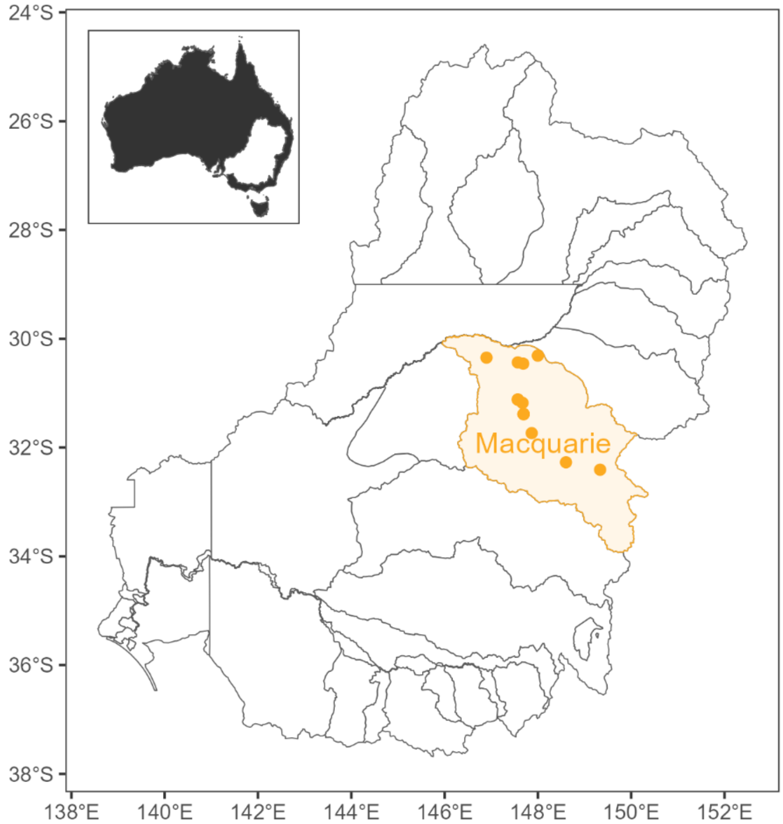
Supplementary material

Supplementary text 1

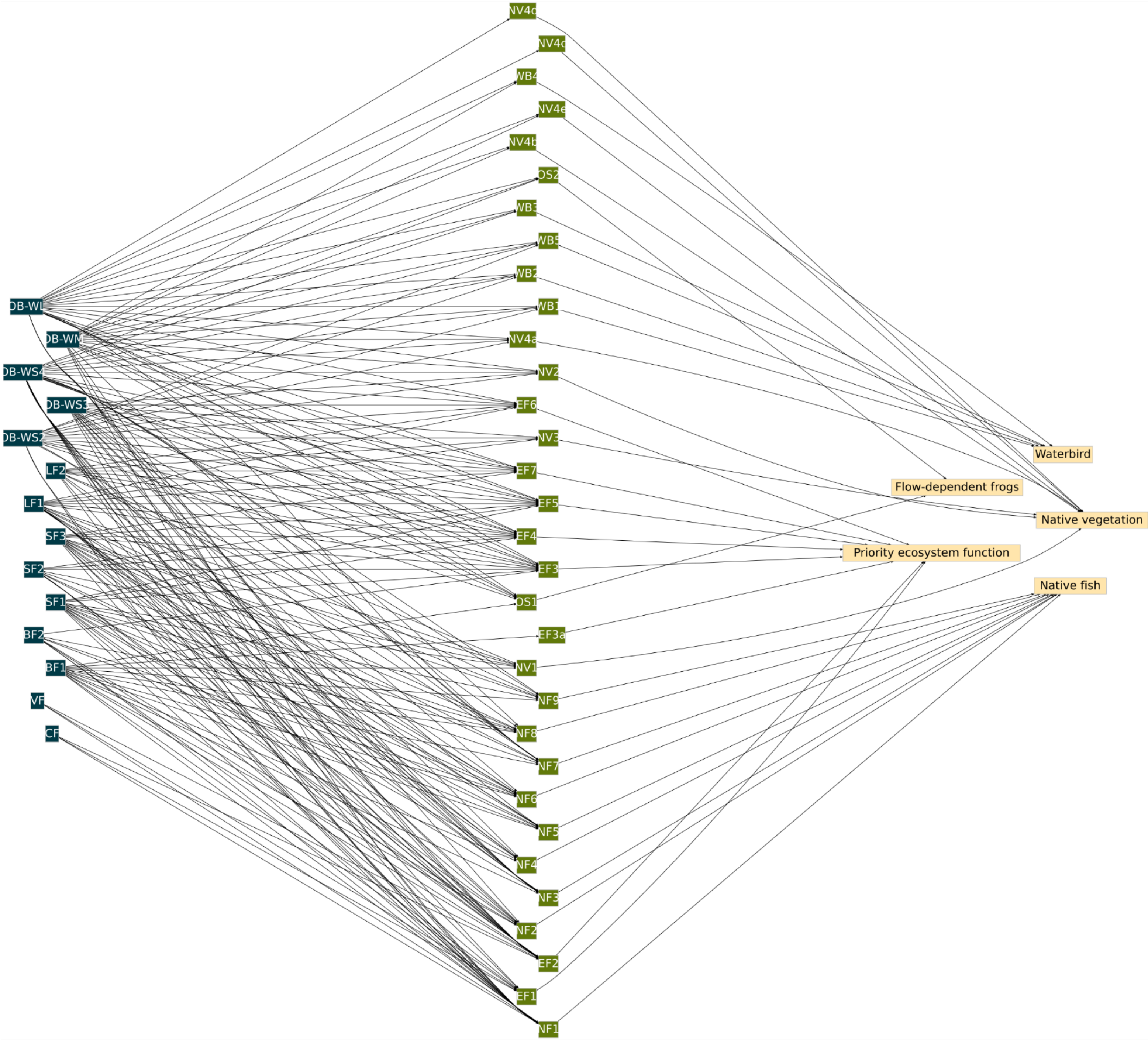
The Macquarie catchment is located in the centre of the Murray-Darling Basin, Australia (Supplementary Fig. 1). For the catchment, environmental water requirements (EWRs) are specified at each gauge location. Flow components are specified with a requisite timing, duration, flow volume and spell characteristics. An example is provided for one gauge within the catchment (Supplementary Table 1). These are then aggregated via a pathway of causal links to represent overarching environmental outcomes. An example of such a causal network is provided for part of one gauge (Supplementary Fig. 2). These causal networks are defined by the relevant environmental managers and are published in the LTWP for each catchment[e.g. 5]. The causal links between EWRs and environmental outcomes are frequently highly complex and vary from gauge to gauge.



Supplementary Figure 1. Location of the cast study catchment the Macquarie River catchment in the Murray-Darling Basin, Australia (see inset). The Macquarie catchment is highlighted in yellow among the other catchments (outlined in black) in the Basin.

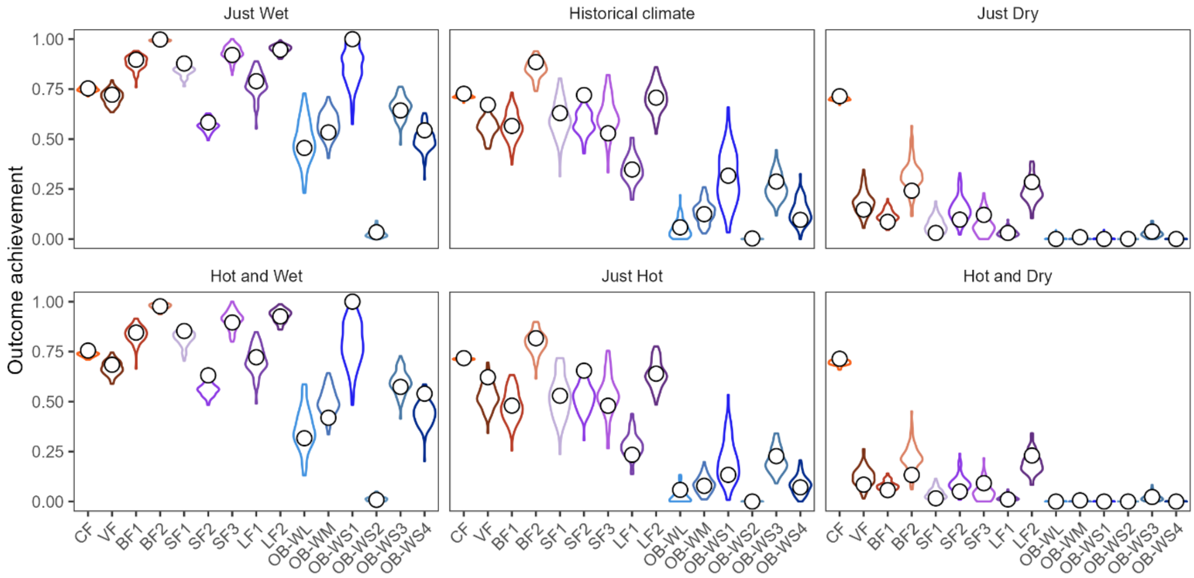
Supplementary Table 1. Example environmental water requirements for a single gauge (421019) in the Macquarie River catchment in the Murray-Darling Basin, Australia. EWR codes include the following abbreviations: CF – cease to flow, VF – very low flow, BF – base flow, SF – small fresh, LF – large fresh, OB_WS – small overbank wetland-inundating flow. Numbers and subsequent letters specify particular EWRs for particular environmental outcomes. Refer to [20] for additional details.

Code	Start Month	End Month	Target Frequency (% of 10 years)	Target Frequency Min (% of 10 years)	Target Frequency Max (% of 10 years)	Events Per Year	Number of Days Required Per Year (days)	Number of Consecutive Days Required (days)	Flow Threshold Min (ML/day)	Flow Threshold Max (ML/day)	Max Inter-event period (years)
CF_a	7	6				1	27	27	0	0	0
CF_b	7	6	5			1	138	138	0	0	0
CF_c	7	6	69			1	1	1	0	0	0
VF_a	7	6	50			1	267	1	10		1.23
VF_b	7	6	96			1	34	1	10		1.23
BF1_a	7	6	50			1	208	1	100		1.23
BF1_b	7	6	96			1	13	1	100		1.23
BF2_a	9	3	50	50	100	1	128	1	100		2
BF2_b	9	3	75	50	100	1	42	1	100		2
SF1	7	6	100			1	10	10	140		1
SF2	9	4	75	50	100	1	14	14	140	700	2
SF3	7	6	50			1	28	28	140		4
LF1	7	6	75	50	100	1	5	5	700		2
LF2	10	4	40	30	50	1	5	5	700		4
OB_WS2	7	6	75	50	100	1	10	10	1900		4
OB_WS3	7	6	25	20	30	1	5	5	1900		5
OB_WS4	7	6	65	30	100	1	5	5	1900		5



Supplementary Figure 2. Causal network showing the relationship between hydrologic indicators (EWRs) in blue on left to proximate environmental objectives (green, middle), which often capture particular parts of the life cycle of target species, and the broader ecological groups on the right to which they contribute. There are different causal networks at each gauge, this one is at 421012 in the Lower Macquarie River planning unit, with the EWRs here corresponding to those in Supplementary Table 1.

Supplementary text 2

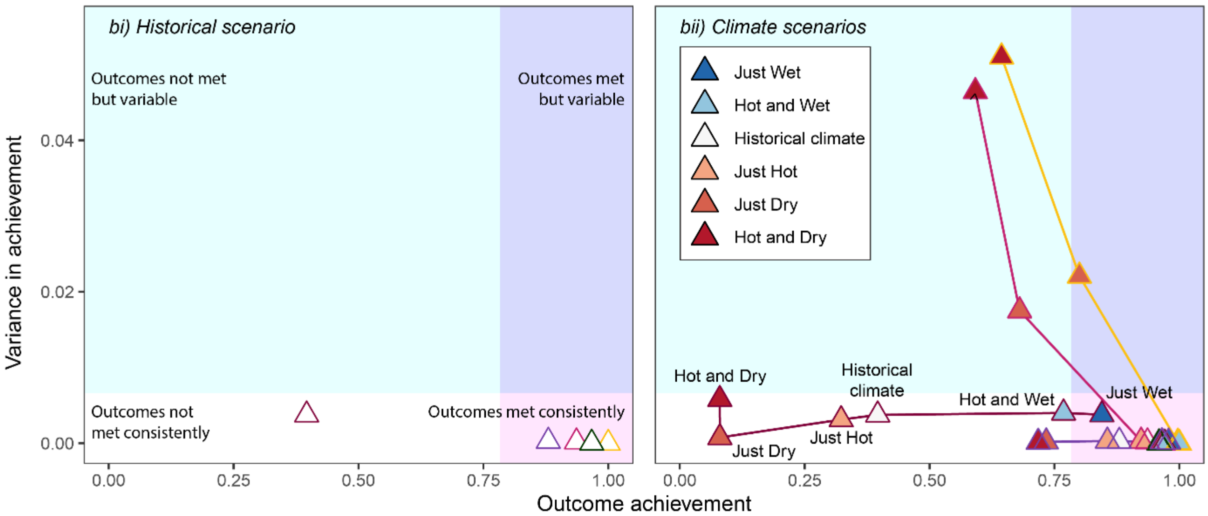


Supplementary Figure 3. Distribution of environmental water requirements (EWRs) as captured by the variability across 76 stochastic runs for each of six climates. The climates modelled included scaling of 0.8, 1.0 and 1.2 times daily rainfall for each of 1.00 and 1.07 times daily potential evaporation (equivalent to 2 ºC warming). Outcomes are relativised for this figure for ease of comparison but were modelled in their native units. The dots illustrate the mean for the outcome for that scenario while the violins illustrate the distribution of values over the stochastic runs.

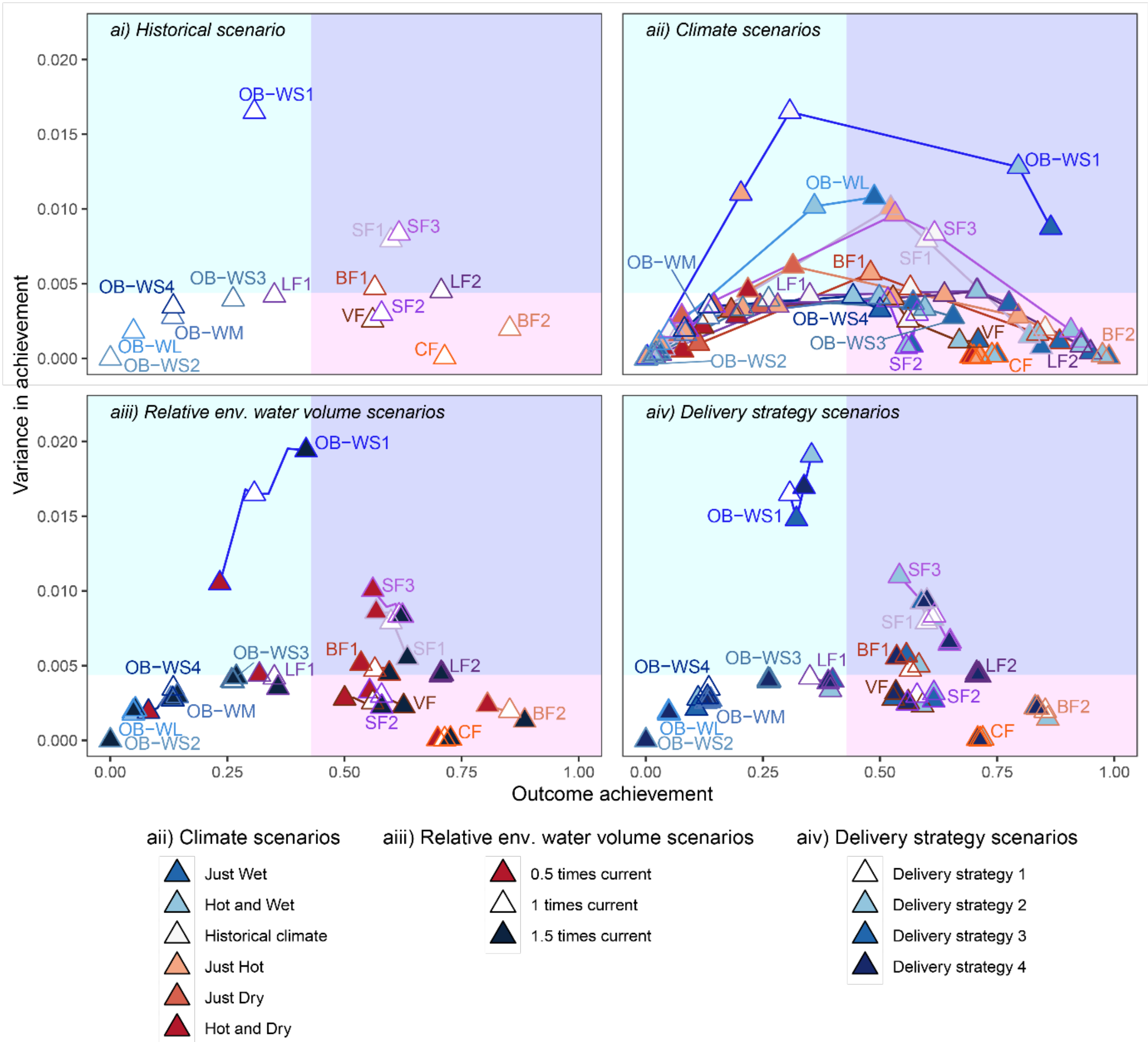
Supplementary text 3

To identify the impact of climate shifts and vulnerability to the sequencing of years, we measured the relative change in the outcomes achieved associated with each scenario modelled, as well as the variance across the 76 stochastic runs for each and plotted these (Fig. 3). Here, we provide an extract of Fig. 3 to assist with the interpretation of those figures if required. For each of the environmental (not shown), water allocation and agricultural benefit outcomes, we plotted the relative proportion of outcomes achieved and the variance of that proportion (Supplementary Fig. 4). In the left-hand panel, we illustrate the baseline achievement of each outcome under the historical scenario (plotted at triangles with labels identifying each specific outcome). The coloured quadrats provide an indication of the degree of vulnerability for each outcome. Those outcomes that fall in the bottom left quadrant (white) were consistently rarely achieved. Those that fall in the top left quadrant (blue) were rarely achieved but that degree of achievement was highly variable depending on the sequence of wet and dry years across the 76 stochastic runs. Outcomes in the top right quadrant (purple) were more regularly achieved, but that outcome was also highly variable. Outcomes in the bottom right (pink) quadrant were consistently and frequently achieved (annotated on the left-hand panel; Supplementary Fig. 4). The quadrats are defined as greater or less than the mean outcomes variance (on the y-axis) and greater or less than the mean outcome achievement (on the x-axis) for each of the sets of scenarios modelled.

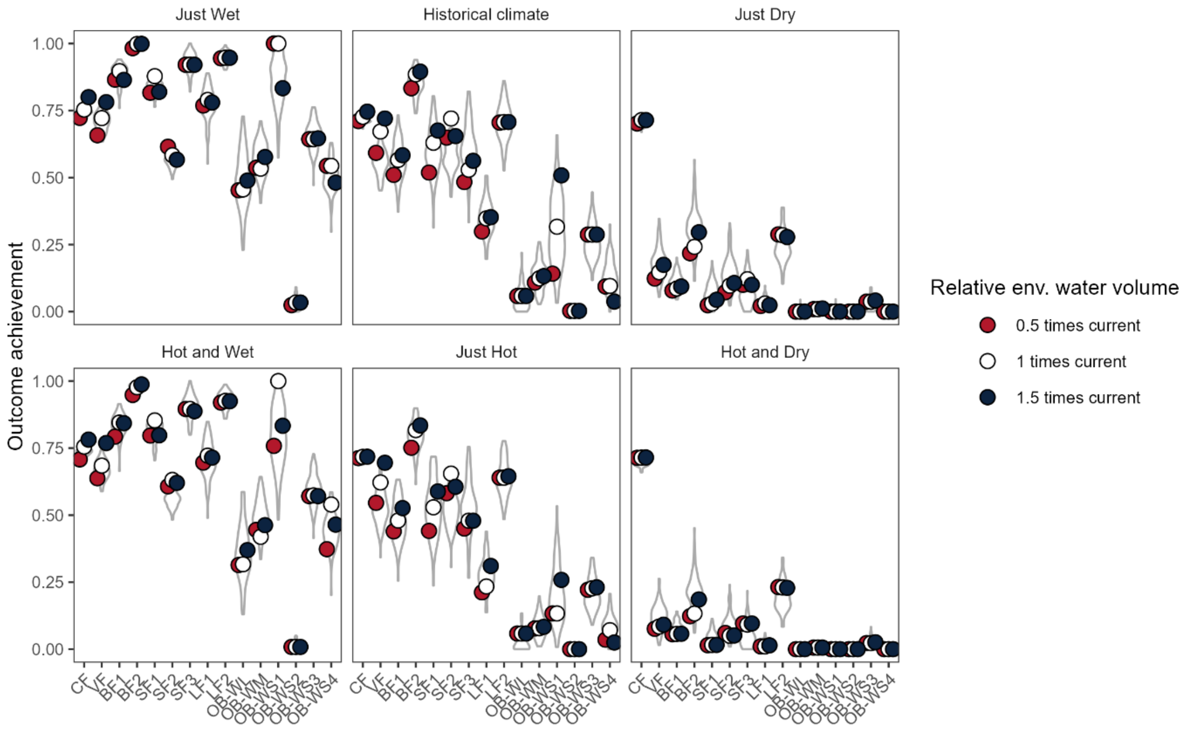
For sets of scenarios where we systematically adjusted settings (e.g. climate scenarios, annotated on the right-hand panel; Supplementary Fig. 4), we have connected the outcomes for that set with a coloured line. For example, the delivery ability outcomes for each of the six climate scenarios modelled are connected with a yellow line. This enables easy visualisation of the changes in vulnerability for a particular outcome associated with that set of scenarios, both in terms of the overall likelihood of achieving the outcome, but also regarding whether the variability in achieving that outcome changes across the sequence.



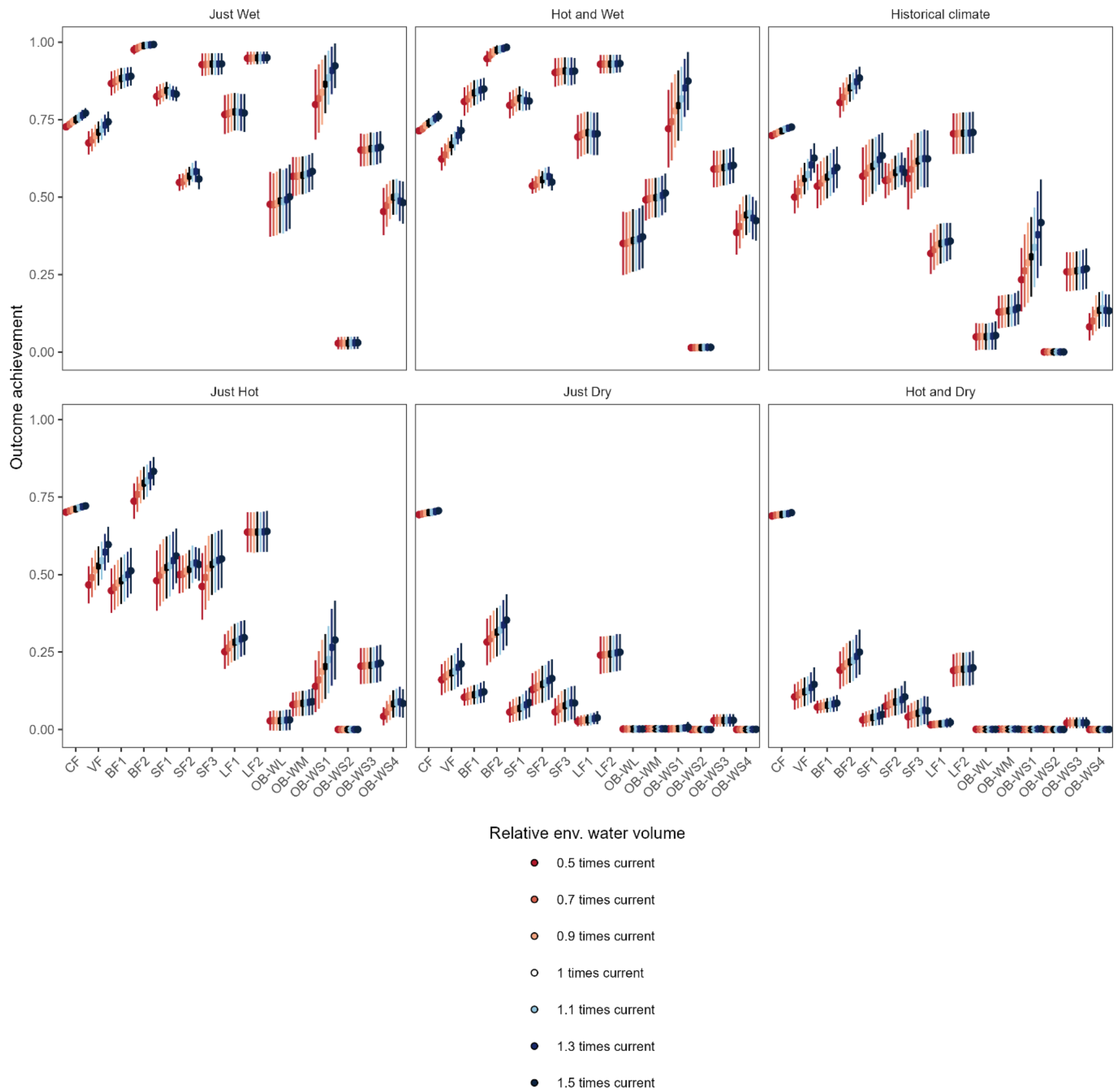
Supplementary Figure 4. Extract from Fig. 3 in the main text, with additional annotation to aid in the interpretation of the diagram.



Supplementary Figure 5. Relative vulnerability of each environmental water requirement (EWR), illustrating the interaction between the mean ability to meet the outcomes and the variance of that measure across the 76 stochastic runs. For EWRs, i) illustrates the historical scenario and ii) illustrates the impact of climate change scenarios (with solid fills indicating hotter drier scenarios and open shapes wetter scenarios). For the environmental outcomes only, iii) illustrates the impact of changes to the relative environmental volume (with solid fills indicating a greater volume to 1.5 times current and open shapes smaller volumes to 0.5 times current) and iv) illustrates the impact of changes in delivery strategy for four different delivery strategies. In each panel, a line links the scenarios for each outcome to assist in identifying associated change in that outcome. Quadrants are divided as greater or less than mean outcome variance (y) or mean outcome achievement (x) of climate scenarios for environmental and water allocation themes. Outcomes that fall in the bottom left quadrant (white) are consistently rarely achieved. Outcomes that fall in the top left quadrant (blue) are rarely achieved but highly variable across the stochastic runs. Outcomes that fall in the top right quadrant (purple) are highly variable but achieved more regularly and outcomes in the bottom right are consistently and frequently achieved (pink). Additional information on how to interpret this figure is provided in Supplementary text 3.



Supplementary Figure 6. Changes in the achievement of environmental water requirements (EWRs) based on changes in the total environmental water volume (relative to current volumes) superimposed on the distribution for the historical stochastic run for reference. Environmental water volume varies between half (0.5x) to 1.5 times the current volume.

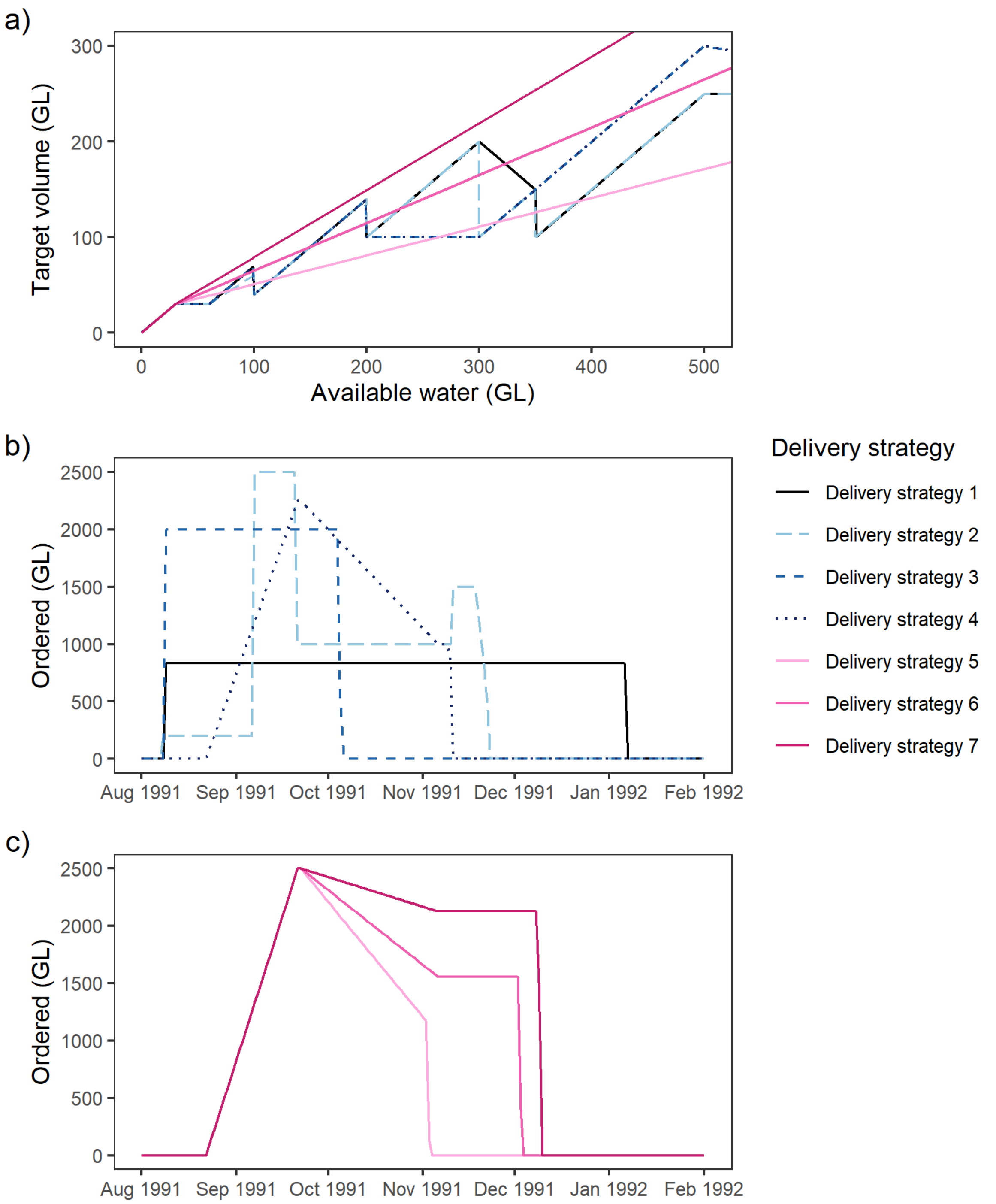


Supplementary Figure 7. Distributions around the achievement of environmental water requirements (EWRs) based on changes in the total environmental water volume (relative to current volumes) superimposed on the distribution for the historical stochastic run for reference. Environmental water volume varies between half (0.5x) to 1.5 times the current volume.

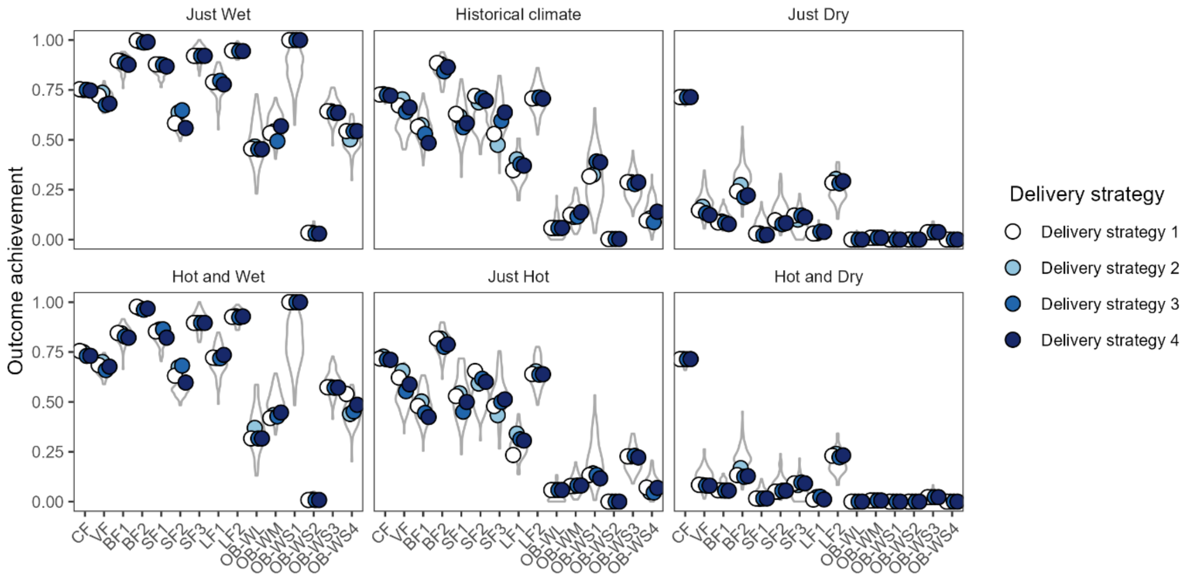
Supplementary text 4

Seven delivery strategies were tested in this study. These strategies differ in two key aspects. First, at the decision point on 1 August, the decision maker decides what portion of the available water should be used in a given year (target volume), with the remainder being carried over to the next year. The volume of water licences accessible by environment water managers consists of two parts: (a) an Environmental Water Allowance that is specified in the water sharing plan and (b) a volume of General Security licence owned by environmental water managers. Each year water is allocated to each of these components according following general security rules, and the available water on 1 August corresponds to the sum of the current allocation for the year and volume carried over from previous years. This rule dictates how conservative the delivery strategy is in terms of reserving water to secure environmental needs for the following year. The second aspect is the temporal pattern in which these volumes of water are ordered throughout the year varies. The temporal patterns of water use investigated represent approximations of current (Delivery Strategy 1), past (Delivery Strategy 2) and alternatives that target targeting different Environmental Water Requirements (EWR).

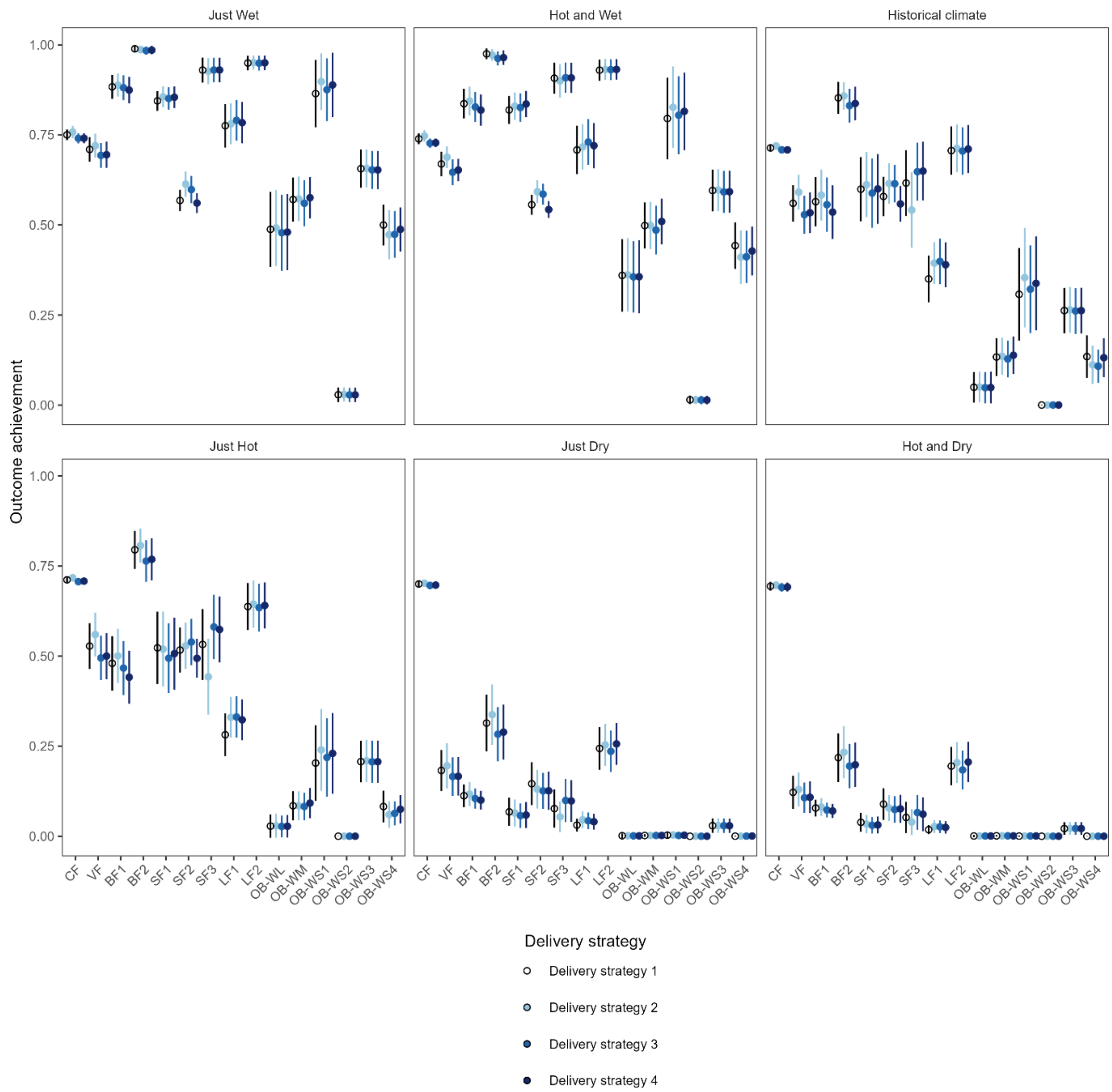
Supplementary Fig. 8 shows the difference between the delivery strategies for environmental water simulated in this study. The top panel shows the amount of water targeted for each year to be ordered throughout the season, with the remaining available water carried over to the next year. The second and third panels show a sample of simulated water orders for the year 1991-92.



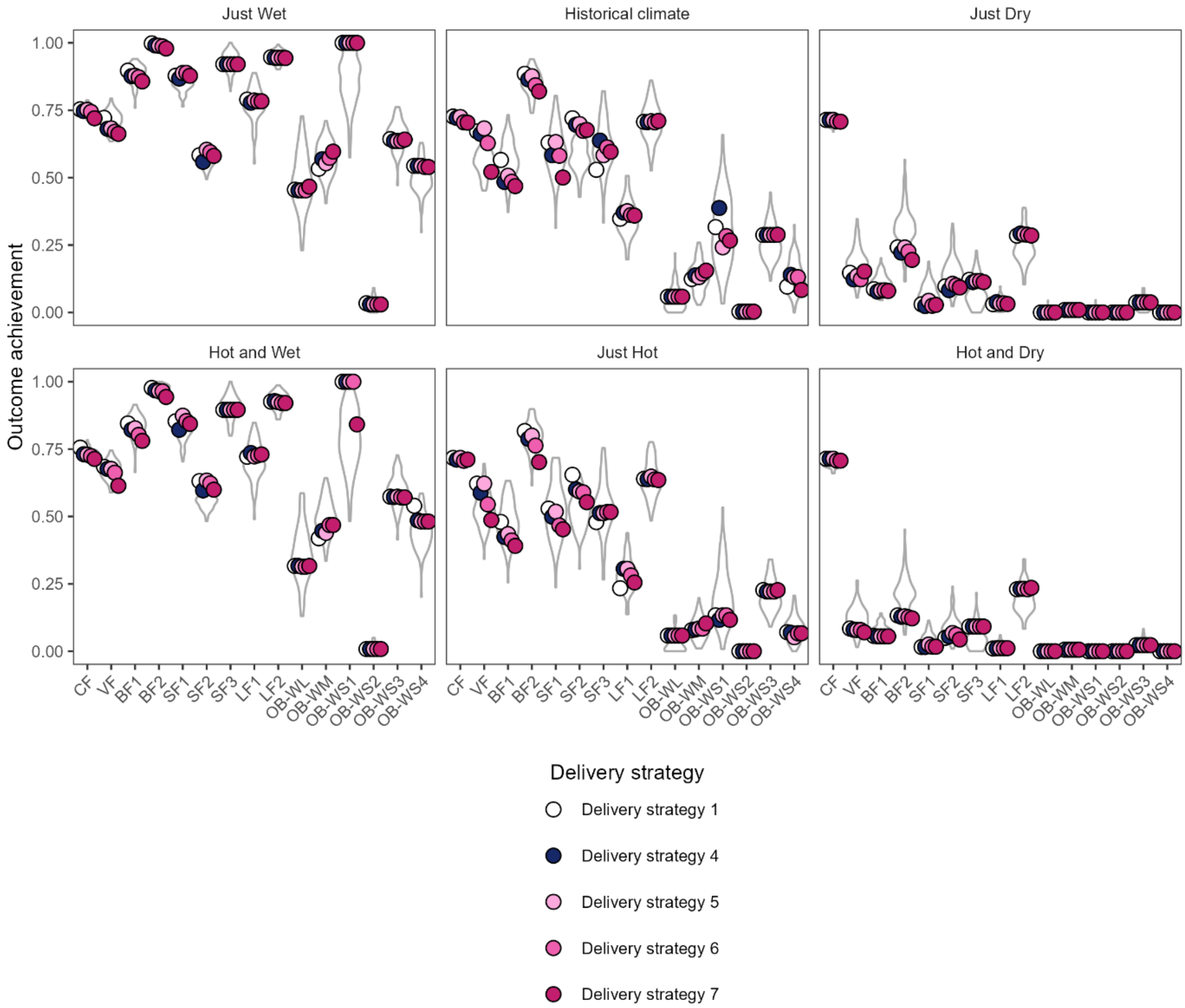
Supplementary Figure 8. Differences in the delivery strategies used to explore the impact of changing delivery strategy on outcome achievement. Panel a) illustrates the target environmental water order volume as a function of available water at decision date (Aug 1st). Delivery strategies 3 and 4 overlap entirely. Panel b) illustrates the timeseries of ordered water using different delivery strategies (1, 2, 3, 4) for 1991-92. Panel c) illustrates the timeseries of ordered water using different delivery strategies (5, 6, 7) for 1991-92.



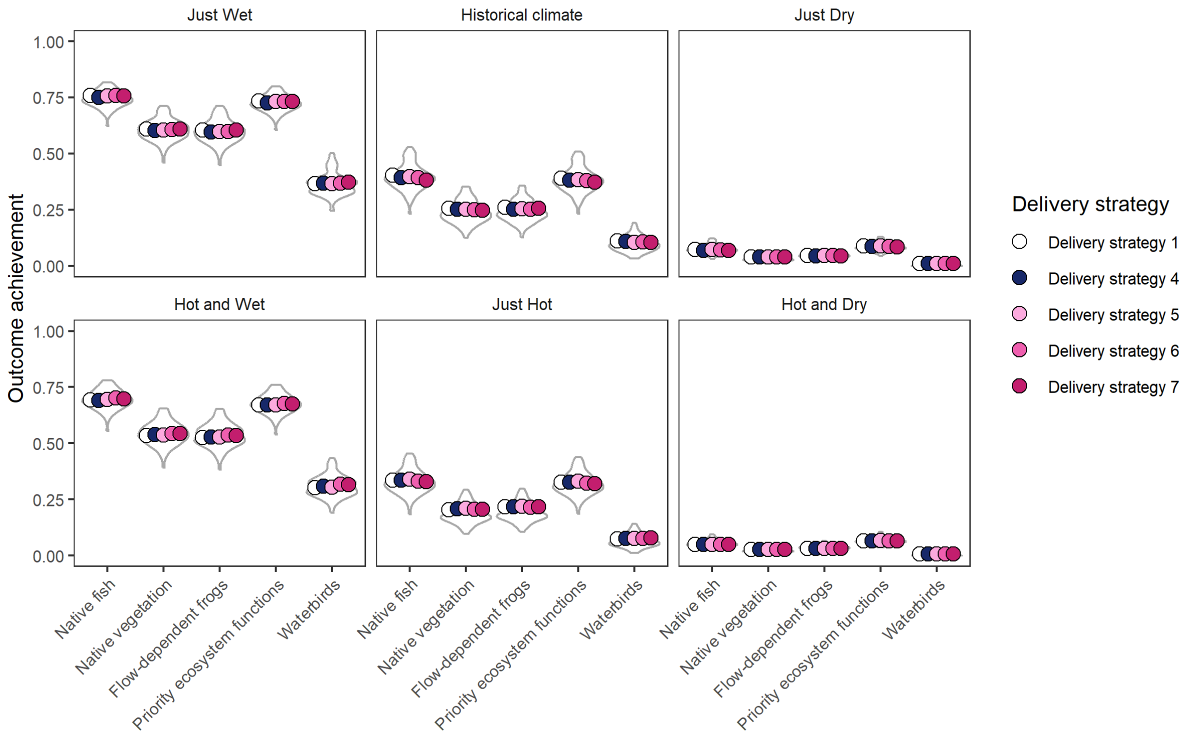
Supplementary Figure 9. Changes in the achievement of environmental water requirements (EWRs) based on changes in the strategy of delivery for environmental water volume superimposed on the distribution for the historical stochastic run for reference. Delivery strategies alter the complex series of rules regarding how water is ordered depending on water availability (example sequences are shown in Supplementary text 4).



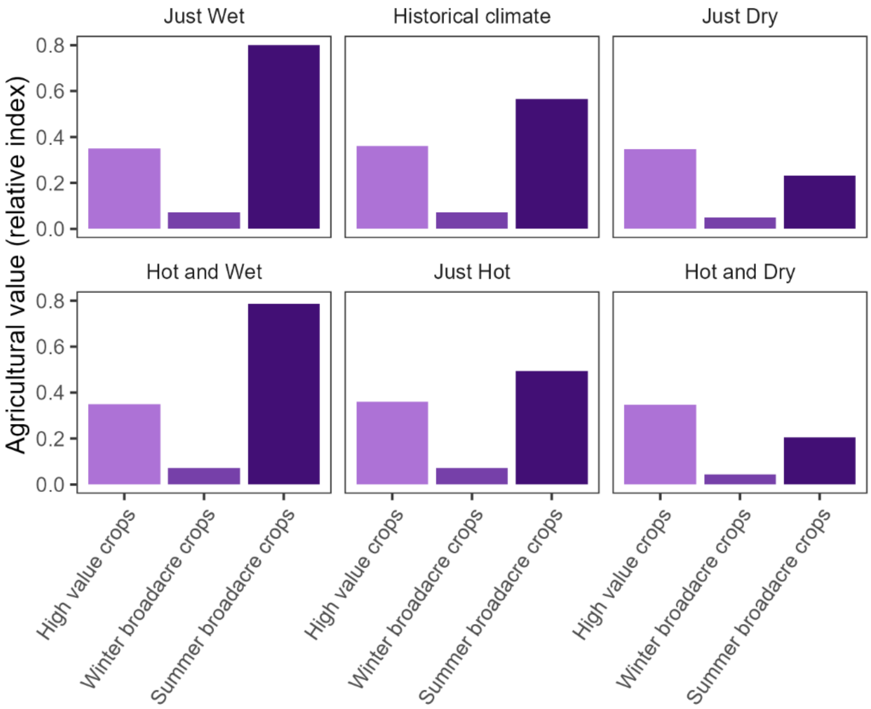
Supplementary Figure 10. Distributions around the achievement of environmental water requirements (EWRs) based on changes in the strategy of delivery for environmental water volume. Delivery strategies alter the complex series of rules regarding how water is allocated depending on water availability (example sequences are shown in Supplementary text 4).



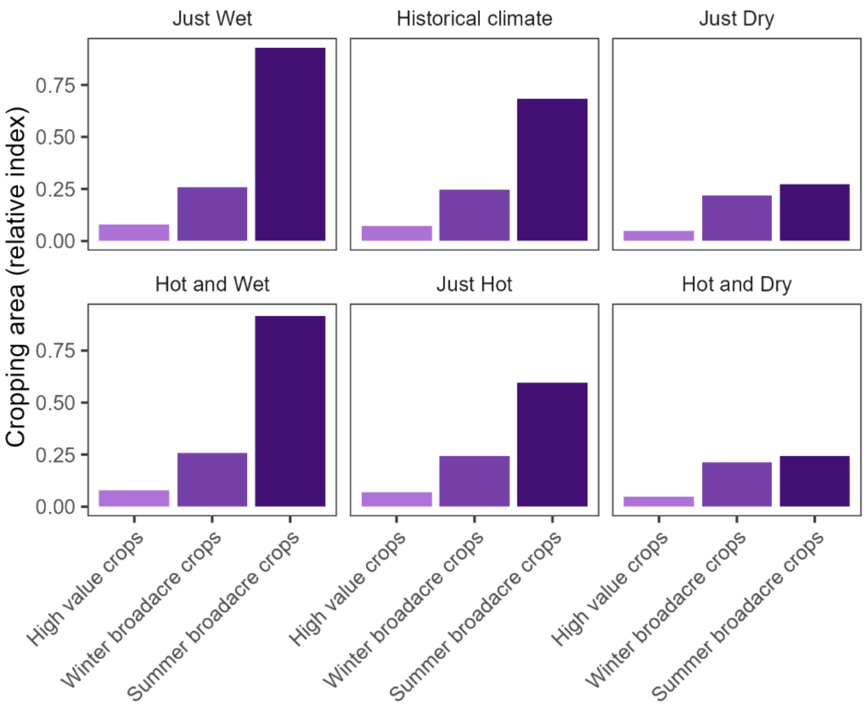
Supplementary Figure 11. Changes in the achievement of environmental water requirements (EWRs) based on changes in the strategy of delivery for environmental water volume, designed to target a specific small fresh EWR, superimposed on the distribution for the historical stochastic run for reference. Delivery strategies alter the complex series of rules regarding how water is allocated depending on water availability (example sequences are shown in Supplementary text 4).



Supplementary Figure 12. Environmental outcomes associated with changes in the strategy of delivery for environmental water volume, designed to target a specific small fresh EWR, superimposed on the distribution for the historical stochastic run for reference. Delivery strategies alter the complex series of rules regarding how water is allocated depending on water availability (example sequences are shown in Supplementary text 4).



Supplementary Figure 13. Relative value of average irrigated agricultural benefits from different categories of crop under six climate scenarios. The relative index is calculated so that total agricultural value (the sum of the three crop categories) is relative to the historical climate, i.e. the total agricultural value is equal to 1 for the historical climate and the totals for other climates are greater or less than 1 relative to the change from the historical climate. Within each climate, the proportions of the three crop categories are then illustrated.



Supplementary Figure 14. Relative area of cropping classes under the six climate scenarios. The relative index is calculated so that total cropping area (the sum of the three crop categories) is relative to the historical climate, i.e. the total cropping area is equal to 1 for the historical climate and the totals for other climates are greater or less than 1 relative to the change from the historical climate. Within each climate, the proportions of the three crop categories are then illustrated.