigation is used on farm and does not track conveyance losses in built capital infrastructure as the complex nature of the channels, the number of channels and the temporal nature of how water is transported throughout the Basin cannot be represented within the model's coarse hydrological settings. Importantly, this model aims to provide results at a policy and not operational level. To overcome the deficiency in this assumption, please consult the discussion in Section 5.2.

Eqs. (13)–(19) allow irrigation water to be carried over between states of nature by simply requiring water on average to equal the specified SDL. For the *SRWUI* programme Eq. (19) replaces Eqs. (15)–(17) to allow the model to find the best places within the southern-connected MDB to undertake capital works in order to recover 971 GL for the environment (Table 5).

$$\sum w_k \pi_s \le \sum Surface\ SDL_k \tag{13}$$

Table 5
Equation symbol definitions (2).

Symbol:	Definition:
SurfaceSDL	Total volume of surface water allowed for irrigation use
SurfaceSDL	Total volume of ground water allowed for irrigation use
NTS	Water trading zones in the northern catchments ($K=1, \ldots, 8$)
STN	Water trading zones in the southern New South Wales catchments ($K=10,12,14,16,18$)
STS	Water trading zones in the southern South Australian catchments ($K=19$)
STV	Water trading zones in the southern Victorian catchments ($K=11, 13, 15, 17$)
STA	Water trading zones in all southern catchments ($K=10, \ldots, 19$)
CTZ	Water from capital program in southern trading zones ($K=10, \ldots, 19$)

[5] Since this paper was submitted, greater detail concerning environmental targets has been released. However, these do not alter the overall outcomes from out analysis or the basic findings of the paper.

Table 6
Summary of model assumptions.

Model	Intervention	Return flow (%)	State probability	Climate assumption
Base	Full trade	100	(0.5,0.2,0.3)	Current
WRF-100	Capital works	100	(0.5,0.2,0.3)	Current
WRF-50 *ex-ante*	Capital works	50	(0.5,0.2,0.3)	Current
WRF-50 *ex-post*	Capital works	50	(0.5,0.2,0.3)	Current
2050 CC scenario	Capital works	50	(0.5,0.2,0.3)	450 GL average, 2050
2100 CC scenario	Capital works	50	(0.5,0.2,0.3)	450 GL average, 2100
Droughts	Capital works	50	(0.5,0.3,0.2)	Current

Table 7
Summary of model outcomes.

Model	Normal water use (GL)	Normal Coorong flows (GL)	*Drought Coorong flows (GL)*	Normal salinity (EC)	Normal $ returns ($million)	Area under production ('000 Ha)	Annual Capital Repayments ($'m)
Base	10,127	5546	*1164*	282	$2436	1800	$1674
WRF-100	10,120	5565	*867*	243	$7762	1269	$5755
WRF-50 (*ex-ante*)		4841	*582*	277			
WRF-50 (*ex-post*)	10,133	4832	*650*	280	$7763	1269	$5756
2050 CC scenario		2524	*0*	474			
2100 CC scenario		2374	*0*	497			
Droughts	11,365	3894	*650*	353	$8336	1348	$6109

Note: Full outcome sets were not always calculated for each model where they involved minor alterations to previous runs (e.g. 2050 CC scenario effects based on WRF-50 ex post). This accounts for any missing values above.

$$\sum w^{NTV}\pi_s \leq 143\,\text{GL} \quad (14)$$

$$\sum w^{STV}\pi_s \leq 425.3\,\text{GL} \quad (15)$$

$$\sum w^{STN}\pi_s \leq 462.9\,\text{GL} \quad (16)$$

$$\sum w^{STS}\pi_s \leq 82.8\,\text{GL} \quad (17)$$

$$\sum w^{STA}\pi_s \leq 450\,\text{GL} \quad (18)$$

$$\sum w^{CTZ}\pi_s = 971\,\text{GL} \quad (19)$$

3.4. Water resources and climate change

The data concerning the impact on water resources under a changing climate were obtained while providing input into the 2008 Garnaut Climate Change Review (Garnaut, 2008). Quiggin et al. (2010, 2008) describe the data and the assumptions for converting climate variables into changes in runoff to re-parameterize θ. From the Quiggin et al. (2008) review, the best-case climate change scenario (450 Average) was chosen to make this paper comparable with other published material. This is described as the strong mitigation scenario, in which CO_2 equivalents are stabilized at 450 ppm by 2100. At this level, mean global temperature is expected to increase by ~1.5 °C. This scenario uses 50th percentile projections for rainfall, relative humidity and surface temperature across Australia. This paper examines the impact on water resources in two time periods: 2050 and 2100; which equates to approximately an average decline in water resources of 10% and 20%, respectively.

The second approach to modelling climate change is undertaken by changing the frequency of the droughts. In this approach, the data for the Base model where the normal, drought and wet states occur with a frequency of 0.5, 0.2 and 0.3, respectively, are now altered to 0.5, 0.3 and 0.2.

4. Results

Table 6 summarizes the model runs undertaken in this paper. The Base model assumes what would occur if the SDL was achieved by simply trading the water away from irrigators. All other runs examine the *SRWUI* and assume that 971 GL of water must come from water savings via capital works. In the southern trade zones, the base full-trade model converged in all states of nature without violating the imposed water use, flow to Coorong or salinity constraints. Average annual capital investment required to achieve this outcome was $1674 million (Table 7). We then also relaxed strict return flow constraints across these trade zones. This model (WRF-100) optimized, providing a basis for further model comparisons. WRF-100 assumed that return flow rates did not alter in response to capital works investment (i.e. 100% return flows).

The WRF-100 results provided Coorong flows of 867 GL under drought conditions while salinity was maintained at 308 EC, thereby meeting important constraints. By comparison, in the model where it was known that capital works would result in 50% return flow reductions (WRF-50 *ex-post*) constraints were still able to be met. That is, Coorong flows of 650 GL were achieved in drought conditions with a moderate increase in salinity (348 EC), providing a feasible outcome from the capital works program (see italicized Coorong flow volumes in Table 7). In the normal state of nature, agricultural water use remained reasonably consistent between the Base and WRF-100/WRF-50 (*ex-post*) models. However, economic returns increased dramatically (from $2436 to $7760 million) as the subsidization of capital investment transformed the southern Basin towards increased production of citrus and grape perennials. This transformation naturally involved corresponding increases in farm capital exposure to risk under different states of nature. However, to achieve this increased income the annual cost of capital would need to be $5755 million.

In all further models we treated capital investment as a sunk-cost. Interest turned to what may occur during future periods of water scarcity under climate change and/or prolonged drought conditions, similar to those experienced in the MDB between 2000–01 and 2009–10. Climate change impacts on achieving 450 GL average recovery outcomes in the *southern All* trade zone were modelled using MDB scenarios out to 2050 (2050 CC) and 2100 (2100 CC).

Although not optimized, the models showed decreasing return flows in northern Basin catchments in normal and wet states, and large southern Basin catchment return flow reductions in the drought state of nature. In both models, Coorong flows are reduced to zero, and salinity impacts range between 1750 EC (2050 CC) and 2371 EC (2100 CC). This suggests that any early environmental benefits derived from a MDB capital works program could be entirely undone by 2100 under climate change impacts. It also suggests a significant requirement for future MDB structural adjustment under a capital works intervention approach.

An increased frequency of MDB drought states (i.e. the probability of drought increases to 0.3, while wet state probability falls to 0.2) also produced some interesting capital works outcomes. While the model did optimize, meeting the 650 GL Coorong flow and (largely) the salinity constraints, water and land use actually increased across the Basin. Setting return flows at 50% allows an additional 492 GL of water use during the drought states and—as the model seeks to be as flexible as it can be under those constraints—another 79,000 hectares of land use. In this case, southern Basin production mainly transforms towards annual vegetable crops, consistent with expected agricultural water use under drought conditions and assumed irrigator risk aversion. However, in line with our technical efficiency discussion above, perennial crop production also decreases suggesting negative capital returns for the Basin as a whole. Overall, the model estimates an increase in economic returns under the drought state, rising from $957 million (Base) to $4935 million (Drought). Notably, the annual capital repayment required to achieve this needs to increase to $6109 million.

5. Implications for water managers

The capital works models performed according to a priori expectations of water user behaviour, within the context of severely relaxed Basin constraint parameters. Irrigators adopt subsidized capital works readily and adjust their water and land use to accommodate changed availability. However, this clearly has a number of implications for irrigators, water managers and projected MDB governance arrangements. Our findings indicate that full agricultural water reduction requirements cannot be achieved through capital works models, particularly in southern MDB catchments without significant relaxation of existing flow, trade and zone constraints. The use of capital works as a policy instrument appears to: (i) expose agricultural water users to increased economic risk under production transformations; (ii) decrease social wealth via large public to private transfers to achieve capital investment (relative to Base trade model results); and (iii) where capital investment results in return flow reductions, undermine Basin Plan environmental flow objectives. We detail each of these in turn.

5.1. Production transformation

Generally, a public subsidization of private on-farm infrastructure will lead to suboptimal allocation of resources, with high net social costs. More specifically in the MDB, any transformation of production towards perennial cropping in response to subsidized capital works programmes, possibly as a consequence of perceived water supply increases from efficiency, may drive a number of additional specific perverse outcomes. For example, if annual cropping production shifts towards higher rates of perennial production reduced non-planting during scarcity will decrease future water flexibility and increase the need for water market allocation purchasing (Wheeler et al., 2013). Further, although some irrigators improve their reliability of supply via the transformation of lower

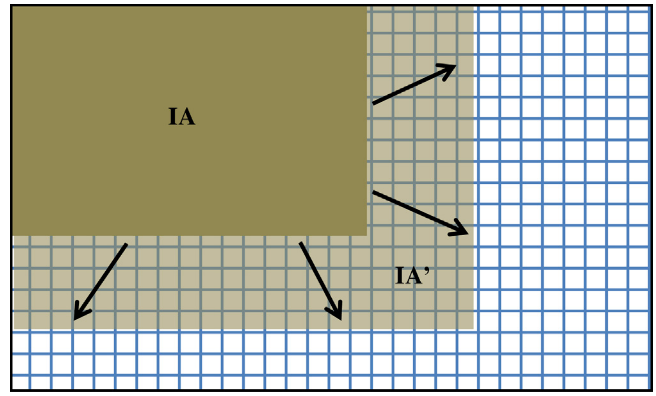

Fig. 3. Possible efficiency gain effects on total irrigated area (IA).

security licenses (e.g. general security licenses in New South Wales) into high security licenses, overall the reliability of water supply will not be improved via capital works. During a return to reduced supply conditions, increased on-farm capital investment will raise perennial irrigator exposure in the form of subsidized (public) or individual (private) risk. Where irrigators more generally choose to expand their irrigated cropping area in response to subsidized capital investment (i.e. shifts from IA to IA′ in Fig. 3), such that all ‘saved’ water is applied on-farm, they will also be exposed to increased levels of private risk during adverse states of nature.

This increased exposure to risk is underlined in the climate change and drought models, where any future reductions in water supply will logically need to be borne by irrigators, the environment and society as a consequence of the capital works subsidy incentives. An example helps illustrate the link between efficiency improvements from capital works and possible perverse contributions to environmental flow objectives (Table 8).

In this example, a 30% efficiency improvement from the adoption of new technology reduces water use per hectare from 10 ML/Ha to 7 ML/Ha. Originally, return flows contributed 3 ML/Ha in normal and wet states of nature, and 1 ML/Ha in the drought. Savings generated from capital works lower return flows by 50%—but since water use is also reduced this has a proportional impact on return flows. Consequently, return flows fall to 1.05 ML/Ha in the normal and wet states, and 0.35 ML/Ha in drought. If savings are shared on a proportional basis between irrigators and the environment then irrigators effectively receive 1.5 ML/Ha for existing or increased use. While this use contributes to return flows it does so at a reduced rate, resulting in 0.22 ML/Ha relative environmental flow reductions during normal and wet states of nature. Note that in the drought state environmental return flow increases by 0.93 ML/Ha as a consequence of the capital works, which may be considered positive. It should be noted that some irrigators might choose not to utilize their saved water in this way, electing instead to retain that water as a buffer for risk-management purposes, and thereby decrease their risk exposure (Wheeler and Cheesman, 2013). However, if MDB environmental watering plan objectives seek to mimic natural conditions then increased flows during dry periods may be at odds with management goals. This strategy of preserving water to minimize risk during dry periods is evident in the drought model where, instead of investing all subsidized capital into perennial crops that require water in all states of nature (see Table 4), investment in vegetables occurs (i.e. 193,000 Ha, Table 9) where water is not needed in the drought state of nature. If irrigators are then not utilizing their water resources it may suggest that the recent drought may have left a permanent transition towards greater flexibility in the management systems.

Table 8
An example of potential capital work reductions to exiting environmental flows.

	Existing technology	New technology
Water use/Ha	10 ML	7 ML (=3 ML saving)
Return flows by state (normal, drought, wet)	100% return flows (0.3, 0.1, 0.3)	50% return flows (0.15, 0.05, 0.15)
Return flow outcomes	3.0 ML, 1.0 ML, 3.0 ML	1.05 ML, 0.35 ML, 1.05 ML (extra water)
Water saving split (50/50)		1.50 ML (increased use)
Increased farm water use		2.55 ML, 1.85 ML, 2.55 ML
Environmental supply	3.0 ML, 1.0 ML, 3.0 ML	2.55 + (0.15 × 1.5) = −2.78, 1.85 + (0.05 × 1.5) = 1.93, −2.78
Difference:	3.0 ML − 2.78 ML = −0.22 ML(N), 1.0 ML + 1.93 = 0.93 ML(D), 3 ML − 2.78 ML = −0.22 ML(W)	

Table 9
Land allocated ('000 Ha) by model run.

Production system name	WRF-100, 250 CC, 2100 CC	Drought run
Citrus-H	402	366
Citrus-L		
Grapes	867	790
Stone Fruit-H		
Stone Fruit-L		
Pome Fruit		
Vegetables		193

5.2. Wealth transfer misallocation

Under the *SRWUI* programme a proportion of public expenditure will also be allocated to owners of large scale capital (i.e. those that manage diversions before allocating water to farmers). The limited public data on proposed MDB capital works prevents a breakdown on which group (i.e. irrigators or irrigation infrastructure operators (IIOs)) in the MDB would receive the funding. This prevents a clear understanding of whether rent seeking is occurring and, if so, whether the wealth transfer is equalized between the groups. However, interpretation of our model results suggests water savings are predominantly created by conveyance system improvements, not on-farm efficiencies. As capital works programmes would likely not reduce the volume required to irrigate (Table 6), total farm equity growth to offset debt (private or public) required to obtain efficiency improvements would not eventuate (Adamson, 2012).[6] Thus, although the policy intent may be to allocate wealth transfers across irrigators, IIOs and the environment actual intervention conclusions may heavily favour IIOs by 'gold-plating' the MDB delivery arrangements. As a consequence, irrigators (in particular) and environmental water managers will be adversely impacted through exposure to higher infrastructure operating costs over time. Economically marginal irrigators may be forced to exit sub-systems, thus increasing the cost-burden for remaining water users. This in turn may produce a cycle of reducing economic margins for remaining irrigators, forcing further exit.

In addition, our state of nature analysis highlights the importance of considering climate change impacts. Wealth transfers to capital works programmes constituting sunk costs across the MDB may be significantly misallocated if future climate trends force southward shifts of irrigated agriculture (e.g. in temperate zones a 3 °C mean annual temperature increase may correspond to an isotherm shift of approximately 300–400 km in latitude towards the poles, or 500 m in altitude (Kingwell, 2006)). Such results can be observed in our 2050 CC and 2100 CC models where irrigated land use trends towards southern catchments near the Coorong in response to capital works. Further delivery infrastructure and on-farm transition costs to accommodate climate change outcomes would be of significant magnitude, and result in further wealth transfers towards irrigators and IIOs.

Importantly, these irrigation water delivery schemes were originally public assets, which were increasingly privatized (New South Wales) or corporatized (Victoria) to meet reform requirements (Cummins and Watson, 2012). If the economic benefits from water savings were obvious to MDB IIOs we might expect them to finance capital works investments themselves. Since they are no longer public assets, private incentives to invest appear limited and industry privatization no longer enjoys the political support afforded it in previous periods (Sirasoontorn and Quiggin, 2007). Questions should therefore be raised about why public investments is being undertaken to 'gold-plate' these assets where economic capital losses are likely in future. Affecting such a substantial public investment (i.e. $7.75 billion) to not achieve Basin Plan outcomes—as suggested in our models—indicates that capital works do not provide an appropriate economic intervention approach. This contention is detailed further below.

5.3. Inconsistency with Basin Plan environmental objectives

Our model results show that, if water recovered for environment benefit is not fully stipulated, the short-term gains of the program will be potentially undone through significant water resource losses; especially via climate change impacts. Importantly, no capital works model is able to achieve the required Basin Plan full trade zone water reduction target. Further, if return flows reduce as a consequence of this investment then we also jeopardize Basin Plan environmental objectives. This is because return flow reductions diminish supply reliability for downstream users, particularly the environment (Table 6). Within a reduced return flow context failure to fully consider states of nature and climate change in Basin planning may result in over-investment in capital programmes, leading to additional diminution of environmental gains from other policy approaches (e.g. buyback).

Finally, if we persist with previous proportional water saving sharing arrangements (50/50) we will likely reduce environmental flows even further. This implies that such arrangements may have to be reviewed to either alter share proportions to account for this imbalance (e.g. 75% environment, 25% irrigation), or scrap proportional sharing arrangements altogether.

5.4. Implications from model limitations

Like all models there are limitations in the approach and assumptions. A major limitation is the use of discrete parameters in the optimization solution, which implies perfect knowledge about the future. If the model used stochastic information relating to the state of nature (i.e. total volume of conjunctive water) or the inputs required by state of nature (i.e. how much water is required to produce one hectare of a commodity) then the results would transition towards less area being irrigated and more water being saved to mitigate climatic variability in the drought state of nature and ensuring that the minimum flow and salinity levels are achieved.

[6] Contrary to the buyback recovery programme, capital works creates net debt; whereas Wheeler and Cheesman (2013) show reduction of farm debt via buyback investment.

At the same time, the use of stochastic descriptions of returns flows would also highlight the problems with water scarcity in droughts.

Secondly although providing reasonable estimations of flow and conveyance loss throughout the system, the model is flawed by its scale and scope. By modelling at a catchment management region level, clear information about economic return along political boundaries is provided but political boundaries do not align with hydrological boundaries. Consequently the data does not necessarily align well with other studies that use the CSIRO sustainable yields data and/or detailed models that are concerned with diversions versus allocations. However, at the same time this simply allows for additional fundamental questions to be asked: are we irrigating in the right areas; should we be irrigating at all; and what are the benefits of trade?

6. Conclusion

The intended MDB capital works programme is at odds with the Basin Plan objectives in terms of economic, social and environmental outcomes. By subsidizing capital investment, irrigation farmers in the MDB will take the opportunity to modernize their water use arrangements, in turn increasing farm debt levels and reducing their flexibility to future water supply shocks. Further, the process of 'gold-plating' MDB irrigation infrastructure will not increase the reliability or security of water assets owned by irrigators or IIOs. This mixture of increasing risk exposure and over-investment in capital works will compound losses under a future return to drought states of nature, or climate change impacts. In that eventuality, irrigators (and IIOs) will: still have to cover the costs of maintaining that capital; and when the face value of entitlements is re-discovered under drought the pressure to meet new use charges and debt liabilities will likely require governments to again act as the final insurer. Capital investments may marginally increase: (i) on-farm water use efficiency; (ii) irrigators' capacity to improve farm viability and sustainability; and (iii) rural structural adjustment to water reforms through regional job creation—resulting in reduced short-term political risk. However, there is a potential trade-off associated with return flows that requires greater investigation. These unknowns and increased on-farm efficiency may be exposed under climate change. Importantly for this analysis, the long-term effects of climate change constitute a low-probability political risk factor, potentially negating its impact on present policy choices.

Thus, where climate change or, drought-induced water scarcity present management issues for federal basin water managers we would recommend reallocation policy options that accommodate requirements to flexibly manage inherent variability and uncertainty. Capital works investment policy solutions do not facilitate long-term flexible responses to future scarcity problems.

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