Journal of Hydrology 518 (2014) 120–129

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

# Climate change and environmental water reallocation in the Murray–Darling Basin: Impacts on flows, diversions and economic returns to irrigation

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ARTICLE INFO

*Article history:*
Available online 23 January 2014

*Keywords:*
Murray–Darling Basin
Climate change
Environmental flows
Irrigation economics
Water allocation

SUMMARY

Increasing river environment degradation from historical growth in withdrawal is leading to reallocation of water from irrigation in many basins. We examine how potential reduction in irrigation allocations under a newly enacted environmental water plan for the Murray Darling Basin in Australia, in combination with projected climate change, impact on flows, diversions and the economic returns to irrigation.

We use an integrated hydrology–economics model capable of simulating the year-to-year variability of flows, diversions, and economic returns to model three levels of reallocation (2400, 2750 and 3200 GL) under the historical climate, and under a dry, a median and a wet climate change projection. Previous assessments of the reallocation plan do not address climate change impacts, nor the impact of year to year variability in flows on economic returns.

The broad results of this analysis are that estimated river flows and diversions are more sensitive to the range of climate change projections than to the range of diversion reallocation scenarios considered. The projected median climate change more or less removes from flows the gains to the environment resulting from reallocation. Reallocations only in combination with no climate change, or climate change at the wetter end of the range of projections, will lead to flows greater than those experienced under the water management regime prior to reallocation.

The reduction in economic returns to irrigation is less than the reduction in water available for irrigation: a 25% reduction in the annual average water availability is estimated to reduce the annual average gross value of irrigated agricultural production by about 10%. This is consistent with expectation of economic theory (since more marginal activities are reduced first) and also with observations of reduced water availability and returns in the recent drought in the Murray–Darling Basin. Irrigation returns vary less across the range of climate change projections considered than across the range of reallocation scenarios considered.



## 1. Introduction

Increasing withdrawals of water from rivers has led to concerns about the river environment and in turn to debates or plans to reallocate water to the environment in many rivers systems around the world. Katz (2006) reviews examples from around the world of establishing environmental water allocations, including reallocating water from other uses. Garrick et al. (2012) and Landry (1998) document the market acquisition of water for the environment in several river basins in the western USA. Specific examples include: various rivers in South Africa (Walmsley, 1995); the Colorado River (Postel et al., 1998), the Klamath Basin (Jaeger, 2004), the Walker River (Seung et al., 1998) and the Columbia River (Garrick et al., 2009) in the USA; the Yellow and other rivers in China (Xu et al., 2005; Cai and Ringler, 2007); and the Murray–Darling Basin in Australia (MDBA, 2012a).

Reallocation of water can be contentious, particularly in river basins where water is perceived as scarce relative to the demand, or the reallocation involves large volumes (Scheierling, 2011). In the Klamath River Basin, reallocation of irrigation water under a 2001 plan led to protests and demonstrations, and calls for the repeal of the US Endangered Species Act (Jaeger, 2004). The planned reallocation of irrigation water in the Murray–Darling

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http://dx.doi.org/10.1016/j.jhydrol.2014.01.024
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Basin under the Guide to the Proposed Plan (MDBA, 2010) led to protests, and a reduction of the proposed reallocations in the later Basin Plan (MDBA, 2012a).

One reason for the controversial nature of proposed reallocations is that costs and benefits are often difficult to assess, and the results of analyses open to question (Scheierling, 2011). There are many studies of costs and benefits. Many such studies are purely economic, focussing on improving the efficiency of allocation and thus improving economic welfare: several such studies are reviewed by Scheierling (2011), who focuses particularly on foregone direct benefits in irrigated agriculture. These approaches make no reference to the hydrology of the situation. Houk et al. (2007) show that, to satisfy particular habitat water requirements in downstream areas of the Platte Basin in the USA, reallocation of water entails different costs and requires different volumes to be reallocated depending on where the water is acquired from. The different volumes arise from the interactions of the flows and the diversion opportunities between the region from which the irrigation water is reallocated and that of the habitat to receive the reallocated water. Similarly, Mainuddin et al. (2007), with reference to the Murray–Darling Basin, show that optimal reallocations are affected by the location of the irrigation area from which water is transferred; the differences in this case arose partly from losses of water from river, as well as the foregone opportunity costs in different regions from which the water might be transferred. Furthermore, as shown by Mainuddin et al. (2007), different reallocation strategies lead to different flows in the river, and the different flows may result in different environmental benefits; however, they did not directly quantify the benefits. Thus, an account of the costs and benefits requires (at least) an assessment of the impacts on economic returns to irrigation and an assessment of the impacts on flows as a precursor to the estimation of benefits resulting from the changes to flows (CSIRO, 2012).

In contrast to the studies of optimal water reallocation, the reallocation in the Murray–Darling Basin has, within identified ranges of volumes from different regions within the basin, been specified under the Murray–Darling Basin Plan (MDBA, 2012a). The proposed Plan was accompanied by several studies of the impacts on irrigated agriculture and the more general economy of and employment in the basin, compiled and summarised in MDBA (2011). Several analyses suggest that the impact on irrigated agriculture and the basin economy is likely to be small overall, but some communities could bear more substantial costs. For example, ABARES (2011) estimated that the gross value of irrigated agricultural production would decline 12.7% with a reduction of 2800 GL/year in water available to irrigation, but this would be somewhat offset by compensatory effects of other government programs. (Note: the gigalitre is the preferred unit in Australia and 1 gigalitre or 1 GL is equal to 1 million cubic metres.) These studies, however, are not directly linked to flow impacts, nor do they examine the impacts of the substantial year-to-year variation in flows.

Despite potentially large impacts of projected climate change in the Murray–Darling Basin (CSIRO, 2008), the Plan (MDBA, 2012a) does not deal with climate change directly. Rather, it recognises climate change as a significant risk, with potential impacts both to water requirements and to water availability.

Our aim is to explore the impact of water reallocations and climate change on flows available to the environment, diversions for irrigation, and on the economic returns to irrigated agriculture in the Murray–Darling Basin. We use an integrated hydrology and economics model to assess the year-to-year variability of flows, diversions and economic returns. We examine the sensitivity of the analysis to different levels of water reallocation, and to different climate change projections.

## 2. Methods

### 2.1. Integrated hydrology–economics model

The hydrology component of the integrated hydrology–economic model is based on a simple, monthly water balance stocks and flows model of the Murray–Darling Basin, subdivided into 58 catchments (Fig. 1). In each catchment, the simple, conceptual mass balance model shown in Fig. 2 is applied. It comprises three sub-models: a rainfall–runoff partition; river flow and storage; and irrigation water demand and delivery. Each element of the water balance obeys basic mass balance given by

$$\sum Inflows - \sum Outflows + \sum \Delta storages = 0 \tag{1}$$

A rainfall–runoff sub-model is used to partition the rain between actual evapotranspiration and runoff. The partitioning is based on the supply limit–capacity limit reasoning of Budyko (1974), which applies to average annual runoff, with the addition of a storage that varies from month to month; the monthly extension is based on Zhang et al. (2008). A conceptually identical rainfall–runoff model, but with equations formulated differently, was shown by Wang et al. (2011) to perform well for Australian catchments, including many within the Murray–Darling Basin. In the sub-model, rain, $P$, is first apportioned into infiltration, $I$, and runoff, $R_o$:

$$P - I - R_o = 0 \tag{2}$$

The partition is governed by rainfall as the supply limit rainfall and the unfilled portion of a generalised surface storage, $\Delta S_{s\,max}$, as the capacity limit. We use a Budyko-like equation to smooth the transition from the supply limit to the capacity limit:

$$\frac{I}{\Delta S_{s\,max}} = \left(\frac{(P/\Delta S_{s\,max})^{a_1}}{1 + (P/\Delta S_{s\,max})^{a_1}}\right)^{1/a_1} \tag{3}$$

where $a_1$ is a parameter.

The evapotranspiration depends on the potential evapotranspiration, $ET_{pot}$ (the capacity limit), and the surface storage, $S_s$ (the supply limit). An equation similar to Eq. (3) above, with a second adjustable parameter, $a_2$, is used to smooth the transition from the supply limit to the capacity limit:

$$\frac{ET}{ET_{pot}} = \left(\frac{\left(S_s^{t-\Delta t}/ET_{pot}\right)^{a_2}}{1 + \left(S_s^{t-\Delta t}/ET_{pot}\right)^{a_2}}\right)^{1/a_2} \tag{4}$$

Infiltration increases the water stored in the generalised surface store, while it is decreased by evapotranspiration:

$$S_s^t = S_s^{t-\Delta t} + I - ET \tag{5}$$

where $t$ is time and $\Delta t$ is the time step (one month).

River flows are modelled in terms of a reach water balance:

$$Q_o = Q_i + Q_t + R_o - D - L + \Delta S_r \tag{6}$$

where $Q_o$, is the outflow from the reach, $Q_i$ is the inflow, $Q_t$ is any tributary inflows plus, $R_o$ is the runoff from the adjacent catchment (as calculated above), $D$ is diversions (for urban or agricultural use), $L$ is evaporation and seepage losses, and $\Delta S_r$ is the change in reach storage. Inflow is generally zero in a headwater catchment but the Murray and Murrumbidgee catchments receive inflows from inter-basin transfers from the Snowy River hydroelectricity scheme.

Losses are calculated as a function of inflow:

$$L = Q_i(1 - c_{loss}) \tag{7}$$

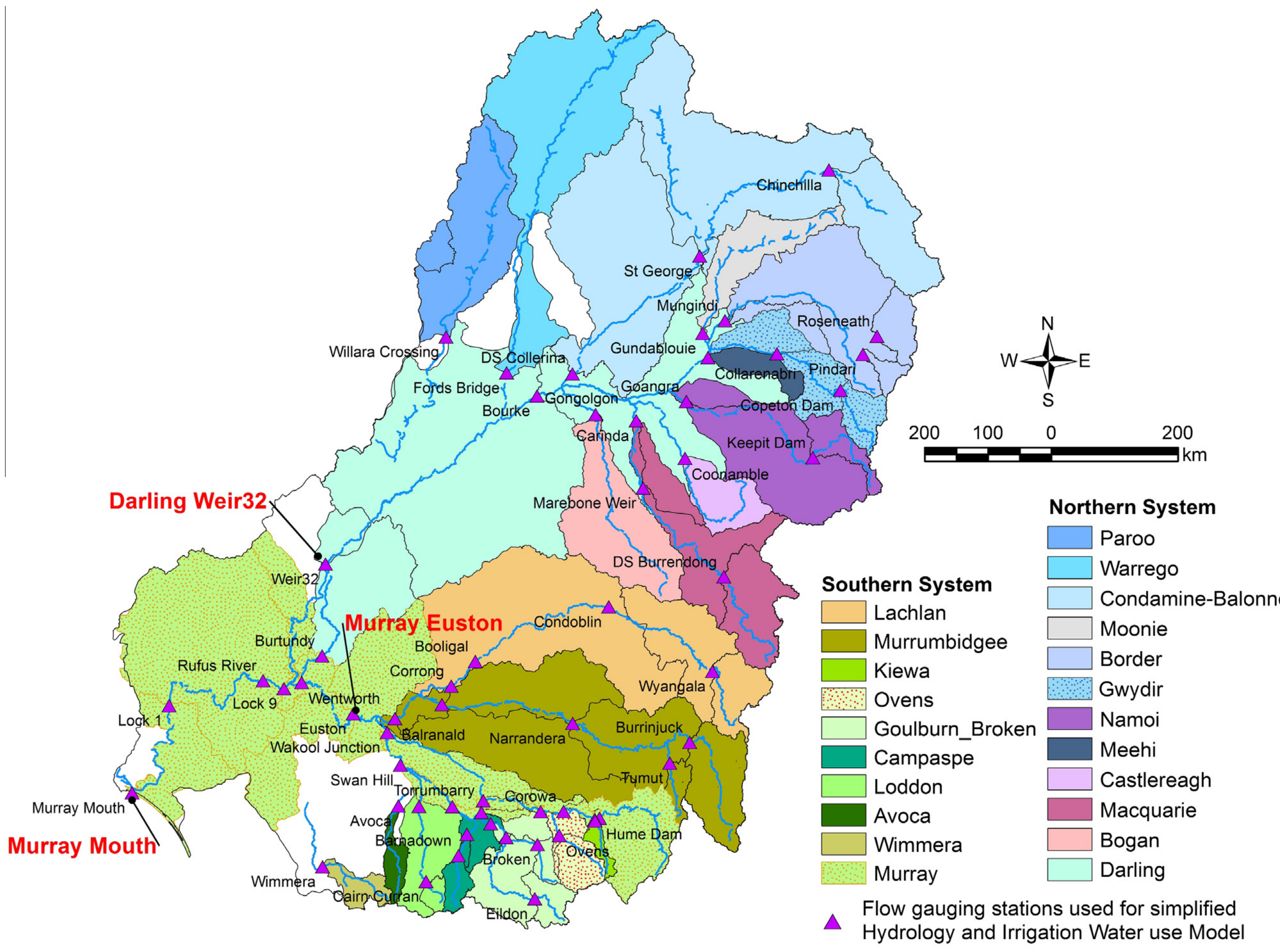


**Fig. 1.** The 58 catchments of the integrated hydrology–economic model. The arrows show the locations at which flow results are reported in the text: Weir 32 on the River Darling, Euston on the Murray River, and the mouth of the Murray.

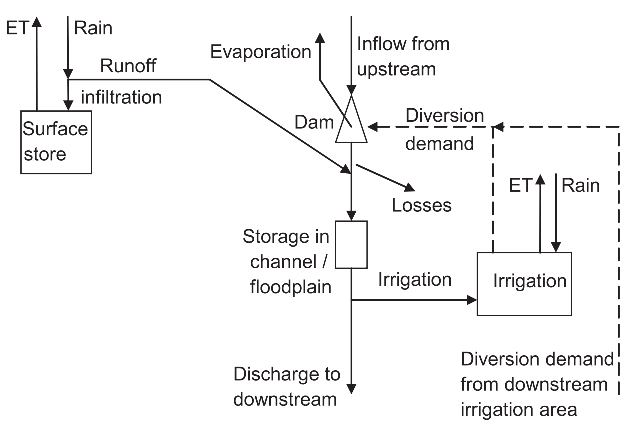


**Fig. 2.** Conceptual model of a single catchment.

where $c_{loss}$ is a parameter with value $0 \leqslant c_{loss} \leqslant 1$.

The reach storage is also a function of the inflow:

$$S_r = c_1 Q_i \tag{8}$$

where $c_1$ is a parameter.

The change in reach storage is the difference between reach storage at two time steps:

$$\Delta S_r = S_r^t - S_r^{t-\Delta t} \tag{9}$$

We assume storages in lakes and reservoirs, $S_D$, fill and empty according to:

$$S_D^t = MIN\left[S_{D\,max}, \left(S_D^{t-\Delta t} + c_6 Q_i - L - E - c_7 D_j\right)\right] \tag{10}$$

The minimum function gives the capacity limit of the storages. The inflows, $Q_i$, are multiplied by a constant, $c_6$ $(0 \leqslant c_6 \leqslant 1)$, which, if it is less than 1, allows for some of the inflows to pass through the dam and contribute to an environmental flow. The diversions are those calculated below as $D_j$ from Eq. (14), the total for all the irrigation areas that the dam serves, multiplied by a constant, $c_7$ $(0 \leqslant c_7 \leqslant 1)$, which allows for losses between the dam and diversion point. The diversion term is absent for lakes that do not supply water for irrigation.

Evaporation is given by:

$$E = c_4\, ET_{pot} S_D^{c_5} \tag{11}$$

where the term $c_4\, ET_{pot}$ accounts for evaporation demand from open water, and $c_4$ is often assumed to be about 0.7, although usually when pan evaporation rather than potential evapotranspiration is used, see Gippel (2006). The term $S_D^{c_5}$ is the conversion from storage volume to surface area and $c_5$ will often be around 2/3 (because volume is proportional to the cube of the depth, whereas the evaporating surface area is proportional to the square of depth). We do not explicitly consider evaporation from rivers, since it is implicit in the loss term, $L$, in Eq. (7).

The change in lake or reservoir storage is given by:

$$\Delta S_D = S_D^t - S_D^{t-\Delta t} \quad (12)$$

To model irrigation supply and demand, we use a crop coefficient approach (Allen et al., 1998). We assume that crops are always well watered, and that the area cropped is reduced when water supply is limited. Thus, decreased crop water-use result from reduction in the area cropped, not reduced crop growth and yield. The area under irrigation in any year is determined from the dam or reservoir storage in the month prior to the start of irrigation and the total mean annual irrigation demand for all irrigated crops.

The monthly irrigation demand per unit area, $Irr_{Demandij}$ for crop $i$ in month $j$ is:

$$Irr_{Demandij} = MAX\left[\frac{(K_{cij}ET_{potj} - P_{eij})}{IE_i}, 0\right] \quad (13)$$

where $K_{Cij}$ is the crop coefficient for crop $i$ in month $j$, $IE_i$ is the irrigation efficiency, and $P_{eij}$ and $ET_{potj}$ are respectively the effective rainfall and potential evapotranspiration for month $j$. The *MAX* function ensures that if there is sufficient rain in a month, $Irr_{Demandij} = 0$.

The monthly irrigation demand for each crop is summed to give a mean annual irrigation demand per unit area for the crop. The demand per unit area is used to calculate the area that can be irrigated from the water in storage. The area of irrigated crops in any year is, in each catchment, set to that which can be supplied by the water stored in the dams supplying that catchment, up to a maximum area which is taken as the largest measured area.

The total volume of irrigation, $Irr_{DemandTj}$, required to satisfy the demand of $n$ crops in any month $j$ is:

$$Irr_{DemandTj} = \sum_{i=1,n} (Irr_{Demandij}A_{ij}) \quad (14)$$

where $A_{ij}$ is the area of crop $i$ in month $j$. If there is adequate water storage in the dam, the total volume available for diversion to irrigate crops, $D_J$, is equal to the total irrigation demand. If the volume stored is less than the irrigation requirement, then the volume available for diversion is equal to the dam storage.

The calibration of the hydrology part of the model is described in Kirby et al. (2013a).

The economics part of the model is described in detail by Connor et al. (2012), with the incorporation into the integrated hydrology–economics model described by Kirby et al. (2012). Whereas the hydrology model above is based on 58 catchments, the economics model is based on 17 regions for which crop production, area, price and gross value (revenue) data are given by ABS (2010). The volume available for diversions determined by the hydrology model is aggregated from the 58 catchments to give water allocations for the 17 crop regions.

The economics model is based on regressions of the observed areas and gross value of irrigated agricultural production as a function of water available, evaporation and rainfall, and crop prices, for 10 major commodity groups and for 17 regions and four recent years during the drought.

The area of crops in each region is calculated as:

$$A_{iry} = \alpha_i^0 + \alpha_i^{wa} wa_{iry} + \alpha_i^p p_{iy} + \alpha_i^c c_{iry} + \alpha_i^n n_r + e_{iry} \quad (15)$$

where $A_{iry}$ is the area of crop $i$ in region $r$ for year $y$, $\alpha_i^0$ is the regression intercept coefficient, and $\alpha_i^{wa}$, $\alpha_i^p$, and $\alpha_i^c$ are the regression coefficients for the explanatory variables of water allocation, *wa*, price, *p*, and climate, *c*, is a climatic drought index measured as evapotranspiration minus the rainfall. The units of *wa* (volume), *p* (price per unit of produce) and *c* (depth of water) differ from one another and from the area, *A*, so the implied units of the regression coefficients differ from one another such that the overall unit is that of area. Climate influences the area of crop partly through the water allocation, *wa*, and partly through the climate variable, *c*. The regression coefficient $\alpha_i^n$ is for the binary variable $n_r$ is included to account for distinct differences influencing land and water allocation and revenues from production in the northern Basin versus the southern basin that are not picked up in the other explanatory variables. As described in the introduction, our aim is to explore the impact of water reallocations and climate change on flows, diversions and the economic return to irrigation. In simulating future behavioural response to reduced water allocations, the price is held constant at its mean observed value. We recognise that price changes in the future, together with other changes such as improved water use efficiency, will cause both short and long term adjustments, but quantifying these is beyond the scope of this paper.

The gross value of irrigated agricultural production, GVIAP, is given by the crop area predicted from Eq. (15), price and climate.

$$GVIAP_{iry} = \phi_i^0 + \phi_i^A A_{iry} + \phi_i^p p_{iy} + \phi_i^c c_{iry} + \phi_i^n n_r + e_{iry} \quad (16)$$

where $\phi^o \ldots \phi^n$ are the regression coefficients. Climate influences the gross value partly through the area which itself is affected by climate as described above and partly through the climate variable, *c*, which is the evapotranspiration minus the rainfall. The impact of climate on yield per unit area expresses itself both through the influence of reduced water allocation on land area (as Eq. (15)determines the value of $A_{iry}$) and also through the influence of drought conditions on yields expressed as high evapotranspiration and low rainfall leading to high values of the $c_{iry}$ variable. Again, the price is held constant at its mean observed value for simulating future behaviour.

The observed data covered a wide range of water uses, water availability, rainfall, evaporation and commodity price circumstances observed during the drought. The regression model captures an intermediate time frame response; it is neither a truly short-run (within year) nor a long-run (full capital adjustment) model, but has a mixture of effects resulting from the actual experience of the drought.

In the integrated model, the hydrology model first determines the availability of water for irrigation in the 58 catchments and also calculates the flows, on a monthly cycle. Once per year, the water availability values are aggregated to the 17 economic regions. The regression equations estimated in Connor et al. (2012) are then used in statistical simulation. This involves holding levels of prices at the mean observed in the regression data and varying the rain, evapotranspiration, and water available for irrigation based on 114 year hydrology simulation to determine areas and the gross value of production of each commodity group in each region.

### 2.2. Scenarios

We applied the model to 13 scenarios to assess the interactions of reallocations of irrigation water to the environment with projected climate change. In each of the scenarios, we simulate flows, diversions and economic returns to irrigation for a 114 year period. The period is based on historical records of climate and calibrated flows in the Murray–Darling Basin for the period 1895–2009. The scenarios are:

- A base case scenario against which to compare the impacts of reallocation and climate change. The base case has the current dams and irrigation, and with historical rainfall and potential evapotranspiration. All dams are assumed to be present from the first time step; hence, irrigation operates fully throughout the 114 year simulation period.

- Three scenarios comprising three levels of reallocation, each with the historical climate sequence. The rainfall and other climate data are 114 year sequence from 1895 to 2009, taken from the datasets used in the Murray–Darling Sustainable Yields study (CSIRO, 2008) extended to 2009 in more recent work by CSIRO (Vaze et al., 2011). These scenarios allow the assessment of the impact of reallocation alone, unconfounded by climate change impacts. The annual average reallocation levels are 2400 GL, 2750 GL and 3200 GL. These are the reallocations considered by the MDBA (2012b). The 2750 GL reallocation is the preferred option, but under the Basin Plan, the actual amount by which irrigation diversions are reduced can vary if gains are made in conveyancing efficiency by reducing losses to the system (MDBA, 2012b).
- Nine scenarios comprising the three levels of reallocation above for each of three projected climate sequences under three climate change assumptions. The projected climate sequences are the dry extreme, median and wet extreme climate change defined by CSIRO (2008) to evaluate future water availability in the Murray–Darling Basin, extended by (Vaze et al., 2011). These scenarios allow the assessment of the impact of climate change under different levels of reallocation.

There are many ways to implement a reallocation from diversions to environmental flows. For this simulation, we used a simple, direct approach of reducing the maximum irrigable area in each catchment until the reduction in diversions and the reallocation to the environment reached the target amount. The distribution of reductions to diversions and hence to reallocations is the same as in the Basin Plan (MDBA, 2012a). According to the Plan, 390 GL are to be reallocated from the River Darling and its tributaries, 2289 from the Murray River and its tributaries (excluding the Darling), and 71 from disconnected streams (which lose all flow before reaching the Murray or the Darling).

Similarly, there are many ways to implement flows with the reallocated water. For this simulation, we used a simple approach of allowing reallocated water to accumulate in storages, until full storages resulted in spills and hence flows down the river. Storages emptied with release to fulfil irrigation demands and, to a small extent, with evaporation. The actual management of flows for the environment will be subject to environmental watering plans, yet to be formulated in accordance with the Murray–Darling Basin Plan (MDBA, 2012a).

As noted, the different assumptions could be made about how allocations to irrigation are made, and about how water is released to provide environmental flows. Plans to govern the allocations and releases are yet to be made. The results of our simulations are therefore not predictions of what will happen. They are projections of what might happen, and are designed to shed light on the potential impacts of reallocation and climate change.

## 3. Results

### 3.1. Flows

The Murray River has larger and more reliable flows than the River Darling (Kirby et al., 2006). Furthermore, as described above, the reallocations are greater from the Murray River than the Darling. We therefore present the results in terms flows at a point on the lower part of the Darling, and on the Murray just above its confluence with the Darling (Fig. 1). We also show the results for the discharge at the mouth (Fig. 1). These flow points show the different impacts of the lesser reallocations in the Darling and the greater reallocations in the Murray, as well as the combined impact of the two.

The impact of reallocations and projected climate change on calculated flows in the Darling, the Murray and at the Murray Mouth is shown in Fig. 3. The figure shows the ratio of the monthly flows in a scenario to those in the base case (no reallocations, historical climate), with flows ranked from greatest to least. (Plotting

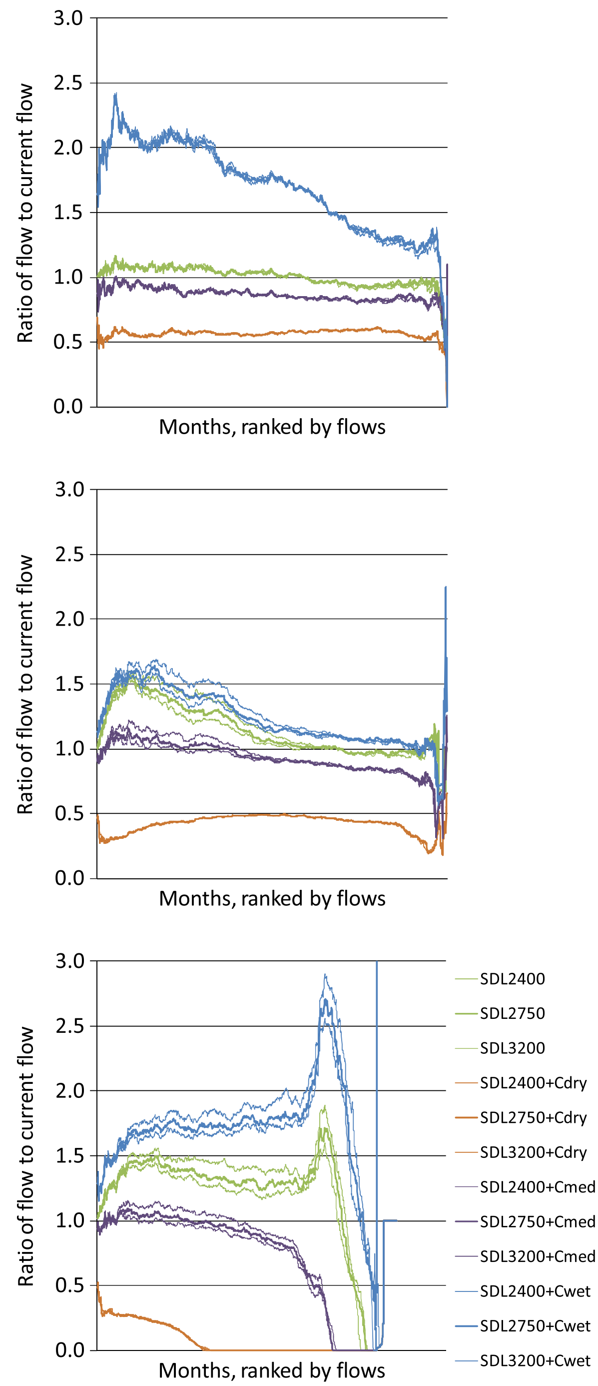


**Fig. 3.** Ratios of monthly flows in a scenario to those in the base case (no reallocations, historical climate) at Weir 32 on the River darling (top), Euston on the Murray River (middle), and at the mouth of the Murray (bottom). The ratios are plotted in the rank order of the monthly flows, from greatest to least.

the results as ratios shows the differences more clearly than plotting them as flow volumes, which must be plotted on a logarithmic scale to show the great range; differences do not show well on such a scale.)

The figure shows that reallocation in the absence of projected climate change increases calculated flows, particularly at Euston and the Murray mouth. The lesser impact at Weir 32 on the lower Darling is expected partly because of the proportionately lesser reallocations in the River Darling and its tributaries, and partly because the Weir 32 is low down on the river, and losses (to seepage, evaporation and spills onto the floodplain) to this point diminish the gains from reallocation. The figure also shows that the projected wet extreme climate (with reallocations) is calculated to increase monthly flows substantially at all three locations. The projected median climate change (with reallocations) is calculated to result in monthly flows not dissimilar to those of the base case, except for the lesser volumes of low flows at the mouth of the Murray.

The reallocations are calculated to increase medium sized flows more than the largest and smallest flows (Fig. 3). At the mouth of the Murray, the smallest flows are calculated to diminish in many months, increasing the number of months with no discharge to the sea. The wet extreme and median climate change projections are also calculated to increase medium sized flows more than the largest and smallest flows, except in the Darling River where the median climate change is calculated to reduce all flows. The projected dry extreme climate change (with reallocations) is calculated to result in monthly flows of about a half or less of those of the base case; at the mouth of the Murray, many months are calculated to have no flow.

### 3.2. Diversions

With greater and more reliable flows in the southern Murray part of the basin, approximately three times as much water is used for irrigation there than in the Darling part of the basin, even though the Darling drains about two-thirds of the basin. As well as the much greater intensity of irrigation in the south, the greater part of the reallocations to the environment are planned to come from Murray part of the basin. Therefore, we present the results in terms of the total diversions from the Darling River and its tributaries, the River Murray and its tributaries except for the Darling, and the total diversions from the basin.

Fig. 4 shows the diversions calculated for the base case and the 12 scenarios in the two parts of the basin, and the basin overall. In all cases, the reduction in diversions calculated to result from the reallocations is clearly evident. As expected, the reduction in diversions is greater in the Murray part of the basin than the Darling part. The calculated diversions are not greatly different under the historical climate (with reallocation), the median climate change and the wet extreme climate change (both with reallocation). However, the diversions are calculated to reduce substantially under the dry extreme climate change (with reallocation).

### 3.3. Economic returns to irrigation

During the recent drought, different cropping sectors responded differently in terms of reductions in water use (Kirby et al., in press). In particular, low value annual crops reduced their water use (and overall activity) substantially, whereas high value

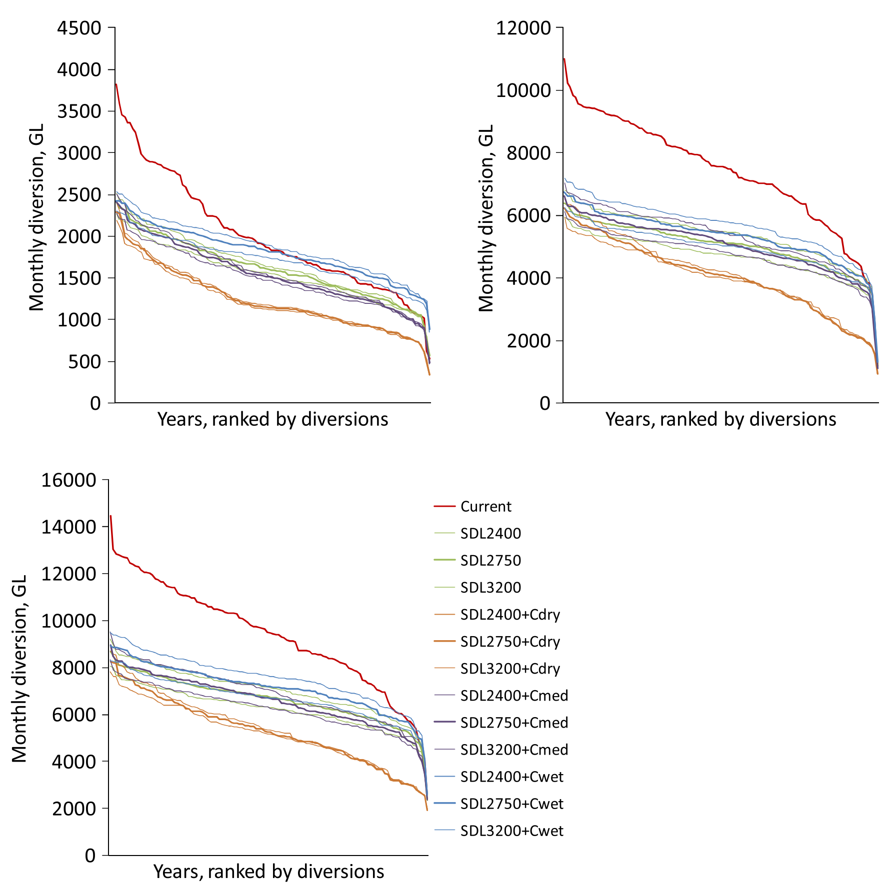


**Fig. 4.** Annual diversions in a scenario at from the River Darling and its tributaries (top left), the Murray River and its tributaries (excluding the Darling (top right), and the whole Murray–Darling Basin (bottom left). The diversions are plotted in the rank order of the annual diversions, from greatest to least.

perennial crops maintained their water use by purchasing water from the market. This in turn led to regions responding differently. Therefore, we present the results for some regions and crops selected to show the main differences in response. For clarity, we show the three reallocation levels in the absence of climate change, and the three projected climate changes for the 2750 GL reallocation only.

Fig. 5 shows the calculated economic returns to irrigation for several crops. Rice reduced its water use (and overall activity) in the drought more than any other sector (Kirby et al., in press), and is calculated to receive substantially lower returns in response to reallocation. The returns are also affected by projected climate change, particularly in the dry extreme scenario which results in further reductions in returns over and above those due to the reallocations. Cotton, another lower value annual crop, also reduced water use substantially during the drought, and its economic returns are calculated to be affected by reallocation and climate change in a similar way to those of rice, but not to the same extent. Returns to dairy, which reduced its water use in the drought substantially but substituted irrigated pasture with bought-in feed, are calculated to be less affected by either reallocations or climate change than the returns to rice or cotton, and returns to the high value grape crop are calculated to be barely affected at all (Fig. 5). The main crop groups not shown are: cereals, a low value annual crop which is calculated to respond like cotton; pasture products including pasture based meat production and hay, which are of middle value and respond like dairy; and high value perennial fruit and nuts which respond like grapes. High value vegetables, although annuals, respond fairly like grapes, but are calculated to show a little more variation in response (in terms of water use and hence economic returns) than grapes.

Fig. 6 shows calculated economic returns to irrigation for several regions within the Murray–Darling Basin. All regions have a mix of crops, and show behaviour that is a mix of the crop sector behaviours shown in Fig. 5. Nevertheless, the mix of crops differs from region to region. Cotton is the principal crop in the Gwydir region in the north of the basin, rice in the Murray region in the south, dairying in the Goulburn also in the south, while high value grape and fruit production dominates in the downstream SA Murray region in South Australia. The economic returns of these regions all show the imprint of the principal crop (Fig. 6), modified by other crops in the region. Murray, for example, shows the substantial reduction in water use and hence economic returns expected from the dominance of rice in the region, but retains substantial activity and returns from other crops (grapes in particular) even in dry years.

## 4. Discussion

Reallocation of water from irrigation to the environment has been implemented or is being contemplated in many river basins around the world (Katz, 2006). Plans are often contentious because costs and benefits are often difficult to assess, and the results of analyses open to question (Scheierling, 2011). Many such studies of costs and benefits are purely economic and focus on direct

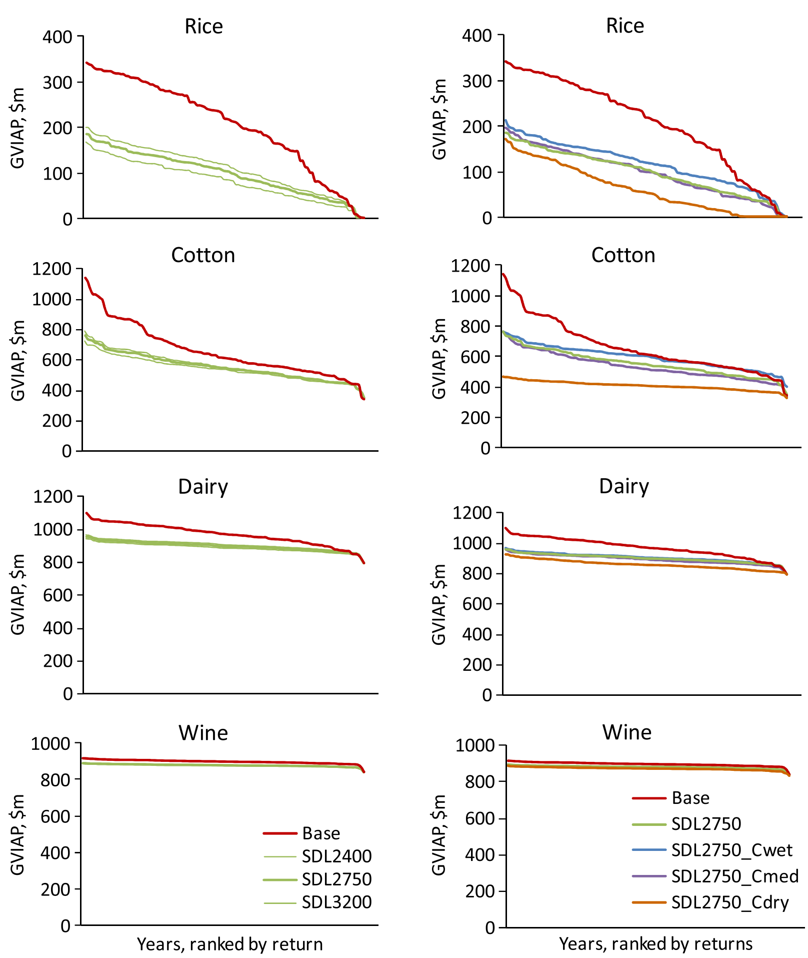


**Fig. 5.** Annual economic returns to irrigation for four irrigation sectors for three reallocation levels (left) and climate change scenarios for the 2750 reallocation level (right). The returns are plotted in the rank order of the annual returns, from greatest to least.

benefits by foregone irrigated agriculture Scheierling (2011). In the Murray–Darling Basin, several economic studies also focus on the direct benefits by foregone irrigated agriculture, together with the wider community costs and benefits resulting from the impact on agriculture (ABARES, 2011; Adamson et al., 2011; Wittwer, 2010). These studies make little or no reference to the impact on flows, despite the known interactions between allocations and economic outcomes (Houk et al., 2007; Mainuddin et al., 2007).

Our approach integrates the impacts of reallocation on flows, diversions and irrigation economics for a large and complex river basin. Furthermore, the approach readily incorporates the impact of other effects such as climate change, and also deals with the full variation of flows, diversion and economic outcomes resulting from a highly variable climate. In contrast, most economic studies deal with either average years, or a small number of years to represent wet, average and dry conditions (ABARES, 2011; Adamson et al., 2011). Such studies examine neither the extremes, nor the impacts of sequences such as a long drought as opposed to several dry years with intervening wetter years. Our approach incorporates extremes and sequence information as observed in the historic record and as projected in alternative scenario climate sequences.

Water trading in the Murray–Darling Basin significantly offset the worst effects of the Millennium Drought (Mallawaarachchi and Foster, 2009; NWC, 2010), by facilitating the transfer of water from low- to higher-valued uses. While the integrated hydrology–economics model does not model trade directly, trading is simulated implicitly through the regression equations relating economic returns to water availability. The regression equations are developed using data observed in a period when trading was important. Brennan (2008) showed that a water market for water storage would facilitate the carry-over of irrigation water from a wet year in which excess water could not be put to profitable use (because the marginal uses would be of low value), to the next when it might be used more profitably. A consequence of such a market would be the smoothing of water use with fewer years of high and low water use, and more years close to the average use. While we do not model carry-over or storage trading, we implemented the reallocation of water in such a way (by capping the maximum irrigable areas) that the diversions were mostly close to the average, with few extreme high or low diversion years. This implementation simulates (without explicitly modelling) outcomes consistent with the economically efficient market suggested by Brennan (2008); however, we do not claim that our results are optimal in this regard. We note that we could have implemented other means of reallocating the water and thereby examined the consequences of other outcomes with minimal carry-over of water from one year to another. We defer that examination for another study.

While we have integrated the hydrological and economic aspects of water management and reallocation, we have not considered the direct ecological benefits or the indirect benefits (such as increased tourism) that might result. CSIRO (2012) examined the social and economic benefits expected to result from the

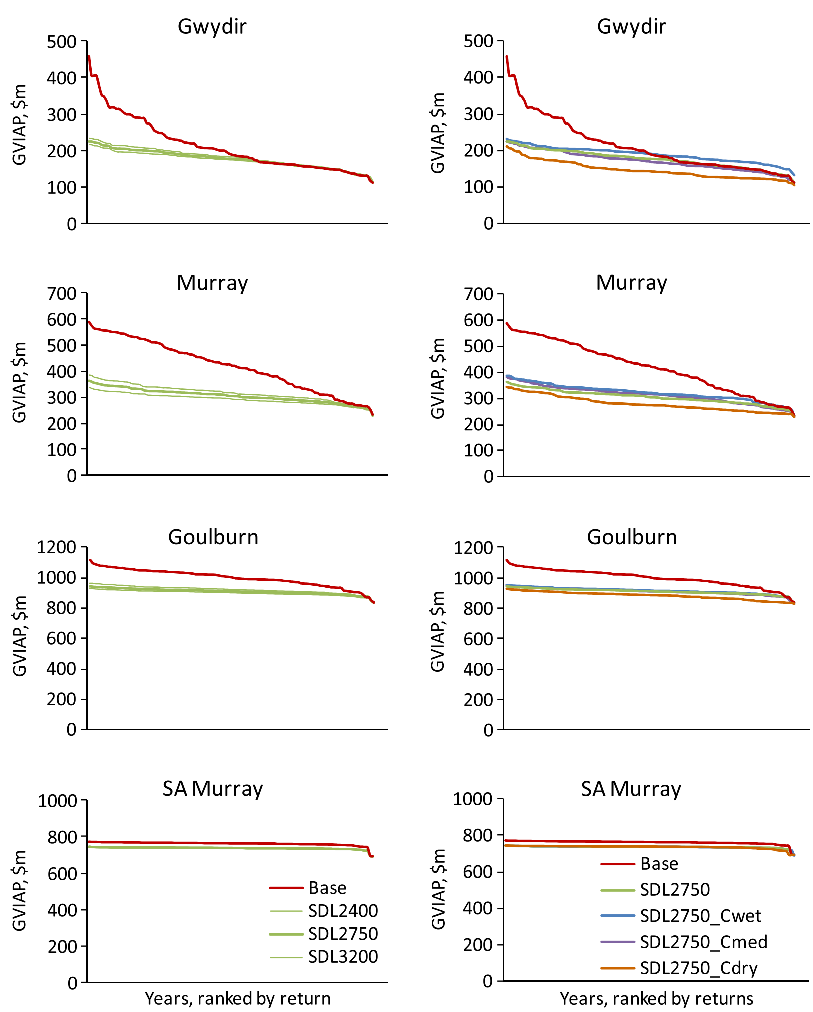


**Fig. 6.** Annual economic returns to irrigation for four regions for three reallocation levels (left) and climate change scenarios for the 2750 reallocation level (right). The returns are plotted in the rank order of the annual returns, from greatest to least.

Murray–Darling Basin Plan, and showed them to be considerable. However, CSIRO (2012) observed that complete and accurate assessment of ecological benefits is difficult, due to an incomplete understanding of the ecology and the benefits that are provided. We have therefore not attempted such an assessment.

The analysis suggests that flows are much more sensitive to climate change than to reallocations, at least within the range of reallocations and climate change projections considered (Fig. 3). (As described in Section 2.2 on the scenarios, the reallocations and climate change projections considered were drawn from other studies, and appear to be the relevant range for consideration of the Murray–Darling Basin Plan.) A median climate change projection more or less removes from flows the additional volumes gained by the reallocations. This result is consistent with the findings of the Murray–Darling Basin Sustainable Yields project (CSIRO, 2008) (which did not consider reallocations), which showed that the median climate change scenario would result in a 13% reduction in the total annual flows of about 24,000 GL, which amounts to an annual average reduction of about 3100 GL – that is, the median climate change scenario takes away roughly what is gained by a 2750 GL reallocation. However, there is great uncertainty in the impact of climate change on flows, with a wet extreme projection showing considerable additional volumes of flow, over and above those due to the reallocations, and a dry extreme climate change reducing flows substantially. As pointed out by Kirby et al. (2013b) the dry extreme climate change projection for the southern parts of the basin would, if realised, be similar to a more-or-less continuous state of what is currently considered as drought.

Climate change therefore appears to represent a major risk to the implementation of the Murray–Darling Basin Plan. Only no climate change, or climate change at the wetter end of the range of projections, will lead to greater flows when the net impact is considered accounting for both climate and diversion reductions for re-allocation to the environment. The plan is to be implemented through regional water resources plans, which must take risks into account (MDBA, 2012a). The current results strongly suggest that the risk posed by climate change should be fully evaluated and options considered in the water resource plans.

The analysis also shows that large, medium and small flows are affected differently. As discussed Section 2.2 on the scenarios, we did not model the active management of flows for the environment, instead simply allowing dams to fill and spill. In essence, this is a default position which environmental watering may seek to vary by managing flows for particular outcomes. It clearly would be possible, for example, to release many small flows and greatly increase the overall volume discharged in small flows, but at the expense of leaving less water for the medium to larger flows.

Diversions as calculated by the model are about equally sensitive to the differences in the three reallocation levels and the wet extreme and median climate change projections. However, the diversions are calculated using a model calibrated to match historic diversions (amongst other things). New water resource plans to come into effect in the next few years (MDBA, 2012b) could change the basis on which water is allocated, for example by changing the priority given to irrigation and the environment, and thus change the sensitivity of diversions to climate change.

The calculated diversions with reallocation show less variation across years than those calculated for the base case (historic climate with no reallocation, Fig. 4). This results from limiting diversions by limiting irrigable areas to a maximum and, as discussed above, is consistent with assumptions large scale use of water storage to carry over water from wet years to drier years. The greater variation amongst years is re-established in the dry extreme climate change projection, when there is insufficient water to carry over in storage from wet years to dry years.

The calculated returns to irrigation of the low value annual rice and cotton crops are diminished considerably by reallocations, and are also sensitive to climate change (Fig. 5) and are particularly affected by the dry extreme climate change projection. Dairying, which is a medium value activity is calculated to be less affected, and high value grape growing is barely affected by either reallocations or climate change. This is consistent with observed behaviour in the recent drought in the Murray–Darling Basin (Kirby et al., in press), during which the production of low value crops dropped sharply, and water available to rice and other crops was traded to higher value horticulture crops which were thus able to maintain production. Overall, during the drought, a decline of about 2/3 in the volume of water available to irrigation led to a reduction of about 26% in the economic returns to irrigation (Kirby et al., in press). The 2750 GL reallocation is equivalent to about a 25% reduction in water available to irrigation, and is calculated to result in a reduction in returns of about 10%. The calculated results are also consistent with observed behaviour in the California droughts (Zilberman et al., 2002; Michael et al., 2010; Christian-Smith et al., 2011). The analysis also shows that the low value rice and cotton crops show the greatest variability in annual returns, with almost zero returns in the driest years in the case of rice. Again, this is as expected, and as observed in droughts – the most marginal production is the first to drop out when inputs become scarce and expensive.

The returns to irrigation in the various regions of the Murray–Darling Basin reflect the crop mix in each region. Rice and cotton regions, exemplified by the Gwydir and Murray regions, are calculated to show a considerable reduction in returns as a result of reallocations, and are also somewhat sensitive to climate change (Fig. 6). Other regions dominated by higher value are calculated to be less affected by reallocations and are not sensitive to climate change. Economic returns to all regions are calculated to vary less across years than in the base case, because of the lesser variation in annual diversions, as discussed above. This is a projection of what might happen (as discussed in Section 2.2 on scenarios) and other assumptions about future water management (as well as future commodity prices) might produce a different result. However, it does suggest that the reallocations can be implemented in such a way that irrigation overall becomes less sensitive to droughts than at present, except perhaps if the dry extreme climate change projection is realised.

Finally, consistent with our aim of examining the impact of water allocation and climate change, we have ignored other effects such as possible future changes to agricultural commodity prices and water use efficiency. We recognise that such effects could be important, and could produce long term adjustments to the areas used to produce different crops, but they are beyond the scope of this paper.

## 5. Conclusions

A simple, monthly hydrology model integrated with a regression-based model of irrigation economics has provided a useful approach to assessing the impacts of reallocating water from irrigation to the environment in a large and complex river basin. It has also provided a useful approach to assessing the interactions of reallocations with projected climate change.

Within the range of likely reallocations and projected climate change, river flows and irrigation diversions are less sensitive to differences in the total volume of water reallocated than to differences among climate change scenarios. Therefore, the risk posed by climate change should be fully evaluated and options considered in the water resource plans.

The returns to irrigation of the low value annual rice and cotton crops are reduced by reallocations, and are also sensitive to projected climate change. Dairying, a medium value activity, is less affected, and high value grape growing is barely affected by either reallocations or climate change. Low value rice and cotton crops show the greatest variability in annual returns, with almost zero returns in the driest years in the case of rice. High value crops show the least variability in annual returns.

In terms of regional impacts, those regions dominated by low value annual rice and cotton crops, such as the Gwydir and the Murray regions, are the most affected by reallocations and projected climate change. Regions dominated by high value crops, such as the South Australian Murray region, are the least affected by either reallocations or projected climate change.

## Acknowledgements

The study was funded by CSIRO Water for a Healthy Country. We thank several colleagues for helpful discussions, particularly Scott Keyworth, Ejaz Qureshi and Geoff Podger.

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