water

Article

Adapting Water Management to Climate Change in the Murray–Darling Basin, Australia

Ian P. Prosser [1,*], **Francis H. S. Chiew** [2] and **Mark Stafford Smith** [2]

[1] Centre for Applied Water Science, University of Canberra, Bruce, ACT 2617, Australia
[2] CSIRO Land and Water, Black Mountain, ACT 2601, Australia; francis.chiew@csiro.au (F.H.S.C.); mark.staffordsmith@csiro.au (M.S.S.)
[*] Correspondence: ian.prosser@canberra.edu.au

Abstract: Climate change is threatening water security in water-scarce regions across the world, challenging water management policy in terms of how best to adapt. Transformative new approaches have been proposed, but management policies remain largely the same in many instances, and there are claims that good current management practice is well adapted. This paper takes the case of the Murray–Darling Basin, Australia, where management policies are highly sophisticated and have been through a recent transformation in order to critically review how well adapted the basin's management is to climate change. This paper synthesizes published data, recent literature, and water plans in order to evaluate the outcomes of water management policy. It identifies several limitations and inequities that could emerge in the context of climate change and, through synthesis of the broader climate adaptation literature, proposes solutions that can be implemented when basin management is formally reviewed in 2026.

Keywords: climate change; water policy; climate adaptation; Murray–Darling Basin

Citation: Prosser, I.P.; Chiew, F.H.S.; Stafford Smith, M. Adapting Water Management to Climate Change in the Murray–Darling Basin, Australia. *Water* **2021**, *13*, 2504. https://doi.org/10.3390/w13182504

Academic Editor: Glen R. Walker

Received: 15 July 2021
Accepted: 8 September 2021
Published: 12 September 2021

1. Introduction

Climate change is impacting on water security in water-scarce regions across the world, via declining precipitation, increasing potential evapotranspiration, and increased water demands [1,2]. By 2025, up to two-thirds of the world's population will live in water-stressed regions [3]. This has resulted in calls to improve water management in order to adapt to the challenges of climate change. In addition to numerous engineering solutions to water security problems, there are proposals for transformative approaches to water management policies [4–7]. Despite this, current management policies remain largely unchanged in most countries [6,7]. Part of this tenacity might be due to the fact that the unsatisfactory consequences of current water management under climate change have not been made clear compared to the difficulties of implementing transformative change.

The Murray–Darling Basin (the Basin) in Australia is a leading example of this dilemma. Water policies in the Basin have been of wide international interest because they are highly sophisticated, and because they went through a major transformation around a decade ago, returning a significant proportion of consumed water to the environment [8,9]. Both the sophisticated management and transformation have been cited as good adaptations to future climate change [10–12], although others claim that they are insufficient [13–15]. However, neither claim has been properly evaluated against the hydrology and water use of the Basin, nor against the outcomes sought from water management policies.

The first step in any calls for new approaches to water management should be to learn from the outcomes of the current water management policies, identifying deficiencies and proposing solutions [6]. Part of the tension surrounding the adaptability of current policies is probably a result of the difference between the theory of adaptive management and its actual practice. If improvements can be made in the Murray–Darling Basin, even where management has been transformed and is relatively sophisticated, there may be lessons for other basins that go beyond using the Basin as an example of good practice, as sometimes occurs.

In this paper, we undertake a critical review of water management policies in the Basin as adaptations to climate change. Under a drying climate, water management is most under pressure during prolonged droughts, when supplies may not meet all water needs. First, we examine climate change projections and climate records to show how the frequency of future droughts might compare to recent intense droughts. We then synthesise published data, recent literature, and published water plans in order to identify six problems of current policies as adaptive management practices for climate change. We use the broader literature on approaches to climate adaptation to suggest improvements that could be made to the overarching policy framework (the Basin Plan) when it is formally reviewed in 2026. This paper focuses on surface water management. A companion analysis of groundwater and climate change is given in [16].

2. The Murray–Darling Basin

The Murray–Darling Basin is Australia's largest river basin, producing 50% of Australia's irrigated agriculture, and spanning five state jurisdictions responsible for water management, making it a transboundary river basin. The Commonwealth Water Act (2009) and the Basin Plan (2012) placed a new lower limit on water use across the Basin, transferring the equivalent of over 2700 GL/y of water entitlements from irrigators (~20% of total use) to public management in order to restore degraded water-dependent ecosystems, including 16 Ramsar wetlands of international significance [17–19]. The limit on water use across the basin—termed the Sustainable Diversion Limit—aims to balance water use to support healthy water environments, irrigated agriculture, and regional communities.

In principle, water management in the Basin is fundamentally adaptive to climate change. The Basin Plan will be reviewed every 10 years, starting in 2026, and the Diversion Limit and policies within the Plan can potentially be altered to accommodate a changing climate. The Basin's states set water resource plans for each valley, compliant with and accredited under the Basin Plan. These are also renegotiated every 10 years and reviewed every 5 years. Risks to the plans need to be identified and managed as part of the accreditation process; however, a review of the published plans, given below, shows that the principles of adaptive management to climate change are not always well implemented in practice.

3. Climate Change and Water Availability in the Basin

3.1. Droughts and Climate Variability

The inter-annual and multiyear variability of streamflow in the Murray–Darling Basin (Figure 1) is very high, and is higher than in rivers in regions with similar hydroclimates elsewhere in the world [20,21]. There are frequent periods of low flow, often extending for a few years, but within that overall pattern there has been a high frequency of low flows in recent decades. Of the lowest 11 years of flow over the last 120 years, 6 have occurred since 1997. These include the unprecedented 1997–2009 Millennium Drought in the southern Basin, which resulted in a significant decline in storage levels in reservoirs, several years of severe water restrictions in regional towns, prolonged low water allocations to irrigators, and the suspension of water-sharing arrangements in some valleys because they were not designed for such extreme conditions [22,23]. The subsequent intense drought of 2017–2019 in the northern and central Basin significantly impacted agriculture and town water supplies, and triggered major fish deaths in the Lower Darling [24].

Low streamflows in the Murray River in recent decades are mainly caused by low cool season rainfall [25–27], which is amplified as a decline in streamflow [28]—particularly in the southern Basin, where most of the streamflow occurs in winter and spring [26,27]. This decline in cool season rainfall has been partly attributed to anthropogenic climate change, with warmer conditions shifting the mid-latitude weather systems, pushing the winter storm tracks further south [27,29,30]. It is difficult to statistically quantify the effects of climate change on trends and changes in rainfall and streamflow, because of the large natural variability in the climate system. Nevertheless, analysis of global climate model simulations has concluded that ~20% of the decline in rainfall could be attributed to global warming [31].

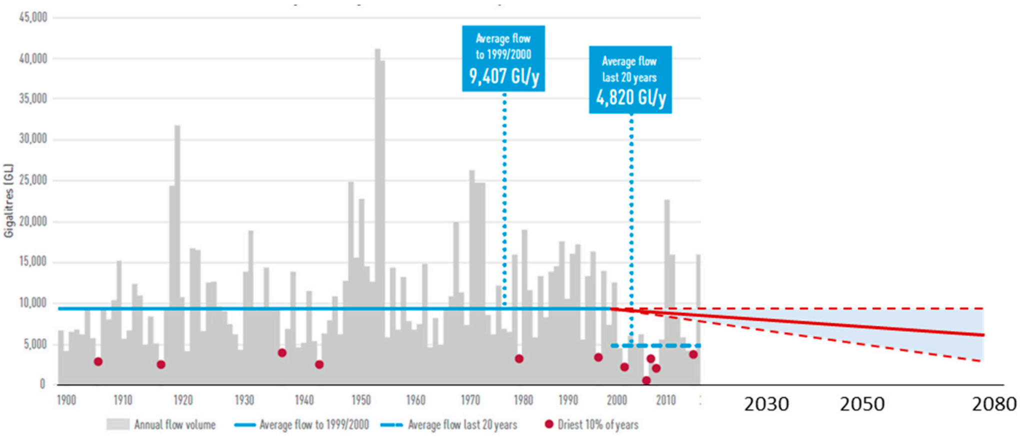

Figure 1. Annual time series of streamflows to the Murray River (from [27]), showing the high inter-annual and multiyear variability, with projected changes in annual average streamflow under 2 °C global average warming (RCP8.5) climate change. Projections are for the median, 10th, and 90th percentile results from hydrological modelling of climate change from 42 CMIP GCMs (see Figure 2).

Likewise, a hundred years of instrumental historical records is limited in characterising low return period (low frequency) and longer droughts such as the 1997–2009 Millennium Drought (which was the worst drought in the instrumental record). Statistical analysis of observed and modelled streamflow records quantified the Millennium Drought as having a return period of more than 100 years [32]. Paleoclimate data—preserved in tree rings, sediments, and coral reefs—can help explain longer term climate variability. For example, paleo-reconstruction of streamflow in the Murray River back to the late 1700s indicates that the return period of the Millennium Drought is more than 100 years [33]. A composite of paleoclimate data from several sources also suggests that the Millennium Drought was an extreme drought compared to droughts in the past 500 years, but less exceptional compared to the frequent droughts in the 500 years before that [34].

The decline in streamflow has been further accentuated by changing hydrological processes in long dry periods, particularly reduced connection between surface and groundwater systems, subsurface evapotranspiration, and vegetation behaviour [35–38]. Many catchments have not fully recovered from the Millennium Drought, despite a return to wetter conditions due to higher summer rainfall [27,38]. The streamflow decline under climate change will be further accentuated by higher temperature and evaporative demand [26,35], transpiration from tree regrowth following more frequent and severe bushfires [39], and landscapes intercepting proportionally more water during dry periods (mainly through farm dams) [40]. Over the longer term, streamflow will also be affected by changes in vegetation and surface–atmosphere feedback in a warmer and higher atmospheric CO_2 environment [41,42]. Thus, the observed historical relationships between rainfall and streamflow may not be representative of future runoff behaviour [7].

3.2. Projections of Streamflow under Climate Change

The components in developing projections of climate change's impact on streamflows are as follows: (1) determining global warming from different greenhouse gas emission scenarios, (2) evaluating the change signal from global climate models (GCMs), (3) downscaling of GCM outputs to catchment-scale climate variables, and (4) hydrological modelling of the impact on streamflow. Each component has its own inherent uncertainty, which can be compounded through the modelling process.

The projected change to the average annual streamflow in the Basin, developed by following these steps, is shown in Figures 1 and 2. The data and precise methods used to follow the steps are described in [43]. The future climate series was determined by the seasonal change signal from 42 CMIP5 global climate models (models used in the IPCC AR5–Intergovernmental Panel on Climate Change Fifth Assessment Report). The projections compare hydrological model outputs under scaled future climates against the historical climate. Here, we replot the data just for the Basin as a timeline in Figure 1, and as maps in the top row of Figure 2. The median projection is for streamflow in the Basin to reduce by ~20% under 2 °C global average warming (centred around 2060 relative to 1976–2005) [43,44]. The projected decline in streamflow largely results from the projected decline in cool season rainfall, accentuated by higher potential evapotranspiration. The higher temperature will also increase water demand, accentuating the gap between supply and demand. Figure 1 shows the uncertainty range (10th to 90th percentiles) in the projections, largely due to the range in the future rainfall projections. The inter-annual and multiyear variability will remain high, with wet and dry years on the background of a drying trend. However, because of the decline in average annual streamflow, droughts will become more frequent and severe. Figure 1 illustrates that the current interannual variability in streamflows is larger than the projected changes to mean annual flow for a least a couple of decades. This does not mean that the changes will not impact on water resources and their use, but that climate change is most likely to be experienced as more severe extremes—especially of droughts.

The middle row of Figure 2 reanalyses the data from [43] to show the projected frequency of low flows (expressed as the number of days with streamflow below the 5th percentile daily value, Q_{05}) in order to illustrate the projected impacts on droughts. The bottom row of Figure 2 shows the increase in the number of 3-year hydrological droughts under a future climate (see [45] for meteorological/rainfall droughts). The plots show that 3-year hydrological droughts experienced once every 20 years under the historical climate could occur once every 10–15 years under a future climate in the median projection, and as often as once every 5 years in the dry end scenario. The projections in Figure 2 were modelled by scaling the historical climate input data to reflect the climate change signal, therefore assuming no change in the inter-annual variability [43], and reflect that a shift in the mean annual rainfall and streamflow can greatly increase the frequency of droughts. Climate models currently have much less skill in simulating variability compared to change in the mean, which is why the current inter-annual variability has been retained in this modelling example. If the annual rainfall and streamflow under a future climate is more variable, the impact on droughts will be even more severe.

The hydrological projections shown in Figures 1 and 2 were based on IPCC AR5 projections. The IPCC AR6 assessment has just been released, and analysis of limited archived CMIP6 global climate models shows similar broad-scale projections [46]. There are finer spatial-scale dynamic downscaled projections developed separately by the different states (Queensland, New South Wales, Victoria). These can potentially add value, particularly for local-scale assessments in high-elevation and coastal regions [47]. Nevertheless, although dynamic downscaling is improving, there is significant bias in the downscaled rainfall that needs to be robustly bias-corrected for hydrological application [48,49]. The availability of multiple climate projection products or datasets, as well as the different methods that can be used to develop hydrological projections, can add to the confusion and challenge in interpreting the projections [50,51]. However, projections from all of the different products and methods fall within the range of the projections presented in Figures 1 and 2, and point to the same hotter and drier future in the Basin.

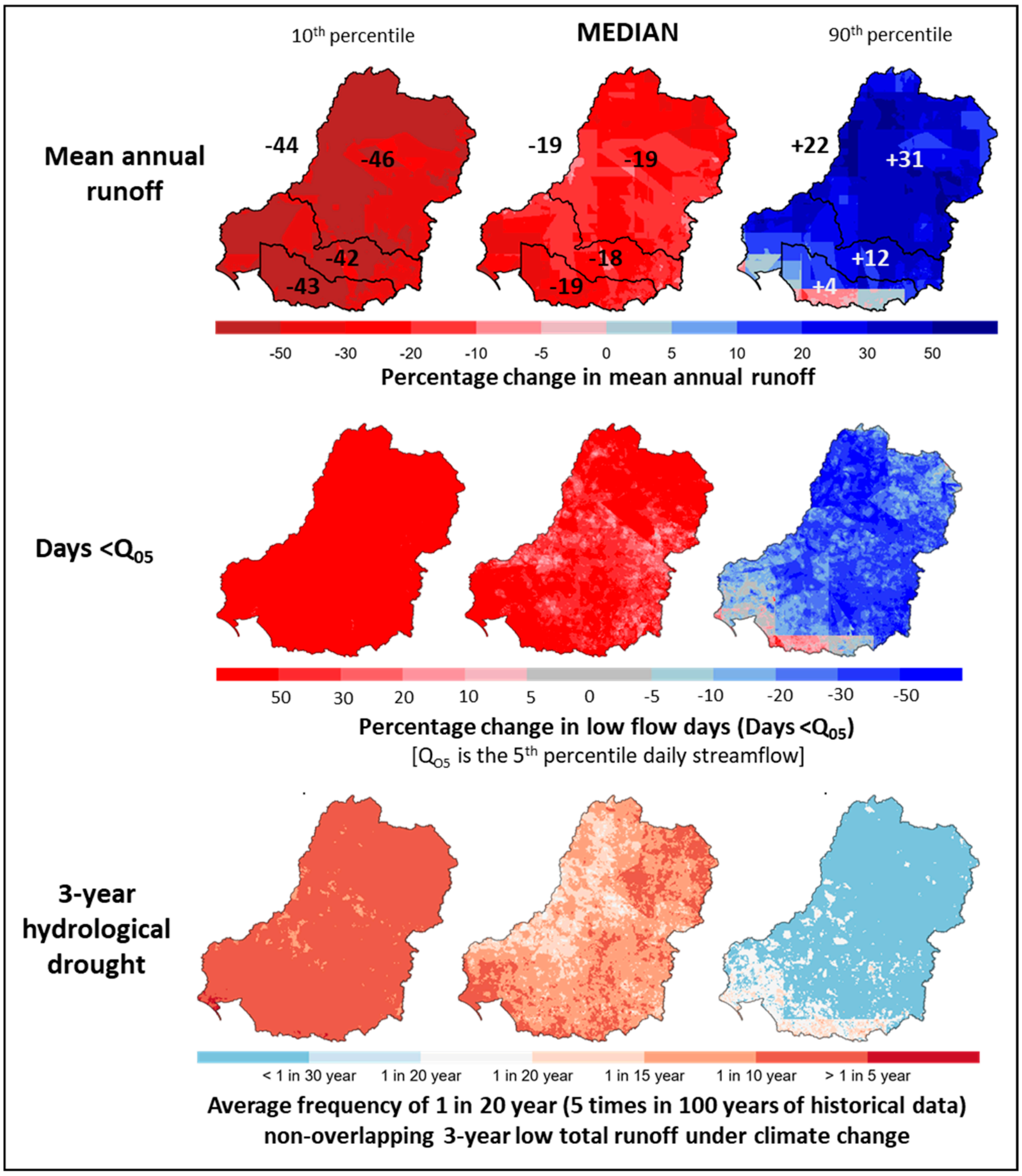

Figure 2. Projected change in streamflow characteristics for 2046–2075 relative to 1976–2005 for the high RCP8.5 emissions scenario (representative of projected change under a 2 °C global average warming). Data from [43,50].

The science and modelling of hydroclimate projections have improved considerably in the last two decades, particularly through analysis of more observed data, a better understanding of the causes of the drying climate, improved modelling of changing hydrology, and higher spatial resolution modelling of the local impacts [27]. The decline in cool season rainfall over recent decades is consistent with our understanding of atmospheric and oceanic processes in a warmer world; virtually all of the climate models project a drier cool season under climate change, and hydrological modelling indicates a decline in future streamflow. However, uncertainty in the projections will remain given the complexity in understanding and modelling the processes and uncertainties over future greenhouse gas emissions. Below, we consider how suited the current management approaches might be in the face of these changes.

4. Evaluating Current Management as Adaptations to Climate Change

There is debate about whether current water management—as sophisticated as it is, and despite it being the result of decades of hard-fought reform [8,17]—will be sufficient under a drier climate [10,12–14]. We use published data and synthesise recent scientific literature to identify management outcomes during droughts as an analogue of how policies will perform in the context of climate change. We also review how climate change has been dealt with in the Basin Plan and the 11 published subsidiary water resource plans [52]. The evaluation identifies several limitations of current policies, and proposes possible solutions through reference to the broader climate adaptation literature.

4.1. Uneven Sharing Arrangements

A major achievement of the Basin Plan was to reset the balance between consumptive water use and water for the environment by returning significant volumes of consumed water to the environment. The balance is expressed in terms of the long-term average level of use (the Sustainable Diversion Limit) calculated over the historical flow record. The Diversion Limit was a highly contested decision requiring judgement over competing values of water resources.

Within the overall Diversion Limit, annual allocations of water to licenced users vary from year to year to reflect annual water availability in each river. These allocations effectively deal with the high streamflow variability. Some argue that this will provide good adaptation to climate change, because if water availability declines in the future then annual water allocations will adjust accordingly so that, over time, levels of water use will decline to match the availability of water [10–12]. We show here that under the rules of annual allocations, water for the environment reduces by a greater proportion than water for consumptive use if the climate dries, undermining the agreed sharing arrangements.

There are three types of water that provide benefit to the environment in the Basin: The first is environmental water entitlements. These are water entitlements purchased from irrigators and now managed by governments to water environmental assets and meet environmental objectives. This is the water returned to the environment from the Basin Plan; it retains the same entitlement conditions and the same seasonal water allocations as the consumptive water users. This allocation of water for the environment will reduce by the same proportion under a drier climate as that for equivalent consumptive users. The second type of environmental water is termed planned water; this is water that is preserved for the environment in the rules of water plans. Such rules include allowing some flood flows to pass through dams, or rules to maintain baseflow in rivers. The third type of water for the environment is unplanned, in that it is neither protected as entitlements nor specifically planned for. This is particularly prevalent in wet years or floods in unregulated sections of rivers, when significant volumes of water flow downstream. On average, the volume of environmental water entitlements is ~12–15% of the total water available to the environment.

The volume of planned and unplanned environmental water reduces more strongly during drought than the amount of water used under entitlements. This is illustrated in Figure 3, which shows river model predictions of water consumed as a result of the allocations and rules in water resource plans. The data in Figure 3 are a scatter plot of the data shown in [53] page 33. The figure plots modelled water use against undeveloped flows at Wentworth—the point of maximum flow in the Basin. The river models are those used for water planning in the Basin, and run over 111 years of historical climate. Water use is for the current level of development, which is capped, and undeveloped flows show how much flow there would be without dams and water use. Full details of the methods are given in Sections 1 and 4.2 of [54]. Figure 3 shows that the proportion of river flow that is used increases in years of low flow—partly because of high water demand, and partly because there is less planned and unplanned environmental water. The average proportion of surface water consumed across the Basin is 56%, but in 25% of years this increases to > 70% of all water, and can be higher than 80%, both occurring in dry years, leaving very little additional water for the environment. In dry years water for the environment is more strongly reduced in rivers of the southern Basin, and impacts are greater in downstream reaches, where several of the Ramsar-listed wetlands are located [22].

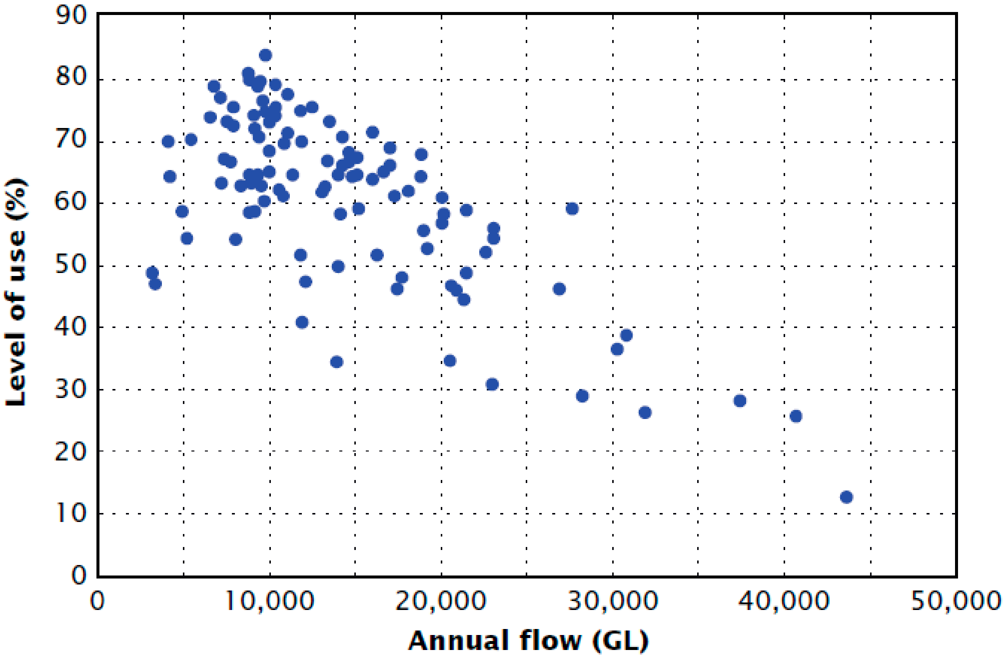

Figure 3. Predicted annual level of surface water use across the Basin versus natural river flow. Annual flow and water use were modelled using water plan river models for 2006 (before the Basin Plan), and run over the 1896–2006 period. Data from CSIRO [53].

The data in Figure 3 are for water resource plans before the Basin Plan, but there is nothing in the Basin Plan arrangements or revised water resource plans that changes the protection of water use under entitlements to reduced flows (although with the buyback of entitlement for the environment under the Basin Plan, the level of consumptive use in the dry years would be slightly lower than that shown in Figure 3). In fact, it is one of the aims of water plans to ensure a continuing supply of water under dry conditions as much as possible. The patterns of Figure 3 are a result of the entitlements and rules in water resource plans. They will remain under any future climate, and under any changes to irrigation commodities.

The patterns of Figure 3 are summarised in Figure 4 as indicative use of water in wet (wettest 10%), average, and dry years (driest 10%). Total water available and consumption are taken from Figure 3; the volume of environmental water holdings is taken from [55], recognising that ~75% are lower security entitlements that receive little water in the driest years, while uncertainty in volumes is set at 15%, as described in the next section. Under a drying climate, the average condition will move toward the right-hand column, which will be experienced more frequently. The situation in dry years has been improved relative to before the Basin Plan as a result of now having environmental entitlements to provide water to drought refuges. However, climate change can more than erode this improvement if dry conditions become more frequent, as there will be less water overall for the environment than under the historical climate.

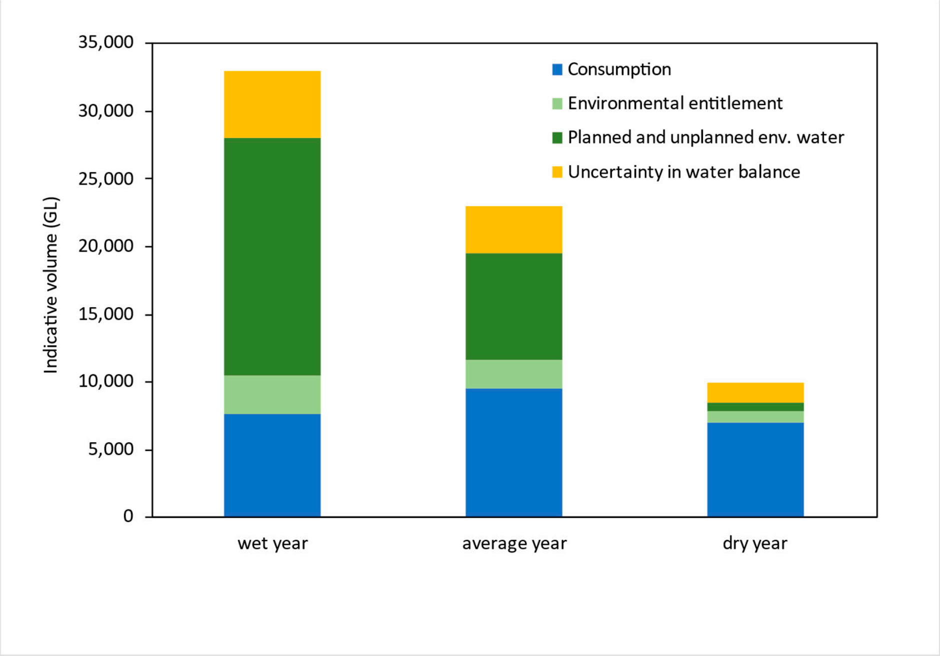

Figure 4. Indicative volumes of water in the Basin in wet, average, and dry years in the Basin. Volumes are subdivided into water consumption, water allocated under environmental entitlements, remaining water available to the environment, and uncertainties in the water balance (which may or may not be available to the environment). Based on data from [53,55,56].

There was a very long and difficult negotiation of the Diversion Limit in the Basin Plan as a new balance between consumption and water for the environment. That balance will change substantially under a drying climate, threatening the condition of wetlands and river ecosystems that were the focus for reducing water consumption. The primary solution to this problem is to reset the Diversion Limit to reflect the drying climate and its impacts on planned and unplanned environmental water.

4.2. Uncertainties in Water Balance

The high proportion of water consumption in dry years, with little water remaining for other purposes, poses a second risk of unpredicted additional losses of flow, and even complete drying out of rivers in the Basin. There are uncertainties in flow volume, which in dry years are biased toward overprediction of the amount of water available downstream. Diversions of water for consumptive use are measured relatively accurately compared to other elements of the water balance, so the impacts of overestimating water availability are disproportionately borne by the environment. In wet years, when there is ample water available, uncertainties in the water balance are relatively small compared to the total volume of water (Figure 4), and do not significantly impinge on water management. However, if 70–80% of river flow is being consumed, there is less room to accommodate for lower than anticipated water volumes.

Uncertainties in surface water balances were assessed as part of the Murray–Darling Basin Sustainable Yields Project [53]. The analysis found good overall river model performance and good gauging networks, but 10–30% of the water balance in each region could not be attributed to components of water accounts [56]. There were considerable unattributed losses of water within regions, and prediction of low flow volumes was poor. Gauging errors can be significant for low flows, and tend to overestimate actual flows [57].

There are risks of higher than planned use of water through uses that are outside water entitlements, with a prominent past example of excess water use occurring in the NSW part of the northern Basin [58]. Flows may also be less than expected for a given rainfall. Water plans are based on observed historical relationships between rainfall and streamflow but, as outlined in the drought section above, less streamflow was observed in recent droughts than was expected from past catchment behaviour, and some catchments have not recovered to their previous behaviour. Further downstream there are uncertainties in the maintenance of low flows, as a result of reduced groundwater inputs arising from increased groundwater extraction or reduced returns of excess water from irrigation areas [16,59]. The overall volumes are probably small, but can be significant in dry years.

These behaviours all result in less water being available to the environment in extended droughts than predicted from prior history. A stark example of the impacts of uncertainties compounding on one another was the mass fish deaths in the Darling River during the most recent drought [24].

The solution to this problem is to include a buffer for uncertainties in calculations of the amount of water needed for the environment. Further work can be done to reduce uncertainties through improved measurements, modelling, and compliance actions so that the size of the buffer can be reduced and additional volumes can be allocated.

4.3. Limitations of the Historical Record

How suitable the current management arrangements are for a future drier climate is largely untested. Some have argued that the current arrangements dealt well with historical droughts (e.g., [11,12]), while others have argued the opposite by pointing to particular failures (e.g., [15,60,61]). Putting aside subjective assessment of past success or otherwise, the use of historical droughts and outcomes to assess resilience to climate change is a quite limited test.

The last 100 years or so of Basin climate and hydrology are used to test water plans in the Basin. The argument is that if water management can be shown to be effective across the last 100 years of hydrological variability, then it should be effective in the future. Using a hundred years of record is much better than using shorter periods, but there are two problems with using the historical record alone.

The first problem is how to deal with the recent extreme droughts and the probabilities of future drought. As outlined in the drought section above, the Millennium Drought in the southern Basin was unprecedented in the instrumental records. It was an improbable event with a return period of 100 years or more, so perhaps the impacts it had on water management were acceptable. Reflecting this view, the NSW government now removes the recent droughts from modelling of water operations, as they believe they skew water availability to unnecessarily low averages [62].

There is, however, an alternative explanation that poses greater risk: Recent droughts could be part of a new drier climate where droughts are more frequent. The longer millennial history of dry and wet periods in Flack et al. [34] contains significant patterns of more than century-long periods of wetter conditions, and others with drier conditions. There is structure to the extended dry periods in the last thousand years—not just random variability. There have been periods of beyond a century in length with strengths of the Indian Ocean Dipole and the El Nino/Southern Oscillation in the Pacific Ocean quite different to those in the last century [63,64]. These are both known drivers of rainfall, drought, and hydrology in eastern Australia [26,27]. Combining the broader paleoclimatic evidence with the drought inferences of Flack et al. [34] suggests that the occurrence of extreme droughts is quite sensitive to small changes in global climate, as well as to the behaviour of oceanic climate drivers. This is also shown in the drought projections of Figure 2, which predict that 2 °C of global warming could more than double the frequency of multiyear droughts. The mean annual temperature of the Basin has already risen by 1.4 degrees [65], and further warming is locked in by lags in the climate system. Thus, for current and future conditions, the probability of the Millennium Drought and the 2017–2019 drought is likely to be higher, and may be indicative of a new drought-dominated regime for the foreseeable future. Such a change started in southwest Western Australia in the 1970s, and continues to this day [66].

The second problem of using the historical record is that the precise sequencing of flows from one year to another, or the socioeconomic circumstances—such as commodity prices—during a drought can strongly influence outcomes, and so may not well represent the full range of possible impacts and outcomes of future droughts [67,68].

The solution to both of these problems is to use a wider range of stochastic flow scenarios, which can still be based upon statistics of the historical record, that incorporate various sequences of events and various scenarios of climate change. Scenarios could explore conditions such as the continuation of the last 23 years of drought-dominated conditions, as NSW has done (e.g., [69]). Basin states are using scenarios of different conditions rather than just the historical record in hydrological modelling. However, after reviewing the published water resource plans, we found no changes to water management arising from these scenarios. This is possibly because no clear failure points, vulnerabilities, or measurable objectives are used to examine the implications of the different scenarios, or because uncertainty over future projections is used as a reason to defer action. These issues are considered in the following section.

4.4. Assessing Vulnerabilities to Climate Change

So far, we have looked at possible changes to river flows, and what these mean for the sharing of water between consumers and the environment. What really matters is the consequences of these changes for the environmental, economic, and social objectives of water management plans such as the Basin Plan. These objectives may have different vulnerabilities to a drier climate than to the historical climate. Vulnerabilities will also be different between regions, agricultural sectors, and water environments. Historical resilience to drought is no guarantee of future resilience, and the resilience of the objectives of the Basin Plan to climate change remains largely unexplored. If recovery from the impacts of drought is longer than the interval between them, or if drought intensity causes local failures from which recovery is not possible, then impacts will get worse, could be deemed unacceptable, and new adaptations may be called for.

Recent water reforms have strengthened water markets, and there is evidence from the Millennium Drought that overall irrigated agriculture outcomes are relatively resilient to drier conditions through effective operation of the water market. Water is traded to higher value crops; higher water prices and limited water availability stimulate improved water use efficiency, and those selling water invest in alternative farming, such as dryland crops or purchase of feed for dairy [13,68,70]. This means that the gross value of irrigation production decreases less than the reduction in water use, but it can mask significant problems. There may still be water shortages during droughts for long-lived crops such as nuts and grapes with longer term consequences of failure [71]. There are also significant impacts on lower water security users, and sectors such as rice and dairy have diminished significantly, with consequent community impacts in some regions [71,72]. Long-term trade of water to downstream regions, where high-value horticulture crops predominate, can create operational problems for water supply, with consequences for other water users. Management reforms to date have also not improved access to water for indigenous communities [72].

Similarly, wetlands or populations of aquatic species such as fish or water birds may not recover from repeated droughts [73]. Under a significantly drier climate, the held environmental water may be insufficient to protect all aquatic ecosystems. Ecosystems may need to be prioritised based upon their conservation value [74,75] or assisted to transition to a different state, and environmental water management adjusted accordingly.

For the Basin Plan, flow requirements of ecosystems were expressed as threshold flows that need to be met at average frequencies [76]. These often represent specific parts of the life cycle, such as reproduction, and necessarily greatly simplify the complex relationships between flow and ecology. Sometimes individual extreme events, such as the recent drought, can decimate populations or ecosystems for years despite average requirements being met. Vulnerabilities need to be considered across all stages of the life cycle of populations. For these reasons and others, there are calls to use simplified ecosystem or population-response models applied to a range of stochastic flow scenarios to determine the vulnerability of ecosystems and populations to future climate change [68,77]. This may require additional ecosystem knowledge in some cases. Without confidence about ecosystem or population resilience, a precautionary approach of holding more environmental water would be prudent until we know better. Some ecosystems have a critical reliance on large, infrequent floods, such as to flush accumulated salts from high floodplain woodlands. These floods are largely dependent on the external climate, and are hard to influence with either planned or held environmental water.

Because of the diversity of hydrology, ecosystems, and socioeconomic circumstances across the Basin, there will be specific impacts of drier conditions and locally significant impacts even if the basin-wide conditions remain strong. Assessments of vulnerabilities to future climate should be specific to each region. Regional communities should be given the opportunity to explore their own adaptation strategies to a range of pressures, including climate change.

NSW assesses risks from climate change in its regional water strategies, including analysis of vulnerabilities to water supply reliability—especially to town water supplies—but it does not assess consequent impacts and vulnerabilities for industries, communities, or ecosystems. Perhaps these outcomes are considered external to water planning. The strategies do identify a list of possible options for adaptation, which will be assessed, prioritised, and potentially acted upon in future (e.g., [69]).

4.5. Uncertainty over Climate Change

A criticism of the Basin Plan was that in making the major reforms necessary to reset the balance of water use between consumption and the environment, a drying climate was not included in the new limits on use [14,60,78]. Reasons given for not doing this include that there was too much uncertainty over future impacts to incorporate it into the Plan, and that the Basin Plan settings are subject to major review every 10 years starting in 2026, so adaptations can be made then [10,12,78–80].

Climate projections have been available for Australia since 1987, and a drier future in southern Australia has consistently been projected. In 2008, four years prior to the agreement of the Basin Plan, the summary projections for streamflow in 2030 were −40% to +20% (median of −15%) relative to the historical record [54]; today, they remain roughly the same at −38% to +8% (median of −14%) [25]. The drivers of climate change are now better understood, but fundamental uncertainties about predicting future streamflow will remain for the foreseeable future. Uncertainties over climate change are unlikely to be much different in 2026 than in 2012; however, given the projections of Figure 2, and observations that runoff in recent droughts has been less than predicted by models [27,38], there is a very high probability of a drier future for the basin. It would be prudent to base plans on this, rather than the far less likely event of no drying of the Basin.

The consequences of ignoring a drying climate are likely to be far greater than those of underestimating future water availability. There is already social and economic hardship being felt in Basin communities [72,81], requiring assistance for the Basin Plan to be supported into the future with long-term impacts. If more water is available in future than is expected, it will be easier and quicker to allocate and use the additional water. Consequently, there is asymmetry and hysteresis. This again suggests a precautionary approach with the flexibility to adapt in the unlikely event that the drier conditions and their consequences do not occur.

An independent review of the Basin Plan in 2019 [82] recommended action on climate change, but the responses have largely been limited to acquiring further information and incorporating climate change risks and scenarios into broad water strategies [83] emphasising the uncertainties that remain. No adaptations to water management policy were foreshadowed. At a minimum, the 2020 Basin Plan evaluation recommended that governments prepare to adapt the Basin Plan in 2026 to possible future climates [80].

There are several well-developed frameworks for climate change adaptation (e.g., [4,5,84,85]), including those specific to Australia [86,87] and specific to water resources [88]. Adaptation frameworks include ways of making decisions in the face of various sources of uncertainty [84,89,90]. They note that uncertainty is often overstated as a reason for inaction, and include ways of dealing with numerous sources of uncertainty (e.g., [91]) beyond climate change. This review notes additional uncertainties, such as in Basin water balance, climate variability, and vulnerabilities of ecosystems. Some of these uncertainties are managed at present in quite sophisticated ways.

The types of adaptations that can be undertaken to reduce decision risks while acknowledging uncertainty include (from [84], with Basin examples added):

- No-regrets decisions that yield benefits regardless of the extent of climate change, such as through improved water use efficiency in viable irrigation areas;
- Reversible and flexible options, such as operational plans for environmental watering;
- Buying safety margins for the future, such as water conveyance improvements to cope with expected shifts in water use downstream;
- Promoting self-adaptation, such as water demand reduction in irrigation crops through selective breeding;
- Reducing decision lifetimes, such as shorter life or climate-resilient supply infrastructure options, rather than new dams that may fail to perform in the face of long-term drying.

Risk assessments in water resource plans go as far as identifying climate change as a risk to the outcomes sought from water management, and running scenarios of possible future conditions. They should go further, by identifying unacceptable vulnerabilities and then putting in place risk management actions of the types of adaptations listed above, regardless of uncertainties. As Walker et al. [16] identify, one of the first impediments to adaptive management of Basin water resources is that the objectives are not specified enough to know when adaptation is required, or to judge whether responses meet the objectives. The best example of evaluating progress on objectives is that for held environmental water, where the achievements of using environmental water entitlements are compared to the counterfactual of not having that water available [92].

Private businesses, finance markets, and governments are increasingly being required by law to consider climate change risks in their decisions. If water management is to continue to be designed to support business and community decisions, it too should be managing future climate risks, and not dismissing them as uncertain.

4.6. Ten-Year Planning Horizon

In theory, revising the Basin Plan and subsidiary valley water resource plans every 10 years provides a good basis for adaptive management to climate change. In practice, so far, it has limited the planning horizon to 10 years, ignoring longer term consequences of change. Consistent with the Sustainable Diversion Limit, which does not include climate change, there are no proposals thus far to adjust state water plans to climate change (see [52]). All water plans accredited to date have included risks from climate change, but it is either considered a low-consequence risk over the next 10 years, or one that does not need to be addressed until later planning cycles. Various current management approaches are invoked as mitigation. Specific adaptations where they are given are limited to seeking a better understanding of climate change risks, sharing that understanding with communities, and using it to develop long-term water management plans. Taking such a short-term perspective, that conclusion could be repeated every 10 years for the next century, resulting in small incremental changes to water plans while, at the same time, the Basin could be transformed as a result of climate change and other drivers.

An alternative idea is to base changes to the Basin Plan and state water resource plans on observed changes to streamflow over recent times [12]. The large year-to-year variability in flows means that change is difficult to measure in the statistics of flow records, even though it may have been happening for years, and may already be having consequences in the form of more frequent droughts. If water plans for the future are based on the past 30 years, while the climate is drying, then management will lag behind climate impacts by decades.

A major limitation of the 10-year planning horizon is that many decisions have much longer lifetimes. The lifetime of a decision includes the lead time it takes from deciding to act to when the decision is implemented, the operational time over which the implementation is active or over which benefits are reaped, and the consequence time over which the legacy of the decision continues [84].

On-farm investments in irrigation infrastructure or permanent horticultural crops take longer than 10 years to pay off. Similarly, decisions to return water to the environment involve AUD billions in expenditure to provide benefits to the environment for several decades. Significant policy changes such as the Basin Plan itself had lead times of a decade to negotiate, and took a similar amount of time to implement through subsidiary state water resource plans [8,17]. Water resource plans are often based on historical reliabilities of annual water allocations. The longer water resource plans aim to maintain these, the stronger the legacy they will have through future expectations, even if that is unrealistic for a drier climate. Local changes to on-farm infrastructure and patterns of water use tend to flow on to longer term legacies for local employment, demography, and social cohesion. These are starting to be experienced now as a consequence of past reforms [72,81]. One of the aims of water reform in the Basin is to provide increased certainty over water entitlements, recognising these as significant assets. This aim will be undermined if major policy settings such as the Diversion Limit are changed every 10 years without such changes being foreshadowed in earlier plans. Figure 5 shows some decision lifetimes and how they are related to projected climate changes, requiring much longer timeframes for planning and adaptation.

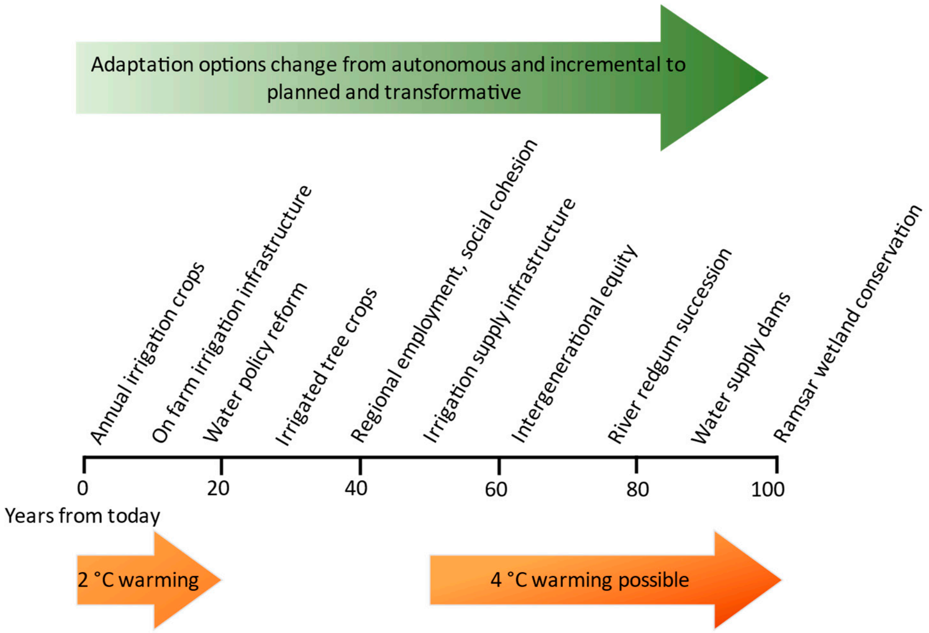

Figure 5. Timeline illustrating the conceptual lifetimes of different types of decisions, compared with the timescales for warming, and the changing types of adaptation. Adapted from [84] to show Basin water management examples.

Significant new public and private infrastructure has been associated with the reform of water management in the Basin, with associated risks of asset anchoring. Water entitlements for the environment have been obtained in part by funding modernisation of irrigation scheme supply infrastructure, and by subsidising farmers to install new on-farm irrigation infrastructure that uses less water. New levees and channel-control structures have been built to direct water to major wetlands more efficiently, and there are now plans to augment water supplies. This infrastructure locks in future expectations to some degree, as there will be resistance to retreating from it, and there will be efforts to protect it, even if they are maladaptive to the consequences of a drying climate. The concept of assets being anchored into the future comes from research examining the similar problem of sea-level rise [93]. Such research also shows that adaptations are more easily made for public infrastructure than for private infrastructure, or for more community-based solutions that do not involve infrastructure [94].

There needs to be some projection of conditions well beyond 10 years and, at minimum, a broad assessment of how management policies can adapt to worsening conditions. Some precautionary and low-risk longer term decisions could be made to improve longer term confidence.

The adaptation pathways approach provides a means of doing this; it combines the types of decisions that can be made for an uncertain future listed in Section 4.5 with decision lifetimes and the progressive nature of climate change [87]. This puts adaptation steps into a sequence of decisions and options that can be taken over time as circumstances change. They might start with incremental and short-term decisions, but evolve over time to more transformative long-term options if climate change deepens, sometimes involving a significant period of planning and preparation before a final decision point is reached, as exemplified by the classic example of the Thames Estuary 2100 study [95]. A feature of the pathways approach is that it focusses on community-based solutions to identified problems, involving locally expressed values [4,5,84,87]. The outcomes are usually summarized graphically, as illustrated for a water resources problem in Figure 6. These processes have been used in some Australian regions (e.g., [96]), but we are not aware of any water management examples from within the Basin. Regionally specific solutions and a history of regional disenfranchisement over the Basin Plan (e.g., [72,81]) suggest that governments may need to change to more polycentric, devolved structures, as has been argued for broader natural resource management in the Basin [97].

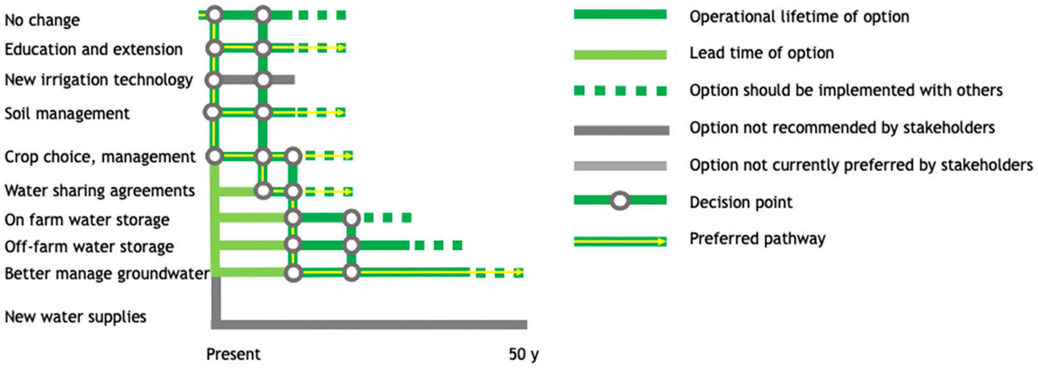

Figure 6. An example of a summary diagram of adaptation pathways for agricultural water use in Hawkes Bay, New Zealand. Adapted from [98].

Given the policy structure of subsidiary state water plans complying with the overall Basin Plan, the Basin Plan review in 2026 will need to take the lead in assessing long-term vulnerabilities from climate change and proposing overall solutions. Then, state water resource plans can be required to respond to the same degree. The Basin Plan review in 2026 should examine under what future conditions the current balance of water for consumption and water for the environment will need to change; it should consider the useful lifetime of decisions and investments made to date, and what changes to laws, policies, and rules can be used as adaptations to respond to the changing conditions; it should also consider what advanced actions should be taken to prepare for those decisions. Incentives and support can be given for regional adaptation solutions, where regional communities can be involved in planning their own futures—especially where regional impacts differ from the overall benefits of the Basin Plan.

5. Conclusions

The climate of the Basin is warming and drying, as seen in recent unprecedented droughts that have tested water management and the objectives sought from it. Projections of climate change have been consistent for at least two decades now, and point to continuing drying, so periods of more intense and frequent droughts can be expected in future. Small changes to average climate conditions can result in larger changes in the frequency of extreme droughts.

The sophisticated water management of the Basin and transformational reforms over the past 20 years provide a good starting point, but these were not designed as adaptations to climate change, and will be increasingly limited in suitability as the climate dries. Under a drier climate, the currently agreed sharing of outcomes between consumptive use and environmental health will change in favour of consumptive uses if current management and policy settings remain.

There are already ecosystems, irrigation farming sectors, and regional communities that are vulnerable to intense drought, and these vulnerabilities are likely to increase in the future. It may not be possible to protect all communities and environmental assets from a drier climate.

Ten-yearly reviews of water plans risk downplaying the significance of climate change and overstating uncertainties if they do not take a longer term perspective to risk. A longer term perspective is required in order to ensure that the substantial reforms and associated major expenditure have enduring value, and to identify new management arrangements or new investments that might require planning and preparations within the next 10 years.

The necessary elements in order for a 2026 review of the Basin Plan to adapt well to climate change, as identified in this review, can be summarised as follows:

- Evaluate Basin Plan outcomes to 2026, and how these compare to expectations and assumptions made in the 2012 Plan. Have climate changes or other drivers contributed to any mismatch between observed and expected responses between 2012 and 2026?;
- Explicitly account for uncertainties in Basin water balance so that they are not borne disproportionately by environmental water;
- Use multiple stochastic climate scenarios that consider possible climate variability and climate change for the next 50 years to provide a better test than the historical sequence of flows;
- Combine a few scenarios of future climate with other major changes in factors such as population, technology, and economics in an integrated system analysis. Climate combines with hydrology, ecology, farm production, demography, markets, and communities to influence outcomes;
- Use conservation planning principles to prioritise which environmental assets to protect;
- Ensure that the objectives of the Plan are specific and measurable, and evaluate their vulnerability to future changes. Require risk management actions to mitigate vulnerabilities;
- Devise and evaluate options for adapting to future risks, setting out potential decision points for the future beyond the 10-year horizon;
- Be locally specific in assessing impacts and vulnerabilities, and support local communities to express their values and priorities for adaptation;
- Use the longer term perspective of 50 years to identify actions that should be taken over the next 10-year iteration of the Plan to improve long-term adaptability.

These principles are applicable to basin water planning in other basins where a drying climate threatens water security. Two additional lessons from this review are that current best water management practice may not produce equitable outcomes under a drier climate, and that theoretically good adaptive management is not necessarily matched by its practice.

Author Contributions: Conceptualization, writing, and editing, I.P.P., F.H.S.C. and M.S.S.; climate change and water availability section, F.H.S.C.; evaluating current management section, I.P.P. and M.S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

Acknowledgments: I.P. developed several of the ideas for this paper while working as an independent consultant to the Murray–Darling Basin Authority to help plan their Water and Environment Research Program. He thanks the MDBA and the researchers he consulted for the opportunity. The ideas presented here are those of the authors, and do not necessarily represent those of the MDBA. The authors thank Hongxing Zheng for the additional analysis and modelling to develop Figure 2.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Jiménez Cisneros, B.E.; Oki, T.; Arnell, N.W.; Benito, G.; Cogley, J.G.; Döll, P.; Jiang, T.; Mwakalila, S.S. *Freshwater resources In Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2014; pp. 229–269.
2. UNESCO. *UN-Water, United Nations World Water Development Report 2020: Water and Climate Change*; UNESCO: Paris, France, 2020.
3. Vörösmarty, C.J.; McIntyre, P.B.; Gessner, M.O.; Dudgeon, D.; Prusevich, A.; Green, P.; Glidden, S.; Bunn, S.; Sullivan, C.A.; Liermann, C.R.; et al. Global threats to human water security and river biodiversity. *Nature* **2010**, *467*, 555–561. [CrossRef]
4. Pahl-Wostl, C.; Jeffrey, P.; Isendahl, N.; Brugnach, M. Maturing the New Water Management Paradigm: Progressing from Aspiration to Practice. *Water Resour. Manag.* **2010**, *25*, 837–856. [CrossRef]
5. Huntjens, P.; Lebel, L.; Pahl-Wostl, C.; Camkin, J.; Schulze, R.; Kranz, N. Institutional design propositions for the governance of adaptation to climate change in the water sector. *Glob. Environ. Chang.* **2012**, *22*, 67–81. [CrossRef]
6. Allan, C.; Xia, J.; Pahl-Wostl, C. Climate change and water security: Challenges for adaptive water management. *Curr. Opin. Environ. Sustain.* **2013**, *5*, 625–632. [CrossRef]
7. Milly, P.C.D.; Betancourt, J.; Falkenmark, M.; Hirsch, R.; Kundzewicz, Z.; Lettenmaier, D.P.; Stouffer, R.J. Stationarity Is Dead: Whither Water Management? *Science* **2008**, *319*, 573–574. [CrossRef]
8. Doolan, J. *The Australian Water Reform Journey*; The Australian Water Partnership and eWater Ltd.: Canberra, Australia, 2016.
9. Hart, B.T.; Alexandra, J.; Bond, N.R.; Byron, N.; Marsh, R.; Pollino, C.A.; Stewardson, M.J. The way forward: Continuing policy and management reforms in the Murray-Darling Basin. In *Murray-Darling Basin: Its Future Management*; Hart, B.T., Bond, N.R., Byron, N., Pollino, C.A., Stewardson, M.J., Eds.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 389–429.
10. Neave, I.; McLeod, A.; Raisin, G.; Swirepik, J. Managing water in the Murray-Darling Basin under a variable and changing climate. *Water* **2015**, *42*, 102–107.
11. MDBA. *Climate Change and the Murray–Darling Basin Plan*; Murray-Darling Basin Authority: Canberra, Australia, 2019.
12. Slatyer, A. Adaptation and policy responses to climate change impacts in the Murray–Darling Basin. In *Murray-Darling Basin: Its Future Management*; Hart, B.T., Bond, N.R., Byron, N., Pollino, C.A., Stewardson, M.J., Eds.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 275–286.
13. Grafton, R.Q.; Pittock, J.; Williams, J.; Jiang, Q.; Possingham, H.; Quiggin, J. Water Planning and Hydro-Climatic Change in the Murray-Darling Basin, Australia. *Ambio* **2014**, *43*, 1082–1092. [CrossRef] [PubMed]
14. Pittock, J.; Williams, J.; Grafton, R.Q. The Murray-Darling Basin plan fails to deal adequately with climate change. *Water* **2015**, *43*, 26–30.
15. Carmody, E. *Analysis: Are Our Water Laws Climate Ready?* Environmental Defenders Office: Sydney, Australia, 2019. Available online: https://www.edo.org.au/2019/12/19/are-water-laws-climate-ready/ (accessed on 12 July 2021).
16. Walker, G.; Crosbie, R.; Chiew, F.; Peeters, L.; Evans, R. Groundwater impacts and management under a drying climate in southern Australia. *Water*. in press.
17. Hart, B.T. The Australian Murray-Darling Basin Plan: Factors leading to its successful development. *Ecohydrol. Hydrobiol.* **2016**, *16*, 229–241. [CrossRef]
18. Horne, J. The politics of water reform and environmental sustainability in the Murray–Darling Basin. *Water Int.* **2017**, *42*, 1000–1021. [CrossRef]
19. Dyson, M. Current water resources policy and planning in the Murray–Darling Basin. In *Murray-Darling Basin: Its Future Management*; Hart, B.T., Bond, N.R., Byron, N., Pollino, C.A., Stewardson, M.J., Eds.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 163–202.
20. Chiew, F.H.S.; McMahon, T.A. Global ENSO-streamflow teleconnection, streamflow forecasting and interannual variability. *Hydrol. Sci. J.* **2002**, *47*, 505–522. [CrossRef]
21. Peel, M.C.; McMahon, T.A.; Finlayson, B.L. Continental differences in the variability of annual runoff—Update and reassess-ment. *J. Hydrol.* **2004**, *295*, 185–197. [CrossRef]

22. Young, W.J.; Chiew, F.H.S. Climate change in the Murray-Darling Basin: Implications for water use and environmental consequences. In *Water Resources Planning and Management: Challenges and Solutions*; Grafton, R.Q., Hussey, K., Eds.; Cambridge University Press: Cambridge, UK, 2011; pp. 439–459.
23. Van Dijk, A.I.J.M.; Beck, H.E.; Crosbie, R.; De Jeu, R.A.M.; Liu, Y.Y.; Podger, G.M.; Timbal, B.; Viney, N. The Millennium Drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy, and society. *Water Resour. Res.* **2013**, *49*, 1040–1057. [CrossRef]
24. Vertessy, R.V.; Barma, D.; Baumgartner, L.; Mitrovic, S.; Sheldon, F.; Bond, N. *Final Report of the Independent Assessment of the 2018–2019 Fish Deaths in the Lower Darling*; Independent Panel for the Australian Government: Canberra, Australia, 2019.
25. Whetton, P.; Chiew, F. Climate change impacts in the Murray-Darling Basin. In *Murray-Darling Basin: Its Future Management*; Hart, B.T., Bond, N.R., Byron, N., Pollino, C.A., Stewardson, M.J., Eds.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 253–274.
26. Potter, N.J.; Chiew, F.H.S. An investigation into changes in climate characteristics causing the recent very low runoff in the southern Murray-Darling Basin using rainfall-runoff models. *Water Resour. Res.* **2011**, *47*. [CrossRef]
27. DELWP; BoM; CSIRO; Uni. Melbourne. *Victoria's Water in a Changing Climate*; Department of Environment, Land, Water and Planning: Melbourne, Vic, Australia, 2020. Available online: VICWACl_VictoriasWaterInAChangingClimate_FINAL.pdf (accessed on 12 July 2021).
28. Chiew, F.H.S. Estimation of rainfall elasticity of streamflow in Australia. *Hydrol. Sci. J.* **2006**, *51*, 613–625. [CrossRef]
29. Timbal, B.; Hendon, H. The role of tropical modes of variability in the current rainfall deficit across the Murray-Darling Basin. *Water Resour. Res* **2011**, *47*, W00G09. [CrossRef]
30. Post, D.A.; Timbal, B.; Chiew, F.H.S.; Hendon, H.H.; Nguyen, H.; Moran, R. Decrease in southeastern Australian water avail-ability linked to ongoing Hadley cell expansion. *Earth's Future* **2014**, *2*, 231–238. [CrossRef]
31. Rauniyar, S.P.; Power, S.B. The Impact of Anthropogenic Forcing and Natural Processes on Past, Present, and Future Rainfall over Victoria, Australia. *J. Clim.* **2020**, *33*, 8087–8106. [CrossRef]
32. Potter, N.; Chiew, F.; Frost, A. An assessment of the severity of recent reductions in rainfall and runoff in the Murray–Darling Basin. *J. Hydrol.* **2010**, *381*, 52–64. [CrossRef]
33. Gallant, A.J.E.; Gergis, J. An experimental streamflow reconstruction for the River Murray, Australia, 1783–1988. *Water Resour. Res.* **2011**, *47*. [CrossRef]
34. Flack, A.L.; Kiem, A.S.; Vance, T.R.; Tozer, C.R.; Roberts, J.L. Comparison of published palaeoclimate records suitable for re-constructing annual to sub-decadal hydroclimatic variability in eastern Australia: Implications for water resource management and planning. *Hydrol. Earth Syst. Sci.* **2020**, *24*, 5699–5712. [CrossRef]
35. Chiew, F.H.S.; Potter, N.; Vaze, J.; Petheram, C.; Zhang, L.; Teng, J.; Post, D.A. Observed hydrologic non-stationarity in far south-eastern Australia: Implications for modelling and prediction. *Stoch. Environ. Res. Risk Assess.* **2013**, *28*, 3–15. [CrossRef]
36. Saft, M.; Peel, M.C.; Western, A.W.; Zhang, L. Predicting shifts in rainfall-runoff response during multiyear drought: Roles of dry period and catchment characteristics. *Water Resour. Res.* **2016**, *52*, 9290–9305. [CrossRef]
37. Hughes, J.D.; Petrone, K.C.; Silberstein, R.P. Drought, groundwater storage and streamflow decline in southwestern Australia. *Geophys. Res. Lett.* **2012**, *39*, L03408. [CrossRef]
38. Peterson, T.J.; Saft, M.; Peel, M.C.; John, A. Watersheds may not recover from drought. *Science* **2021**, *372*, 745–749. [CrossRef] [PubMed]
39. Brookhouse, M.T.; Farquhar, G.D.; Roderick, M.L. The impact of bushfires on water yield from south-east Australia's ash forests. *Water Resour. Res.* **2013**, *49*, 4493–4505. [CrossRef]
40. Fowler, K.; Morden, R.; Lowe, L.; Nathan, R. Advances in assessing the impact of hillside farm dams on streamflow. *Australas. J. Water Resour.* **2015**, *19*, 96–108. [CrossRef]
41. Ukkola, A.M.; Prentice, I.C.; Keenan, T.F.; van Dijk, A.I.J.M.; Viney, N.R.; Myneni, R.B.; Bi, J. Reduced streamflow in water-stressed climates consistent with CO2 effects on vegetation. *Nat. Clim. Chang.* **2016**, *6*, 75–78. [CrossRef]
42. Cheng, L.; Zhang, L.; Wang, Y.; Canadell, J.G.; Chiew, F.H.S.; Beringer, J.; Li, L.; Miralles, D.G.; Piao, S.; Zhang, Y. Recent increases in terrestrial carbon uptake at little cost to the water cycle. *Nat. Commun.* **2017**, *8*, 1–10. [CrossRef] [PubMed]
43. Zheng, H.; Chiew, F.; Potter, N.; Kirono, D. Projections of water futures for Australia: An update. In Proceedings of the MODSIM, Canberra, Australia, 1–6 December 2019. [CrossRef]
44. Chiew, F.H.S.; Teng, J.; Vaze, J.; Post, D.A.; Perraud, J.M.; Kirono, D.G.C.; Viney, N. Estimating climate change impact on runoff across south-east Australia: Method, results and implications of modelling method. *Water Resour. Res.* **2009**, *45*, W10414. [CrossRef]
45. Kirono, D.G.; Round, V.; Heady, C.; Chiew, F.H.; Osbrough, S. Drought projections for Australia: Updated results and analysis of model simulations. *Weather. Clim. Extremes* **2020**, *30*, 100280. [CrossRef]
46. Grose, M.R.; Narset, S.; Delage, F.P.; Dowdy, R.J.; Bador, M.; Boschat, G.; Chung, C.; Kajtar, J.B.; Rauniyar, S.; Freund M., B.; et al. Insights from CMIP6 for Australia's future climate. *Earth's Future* **2020**, *8*, e2019EF001469. [CrossRef]
47. Grose, M.R.; Syktus, J.; Thatcher, M.; Evans, J.P.; Ji, F.; Rafter, T.; Remenyi, T. The role of topography on projected rainfall change in mid-latitude mountain regions. *Clim. Dyn.* **2019**, *53*, 3675–3690. [CrossRef]
48. Potter, N.J.; Chiew, F.H.S.; Charles, S.P.; Fu, G.; Zheng, H.; Zhang, L. Bias in downscaled rainfall characteristics. *Hydrol. Earth Syst. Sci.* **2020**, *24*, 2963–2979. [CrossRef]

49. Charles, S.P.; Chiew, F.H.S.; Potter, N.J.; Zheng, H.; Fu, G.; Zhang, L. Impact of downscaled rainfall biases on projected runoff changes. *Hydrol. Earth Syst. Sci.* **2020**, *24*, 2981–2997. [CrossRef]
50. Chiew, F.H.S.; Zheng, H.; Potter, N.J.; Ekstrom, M.; Grose, M.R.; Kirono, D.G.C.; Zhang, L.; Vaze, J. Future runoff projections for Australia and science challenges in producing next generation projections. In Proceedings of the 22nd International Conference on Modeling and Simulation, Hobart, Australia, 3-8 December 2017; pp. 1745–1751. Available online: https://www.mssanz.org.au/modsim2017/L16/chiew.pdf (accessed on 5 August 2021).
51. Ekström, M.; Grose, M.; Heady, C.; Turner, S.W.D.; Teng, J. The method of producing climate change datasets impacts the resulting policy guidance and chance of mal-adaptation. *Clim. Serv.* **2016**, *4*, 13–29. [CrossRef]
52. MDBA Water Resource Plans. Available online: https://www.mdba.gov.au/basin-plan-roll-out/water-resource-plans (accessed on 23 June 2021).
53. CSIRO Water. Availability in the Murray-Darling Basin. In *A Report from CSIRO to the Australian Government Commonwealth Scientific Industrial and Research Organisation*; CSIRO Water: Canberra, Australia, 2008. Available online: https://publications.csiro.au/rpr/download?pid=legacy:530&dsid=DS1 (accessed on 12 July 2021).
54. CSIRO Water. Availability in the Murray. In *A Report from CSIRO to the Australian Government. Commonwealth Scientific Industrial and Research Organisation*; CSIRO Water: Canberra, Australia, 2008. Available online: https://publications.csiro.au/rpr/download?pid=procite:cfc7ab48-acf5-4cff-87aa-f398cfb0287f&dsid=DS1 (accessed on 5 August 2021).
55. Commonwealth Environmental Water Office. Commonwealth Environmental Water Holdings by Catchment and Year. Available online: https://www.environment.gov.au/water/cewo/about/water-holdings (accessed on 11 August 2021).
56. Van Dijk, A.I.J.M.; Kirby, M.; Paydar, Z.; Podger, G.; Mainuddin, M.; Marvanek, S.; Peña Arancibia, J. *Uncertainty in River Modelling across the Murray-Darling Basin. A Report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project*; CSIRO: Canberra, Australia, 2008.
57. Tomkins, K.M. Uncertainty in streamflow rating curves: Methods, controls and consequences. *Hydrol. Process.* **2012**, *28*, 464–481. [CrossRef]
58. Matthews, K. *Interim Report: Independent Investigation into NSW Water Management and Compliance*; NSW Government: Sydney, Australia, 2017.
59. Walker, G.; Horne, A.; Wang, Q.; Rendell, R. Assessing the Impact of Irrigation Efficiency Projects on Return Flows in the South-Eastern Murray–Darling Basin, Australia. *Water* **2021**, *13*, 1366. [CrossRef]
60. Walker, B. *Murray-Darling Basin Royal Commission Report*; South Australian Government: Adelaide, Australia, 2019.
61. Wentworth Group of Concerned Scientists. *Assessment of River Flows in the Murray-Darling Basin: Observed Versus Expected Flows under the Basin Plan 2012–2019*; Wentworth Group of Concerned Scientists: Sydney, Australia, 2020. Available online: https://wentworthgroup.org/wp-content/uploads/2020/08/MDB-flows.pdf (accessed on 12 July 2021).
62. Davies, A. Former NSW Water Minister Defends Exclusion of Driest Years from Sustainable Water Calculations. The Guardian Australia Edition, Tue 14 July 2020. Available online: https://www.theguardian.com/australia-news/2020/jul/13/former-nsw-water-minister-defends-exclusion-of-driest-years-from-sustainable-water-calculations (accessed on 23 June 2021).
63. Cobb, K.M.; Charles, C.D.; Cheng, H.; Edwards, R.L. El Niño/Southern Oscillation and tropical Pacific climate during the last millennium. *Nature* **2003**, *424*, 271–276. [CrossRef] [PubMed]
64. Abram, N.J.; Wright, N.M.; Ellis, B.; Dixon, B.C.; Wurtzel, J.; England, M.H.; Ummenhofer, C.C.; Philibosian, B.; Cahyarini, S.Y.; Yu, T.-L.; et al. Coupling of Indo-Pacific climate variability over the last millennium. *Nature* **2020**, *579*, 385–392. [CrossRef]
65. BoM; CSIRO. *State of the Climate*; Commonwealth of Australia: Canberra, Australia, 2020.
66. Bates, B.C.; Hope, P.; Ryan, B.; Smith, I.; Charles, S. Key findings from the Indian Ocean Climate Initiative and their impact on policy development in Australia. *Clim. Chang.* **2008**, *89*, 339–354. [CrossRef]
67. Kirby, M.; Bark, R.; Connor, J.; Qureshi, M.E.; Keyworth, S. Sustainable irrigation: How did irrigated agriculture in Australia's Murray–Darling Basin adapt in the Millennium Drought? *Agric. Water Manag.* **2014**, *145*, 154–162. [CrossRef]
68. Horne, A.C.; Nathan, R.; Poff, N.L.; Bond, N.R.; Webb, J.A.; Wang, J.; John, A. Modeling Flow-Ecology Responses in the Anthropocene: Challenges for Sustainable Riverine Management. *BioScience* **2019**, *69*, 789–799. [CrossRef]
69. NSW. *DPIE Draft Regional Water Strategy*; Namoi Strategy; PUB20/313 NSW Department of Planning, Industry and Environment: Sydney, Australia, 2021. Available online: https://www.industry.nsw.gov.au/water/plans-programs/regional-water-strategies/public-exhibition/previously/namoi (accessed on 12 July 2021).
70. Qureshi, M.E.; Ahmad, M.D.; Whitten, S.M.; Reeson, A.; Kirby, M. Impact of Climate Variability Including Drought on the Residual Value of Irrigation Water Across the Murray–Darling Basin, Australia. *Water Econ. Policy* **2018**, *4*, 1550020. [CrossRef]
71. Gupta, M.; Hughes, N.; Whittle, L.; Westwood, T. *Future Scenarios for the Southern Murray-Darling Basin, Report to the Independent Assessment of Social and Economic Conditions in the Basin*; Australian Bureau of Agricultural and Resource Economics and Sciences: Canberra, Australia, 2020. [CrossRef]
72. Sefton, R.; Peterson, D.; Woods, R.; Kassebaum, A.; McKenzie, D.; Simpson, B.; Ramsay, M. *Independent Assessment of Social and Economic Conditions in the Murray–Darling Basin*; Panel for Independent Assessment of Social and Economic Conditions in the Murray–Darling Basin: Melbourne, Australia, 2020.
73. Kirsch, E.; Colloff, M.J.; Pittock, J. Lacking character? A policy analysis of environmental watering of Ramsar wetlands in the Murray–Darling Basin, Australia. *Mar. Freshw. Res.* **2021**. [CrossRef]

74. Linke, S.; Hermoso, V.; Januchowski-Hartley, S. Toward process-based conservation prioritizations for freshwater ecosystems. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **2018**, *29*, 1149–1160. [CrossRef]
75. Bino, G.; Kingsford, R.; Porter, J. Prioritizing Wetlands for Waterbirds in a Boom and Bust System: Waterbird Refugia and Breeding in the Murray-Darling Basin. *PLoS ONE* **2015**, *10*, e0132682. [CrossRef]
76. Swirepik, J.L.; Burns, I.C.; Dyer, F.J.; Neave, I.A.; O'Brien, M.G.; Pryde, G.M.; Thompson, R.M. Science informed policy: Establishing environmental water needs for Australia's largest and most developed river basin. *River Res. Appl.* **2016**, *32*, 1153–1165. [CrossRef]
77. Tonkin, J.D.; Poff, N.L.; Bond, N.R.; Horne, A.; Merritt, D.M.; Reynolds, L.V.; Olden, J.; Ruhi, A.; Lytle, D.A. Prepare river ecosystems for an uncertain future. *Nature* **2019**, *570*, 301–303. [CrossRef]
78. Alexandra, J. The science and politics of climate risk assessment in Australia's Murray Darling Basin. *Environ. Sci. Policy* **2020**, *112*, 17–27. [CrossRef]
79. Horne, J. The 2012 Murray-Darling Basin Plan—Issues to watch. *Int. J. Water Resour. Dev.* **2013**, *30*, 152–163. [CrossRef]
80. MDBA. *The Basin Plan 2020 Evaluation*; Murray-Darling Basin Authority: Canberra, Australia, 2020.
81. Keelty, M. *Impact of Lower Inflows on State Shares under the Murray–Darling Basin Agreement*; Interim Inspector-General of Murray–Darling Basin Water Resources Commonwealth of Australia: Canberra, Australia, 2020. Available online: https://www.igwc.gov.au/sites/default/files/2020-09/iig_final_report.pdf (accessed on 12 July 2021).
82. Productivity Commission. *Murray-Darling Basin Plan: Five-Year Assessment*; Final Report no. 90; Productivity Commission: Canberra, Australia, 2018. Available online: https://www.pc.gov.au/inquiries/completed/basin-plan/report (accessed on 12 July 2021).
83. COAG. Improving Implementation of the Murray-Darling Basin Plan. In *Council of Australian Governments Meeting Communique 9 August 2019, Commonwealth of Australia*; COAG: Canberra, Australia, 2019. Available online: https://www.pc.gov.au/inquiries/completed/basin-plan/basin-plan-government-response.pdf (accessed on 12 July 2021).
84. Smith, M.S.; Horrocks, L.; Harvey, A.; Hamilton, C. Rethinking adaptation for a 4 °C world. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2011**, *369*, 196–216. [CrossRef] [PubMed]
85. Dovers, S.R.; Hezri, A.A. Institutions and policy processes: The means to the ends of adaptation. *Wiley Interdiscip. Rev. Clim. Chang.* **2010**, *1*, 212–231. [CrossRef]
86. CSIRO Climate Compass. *A Climate Risk Management Framework for Commonwealth Agencies*; Commonwealth Scientific and Industrial Research Organisation: Canberra, Australia, 2018.
87. Siebentritt, M.; Stafford Smith, M. *A User's Guide to Applied Adaptation Pathways Version 1*; Seed Consulting Services and CSIRO: Adelaide, Australia, 2016. Available online: http://www.adaptationpathways.net (accessed on 5 December 2020).
88. WSAA. *Climate Change Adaptation Guidelines*; Water Services Association of Australia: Melbourne, Australia, 2016.
89. Haasnoot, M.; Kwakkel, J.H.; Walker, W.E.; ter Maat, J. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Glob. Environ. Chang.* **2013**, *23*, 485–498. [CrossRef]
90. Walker, W.E.; Haasnoot, M.; Kwakkel, J.H. Adapt or Perish: A Review of Planning Approaches for Adaptation under Deep Uncertainty. *Sustainability* **2013**, *5*, 955–979. [CrossRef]
91. Malekpour, S.; Walker, W.E.; de Haan, F.J.; Frantzeskaki, N.; Marchau, V.A. Bridging Decision Making under Deep Uncertainty (DMDU) and Transition Management (TM) to improve strategic planning for sustainable development. *Environ. Sci. Policy* **2020**, *107*, 158–167. [CrossRef]
92. Stewardson, M.J.; Walker, G.; Coleman, M. Hydrology of the Murray-Darling Basin, Murray-Darling Basin, Australia. In *Murray-Darling Basin: Its Future Management*; Hart, B.T., Bond, N.R., Byron, N., Pollino, C.A., Stewardson, M.J., Eds.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 47–73.
93. Gibbs, M.T. Asset anchoring as a constraint to sea level rise adaptation. *Ocean Coast. Manag.* **2013**, *85*, 119–123. [CrossRef]
94. Gibbs, M.T. The two-speed coastal climate adaptation economy in Australia. *Ocean Coast. Manag.* **2020**, *190*, 105150. [CrossRef]
95. Reeder, T.; Ranger, N. *How Do You Adapt in an Uncertain World? Lessons from the Thames Estuary 2100 Project*; World Resources Report; World Resources Institute: Washington, DC, USA, 2011. Available online: http://climatelondon.org/wp-content/uploads/2019/10/wrr_reeder_and_ranger_uncertainty.pdf (accessed on 25 August 2021).
96. Siebentritt, M.; Halsey, N.; Stafford-Smith, M. *Regional Climate Change Adaptation Plan for the Eyre Peninsula*; Prepared for the Eyre Peninsula Integrated Climate Change Agreement Committee; Seed Consulting Services: Port Lincoln, Australia, 2014.
97. Marshall, G.R.; Smith, M.S. Natural resources governance for the drylands of the Murray–Darling Basin. *Rangel. J.* **2010**, *32*, 267–282. [CrossRef]
98. Cradock-Henry, N.A.; Blackett, P.; Connolly, J.; Frame, B.; Teixeira, E.; Johnstone, P.; Wreford, A. Principles and process for developing participatory adaptation pathways in the primary industries. *Elem. Sci. Anth.* **2021**, *9*. [CrossRef]