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Climate change impact on water and salt balances: an assessment of the impact of climate change on catchment salt and water balances in the Murray-Darling Basin, Australia

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Abstract Climate change has potentially significant implications for hydrology and the quantity and quality of water resources. This study investigated the impacts of climate change and revegetation on water and salt balance, and stream salt concentration for catchments within the Murray-Darling Basin, Australia. The Biophysical Capacity to Change model was used with climate change scenarios obtained using the CSIRO DARLAM 125 (125 km resolution) and Cubic Conformal (50 km resolution) regional climate models. These models predicted up to 25% reduction in mean annual rainfall and a similar magnitude of increase in potential evapotranspiration by 2070. Relatively modest changes in rainfall and temperature can lead to significant reductions in mean annual runoff and salt yield and increases in stream salt concentrations within the Basin. The modelled reductions in mean annual runoff were up to 45% in the wetter/cooler southern catchments and up to 64% in the drier/hotter western and northern catchments. The maximum reductions in salt yield were estimated to be up to 34% in the southern catchments and up to 49% in the northern and western catchments. These changes are associated with average catchment rainfall decreases of 13 to 21%. The results suggest that percentage changes in rainfall will be amplified in runoff. This study demonstrates that climate change poses significant challenges to natural resource management in Australia.

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1 Introduction

There is evidence that global climate is changing. The scientific basis for predicting future climate change and its impact on the carbon and water cycles is improving (IPCC 2001a, b), though it is recognised that the climate system is complex and interacts with land surface processes. There are many sources of uncertainty in predicting the impact of climate change on runoff, including the uncertainty associated with climate models, hydrologic models, and in social and economic predictions (Dooge et al. 1999). Increased greenhouse gases will lead to changes in a number of climate variables where rainfall is the main driver of variability in the hydrologic cycle. Changes in temperature and potential evapotranspiration (PET) may also affect the hydrologic cycle and hence runoff.

Australia's natural resources and agricultural systems are likely to be significantly affected by climate change (Pittock and Wratt 2001). These impacts will combine with baseline conditions, current trends in natural resource conditions, and the outcomes of regional natural resource management (NRM) interventions currently being planned and implemented. Climate change may cause some outcomes to differ from what is currently anticipated.

To date however, most NRM planning has assumed a constant climate when making estimates of future natural resource conditions and/or trends. This is due in part to limited understanding of potential impacts and appropriate adaptation strategies, particularly at the regional scale. Inclusion of climate change impact will assist in the setting of appropriate objectives and targets and help maximise the long-term benefits of actions.

The potential impact of climate change on runoff is commonly predicted by applying hydrological models using both current climate data and future climate change scenarios predicted by global climate models (GCMs). There are a number of reported studies addressing the effects of climate change on catchment scale water balance (IPCC 2001a) but these studies assumed no change in land use. On the other hand, there is a stream of research on the effect of land use change on water balance that does not consider climate change impact (Bosch and Hewlett 1982; Bradford et al. 2001; Zhang et al. 2001, 2003; Lane et al. 2005; Brown et al. 2005). These studies showed that changes in land cover such as afforestation can affect the hydrologic cycle and lead to reduction in mean annual streamflow and flow regime. There are few reported studies dealing with the effects of both climate change and land use change on catchment water balance (Herron et al. 2002).

Chiew et al. (1995) and Chiew and McMahon (2002) investigated the effects of climate change on runoff in some catchments across Australia by comparing the water balance components simulated by a hydrologic model using present climate data and future climate change scenarios. They concluded from these modelling studies that changes in rainfall would result in greater percentage changes in runoff, both increasing and decreasing. Changes in rainfall will lead to twice the percentage change in runoff for catchments in wet and temperate climates, while the changes in runoff are even greater for catchments in more arid regions. Annual runoff is estimated to decrease by up to 20% for catchments in the southeast of Australia by 2030 (Chiew and McMahon 2002). Jones and Page (2001) estimated change of 0 to −30% in runoff for the Macquarie River catchment by 2030 with a most likely range of 0 to −15%. Herron et al. (2002) estimated further reductions of 4% to 17% by 2030 from three reafforestation scenarios covering 2% to 10% of the upper catchment area. These reductions could be directly added to reductions due to climate change over most of the range, becoming non linear for larger changes. Beare and Heaney (2002) examined the effects of climate change on water resources and economic returns in the Murray-Darling Basin (MDB) to 2100 and concluded that a moderate increase in the rate of global warming would result in a substantial decline in stream flow and economic returns.

Najjar (1999) examined climate change estimates associated with a doubling in atmospheric CO_2 concentration in North America. They found that changes in rainfall resulted in up to twice the percentage change in runoff. Temperature changes were only very slightly correlated to changes in runoff, and were not significant compared to changes in rainfall. Wilk and Hughes (2002) examined historical land use change and theoretical climate change in a large (4100 km^2) river basin in southern India with 1638 mm of annual rainfall. Increased winter rainfall of 10% resulted in a mean annual increase in runoff of 17%, which is similar to a modelled 19% increase in runoff over 30 years from converting the current 47% native forest to agriculture. Again, the percentage change in runoff is greater than the percentage change in rainfall. More recently, Christensen et al. (2004) investigated the effects of climate change on the hydrology and water resources in the Colorado River Basin and predicted over 14% reduction in annual runoff for a climate change scenario of 3% reduction in precipitation and 1°C increase in average annual temperature.

This study provides estimates of catchment-scale impacts of climate change on water and salt balances. It also evaluates the combined impacts of climate change and revegetation on stream salt concentration. Using these estimates, it is possible to examine how the role of revegetation in catchment management strategies could be influenced by climate change. Specifically, it investigates the impacts of climate and land use change and the combined effects of these two changes on stream flow and stream salinity for the catchments in the MDB.

2 Catchment descriptions and methods

2.1 Catchment descriptions

The MDB is located in south eastern Australia. The majority of the Basin is within New South Wales and includes part of Victoria, Queensland and South Australia (Fig. 1). The geographic extent of the MDB is approximately 24°14′S to 37°30′S latitude and 138°20′E to 152°20′E longitude. For this study the Australian Water Resources Council (AWRC) catchment boundaries (AWRC 1976) were used to divide the MDB into smaller units. The characteristics of these catchments are summarised in Table 1.

Mean annual rainfall for the Basin ranges from 200 mm in the southwest to 1800 mm in the southeast, while elevation ranges from 0 m Australian Height Datum (AHD) at the Murray River mouth to 2225 m in the Upper Murray catchment.

The forest/non-forest data set used for this project is based on the National Carbon Accounting System (NCAS) Forest Extent mapping version 1, 2003 (Furby 2002). This attribute is defined as trees with height greater than 2 m and greater than 20% cover of a 25 m cell. Processing for the current project consisted of aggregating 25 m cells to 250 m and summing the values for the 100 cells. The resulting representation

Fig. 1 Murray-Darling Basin locality map showing the Australian Water Resources Council catchment boundaries and names

of forest cover is actually the percentage of these forested cells and has been termed modified NCAS (mNCAS). While the actual mNCAS forest cover values were used for analysis, for simplicity Fig. 2 shows forest cover as forest (>20% cover) or non-forest (<20% cover). The revegetation scenario involves the conversion of all cells to 100% woody vegetation, including partially-wooded cells. This scenario models the upper boundary of possible water yield impact by revegetation.

2.2 Methods

Potential climate change impacts on water and salt balances and the interactions of these impacts with revegetation were assessed by modelling salt and water balance responses to climate change and changes in land use.

Table 1 Characteristics of the Australian Water Resources Council catchments

ID	Catchment name	Area (km^2)	Mean annual rainfall (mm/year)[a]	Mean annual PET (mm/year)[a]	Forest cover (%)[b]
1	Upper Murray River	15389.9	1238	1545	67.9
2	Kiewa River	1908.8	1244	1547	52.7
3	Ovens River	7961.0	1102	1526	53.4
4	Broken River	7117.8	695	1515	12.4
5	Goulburn River	16855.4	961	1476	34.9
6	Campaspe River	4069.5	660	1493	14.8
7	Loddon River	15309.2	501	1506	14.3
8	Avoca River	14518.6	395	1564	7.6
9	Murray Riverina	15938.4	440	1583	10.8
10	Murrumbidgee River	81411.2	587	1641	16.3
11	Lake George	931.4	687	1547	27.7
12	Lachlan River	90927.2	494	1823	16.3
13	Benanee	24052.9	317	1790	31.8
14	Mallee	41029.6	330	1579	27.6
15	Wimmera-Avon Rivers	30788.5	439	1467	13.6
16	Border Rivers	48618.6	682	2058	25.5
17	Moonie River	14909.0	560	2168	18.0
18	Gwydir River	25004.0	679	2057	15.4
19	Namoi River	43329.6	681	2009	27.2
20	Castlereagh River	17719.9	577	2053	16.2
21	Macquarie-Bogan Rivers	74316.4	567	1986	18.1
22	Condamine-Culgoa Rivers	156939.8	548	2218	21.8
23	Warrego River	68789.9	474	2332	33.0
24	Paroo River	73556.9	315	2296	17.6
25	Darling River	108639.7	304	2028	21.8
26	Lower Murray River	59401.6	286	1750	27.4

[a] Mean annual rainfall and potential evapotranspiration (PET) values are the baseline estimates from the CSIRO Marine and Atmospheric Research regional climate models
[b] Forest cover is estimated from the modified National Carbon Accounting System dataset

2.2.1 Climate change scenarios

The climate change projections have been provided by the CSIRO Marine and Atmospheric Research, from in-house regional climate models (RCMs). These models dynamically downscale GCM outputs by using a finer resolution grid and more realistic topography, producing a more physically realistic simulation of regional climate. The models utilised for the projections include the 125 km resolution CSIRO DARLAM 125 (DAR125) RCM (Whetton et al. 2000) and the 50 km resolution CSIRO Cubic Conformal (CC50) RCM (Suppiah et al. 2004). The DAR125 RCM was nested in the CSIRO Mark2 model forced by the IPCC92a emission scenario and the CC50 RCM in CSIRO Mark3 model forced by the A1B emission scenario. The performance of these models in simulating regional climate has been assessed for all four states covering the Murray-Darling Basin, published in numerous research reports.

Scenarios for both 2030 and 2070 were provided for local changes in temperature, rainfall and atmospheric CO$_2$. The scenarios were constructed from the pattern-scaled local response in temperature and rainfall expressed as change per degree of global warming (Whetton et al. 2005). Given the largest driver affecting changes in

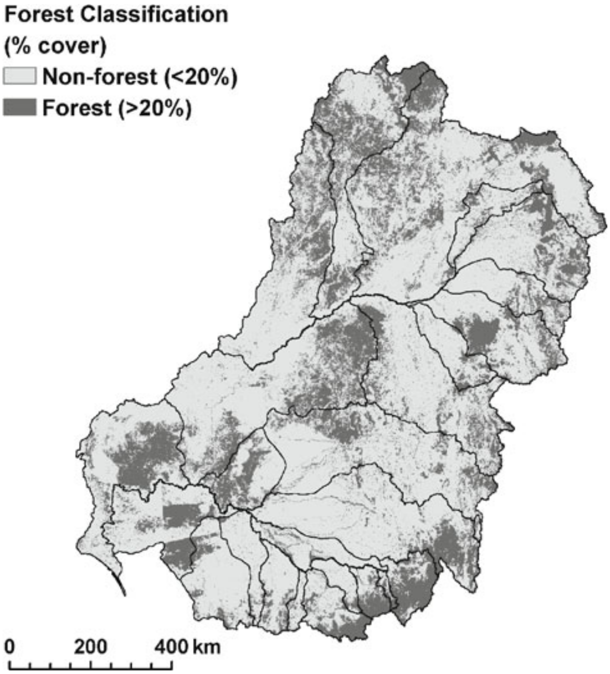

Fig. 2 Modified National Carbon Accounting System forest classification

water and salt balances is likely to be rainfall change we chose to explore the impact of lower and higher rainfall changes (or, more accurately, wetter and drier scenarios) in preference to temperature and atmospheric CO_2 changes.

When constructing the scenarios, we selected a median greenhouse gas emission scenario combined with a median climate sensitivity response (2.6°C; IPCC 2001a) and represented a range of regional rainfall change by using a 'wet' and a 'dry' RCM simulation. This produced a single value of global warming and atmospheric CO_2 for both 2030 and 2070. RCMs were preferred to GCMs because of their finer spatial resolution and the two available covered most of the range of the rainfall change of the models held at the time. The different rainfall responses of the RCMs were due to their being nested in different GCMs and different internal physics, particularly convection and land surface schemes.

The median IPCC SRES A1B marker scenario (IPCC 2001a) was the selected greenhouse gas scenario producing a CO_2 concentration of 454 ppm in 2030 and 611 ppm in 2070. From a 1990 baseline, a mean global warming of 0.85°C is reached by 2030 and 2.30°C by 2070.

Local change patterns were developed from each of the models by determining the pattern of change for the local region compared to the average change across the entire globe (average global warming). This pattern, describing the model change for one degree of global warming, was then scaled by the IPCC SRES A1B scenario. Maps of these changes for the Basin show large decreases in rainfall in CC50 and mixed responses in DAR125 (Fig. 3). The main reasons for these differences in rainfall were due to the RCMs being nested in different GCMs and to the improved convection scheme included in the CC50 RCM (McGregor 2003).

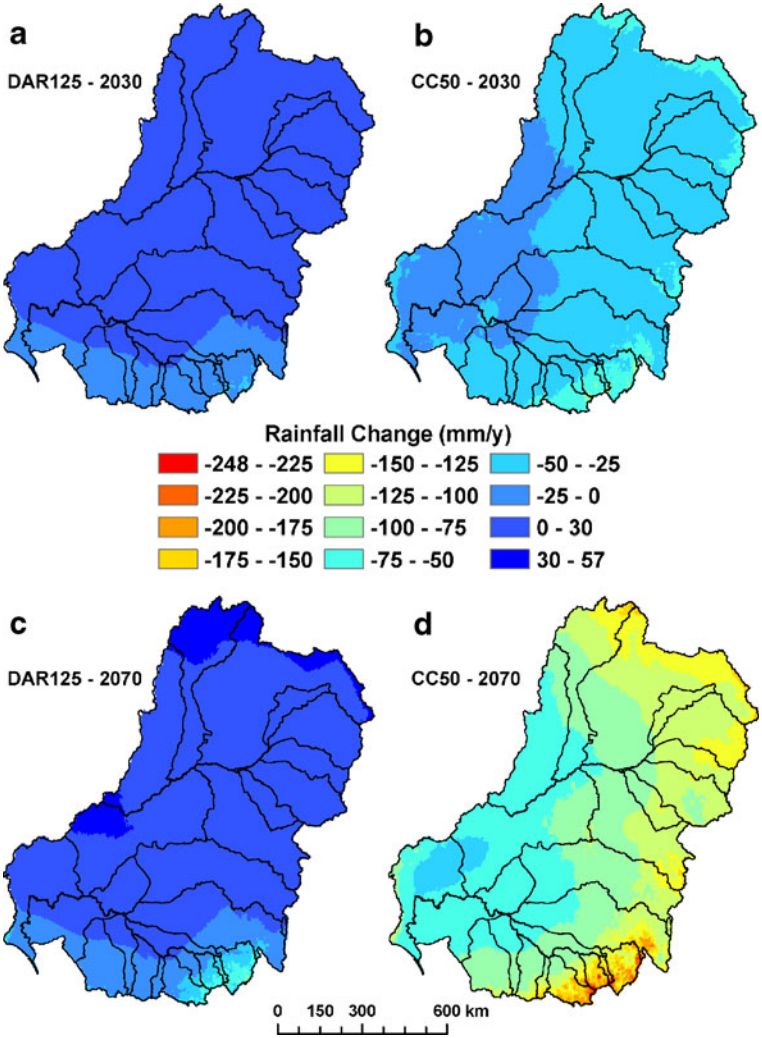

Fig. 3 Projected change in rainfall for 2030 and 2070 from the DARLAM125 (DAR125) and Cubic Conformal (CC50) regional climate models

Figure 3a and b show changes of −30 to +20 mm/year for DAR125 and −90 to −15 mm/year for CC50 over the Basin in 2030 compared to the modeled baseline values. Baseline values are 1961–90 for rainfall and temperature from the Bureau of Meteorology high quality data set. Figure 3c and d show the projected changes for 2070, with DAR125 projecting annual changes in rainfall of −85 to +57 mm/year and CC50 projecting changes of −248 to −40 mm/year. Figure 4 shows the projected annual changes in PET by 2030 and 2070 for both climate scenarios. By 2030, DAR125 shows increases in PET of between 44 and 106 mm/year (Fig. 4a), while CC50 shows increases of between 46 and 259 mm/year (Fig. 4b). By 2070, the changes

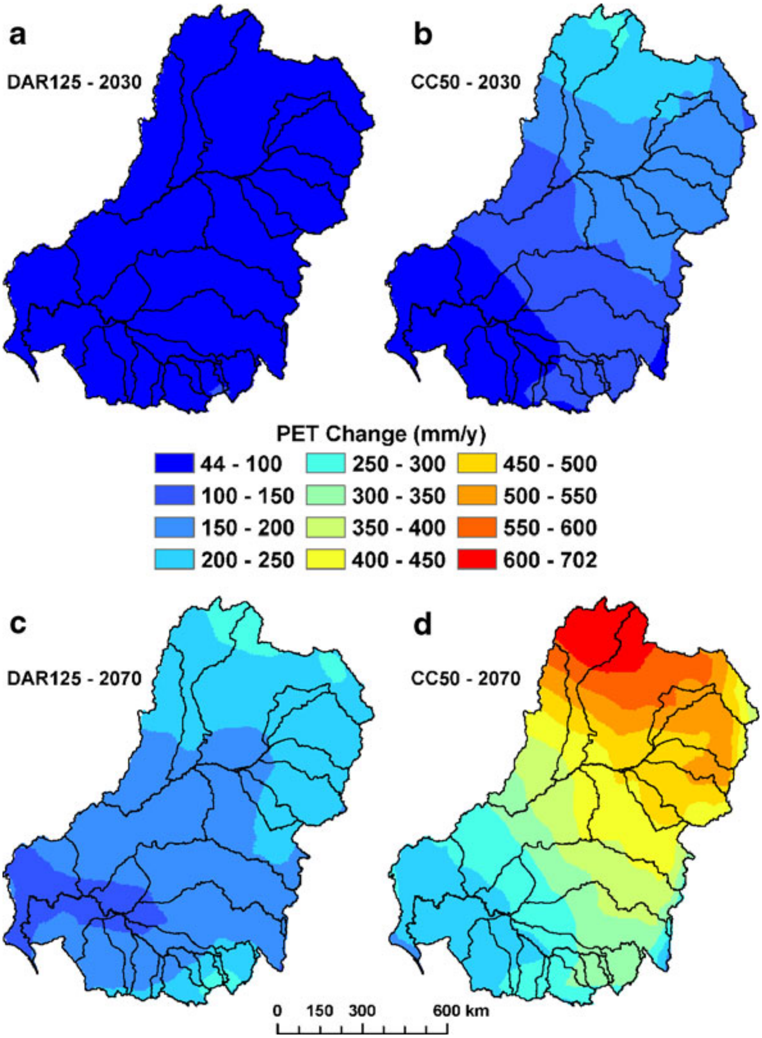

Fig. 4 Projected change in potential evapotranspiration (PET) for 2030 and 2070 from the DARLAM125 (DAR125) and Cubic Conformal (CC50) regional climate models

are much larger, with DAR125 showing increases in PET of 118 to 288 mm/year (Fig. 4c) and CC50 showing increases of 124 to 702 mm/year (Fig. 4d).

These projections result in low and medium/high impacts for the catchments. DAR125 has a less dramatic drying pattern (smaller decreases to annual rainfall in the southern part of the Basin and small increases in the north) and consequently a lower impact. CC50 expresses a more dramatic drying pattern (larger decreases to annual rainfall) and a higher impact to the catchments.

Baseline climate was also modelled using the methods described above to ensure that the projections from the DAR125 and CC50 RCMs could be directly compared.

A no change scenario is the baseline climate where rainfall, temperature and PET remain constant.

2.2.2 Biophysical capacity to change model

This study applies the Biophysical Capacity to Change (BC2C) model to assess the impacts of climate and vegetation changes on runoff and salt balance (Dawes et al. 2004a). The BC2C model is a conceptual framework that links changes in land-use to changes in stream flow volume and salt yield (Dowling et al. 2004; Evans et al. 2004; Gilfedder et al. 2009). The model is aimed at assisting catchment managers and policy makers to make rapid assessments of the gross change in salt and water balance in response to land-use change (van Dijk et al. 2004, 2005, 2008). The water balance model in BC2C is based on Zhang et al. (2001) and considers the effects of changes in rainfall and PET on mean annual water yield. When combined with salt fluxes in ground and surface water, it allows estimation of the impacts of climate change and revegetation on catchment scale water and salt balances. With appropriate assumptions and simplifications (summarised below), changes in mean annual runoff from the baseline can be estimated using only the relative deviations of rainfall and PET projected into the future.

All computations in BC2C were performed in ARC/INFO™ based on grids of input variables at the nominal resolution of 250 m. Individual cell values can be compared to aggregates at sub and whole of catchment scales. The BC2C model used in this study has three steps.

The first step is to estimate total excess water based on mean annual rainfall and tree cover using the model of Zhang et al. (2001). In an equilibrated system, the stream flow is equal to the excess water regardless of the pathway that water takes to the stream, *e.g.* overland, shallow sub-surface, or groundwater flow. When a change is made that affects the water balance, such as modifying the vegetation cover or changing the annual rainfall and PET, it is necessary to follow the fate of water more closely, so excess water is split into surface and groundwater components depending on soil type and geology, as in Dawes et al. (2004b) and Dowling et al. (2004). The second step models salt mobilisation. The surface water is assumed to carry all the salt that falls in rainfall to the stream each year. Groundwater recharge mixes below the ground surface and can discharge slowly to the stream over decades or centuries, flushing salt with it. It is this relatively high salinity water that affects stream salt concentration and it may take many years for this saline groundwater discharge to re-equilibrate. Time dependence is achieved using an analytic logistic curve that converts step changes in recharge to a smooth change over time. This avoids a strict time-stepping model that would otherwise require much more data input and computation time, and the tracking of water and salt through the landscape.

The final step converts water and salt yields to stream salt concentration. One of the key features of BC2C is the spatial prediction of areas which have the greatest impact on salinity and salt yields at any given catchment outlet. This capability is based on: a) maintaining a water and salt balance for each cell throughout calculations; b) considering only local and intermediate groundwater systems that allow a linear aggregation of water and salt from catchments; c) considering any land use change to be a perturbation of the water balance at the catchment outlet. It should be noted that the salinity benefits in any given cell that result from land use change in a small catchment may be completely different from the salinity benefits at the outlet of that catchment.

The formula used to rescale changes in salinity, also referred to as flow-weighted electrical conductivity (FWEC) is:

$$\Delta EC_p = \left(\frac{\Delta S_p}{\Delta W_p} - \frac{S_C}{W_C} \right) \times \frac{\Delta W_p}{W_C} \times \frac{1000}{0.6} \tag{1}$$

where S refers to salt yield, W to water yield, and the subscripts are p for cell (pixel) based values and C for whole catchment values. Units are S_p–t/cell, S_C–t/catchment, W_p–ML/cell, W_C–ML/catchment. The first term in parentheses derives the salinity of the changed salt and water yield compared to the whole catchment before change occurred, the middle term flow weights the change in each cell to the whole catchment flow, and the final term is the conversion of units to electrical conductivity (EC).

The basis of the groundwater salt and water modelling is Groundwater Flow Systems (GFSs) (Coram et al. 2000) (Fig. 5). This is a classification based on the scale of groundwater discharge processes present. The primary level of discrimination is

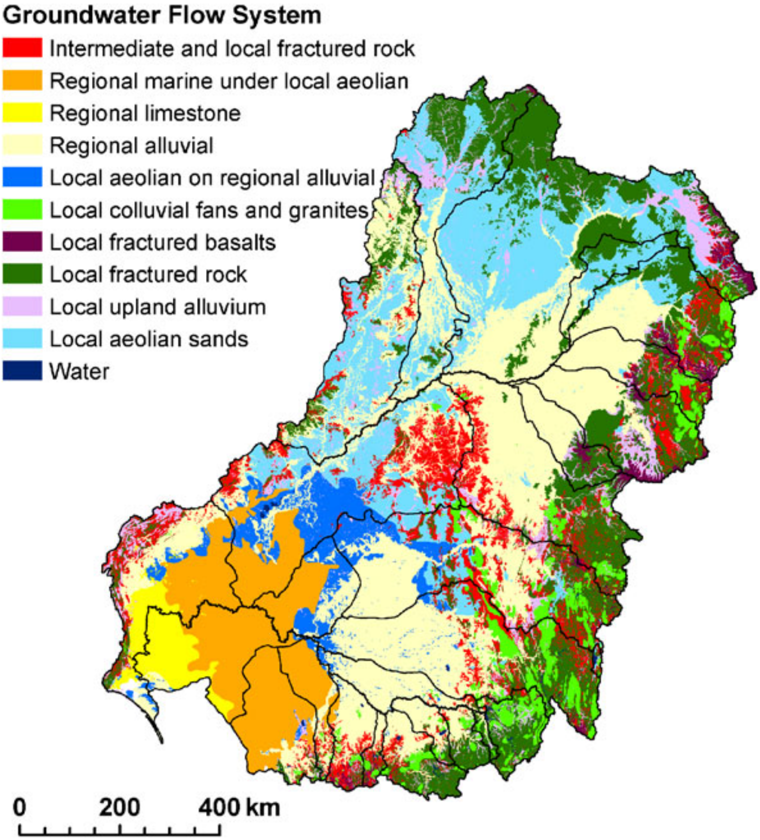

Fig. 5 1:1,000,000 scale Murray-Darling Basin groundwater flow systems

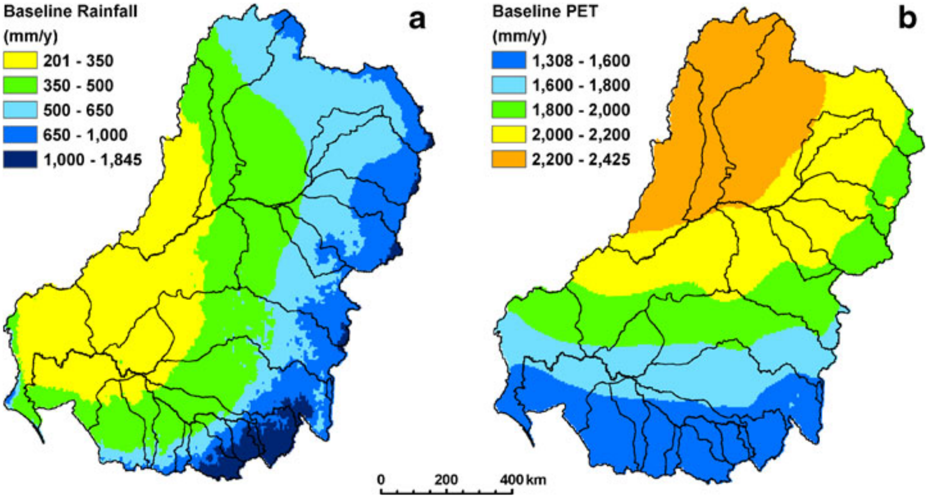

Fig. 6 Modelled baseline mean annual rainfall and potential evapotranspiration (PET)

geology representing the scale of groundwater flow from recharge to discharge areas. Local GFSs are the smallest class (<5 km), usually within a single aquifer, and having a relatively rapid response to recharge change (<25 years). Intermediate GFSs (5–50 km) may contain layered systems, have variable geology and aquifers, and can take up to 100 years to reach a new equilibrium. Regional GFSs are the largest systems (>50 km), are often layered with Intermediate and Local GFSs above, may pass below major discharge features such as rivers, may take many hundreds of years to adjust to a new recharge regime and are not suited to this sort of modelling.

Regional GFSs are assigned an arbitrary small value of salt generation equal to 0.01 t/km^2. In contrast, reductions in surface runoff over Regional GFSs can be modelled in the same way as over Local and Intermediate GFSs, thus the Regional GFSs appear to always suffer a decrease in water yield while maintaining the same salt generation, and incur a corresponding increase in stream salt concentration. Although GFSs have been mapped at a variety of scales, in this study 1:1,000,000 scale GFS data were used because attributes required by this BC2C version were available at the time the modelling was completed.

The inputs required for BC2C include catchment boundaries and vegetation cover as described in Section 2.1 and GFSs as described above. Other required datasets are mean annual rainfall (Fig. 6a), and mean annual PET (Fig. 6b).

3 Results

Mapped results are presented for changes in water and salt yield and FWEC by 2030 and 2070 under scenarios of DAR125 climate change and current land use; revegetation with no climate change; and DAR125 climate change and revegetation. These combinations allow viewing of the independent and combined effects of climate change and revegetation. The baseline water yield, salt yield, and EC maps are included to allow easy comparison with scenarios. Mapped results for CC50 are not presented to simplify figures. Results for both climate change scenarios are presented in tables to show their comparative impact, with salinity shown as changes in EC at the catchment outlet or end-of-valley (EOV).

The BC2C outputs show changes in water and salt yield as increasing or decreasing with respect to the baseline, while the FWEC maps also include a neutral class. A neutral result indicates either (i) that the modelled change is too small to be significant, or (ii) that the cell is water (a dam or reservoir) and that there is no change.

3.1 Water yield impact

Figure 7 shows the spatial distribution of mean annual water yield and predicted changes in the Basin under the scenarios. The baseline mean annual water yield (Fig. 7a) varies from 0.5 mm in the west to nearly 800 mm in the uplands. Generally the results show that areas with higher baseline water yield values have a larger water yield reduction under the different climate and revegetation scenarios, with the greatest impacts appearing in the uplands in the south-eastern part of the Basin.

Assuming only climate change (Fig. 7b and c), water yield will decrease by up to 10 mm/year in the majority of the Basin and between 10 and 40 mm/year for the uplands, under the DAR125 scenario for both 2030 and 2070. On the other hand, with revegetation of non-forested areas (Fig. 7d and e) water yield will reduce by between 10 and 150 mm/year over more than one third of the basin and up to 450 mm/year in some small, very high rainfall areas that are not currently forested. The combined effect of climate change and revegetation on water yield will be greater (Fig. 7f

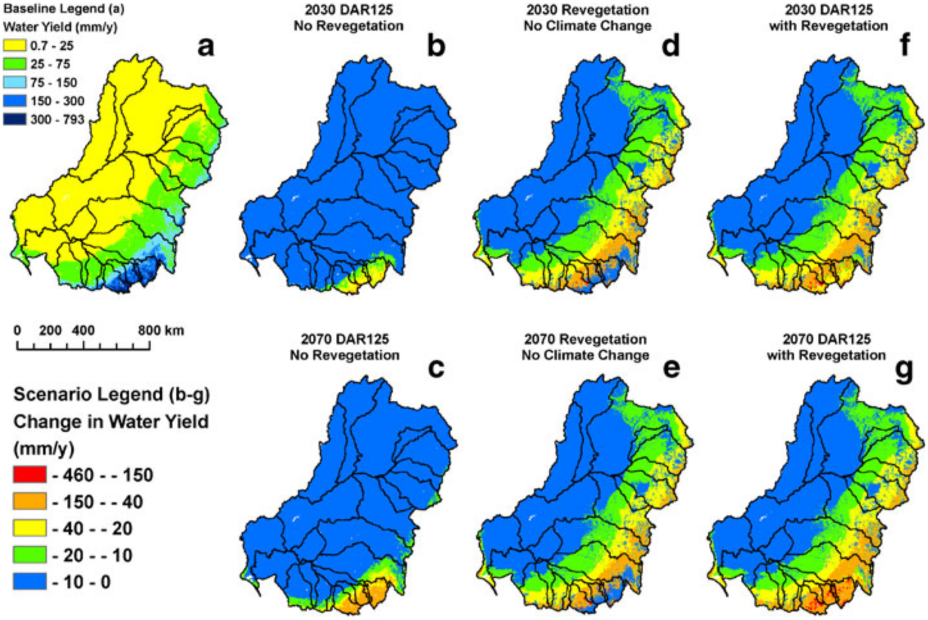

Fig. 7 Maps of change in water yield under DARLAM125 (DAR125) climate and revegetation scenarios for 2030 and 2070

Table 2 Absolute and percentage changes in water yield

ID	AWRC catchment	Climate scenario[a]	2030		2070	
			Absolute (ML/km^2/year)	% change	Absolute (ML/km^2/year)	% change
1	Upper Murray River	Baseline	256.2		256.2	
		DAR125	232.2	−9.34	196.1	−23.46
		CC50	209.3	−18.29	144.8	−43.46
2	Kiewa River	Baseline	288.9		288.9	
		DAR125	262.3	−9.19	222.1	−23.11
		CC50	237.7	−17.72	166.1	−42.51
3	Ovens River	Baseline	228.4		228.4	
		DAR125	207.1	−9.31	175.2	−23.29
		CC50	186.1	−18.53	127.9	−44.02
4	Broken River	Baseline	111.0		111.0	
		DAR125	102.7	−7.52	90.0	−18.92
		CC50	89.7	−19.16	61.2	−44.91
5	Goulburn River	Baseline	212.1		212.1	
		DAR125	195.2	−7.98	169.2	−20.22
		CC50	175.5	−17.26	123.9	−41.60
6	Campaspe River	Baseline	103.3		103.3	
		DAR125	96.3	−6.74	85.6	−17.09
		CC50	82.6	−20.03	54.7	−47.02
7	Loddon River	Baseline	51.0		51.0	
		DAR125	47.7	−6.44	42.7	−16.25
		CC50	40.4	−20.90	26.5	−48.12
8	Avoca River	Baseline	27.1		27.1	
		DAR125	25.7	−5.39	23.4	−13.56
		CC50	21.6	−20.47	14.5	−46.53
9	Murray Riverina	Baseline	34.2		34.2	
		DAR125	32.4	−5.08	29.8	−12.85
		CC50	27.0	−21.02	17.8	−47.92
10	Murrumbidgee River	Baseline	64.9		64.9	
		DAR125	61.2	−5.62	55.6	−14.31
		CC50	51.6	−20.51	34.1	−47.40
11	Lake George	Baseline	75.4		75.4	
		DAR125	71.9	−4.60	66.5	−11.84
		CC50	60.8	−19.31	41.2	−45.37
12	Lachlan River	Baseline	33.8		33.8	
		DAR125	32.7	−3.34	30.9	−8.56
		CC50	26.3	−22.12	16.9	−50.11
13	Benanee	Baseline	8.1		8.1	
		DAR125	8.1	0.19	8.2	0.63
		CC50	6.2	−23.51	3.9	−52.21
14	Mallee	Baseline	13.2		13.2	
		DAR125	12.6	−4.52	11.7	−11.34
		CC50	10.7	−18.74	7.6	−42.20
15	Wimmera-Avon River	Baseline	39.1		39.1	
		DAR125	36.4	−7.01	32.3	−17.46
		CC50	31.4	−19.56	21.6	−44.76
16	Border Rivers	Baseline	32.7		32.7	
		DAR125	31.6	−3.14	30.0	−8.01
		CC50	24.7	−24.25	15.1	−53.67

Table 2 (continued)

ID	AWRC catchment	Climate scenario[a]	2030 Absolute (ML/km^2/year)	2030 % change	2070 Absolute (ML/km^2/year)	2070 % change
17	Moonie River	Baseline	16.6		16.6	
		DAR125	16.2	−2.28	15.6	−5.77
		CC50	11.9	−28.29	6.5	−60.62
18	Gwydir River	Baseline	37.7		37.7	
		DAR125	36.4	−3.30	34.5	−8.42
		CC50	28.9	−23.38	18.1	−51.87
19	Namoi River	Baseline	41.5		41.5	
		DAR125	40.0	−3.66	37.6	−9.40
		CC50	32.6	−21.47	21.4	−48.60
20	Castlereagh River	Baseline	28.0		28.0	
		DAR125	27.1	−3.33	25.6	−8.53
		CC50	21.1	−24.48	12.8	−54.25
21	Macquarie-Bogan Rivers	Baseline	35.4		35.4	
		DAR125	34.1	−3.49	32.2	−8.95
		CC50	27.4	−22.43	17.5	−50.66
22	Condamine-Culgoa Rivers	Baseline	15.1		15.1	
		DAR125	14.9	−1.76	14.5	−4.43
		CC50	11.0	−27.10	6.3	−58.66
23	Warrego River	Baseline	7.1		7.1	
		DAR125	7.1	0.36	7.1	1.12
		CC50	4.9	−30.25	2.6	−63.54
24	Paroo River	Baseline	3.5		3.5	
		DAR125	3.5	1.68	3.6	4.63
		CC50	2.5	−27.27	1.4	−58.75
25	Darling River	Baseline	5.3		5.3	
		DAR125	5.4	1.36	5.5	3.89
		CC50	3.9	−26.09	2.3	−56.68
26	Lower Murray River	Baseline	10.0		10.0	
		DAR125	9.6	−4.15	9.0	−10.53
		CC50	8.1	−19.18	5.6	−44.37

[a] Baseline values of water yield refer to model output for current climate and vegetation cover

and g), with larger areas subject to reductions of up to 450 mm/year. The impacts of the different scenarios are greater by 2070 than 2030, with more areas showing greater reductions in water yield.

Table 2 summarises the impact of climate change on water yield for 2030 and 2070. Water yield reductions of up to 25% are seen by 2070 for various AWRC catchments under the DAR125 scenario, while the CC50 scenario consistently predicts reductions of approximately 50% for many catchments by 2070. For the drier catchments these percentages appear quite large, however in absolute terms the annual water yield reduction estimates are quite small when compared to many of the wetter south eastern catchments. These wetter catchments show reductions of up to 50 mm/year by 2070 with the DAR125 scenario and up to 100 mm/year with the CC50 scenario. A number of the drier northern catchments show very small overall increases in water yield for the DAR125 scenarios. This is due to the climate model predicting small (<60 mm/year) increases in mean annual rainfall for these areas (Fig. 3a and c).

3.2 Salt yield impact

Figure 8 shows the spatial distribution of annual salt yield and predicted changes across the Basin under the scenarios. The baseline salt yield has large spatial variability dictated by the distribution of groundwater flow systems (Fig. 8a). Generally the scenario results show the greatest reductions in salt yield in the upland areas of the south east.

Assuming climate change only for 2030, salt yield will slightly increase (<10 kg/ha/year) in the arid western parts of the Basin and decrease by up to 30 kg/ha/year in most of the remaining areas (Fig. 8b). By 2070 the salt yield reduction pattern remains similar to that of 2030, however in local GFS areas the salt yield reduction will be up to 150 kg/ha/year (Fig. 8c).

The revegetation-only scenarios (Fig. 8d and e) show large reductions in salt yield in local GFS areas for both 2030 and 2070. Local GFSs that are classified as non-forest under baseline conditions show decreases in salt yield of greater than 150 kg/ha/year under the revegetation scenarios. In contrast to the climate change only scenarios, there are no areas with increasing salt yield under revegetation-only.

Under the scenarios with combined climate change and revegetation (Fig. 8f and g) some areas show a small increase in salt yield however the majority show larger reductions than the revegetation-only scenarios. This is due to the combined effect

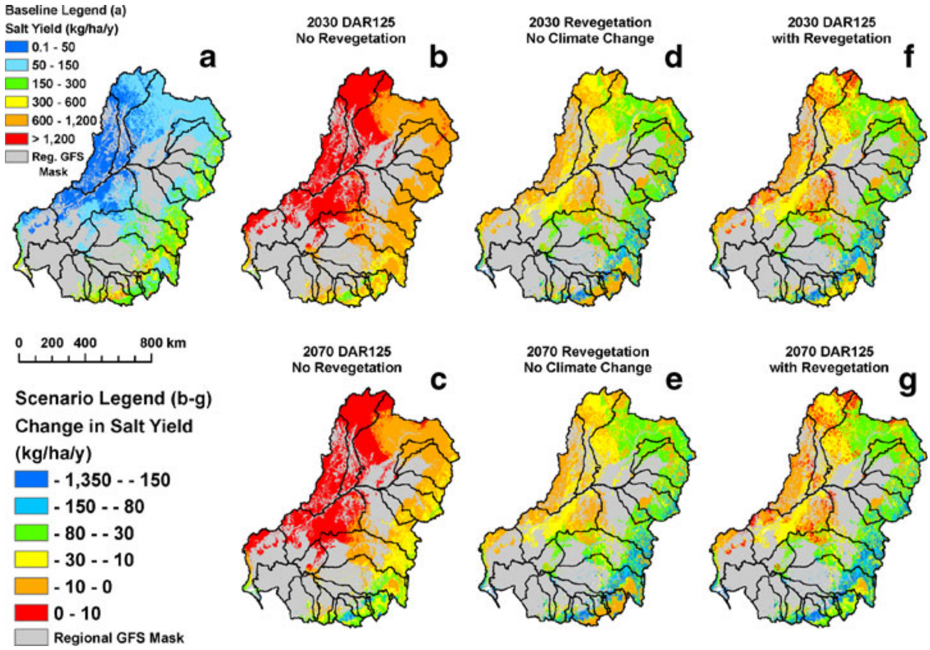

Fig. 8 Maps of change in salt yield under DARLAM125 (DAR125) climate and revegetation scenarios for 2030 and 2070 with regional groundwater flow systems (GFS) masked

Table 3 Absolute and percentage changes in salt yield

ID	AWRC catchment	Climate scenario[a]	2030		2070	
			Absolute (kg/ha/year)	% change	Absolute (kg/ha/year)	% change
1	Upper Murray River	Baseline	260.31		260.31	
		DAR125	244.68	−6.01	217.58	−16.41
		CC50	226.92	−12.83	173.83	−33.22
2	Kiewa River	Baseline	256.10		256.10	
		DAR125	240.59	−6.06	212.85	−16.89
		CC50	222.91	−12.96	167.85	−34.46
3	Ovens River	Baseline	189.71		189.71	
		DAR125	179.64	−5.31	161.85	−14.69
		CC50	167.55	−11.68	131.35	−30.76
4	Broken River	Baseline	199.54		199.54	
		DAR125	191.53	−4.01	176.42	−11.59
		CC50	173.70	−12.95	131.15	−34.27
5	Goulburn River	Baseline	331.32		331.32	
		DAR125	317.06	−4.30	290.78	−12.24
		CC50	296.46	−10.52	236.97	−28.48
6	Campaspe River	Baseline	349.86		349.86	
		DAR125	340.33	−2.73	321.88	−8.00
		CC50	318.96	−8.83	265.82	−24.02
7	Loddon River	Baseline	160.55		160.55	
		DAR125	156.91	−2.27	149.46	−6.91
		CC50	146.73	−8.61	122.55	−23.67
8	Avoca River	Baseline	54.16		54.16	
		DAR125	53.00	−2.14	50.66	−6.46
		CC50	48.59	−10.28	39.35	−27.34
9	Murray Riverina	Baseline	94.50		94.50	
		DAR125	91.06	−3.64	84.60	−10.47
		CC50	79.31	−16.07	55.52	−41.25
10	Murrumbidgee River	Baseline	159.96		159.96	
		DAR125	155.85	−2.57	148.15	−7.38
		CC50	141.68	−11.43	112.58	−29.62
11	Lake George	Baseline	332.51		332.51	
		DAR125	324.74	−2.33	310.51	−6.62
		CC50	298.52	−10.22	244.41	−26.50
12	Lachlan River	Baseline	131.23		131.23	
		DAR125	129.61	−1.24	126.48	−3.62
		CC50	115.90	−11.68	92.46	−29.54
13	Benanee	Baseline	41.10		41.10	
		DAR125	41.25	0.36	41.49	0.95
		CC50	32.76	−20.29	21.35	−48.05
14	Mallee	Baseline	24.67		24.67	
		DAR125	23.91	−3.10	22.52	−8.71
		CC50	19.87	−19.46	12.49	−49.37
15	Wimmera-Avon Rivers	Baseline	36.37		36.37	
		DAR125	35.06	−3.63	32.62	−10.31
		CC50	32.66	−10.21	26.59	−26.89
16	Border Rivers	Baseline	108.17		108.17	
		DAR125	106.72	−1.34	103.99	−3.86
		CC50	93.89	−13.21	72.70	−32.79

Table 3 (continued)

ID	AWRC catchment	Climate scenario[a]	2030		2070	
			Absolute (kg/ha/year)	% change	Absolute (kg/ha/year)	% change
17	Moonie River	Baseline	71.81		71.81	
		DAR125	70.92	−1.25	69.49	−3.24
		CC50	56.39	−21.47	36.85	−48.68
18	Gwydir River	Baseline	114.39		114.39	
		DAR125	112.77	−1.41	109.61	−4.18
		CC50	102.86	−10.08	84.52	−26.11
19	Namoi River	Baseline	120.52		120.52	
		DAR125	118.17	−1.95	113.60	−5.74
		CC50	106.57	−11.58	84.15	−30.18
20	Castlereagh River	Baseline	57.85		57.85	
		DAR125	56.47	−2.39	53.84	−6.93
		CC50	47.68	−17.58	32.22	−44.31
21	Macquarie-Bogan Rivers	Baseline	106.58		106.58	
		DAR125	104.79	−1.69	101.27	−4.99
		CC50	94.28	−11.55	74.25	−30.34
22	Condamine-Culgoa Rivers	Baseline	62.99		62.99	
		DAR125	62.69	−0.47	62.19	−1.28
		CC50	51.28	−18.59	35.62	−43.45
23	Warrego River	Baseline	39.53		39.53	
		DAR125	40.10	1.42	41.09	3.94
		CC50	32.37	−18.12	22.91	−42.04
24	Paroo River	Baseline	19.04		19.04	
		DAR125	19.48	2.30	20.24	6.32
		CC50	16.31	−14.33	12.52	−34.27
25	Darling River	Baseline	34.41		34.41	
		DAR125	35.16	2.16	36.43	5.87
		CC50	29.82	−13.36	23.37	−32.10
26	Lower Murray River	Baseline	45.82		45.82	
		DAR125	44.86	−2.11	43.10	−5.95
		CC50	40.64	−11.30	32.18	−29.77

[a] Baseline values of salt yield refer to model output for current climate and vegetation cover

of reducing groundwater recharge through drier climates and through greater water use by vegetation. It is also clear that the reduction in salt yield increases over time. For example, by 2030 salt yield reduction is estimated to be up to 880 kg/ha/year in the south eastern upland areas of the Basin with climate change and revegetation; this reduction increases to between 150 to 1100 kg/ha/year by 2070. The reductions are significant compared to the baseline salt yield estimates of 300 to 1200 kg/ha/year.

Table 3 summarises the impact of climate change on salt yield for each AWRC catchment by 2030 and 2070 without revegetation. The overall change in salt yield for these catchments is predominantly dependent on rainfall and the salinity of the underlying GFS. Local GFSs are usually well flushed and thus have lower salt concentrations; they contribute less salt than the intermediate GFSs. Generally, there are substantially greater impacts with the CC50 scenario compared to DAR125. The catchments show a reduction of salt yield of up to 17% by 2070 under the DAR125 scenario and up to 50% by 2070 for the CC50. Only the arid catchments of Benanee, Paroo, Warrego and the Darling show increases in salt yield under the DAR125 climate scenario in both 2030 and 2070. The DAR125 climate model predicts an increase in rainfall for some parts of these catchments (Fig. 3a and c), resulting in increased flushing of the GFS and larger salt yields.

3.3 Salinity impact

The salinity impacts from the climate and revegetation scenarios shown in Fig. 9 are displayed as the contribution of each cell (250 m resolution) to the EOV EC change for a given scenario. Although the changes are very small relative to the total EOV catchment change (Table 4) and to the baseline values, it is important to show how the responses vary spatially within each catchment.

The baseline EC in the MDB varies between 150 and 6500 μS/cm (Fig. 9a). BC2C predicts that by 2030 DAR125 climate change will have little impact on FWEC and the AWRC catchments predominantly show areas with EC changes of less than 0.001 μS/cm per cell (Fig. 9b). By 2070 the DAR125 climate impact is more visible (Fig. 9c), with more areas showing changes to FWEC as the corresponding groundwater flow systems respond to the changes in groundwater recharge regime. The areas showing a decreasing FWEC are generally associated with local GFSs. Across the Basin the results vary markedly, with many catchments showing decreases in FWEC per cell and others showing increases.

When revegetation is considered as a scenario (Fig. 9d and e), the unmasked areas in many of the AWRC catchments show unfavourable salinity impacts for

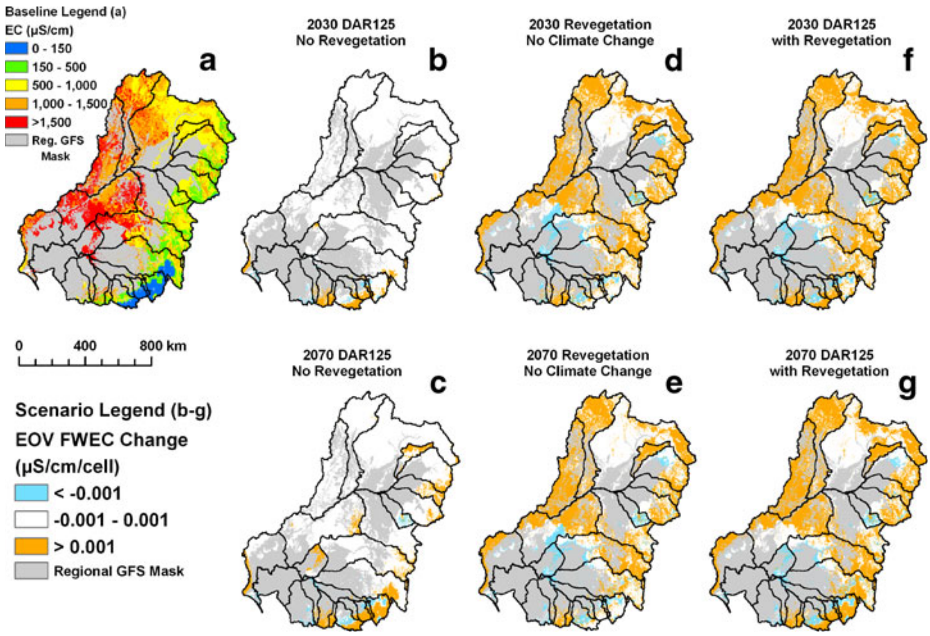

Fig. 9 Maps of end-of-valley (EOV) flow-weighted electrical conductivity (FWEC) change per cell under DARLAM125 (DAR125) climate and revegetation scenarios for 2030 and 2070 with regional groundwater flow systems (GFS) masked

Table 4 Absolute and percentage changes for end-of-valley salinity (electrical conductivity)

ID	AWRC catchment	Climate scenario[a]	2030		2070	
			Absolute (μS/cm)[b]	% change	Absolute (μS/cm)[b]	% change
1	Upper Murray River	Baseline	169.36		169.36	
		DAR125	174.51	3.04	180.77	6.74
		CC50	178.10	5.16	186.22	9.95
2	Kiewa River	Baseline	147.74		147.74	
		DAR125	152.28	3.07	156.84	6.16
		CC50	154.68	4.69	159.55	7.99
3	Ovens River	Baseline	138.42		138.42	
		DAR125	143.51	3.68	149.90	8.30
		CC50	147.42	6.50	156.34	12.95
4	Broken River	Baseline	299.59		299.59	
		DAR125	309.74	3.39	321.19	7.21
		CC50	317.80	6.08	331.12	10.52
5	Goulburn River	Baseline	260.36		260.36	
		DAR125	269.26	3.42	280.51	7.74
		CC50	277.22	6.48	293.90	12.88
6	Campaspe River	Baseline	564.49		564.49	
		DAR125	586.84	3.96	615.51	9.04
		CC50	627.41	11.15	694.02	22.94
7	Loddon River	Baseline	524.58		524.58	
		DAR125	545.42	3.97	572.52	9.14
		CC50	587.98	12.09	651.90	24.27
8	Avoca River	Baseline	332.86		332.86	
		DAR125	342.70	2.96	355.61	6.83
		CC50	365.91	9.93	395.88	18.93
9	Murray Riverina	Baseline	461.25		461.25	
		DAR125	467.03	1.25	471.39	2.20
		CC50	488.98	6.01	491.17	6.49
10	Murrumbidgee River	Baseline	422.25		422.25	
		DAR125	431.69	2.24	448.39	6.19
		CC50	457.60	8.37	494.68	17.15
11	Lake George	Baseline	746.54		746.54	
		DAR125	763.56	2.28	785.77	5.25
		CC50	814.72	9.13	887.99	18.95
12	Lachlan River	Baseline	648.79		648.79	
		DAR125	657.85	1.40	675.94	4.18
		CC50	712.93	9.89	778.94	20.06
13	Benanee	Baseline	842.73		842.73	
		DAR125	843.92	0.14	845.29	0.30
		CC50	869.33	3.16	877.28	4.10
14	Mallee	Baseline	311.26		311.26	
		DAR125	313.09	0.59	316.83	1.79
		CC50	306.42	−1.55	286.40	−7.99
15	Wimmera-Avon Rivers	Baseline	155.09		155.09	
		DAR125	158.40	2.13	164.23	5.89
		CC50	167.65	8.10	180.87	16.62
16	Border Rivers	Baseline	551.98		551.98	
		DAR125	558.78	1.23	571.89	3.61
		CC50	610.77	10.65	666.12	20.68

Table 4 (continued)

ID	AWRC catchment	Climate scenario[a]	2030		2070	
			Absolute (μS/cm)[b]	% change	Absolute (μS/cm)[b]	% change
17	Moonie River	Baseline	722.23		722.23	
		DAR125	728.68	0.89	739.37	2.37
		CC50	771.40	6.81	808.49	11.94
18	Gwydir River	Baseline	505.95		505.95	
		DAR125	513.68	1.53	525.67	3.90
		CC50	571.65	12.99	635.09	25.52
19	Namoi River	Baseline	483.55		483.55	
		DAR125	489.17	1.16	498.95	3.18
		CC50	529.13	9.43	571.20	18.13
20	Castlereagh River	Baseline	344.43		344.43	
		DAR125	347.27	0.82	349.43	1.45
		CC50	367.67	6.75	378.39	9.86
21	Macquarie-Bogan Rivers	Baseline	504.59		504.59	
		DAR125	509.05	0.88	520.28	3.11
		CC50	554.52	9.90	604.63	19.83
22	Condamine-Culgoa Rivers	Baseline	693.49		693.49	
		DAR125	696.24	0.40	706.86	1.93
		CC50	751.78	8.40	798.47	15.14
23	Warrego River	Baseline	933.73		933.73	
		DAR125	940.54	0.73	957.62	2.56
		CC50	1042.92	11.69	1130.87	21.11
24	Paroo River	Baseline	912.41		912.41	
		DAR125	915.77	0.37	925.99	1.49
		CC50	1026.69	12.52	1133.83	24.27
25	Darling River	Baseline	1082.49		1082.49	
		DAR125	1087.74	0.48	1101.25	1.73
		CC50	1215.34	12.27	1343.85	24.14
26	Lower Murray River	Baseline	762.10		762.10	
		DAR125	776.66	1.91	796.12	4.46
		CC50	818.58	7.41	870.04	14.16

[a] Baseline values of end-of-valley electrical conductivity refer to model output for current climate and vegetation cover

[b] Changes in end-of-valley electrical conductivity were calculated by adding the sum of the flow-weighted electrical conductivity cell values to the baseline for each catchment

both 2030 and 2070. The most obvious difference between the 2030 and 2070 revegetation-only scenarios is that while the magnitude of greatest reduction in FWEC remains the same between the two scenarios (−0.213 μS/cm per cell), the magnitude of the largest increase in EC is actually less for 2070 than 2030 (+0.495 and +0.568 μS/cm per cell respectively). This is due to a greater proportion of the GFSs having reached equilibrium by 2070. The scenarios with combined climate change and revegetation (Fig. 9f and g) lead to fewer areas where revegetation could achieve a salinity benefit, however reasonably large areas of EC reduction exist in the Goulburn, Lachlan, Benanee, Darling, Upper Murray, Border Rivers, and Castlereagh catchments. These results indicate that even when climate change impacts are recognised, revegetation can be targeted on a fine scale to achieve EOV salinity benefits in some areas and minimise medium term salinity disbenefits in other areas.

Table 4 summarises the total EOV EC impacts for each AWRC catchment under the DAR125 and CC50 climate scenarios without revegetation. Total EOV EC changes for each catchment were determined by calculating the sum of the 'per cell' change in EOV EC values (as displayed in Fig. 9) and adding that to the baseline EC. Only the Mallee catchment shows an overall decrease in EOV EC under the drier climate scenario (CC50) for both 2030 and 2070. Many catchments, including the Campaspe, Loddon, Avoca, Gwydir, Darling and Lake George, show large increases (>18% by 2070) in EOV EC with CC50. For the DAR125 climate scenario, most catchments show an EC change of less than 5% for 2030 and less than 10% for 2070.

The potential for achieving salinity benefits needs to be considered together with other NRM objectives, such as minimising water yield reductions. For some parts of the Basin with higher baseline water yield (Fig. 7a) and EC (Fig. 9a), climate change and revegetation will lead to limited areas where EC reduction could be achieved with relatively moderate reductions in water yield.

4 Discussion and conclusions

Awareness of the impact of climate change on hydrology and water resources has increased over the last two decades as reflected by the many studies assessing climate change effects on hydrology and water resources (Arnell et al. 2001). It is clear that climate change is just one of many factors affecting catchment salt and water balance, and thus decisions on natural resource management. Land use change, particularly revegetation, is another factor to consider. The impact of revegetation on mean annual water yield has been recognised since Bosch and Hewlett (1982) and predictive tools are now available (Zhang et al. 2001). The work of Chiew and McMahon (2002) and Herron et al. (2002) further reinforces that potential reductions in rainfall due to climate change can only exacerbate any reduction resulting from revegetation. For in-stream salt concentration, this can have both transient and lasting effects that in general cause a reduction in salt yield, but an increase in stream salinity. Ancient buried salt stores have been mobilised by the altered water balance from tree clearing, and reductions in recharge may only lead to a reduction in the amount of saline discharge, not the salinity of discharge.

The full range of water yield, salt yield and stream salt concentration responses to revegetation has been estimated by simulating revegetation of the non-forested parts of the catchments, including partially wooded cells. It is important to recognise that this modelling is a screening analysis to identify areas that could respond most positively or negatively to revegetation. The analysis does not suggest that revegetation of all non-forest parts of catchments is a plausible scenario.

The water balance component of the BC2C model developed by Zhang et al. (2001) has been tested with observations from small experimental catchments (Brown et al. 2005) to large catchments in the Murray-Darling Basin (Bradford et al. 2001; Zhang et al. 2003). The results showed that the model performed well against the observations. The salt balance component of the model has been tested to a lesser extent due to limited salt yield data. Gilfedder et al. (2009) reported a study in which the BC2C model was tested against flow-weighted stream salinity taken to be the total salt yield divided by the total streamflow from 14 catchments in the Murrumbidgee. The BC2C model was found to perform well in reproducing the observed salt yield. These studies provided confidence in the use of the BC2C model for estimating the impact of climate change on catchment scale water and salt balance.

The BC2C model assumes there are no internal storage changes. This applies equally to water and salt. Thus all salt that falls in rain in a cell, sub-catchment, catchment or region, is assumed to be delivered each year to the outlet via surface flow processes. This quantity varies across catchments depending on total annual rainfall and rainfall salinity. With no storage change assumed, this then becomes a lower limit on the annual salt yield. This simplification is most accurate in higher rainfall parts of catchments, where the near surface system is regularly flushed and a large build up of salt does not occur. In the flatter and drier parts of the Basin there is less flushing and the surface material is less permeable. Thus when the simplification is applied to the lower parts of the catchments, the assumptions are less valid and can result in greater errors estimating salt yield rates.

The simulations are started with input data under baseline climate and land use conditions. Outputs from these simulations represent the "current" state of the catchments and are considered as a baseline or benchmark for comparison with salt and water balance simulated using data under changed climate and vegetation conditions. In doing so, it is assumed that there is no underlying trend in stream volume, salt yield or salinity to take into account. Therefore, the estimated responses in catchment salt and water balances give a sense of the magnitude of the effects of climate change and/or revegetation against a baseline situation irrespective of any reasonable underlying trend.

Since this work was completed new global (IPCC 2007) and regional climate projections (CSIRO and BoM 2007) have become available. The two climate change scenarios chosen will still sample the updated range of projected climate fairly well, so continue to demonstrate the potential significance of climate change impacts. Compared to the CC50 RCM, DAR125 projected relatively modest changes in both rainfall and PET into the future. Recent reductions in rainfall and water supply suggest that the stronger projections for drying are more likely over the long term. The spatial variability of the projections is greater for CC50 than DAR125. Such variability within climate variables will also contribute to spatial variability in modelled runoff.

The BC2C model was designed to evaluate the impact of climate and vegetation changes on mean annual water and salt balance. As a result, some approximations are made in the model. For example, the model only considers the effect of the changes in mean annual rainfall and PET on runoff and salt yield. Changes in rainfall variability and seasonality may also affect catchment runoff and salt yield. It is predicted that daily rainfall intensity is likely to increase for most parts of Australia under climate change (CSIRO and BoM 2007). Increased rainfall intensity will result in more surface runoff and less recharge to groundwater, and hence reduction in salt yield. However, to quantify the effects would require a daily time step model. Note also, that the scenarios of PET represent changes in point PET, not areal PET which is far more suitable for assessing large scale changes in hydrology. This suggests that to improve this work the greatest benefits would not be from updating the scenarios within the same modelling framework, but from developing a more sophisticated approach.

Characteristics of the GFSs present in each of the AWRC catchments determine much of the salt export behaviour. Many of the central and southwest catchments have large areas of intermediate and regional GFSs, which means they will take decades to centuries to fully express changes in the surface water balance due to either climate or vegetation change, or a combination of both. Model results show only the short-term effects, where the dilution effect of surface flows has been curtailed long before groundwater discharge can respond similarly, i.e. long-term groundwater changes will occur over a longer period than the model predictions. Thus while salt yield decreases slightly, stream salt concentration increases greatly. The catchments dominated by local GFSs respond differently to the other catchments with respect to climate change or revegetation.

The modelled results showed that climate change will lead to reduction in mean annual runoff or water yield in most of the 26 AWRC catchments. In some catchments however, it is predicted that climate change will lead to slight increases in runoff, although the net change over the whole Basin remains negative. The BC2C model predicted greater change in runoff over time under CC50. The variation in runoff is not consistent across the catchments for the two climate change scenarios. Similar to the changes in runoff, the model predicted a reduction in salt yield for the majority of catchments with the exception of a few very dry catchments such as the Paroo and Darling Rivers. Most of the catchments show an overall increase in scaled EOV EC under the two climate change scenarios. It is noteworthy that EOV EC in some of the drier catchments such as the Avoca, the Murray Riverina, Benanee, the Mallee and Wimmera-Avon Rivers is predicted to decrease under the drier climate scenario (CC50). Even within the catchments with an overall increase in EOV EC, there exist patches of decreasing FWEC and these local areas can be prioritised for salinity benefit.

This study, while demonstrating some potential implications of climate change for catchment salt and water balances and revegetation strategies, also highlights the importance of catchment-wide assessments of climate change impacts to support management decisions. Catchment managers have the dual objectives of returning more perennial vegetation to the landscape and managing water resources security and quality for a range of uses. This study has clearly demonstrated that climate change and revegetation pose significant challenges to these dual objectives, however the uncertainty associated with climate and hydrological models and the generalised nature of the input datasets must be recognised when considering the results. Climate change impacts should be considered in catchment decision making in terms of target setting and identification of appropriate management actions.

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References

Arnell NW, Liu C, Compagnucci R et al (2001) Hydrology and water resources. In: McCarthy JJ, Canziani O, Leary NA et al (eds) Climate change 2001: impacts, adaptation, and vulnerability. Contribution of working group II to the third assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 191–233

Australian Water Resources Council (1976) Review of Australia's Water resources 1975. Australian Water Resources Council, Department of Natural Resources, Australian Government, Canberra, p 170

Beare S, Heaney A (2002) Climate change and water resources in the Murray Darling Basin, Australia; impacts and adaptation. ABARE Conference Paper 02.11, pp33. http://www.abareconomics.com/publications_html/regional/regional_02/cp02_climate.pdf. Accessed on 17 Jul 2006

Bosch JM, Hewlett JD (1982) A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J Hydrol 55(1/4):3–23

Bradford A, Zhang L, Hairsine P (2001) Implementation of a mean annual water balance model in a GIS framework and application to the Murray-Darling Basin. CRC Catchment Hydrology Technical Report 01/8, Canberra, p 40

Brown A, Zhang L, McMahon T, Western A, Vertessy R (2005) A review of paired catchment studies with reference to the seasonal flows. J Hydrol 310:28–61

Chiew FHS, McMahon TA (2002) Modelling the impacts of climate change on Australian stream flow. Hydrol Process 16:1235–1245

Chiew FHS, Whetton PH, McMahon TA et al (1995) Simulation of the impacts of climate change on runoff and soil moisture in Australian catchments. J Hydrol 167:121–147

Christensen NS, Wood A, Voisin N et al (2004) The effects of climate change on the hydrology and water resources of the Colorado river basin. Clim Change 62:337–363

Coram JE, Dyson PR, Houlder PA, Evans WR (2000) Australian Groundwater Flow Systems contributing to Dryland Salinity. Bureau of Rural Sciences for the Dryland Salinity Theme of the National Land and Water Resources Audit, Canberra, CD

CSIRO and BoM (2007) Climate change in Australia, technical report. www.climatechangeinaustralia.gov.au

Dawes WR, Gilfedder M, Walker GR et al (2004a) BC2C technical documentation. CSIRO Land and Water Technical Report 36/04

Dawes WR, Gilfedder M, Walker GR et al (2004b) Biophysical modelling of catchment-scale water and groundwater response to land-use change. Math Comput Simul 64(1):3–12

Dooge ICI, Bruen M, Parmentier B (1999) A simple model for estimating the sensitivity of runoff to long-term changes in precipitation without a change in vegetation. Adv Water Resour 23:153–163

Dowling TI, Dawes WR, Evans R et al (2004) Prioritising upland catchments in the Murray-Darling Basin with respect to salinity benefits from afforestation. CSIRO Land and Water Technical Report 15/04

Evans R, Gilfedder M, Austin J (2004) Application of the Biophysical Capacity to Change (BC2C) model to the Little River (NSW). CSIRO Land and Water Technical Report 16/04

Furby S (2002) Land cover change: specification for remote sensing analysis. National Carbon Accounting System Technical Report No. 9 November 2002. www.greenhouse.gov.au/ncas/reports/tech09.html. Accessed on 17 Jul 2006

Gilfedder M, Walker GR, Dawes WR et al (2009) Prioritisation approach for estimating the biophysical impacts of land-use change on stream flow and salt export at a catchment scale. Environ Model Softw 24(2):262–269

Herron NF, Davis JR, Jones RN (2002) The effects of large-scale afforestation and climate change on water allocation in the Macquarie River Catchment, NSW, Australia. J Environ Manag 65:369–381

IPCC (2001a) Climate change 2001: impacts, adaptation, and vulnerability. In: McCarthy JJ, Canziani OF, Leary NA et al (eds) Contribution of working group II to the third assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, p 1032

IPCC (2001b) Climate change 2001: the scientific basis. In: Houghton JT, Ding Y, Griggs DJ et al (eds) Contribution of working group I to the third assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, p 881

IPCC (2007) Climate change 2007: the physical science basis. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Avery JB, Tignor M, Miller HL (eds) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, 996 pp

Jones RN, Page CM (2001) Assessing the risk of climate change on the water resources of the Macquarie River catchment. In: Ghassemi F, Whetton P, Little R, Littleboy M (eds) Integrating models for natural resources management across disciplines, issues and scales (Part 2). Modsim 2001 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, Canberra, pp 673–678

Lane P, Hickel K, Best A, Zhang L (2005) The effect of afforestation on flow duration curves. J Hydrol 310:253–265

McGregor JL (2003) A new convection scheme using simple closure. In: Meighen PJ, Hollis AJ (eds) Current issues in the parameterisation of convection: extended abstracts of presentations at the fifteenth annual BMRC Modelling Workshop. Bureau of Meteorology Research Centre, BMRC Research Report no. 93. Melbourne, Victoria, pp 33–36

Najjar RG (1999) The water balance of the Susquehanna River Basin and its response to climate change. J Hydrol 219:7–19

Pittock AB, Wratt D (2001) Chapter 12: Australia and New Zealand. In: McCarthy JJ, Canziani OF, Leary NA et al (eds) Climate change 2001: impacts, adaptation and vulnerability. Contribution of working group II to the third assessment report of the intergovernmental panel on climate change. Cambridge University Press, Oakleigh, p 1032

Suppiah R, Whetton PH, Watterson IG (2004) Climate change in Victoria: assessment of climate change for Victoria: 2001–2002. CSIRO Atmospheric Research, Melbourne, p 33

van Dijk AIJM, Cheng X, Austin J et al (2004) Predicted stream flow and salinity changes after afforestation in the Southwest Goulburn. A regional BC2C model application to develop commercial environmental forestry. CSIRO Land and Water Client Report Nov 2004

van Dijk AIJM, Hairsine PB, Gallant J et al (2005) A two-staged modelling approach to catchment water and salt yield prediction. MODSIM Melbourne December 2005

van Dijk AIJM, Gilfedder M, Austin J (2008) Influences of climate, terrain and land cover on stream salinity in southeastern Australiam and implications for management through reforestation. Hydrol Process 22(17):3275–3284

Whetton PH, Hennessy KJ, Katzfey JJ et al (2000) Climate averages and variability based on a transient CO2 simulation. CSIRO Atmospheric Research, Melbourne, p 38

Whetton PH, McInnes KL, Jones RN et al (2005) Australian climate change projections for impact assessment and policy application: a review. CSIRO Marine and Atmospheric Research Paper 001. CSIRO Marine and Atmospheric Research, Melbourne, p 34

Wilk J, Hughes DA (2002) Simulating the impacts of land-use and climate change on water resource availability for a large south Indian catchment. Hydrol Sci J 47(1):19–30

Zhang L, Dawes WR, Walker GR (2001) The response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resour Res 37:701–708

Zhang L, Dowling TI, Hocking M et al (2003) Predicting the effects of large-scale afforestation on annual flow regime and water allocation: an example for the Goulburn-Broken Catchments. CRC for Catchment Hydrology Technical Report 03/5, Canberra