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ORIGINAL ARTICLE

Walking back from the edge: thresholds of change reveal options for adaptation to water scarcity under climate change in the Murray–Darling Basin, Australia

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Abstract

Climate change has increased the variability of river inflows in the Murray–Darling Basin, threatening the viability of irrigated agriculture, food processing industries and ecological condition of wetlands. With increasing water scarcity, decision-makers and communities face heightened contestation over scarce water resources and trade-offs and adaptation have become increasingly necessary. We used a social-ecological systems approach to identify thresholds of change in the Goulburn–Broken Catchment, a major food-producing region, to reveal options for adaptation to climate change. We developed systems models whereby feedbacks are identified between sub-systems of cultural paradigms, policies, human well-being and environmental condition. Models were constructed using data from semi-structured interviews with managers and decision-makers, industry reports and the scientific literature. We found environmental thresholds are fixed, but whether they are exceeded is socially determined. Environmental condition can be maintained by relaxing constraints on volumes of water released into the highly regulated river system and easing rules on the distribution of water among users in the dairy and horticulture industries. Socio-economic thresholds were more flexible. Industries have adapted to water scarcity through irrigation efficiency measures, inter-industry relationships for water-sharing and feed substitutes in dairy production. However, industry interdependence indicates potential for maladaption, whereas investment in adaptation and diversification offers more sustainable options. Current policy and management disconnects between water for the environment and water for food production reveal opportunities for co-benefits between environmental and socio-economic domains. Realising these benefits requires a systemic, inclusive adaptation pathways approach to design and implement options for change.

Keywords Thresholds of potential concern · Systems thinking · Social-ecological systems · Trade-offs · Water markets · Water management and policy · Climate adaptation · Resilience thinking

Introduction

Social-ecological systems are based on the concept that people and ecosystems are inextricably linked through environmental, social, economic and cultural structures, processes and feedbacks. The term was first used to explore how resource management systems based on local, traditional indigenous knowledge might provide lessons for Western resource management (Berkes and Folke 1994). A social-ecological systems approach includes consideration of how such systems have adapted and developed knowledge to address ecosystem dynamics and change, how resilience is maintained or lost under perturbations and what combination of rights, rules and governance have been applied to achieve these objectives. Accordingly, an understanding of the properties of a social-ecological system is required to address sustainability challenges and options for adaptation and adaptive governance (Biggs et al. 2021).

Social-ecological systems exhibit properties of complex adaptive systems in that they (1) are constituted relationally; (2) have adaptive capacities; (3) behave in non-linear ways; (4) are open, without clear boundaries; (5) are context dependent and (6) are characterised by complex causality and emergent properties (Preiser et al. 2018). Interactions within and between sub-systems and internal variables

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produce outcomes that then feed back to affect sub-systems and components. Identification and analysis of these interactions help explain how social-ecological systems persist or transform and why some are sustainable and others collapse (Ostrom 2009).

Persistence and transformation are linked in resilience thinking to system properties that maintain the social-ecological system within a particular stable state. If those properties change, the system transforms to an alternative stable state, quite different from the original state. Central to this framing is the concept of thresholds, defined as 'levels in controlling variables where feedbacks to the rest of the system change – crossing points that have the potential to alter the future of many of the systems that we depend upon' (Walker and Salt 2006, p. 54).

The threshold concept has been operationalised in strategic adaptive management of national parks in South Africa by identifying points at which decisions need to be made to maintain ecosystems in their existing configurations (Biggs and Rogers 2003). 'Thresholds of potential concern' describe the limits or boundaries of the desired state and are essentially working hypotheses about the limits of acceptable change to the system (Roux and Foxcroft 2011). Thresholds of potential concern are co-produced by scientists and practitioners and revised and updated as systems understanding changes. In the context of social-ecological systems, there may be uncertainty about whether thresholds exist and where and how to apply or adjust them where they relate to community preferences, social behaviour or other non-biophysical constructs and attributes (Biggs et al. 2011).

Application of thresholds of potential concern involves identifying thresholds in a social-ecological system that signal changes in social, economic or environmental attributes that lead to unintended, undesirable consequences through cascading interactions and feedbacks (Biggs et al. 2011). Identification of thresholds then forms a basis for the design and implementation of management interventions. A systems approach involves identifying feedback processes operating through causal loops, whereby a change in one system variable can reinforce or balance change in another variable (Dyball and Newell 2015, pp. 114–120) and whether thresholds are likely to be exceeded.

The Murray–Darling Basin in south-eastern Australia (hereafter 'the Basin') supports the majority of irrigated agricultural production in Australia. It contains 16 wetlands listed under the Ramsar Convention on wetlands and over 100 considered of national importance for biodiversity conservation (MDBA 2010, p. 59). Its rivers and wetlands are the focus of cultural and spiritual values for Indigenous peoples, provide water supplies for regional towns and support important tourism and recreational industries.

The interactions among driver and response variables in social-ecological systems are apparent in the Basin through the integrating role of water availability, allocation and use (Colloff and Pittock 2019). Basin water resources have been highly contested, particularly between irrigation and environmental sectors. Historical over-allocation of water for irrigation, combined with severe drought events, prompted long-term and extensive reform in governance and rules for water allocation and use, culminating in the Murray–Darling Basin Plan to return water from irrigators to the environment. Annual inflows to the Basin have declined by almost 40% since 2000 (MDBA 2020, p. 21). Under global warming, dry conditions will persist and become more severe, increasing pressures on water resources and contestation over their management and use (MDBA 2019; Whetton and Chiew 2021). Accordingly, there is an urgent need for Basin communities to adapt to a future with less water.

Under increasingly severe climate change, transformative adaptation will be needed by all sectors because incremental approaches are likely to be insufficient to achieve sustainable water use at a basin scale (Colloff et al. 2016). Transformative adaptation involves systemic changes to societal paradigms of values, rules and knowledge (Colloff et al. 2020). One example of transformative adaptation in the environment sector involves conservation triage, whereby environmental flows are supplied only to those wetlands likely to persist under less water or are considered of high conservation value. Water is supplied to those wetlands most in need, and with the best chance of ecological improvement, by withholding it from those likely to decline (Schweizer et al. 2022).

The connectedness within the social-ecological system means negative effects of climate change can be exacerbated by path dependencies, such as failure to move beyond 'business as usual' or reactive responses (Colloff et al. 2020). Negative effects may be irreversible, unpredictable and lead to undesirable system changes. To counter these effects, an adaptation pathways approach can help communities anticipate change, which involves making adaptation decisions in a sequenced manner that are implemented progressively under conditions of high uncertainty and change (Wise et al. 2014; Werners et al. 2021).

Our objective was to apply the thresholds of change concept using social-ecological systems modelling and identification of systems archetypes to examine how this approach can reveal options for adaptation to increasing water scarcity. Using the Goulburn–Broken Catchment as a case study, we assessed drivers that enabled and constrained water use for irrigation and the environment in relation to the viability of irrigated agriculture, food processing and service industries. We then identified the characteristics of thresholds of change for major socio-economic and environmental values and the consequences of thresholds being exceeded. Finally, based on the identified socio-economic and environmental thresholds, we developed options for the adaptation of existing arrangements of water management and use.

Methods

Case study

The Goulburn–Broken Catchment in north-central Victoria (Fig. 1) was chosen for this research because it is one of the most important regions in the Basin for irrigated agriculture, water availability has declined under climate change, it contains several major wetlands that are managed with environmental flows and the Goulburn–Broken Catchment Management Authority (GBCMA) has a long history of engagement in adaptive management and resilience approaches.

Much of the catchment consists of upland slopes and forests and plains dominated by dryland agriculture (GBCMA 2021). Because the present work is about identifying thresholds associated with water availability and use, we focussed on the irrigation areas covering the riverine plains to the north and west of Shepparton (Fig. 1). The catchment contributes about 11% of inflows to the Basin, ca. 3400 GL year^{-1} under historical climate (1895–2006), with irrigation diversions of about 50% of the surface water available, a very high level of use (CSIRO 2008). A reduction in diversions of 344 GL year^{-1} is targeted under the Basin Plan (DELWP 2019, p. 7). The irrigation sector and the environment are threatened by less water available under climate change. Mean annual rainfall (764 mm) since 2006 has fallen by 15% compared with the long-term average (1895–2006) and runoff between 1997 and 2006 (during the Millennium Drought of 1997–2010) was 41% lower (CSIRO 2008).

The GBCMA is responsible for the management of wetlands of national and international significance, including the Ramsar-listed Barmah Forest and the Lower Goulburn Floodplain. Lake Eildon, a headwater dam on the Goulburn River, is the major source of water for irrigation and the environment, providing flows to the River Murray and its wetlands, including the Ramsar-listed Gunbower Forest and the Koondrook Forest. The average volume of environmental water released in the Goulburn–Broken Catchment

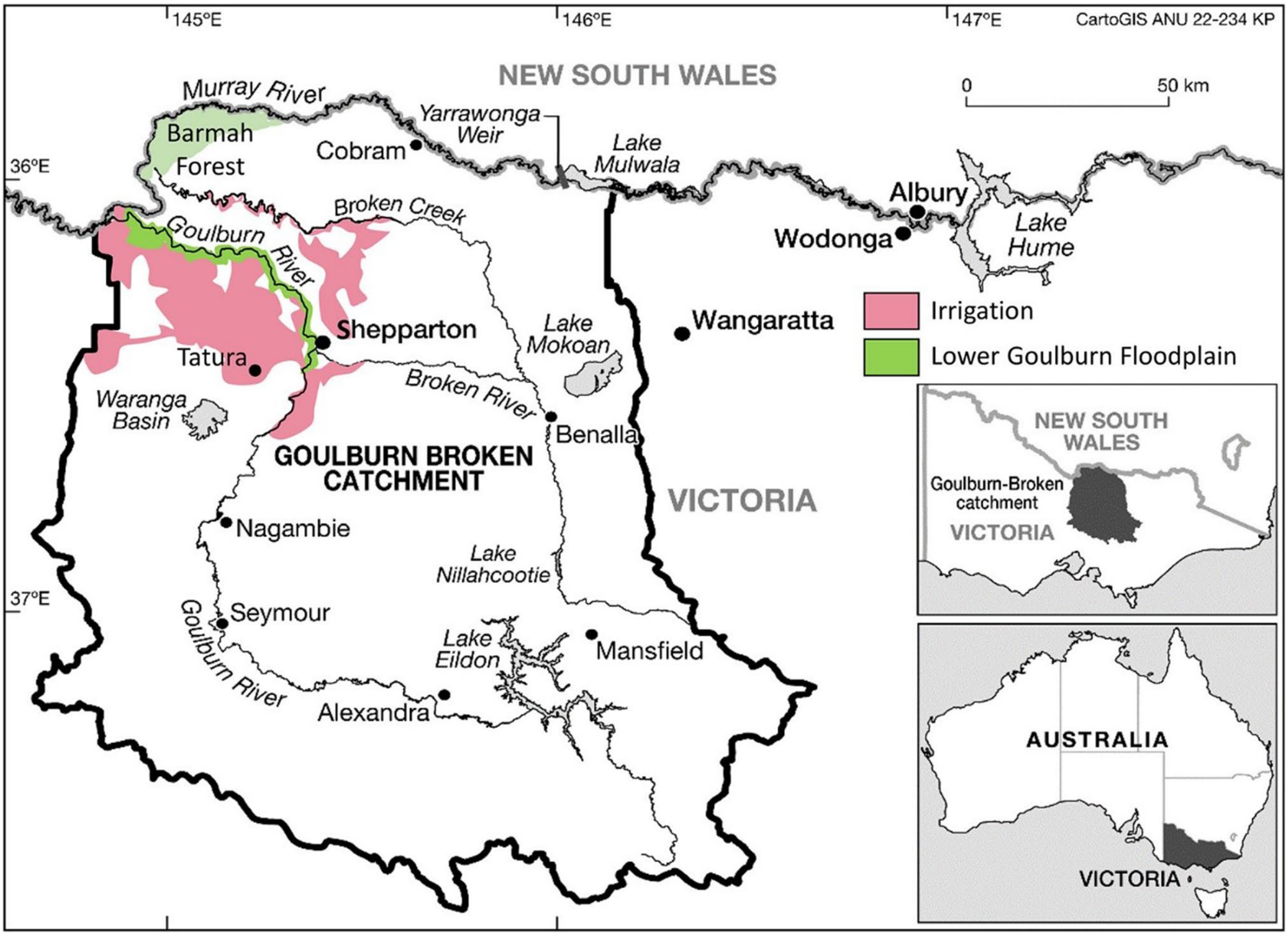

Fig. 1 Map of the Goulburn–Broken catchment and its location within Australia

(2009–2010 to 2018–2019) was 271 GL yea^{-1} (Chen et al. 2021).

Expansion of irrigation followed the completion of Lake Eildon in 1955. Horticulture and dairying became major irrigated agricultural industries, supporting food manufacturing, including fruit canning and dairy processing (Aither 2019). The catchment has been subject to a comprehensive resilience assessment (Walker et al. 2009) that formed the basis of a regional catchment strategy founded on resilience thinking (GBCMA 2013, 2021), adaptation pathways (Abel et al. 2016) and a climate change adaptation plan for natural resource management (GBCMA 2016a).

Sources of data for social-ecological system modelling

We used a mixed methods approach of quantitative and qualitative data as inputs to social-ecological systems models (Layder, 2013). Quantitative and qualitative data were derived from a detailed review of reports and scientific publications on water availability and use in the catchment, including water trading and environmental watering by government agencies and catchment management authorities.

Qualitative data was also collected during semi-structured interviews conducted with leading decision-makers in different sectors who had in-depth knowledge and experience of the social-ecological system of the catchment. Participants were recruited based on recommendations made by previous interviewees. Some 20 participants were interviewed, from agencies (A: state government and local council; $n = 3$), industries (I: Goulburn Murray Water, food processing, consultants; $n = 7$), irrigation farmers (F: dairy and horticulture; $n = 4$) and the environment sector (E: catchment management authorities, conservation groups; $n = 5$). Interviewees are referred to in the results and discussion section by interview number and the initial for their sector. The project was approved by the ANU Human Research Ethics Committee (application 2021/100). Due to research ethics rules on engagement with Indigenous people, it was not feasible to interview Yorta Yorta Traditional Owners.

Each interview consisted of twelve open-ended questions addressing impacts of climate change, thresholds, water use and sharing and adaptation to water scarcity (Supplementary Material S1). Interviews were recorded, transcribed and analysed using NVivo 12 software (QSR International 2020). Analysis involved thematic coding to map and categorise responses to questions into themes based on the content of the responses (Cope 2016). The seven themes, or codes, were climate change, nature of change, thresholds, water management, water sharing, adaptation and resilience. The coding of interview responses, or quotes, enabled a comparison of similarities, differences and relatedness of the responses of participants from each sector in relation to each theme or code.

Systems modelling using the Cultural Adaptation Template

We used a whole-of-systems conceptual modelling approach that integrates social, economic and environmental factors to identify drivers of change and responses, ‘lock in’ effects (i.e. path dependency, whereby part of the system is resistant to change because of prior decisions and actions) and feedback loops (i.e. where an output in one part of the system represents an input in another) in the social-ecological system. First, information from the literature was assessed to identify drivers of change, the environmental, social and economic responses to them and potential thresholds. Drivers, responses and thresholds were identified from the literature and cross-referenced with data from the interviews and mapped as feedback loops. We used Cultural Adaptation Template (CAT) diagrams to identify environmental thresholds associated with constraints management (i.e. relaxing constraints on volumes of water released into the river system) and inter-valley transfers due to downstream demand for water and their environmental, social and economic impacts. The CAT is a form of causal loop model in the form of a systems diagram that details interactions of the four sub-systems common to any social-ecological system: cultural paradigms, institutional arrangements, the state of the environment and the state of human health and well-being (Dyball and Newell 2015). Diagrams were drawn using Vensim® software (Ventana Systems 2015). Having constructed CAT diagrams for constraints management and inter-valley transfers, we were able to identify possible thresholds for the environment and industries. We then constructed CAT diagrams for adaptation options to avoid the crossing of thresholds; how investment in adaptation and economic diversification builds adaptive capacity among irrigators and how dairy and horticultural industries adapt to periods of water scarcity. The processes used to justify the construction of each link and loop in the CAT diagrams are detailed in the Supplementary Material (Tables S1–S4).

Results and discussion

In this paper, we have applied the concept of thresholds of change using social-ecological systems modelling to examine how such an approach can reveal options for adaptation to increasing water scarcity. We emphasise the preliminary nature of our findings and that the Cultural Adaptation Templates, used to identify drivers of change, ‘lock in’ effects and feedback loops, are not intended to represent the entire social-ecological system of the Goulburn–Broken catchment as it relates to water. We focus on water availability and use within the context of a major water reform initiative and have not included, for example, issues of water quality, particularly salinity (Anderies et al. 2006).

Environmental thresholds and constraint management

The frequency of overbank flows of the Goulburn River is now less than required to maintain the condition of the Lower Goulburn floodplain and river channel (DELWP 2017, p. 3). This floodplain was identified in the Murray–Darling Basin Constraints Management Strategy as one of seven areas where relaxation of physical constraints on flows would achieve environmental benefits (MDBA 2013). These measures typically include removal of levee banks, relocation of flood-prone infrastructure, acquisition of flood easements and compensation to landholders for flood damage. Relaxing constraints would allow flooding of 12,000 ha or 92% of the floodplain (DELWP 2016) but has been prevented by state government policies of not flooding private land without agreement, nor acquiring easements by compulsory purchase (Productivity Commission 2018). However, options exist other than treating constraints relaxation as a matter of cost, damage and compensation. For example, multiple co-benefits from ecosystem services are derived from flooding, including improved wetland condition; fodder production; growth of river red gum *Eucalyptus camaldulensis* providing opportunities for forestry; improved water quality; cultural, spiritual and aesthetic appreciation of wetlands; community well-being, nature-based tourism and related employment (Kahan et al. 2021).

Constraint relaxation is highly contested, but interviewees raised no objections, perhaps because as sector leaders they tend to hold progressive views: *We have all this environmental water, but…if the water does flood over the banks, as it always has…that's how you get the maximum environmental benefit…it then floods private property and houses…Suddenly, the government becomes responsible for that …How can you get the maximum benefit out of your environmental water if you can't do that? That's what a floodplain is, the floodplain naturally floods* (F4). Greater community and political support is required if environmental benefits are to be realised: *You would probably inundate private land on the way or as part of that watering. You would need to negotiate through that…the preference is to have permanent title agreement…landholders don't want to come to that, understandably, there's nervousness around it* (E3). Political and policy barriers represent 'soft' limits to adaptation (Barnett et al. 2015) and can be addressed by reframing the decision context to focus on benefits from constraints relaxation, not just costs (Gorddard et al. 2016). Federal government-funded payments for ecosystem services derived from constraints relaxation would provide income for landholders, but the inability of governments to adapt in time creates the risk that environmental thresholds may be crossed.

Governance arrangements are central to environmental condition and socio-economic viability (Fig. 2; Table S1). Willingness of governments to deliver environmental water will benefit wetlands but the socio-economic impacts are perceived as negative (Link 3). Environmental water use cannot exceed bankfull volume and irrigation water is prioritised for within-channel transfer to downstream users, limiting environmental watering to times of year that are sub-optimal for some wetland biota: *In the middle of summer…river levels are running very high because they're transporting water from storages…to consumers that are a long way downstream…In the wintertime, when the rivers normally carry a lot of water, all that water has been kept in storages…we are trying to get the river back to where they were before, naturally. [The] way we're running it now is almost opposite…we think that's creating environmental problems that weren't there before* (F9).

Water availability is unaffected by constraints relaxation, but some irrigators fear more water entitlements will be traded downstream, decreasing irrigated agricultural production and increasing costs over benefits (L7). In reality, overbank flows would be insufficient to support transfers. State policies align with irrigator interests; hence, the loop L1, L3 and L7 is a balancing one. If economic benefits improve, the cost-benefit ratio of constraint relaxation declines: irrigators are financially more secure and willing to realise benefits. Long-term benefits from constraint relaxation can be delivered via the capacity of a healthy environment to support agricultural productivity, for example via the capacity of native vegetation and floodplain wetlands to enhance soil water storage and rehydrate the landscape, enabling crop production (L6). However, interviewees considered only short-term impacts. If constraints management can be re-framed around such benefits, then governments may be more willing to implement it.

Environmental thresholds and inter-valley transfers

Declining water availability in the Goulburn–Broken has reduced irrigator capacity and desire to grow high-value produce and increased inter-valley transfers (Fig. 3, Table S2). The increased transfers are driven by increased demand from downstream irrigators who grow high-value perennial tree crops such as almonds and walnuts (L1; Mallee CMA 2018) and can outbid producers of lower-value crops on the temporary water market. These interactions form a balancing loop (L1, L3, L10, L9). From 2016–2017 to 2019–2020, record volumes were traded from Goulburn to Murray irrigators, with summer-autumn flows in the lower Goulburn River 2–3 times the recommended rate of 940 ML day^{-1} (L4; DELWP

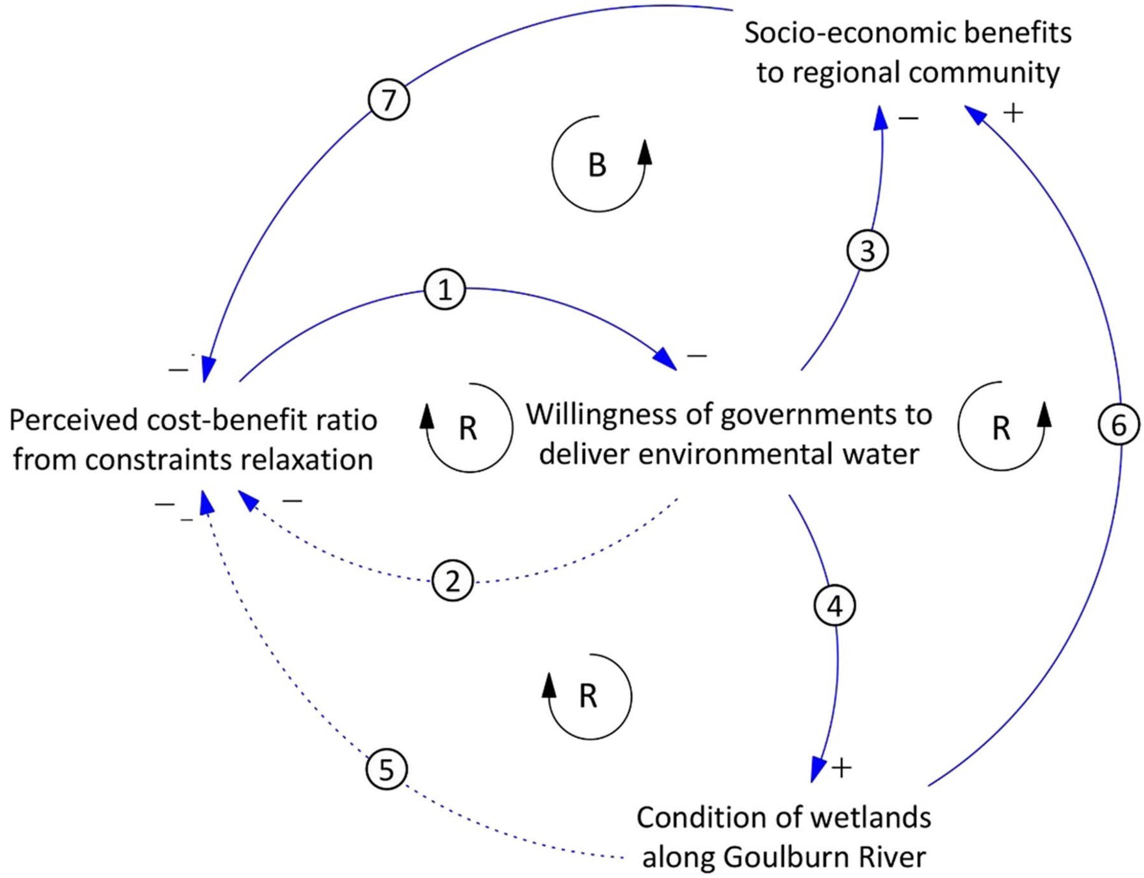

Fig. 2 Cultural Adaptation Template diagram of barriers to constraints management and their environmental and socio-economic impacts. Symbols: numbers indicate links (detailed in text and Table S1); arrows show direction of causal relationship between variables; + indicates positive effect; − indicates negative effect; R is a reinforcing (positive) loop; B = is a balancing (negative) loop; dotted line shows a weak link

2020), causing bank erosion, damage to vegetation and fish habitat (L5). There is strong community concern that environmental thresholds may be crossed if these issues are not addressed (L6): *We're at the threshold of what can be delivered down on the Lower Goulburn…[without causing] environmental damage...our key challenges are…[freeing] up rules to allow [irrigators] to have water delivered from different places, but within environmental tolerances* (A18). Environmental damage prompted changes to the Goulburn to Murray Trade Rule but the effect is unclear (DELWP 2021a). The weak link (L8) between good environmental condition and co-benefits for agricultural productivity constrains policy shifts that could otherwise avert environmental thresholds being crossed.

Environmental degradation may be delayed, but some effects are already clear. The loop L1 and L3–L7 is a balancing one as irrigators become aware of the negative effects of water trades. But community capacity to influence irrigation production is weak (L7) and trade-offs will have to be made between irrigation and the environment. Economic values are strongly favoured over environmental ones and the strength of the reinforcing loop L1, L2 is likely to counteract the balancing loop L1, L3-L7.

The balancing loop (L1, L3-5, L8, L9) forms as agricultural industries benefit from ecosystem services and a healthy environment, reducing negative impacts of high-water demand from downstream producers. Accordingly, Goulburn farmers are likely to be impartial to the production of high-value goods. Payments to landholders for wetland ecosystem services (Canning et al. 2021) provide an adaptation option to diversify farm income, reduce financial risk and offset the reinforcing loop L1, L2, thus enhancing the perception of the link between a healthy environment and agricultural productivity (L8). Payments for ecosystem services could help mitigate the risk of crossing environmental thresholds because farmers would be incentivised to engage in environmental stewardship, conserve rivers and floodplain wetlands and advocate to ensure environmental water is used effectively, but this policy option is not currently being considered.

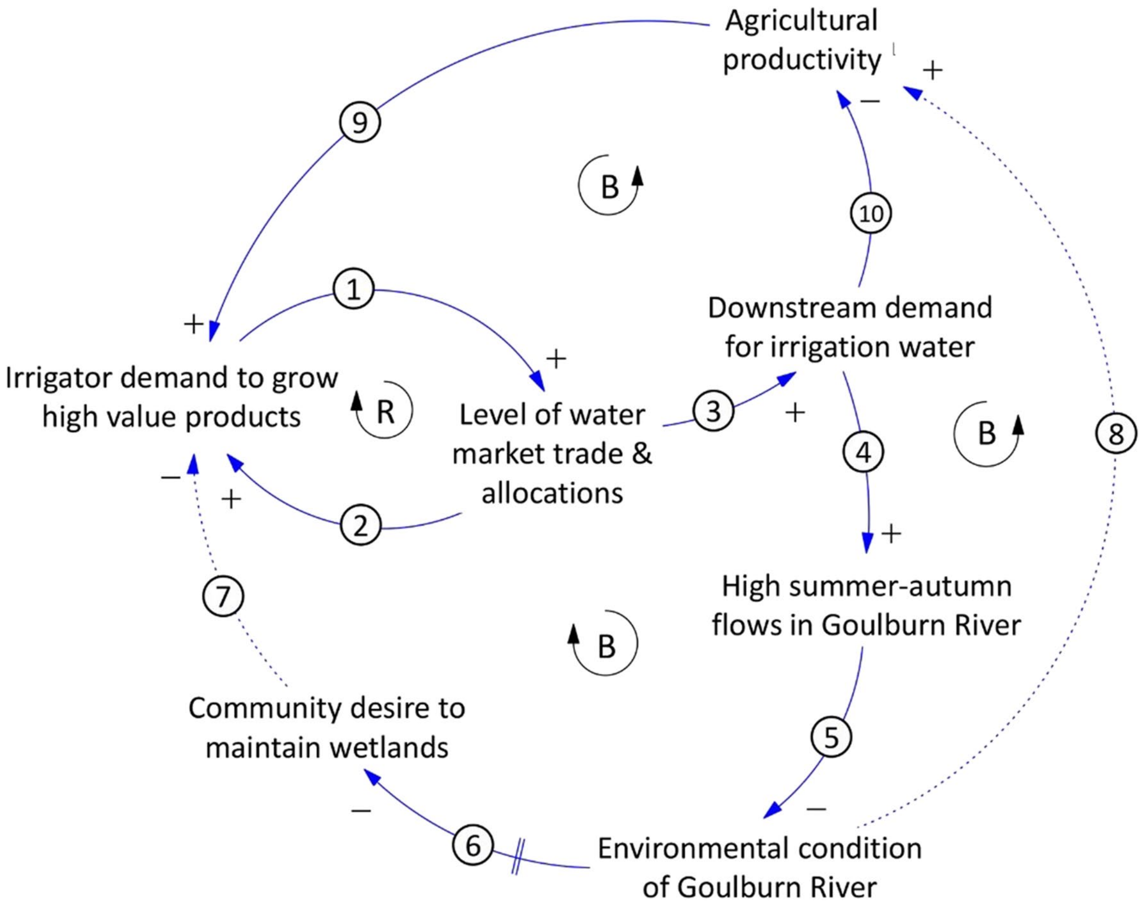

Fig. 3 Cultural Adaptation Template diagram of impacts of high summer-autumn flows and downstream demand for water. Symbols: numbers indicate links (detailed in text and Table S2); arrows show direction of causal relationship between two variables; + indicates a positive effect; − indicates a negative effect; R is a reinforcing (positive) loop; B = is a balancing (negative) loop; dotted lines show a weak link; \\ indicates a time delay

Socio-economic thresholds: irrigation water access

In the Goulburn–Broken, water prices are highly variable due to changing seasonal allocations and high demand from downstream users who set the price (Fig. 4, Table S3, L12, L13), especially during dry periods when supply is limited (GBCMA 2016b). Other irrigators, particularly dairy farmers, are vulnerable to price inflation, creating uncertainty about water access (L11). High prices are not sustainable for horticultural producers: *We've definitely seen a lot more growers go out of business…When it comes to drought, or if they're struggling financially…The worst thing any grower can do is give up any of their permanent allocation…because permanent plantings need permanent water…that's what drives the price up* (F15).

Governments have invested in irrigation efficiency projects, intended to address uncertainty over water access but also recover water for the environment (DCCEEW 2020), but these schemes do not address the need to reduce dependency on water for agricultural production. Irrigation efficiency projects have been criticized for their high cost, reduction in return flows to rivers (Williams and Grafton 2019) and that they do not achieve water savings (Pérez-Blanco et al. 2021). Irrigators maintained or increased their water requirements after the implementation of irrigation efficiency projects and were more willing to buy water in the temporary allocation market (Aither 2017, p. 12). Increased irrigation efficiency means more water available and water use increases; the so-called rebound effect (Wheeler et al. 2020).

Despite evidence that irrigation efficiency projects do not save water, several interviewees considered them adaptive (Table 1). Such projects are likely to continue, particularly because recovery of environmental water via buy-backs from irrigators ceased in 2015 (DAWE 2021). In the Goulburn–Broken, the $2 billion Goulburn–Murray Water Connections Project was claimed to achieve 429 GL in water savings (DELWP 2021b), but interviewees considered government policies on irrigation to align poorly with producers' desires to adapt and diversify: *It's a massive amount*

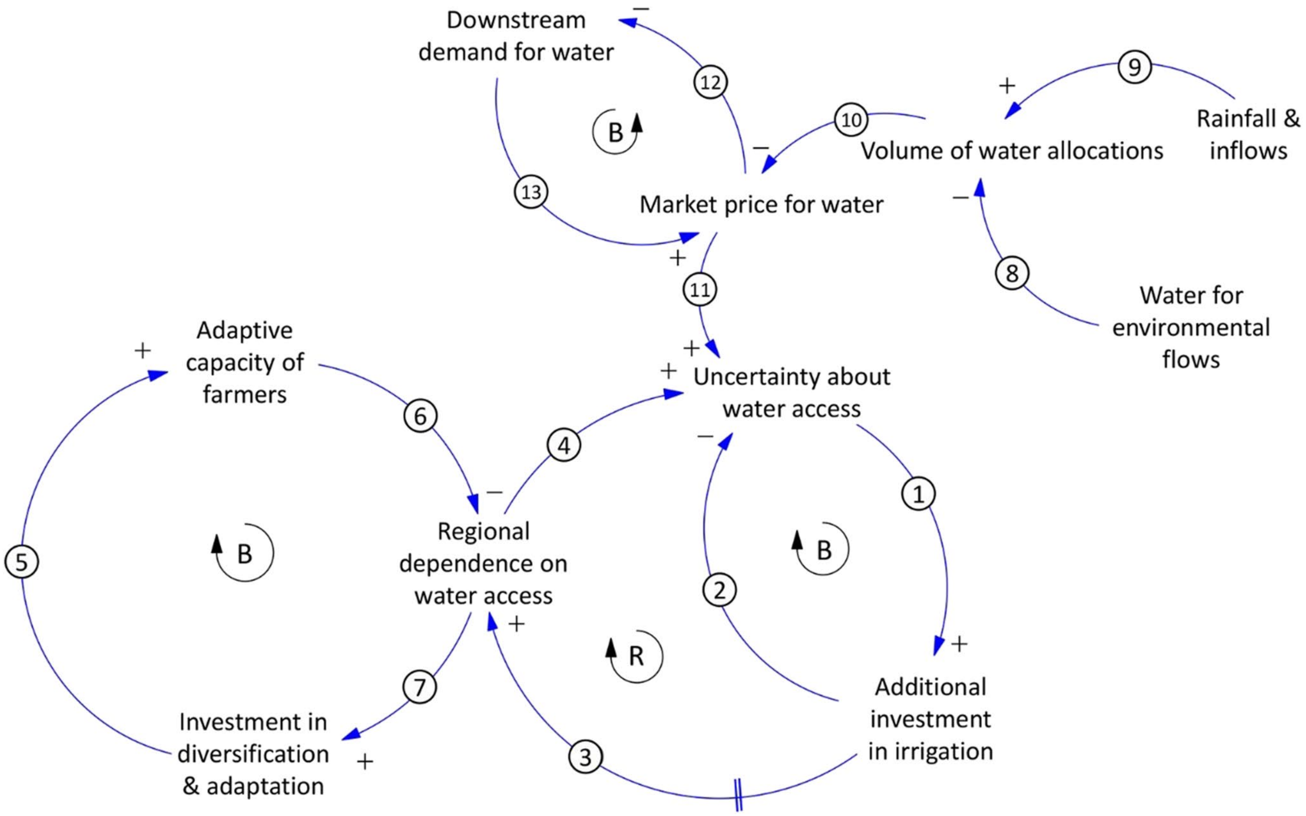

Fig. 4 Cultural Adaptation Template diagram of how investment in adaptation and diversification builds adaptive capacity among irrigators as a more sustainable approach than additional investment in irrigation. Links detailed in text and Table S3. Symbols as in Fig. 3

of money that could have been used to help transition the region. Instead, it was an attempt to kind of reinforce the region back in its old form (I11).

Investment in irrigation efficiency can reduce conveyance losses and improve short-term water access but is maladaptive in the long term because the region becomes more dependent on irrigation water and irrigated agricultural production (Fig. 4, loop L1–L4). This loop is an example of a ‘fixes that fail’ systems archetype (Kim and Lannon 1997; Braun 2002), whereby a solution that is effective in the short-term creates unintended problems in the long-term, requiring further solutions. An alternative to address irrigation water dependency is to increase investment in adaptation and diversification (loop L5-L7). Interviewees considered this approach essential to transition away from irrigation: *We need to invest in people on the ground…it [will] require…a shift in how we’ve always done business… We need to take this time of innovation, to rethink how we respond* (A14). Investing in adaptation and diversification builds adaptive capacity (L5): *One of the strategies…that needs to be put in place is community-government partnerships leading towards the future...government should support that innovation, to generate new options for a low water future* (I11).

Intentional, proactive adaptation provides more options than reactive responses and empowers communities to address power imbalances over access to resources and conflicting values and interests over the use of those resources such as water (Colloff et al. 2021). Options for adaptation and diversification can enable a transition to less reliance on irrigation water (L6; Table 1). The balancing loop (Fig. 4, loop L5–L7) needs strengthening to counter the ‘fixes that fail’ system archetype of the irrigation efficiency reinforcing loop (L1–L4). As climate change drives reduced water availability, investment in adaptation and diversification will become increasingly urgent: *You need a diversity of agriculture. You can’t be a monoculture, just doing the one thing… if that collapses, then you’ve got nothing* (I17).

Socio-economic thresholds: industry

Dairy and horticulture differ in profitability and water use. Horticulturalists must maintain water use during drought to keep permanent tree plantings alive (ca. 105 GL y^{-1} in the Goulburn–Broken; GBCMA 2016b), whereas dairy farmers’ water use for fodder production declines in dry times (ca. 240 GL y^{-1} during drought and 1120 GL in a high-water allocation year). Water trading enables both industries to

Table 1 Thresholds for the environment and various industries

Sector	Are industries cross-sectorial?	Existing thresholds	Are thresholds flexible?	Commentary on thresholds	Adaptation options presented by interviewees	Barriers to adaptation
Environment	Perceived as disconnected An underlying link exists if ecosystem services are valued appropriately	Water availability & flow regimes reflecting natural flows. Highly probable biophysical thresholds will be crossed in future if environmental water is not delivered to floodplains	No	Maintaining ecological processes requires minimal threshold levels, e.g. flooding, population size to sustain species, water quality for aquatic biota & to prevent hypoxic blackwater events & algal blooms	Constraint relaxation. Payment for ecosystem services	Institutional
Dairy	Yes	Water availability for production. Economic threshold for some farms. Potential for an industry threshold to sustain processing	Yes	Millennium Drought led to some farms becoming uneconomic. Farmers who exited were often inefficient or planning to retire. Dairy production has fallen but remains profitable. Upper limit of industry threshold shifted as farmers adapted and improved on-farm management	Mixed feed farming modules. Improved genetics & breeding. Water trade with horticulture. Intensification of farming systems. Irrigation efficiency. On-farm infrastructure. Expansion of extension to enable farmers to make informed decisions. Risk management practices: growing & storing fodder during wet seasons	Economic & demographic
Horticulture	Yes	Water availability for production. Economic threshold for some farms. Potential for an industry threshold to sustain processing	Yes		Fruit netting. Improved pest & disease management. Soil moisture monitoring. Protecting crops from exposure. Flexible farming systems & crop diversification. Product differentiation: high-value & organic produce. Intensification of farming systems. Water trade with dairy. Irrigation efficiency. On-farm infrastructure	Economic & demographic
Processing	Yes	No thresholds identified by interviewees that may result in the crossing of an industry threshold. Existing thresholds relate to decision-making: perishability and volume of milk supplies for dairy processing. Threshold volumes exist for fruit processing. Economic thresholds for processing sectors relate to available market prices for milk and produce, determined by markets (product supply and consumer demand)	Yes	Threatened closure of fruit processing industry shows economic and volume thresholds exist. Closure of dairy processing considered a threshold of potential concern because of falling milk production but product diversification and vertical integration has mitigated this. Threshold volumes exist for fruit & dairy processing, but specific quantities are unclear and were not mentioned by interviewees	Value-adding to products. Product diversification and differentiation. Vertical integration. Greater outsourcing of milk supplies	Economic
Irrigation	Yes	Potential for an industry threshold if share of maintenance costs rises for remaining users	No	Infrastructure costs are high, fixed & shared among users. If number of irrigators declines due to lower water availability and greater competition, costs increase for remaining users. Goulburn–Murray Water has decommissioned outlying channels after farmers exited, as remaining farmers could not fund operation & maintenance	'Fixes that fail' discourages additional investment in irrigation. Proposed changes to delivery charges, but with high uncertainty among interviewees about flow-on effects. Changes to rules that give farmers flexibility to manage their water, e.g. via carry-over rules	Economic & institutional

survive drought through transfers from dairy to horticulture (Fig. 5). To adapt to high water prices and lower water availability during dry years, dairy farmers will buy in feed substitutes from other regions when it is no longer economically viable to irrigate pasture or fodder crops (Fig. 5, L1, L2): *We have this relationship with other industries such as horticulture. If we do go into a dry spell, dairying will trade that water to horticulture, because you can't not water permanent plantings and we benefit from those funds to buy in new fodder. That inter-industry trade is important during those drier periods, but there is a limit…At the end of the day, you still need water to water stock and maintain systems* (I8).

This situation is an example of the 'shifting the burden' systems archetype, whereby a short-term solution is used to avoid developing lasting solutions that address the causes of the problem (Kim and Lannon 1997). Using solutions that address only symptoms undermines incentives to develop ones that address causes. By depending on feed from other regions as a short-term solution, dairy farmers remain vulnerable during drought if feed supplies are low and demand is high. Climate change exacerbates these pressures: *[Many] were buying all their hay…Then they got in a drought, you couldn't get a lot of the hay with the money. [Many] went back to well I've got to grow my own hay…the behaviour shifted from pure economics to more risk management…Put climate change on it…the average might be lower…more variable, bit drier. How do I structure my business…given that uncertainty…that variability over multiple years?* (I5)

There is a high risk of thresholds beyond which dairy and horticulture are no longer viable under a 'business as usual' scenario. The burden on farmers from fixed costs of irrigation infrastructure will increase as the number of irrigators falls (Aither, 2017). It is anticipated that less irrigation water will be available from 2024 as reductions in the Sustainable Diversion Limit are fully implemented under the Basin Plan. Dairying may approach an industry threshold due to high prices for water and feed, low prices for milk and inadequate industry adaptation and diversification, creating a reinforcing loop (L19–L24), with cascading negative impacts on the viability of horticulture. Water trading with dairy farmers would cease and horticulturalists would bear a higher

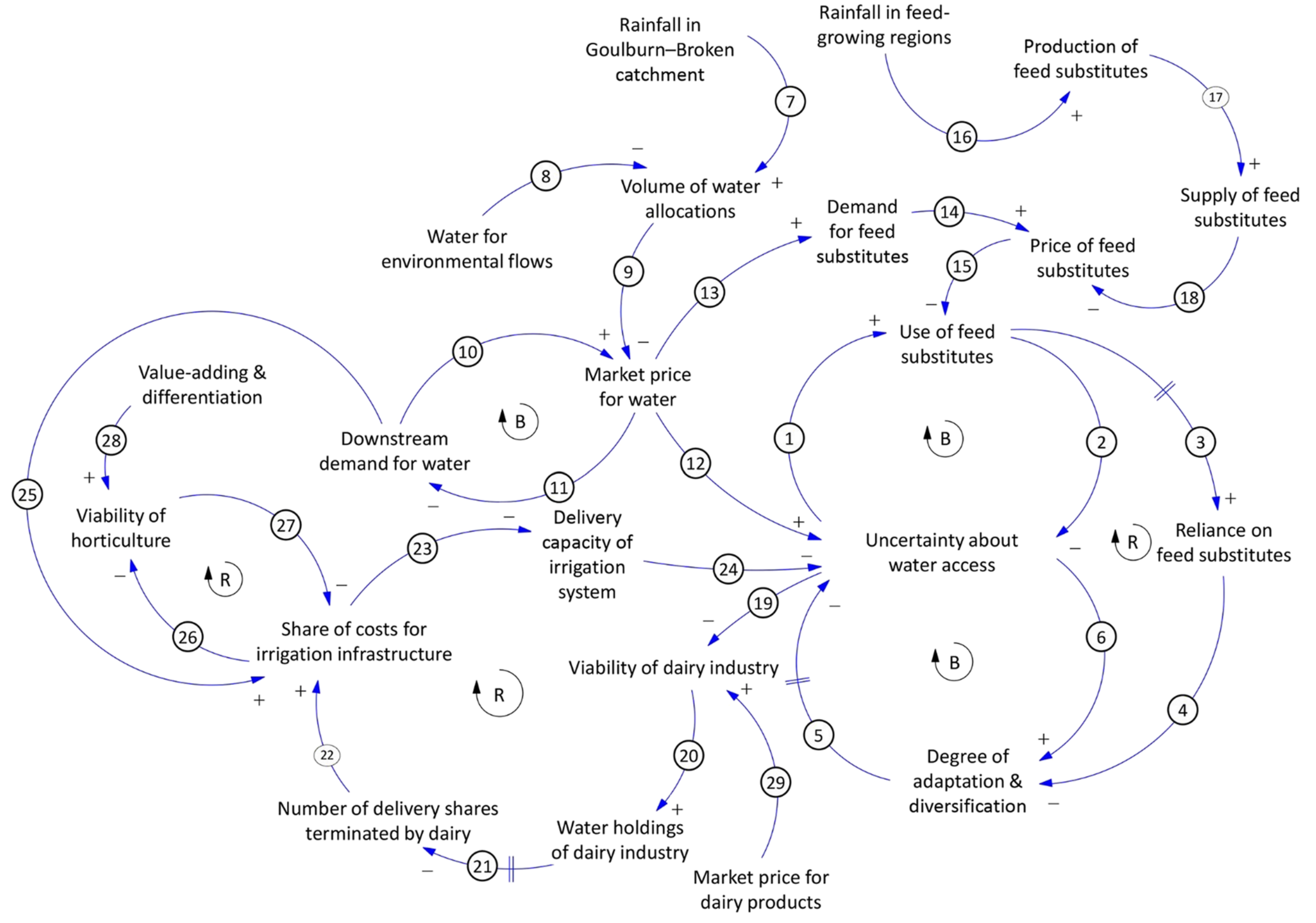

Fig. 5 Cultural Adaptation Template diagram showing inter-relationships between dairy and horticultural industries and dairy industry dependence on feed substitutes that inhibits adaptation and diversification. Links detailed in text and Table S4. Symbols as in Fig. 3

share of irrigation maintenance costs and begin to exit the industry, creating another reinforcing loop (L26, L27). As it becomes harder for irrigation companies to deliver services and maintain infrastructure (L23), the two reinforcing loops will strengthen, reducing the viability of the irrigation system as a whole. Industries will remain stressed until there is greater adaptation and diversification, or less uncertainty about water access, higher market prices for dairy (L29) and increased value-adding and product differentiation in horticulture (L28): *If people [can't] produce things that make money…it's a liability, not an asset….they're the hardest decisions…At what point are you able to identify…something is tipping towards becoming an ongoing liability for the people in the area, rather than an asset or an opportunity?* (A18).

Walking back from the edge—options for adaptation

Our analysis raises several important options for adaptation to water scarcity under climate change, revealed by the identification of thresholds. Declining water availability is the main driver of change for agriculture and the environment, as indicated by thresholds for these sectors (Fig. 6; Table 1). Environmental thresholds relate to institutional barriers and socio-economic drivers impeding implementation of the Constraints Management Strategy (MDBA 2013) and preventing flooding of wetlands on private land. The major environmental threshold is loss of wetland caused by dramatic alterations to the flow regime: cessation of flooding and the consequent erosion caused by unseasonably high flows during summer and autumn due to inter-valley transfers confined within channel. If environmental water is released in late winter–early spring, as under natural flow regimes, a larger volume is required because it cannot be 'piggybacked' on high summer–autumn flows for irrigators. If environmental water continues to be used as it is currently, this threshold for loss of wetlands will likely be exceeded. Easing of constraints would enable overbank flooding and meet water requirements for wetlands.

Environmental water recovery via supply and efficiency measures (double arrow between socio-economic and environmental thresholds, Figure 6) and downstream demand are regarded as threats to the dairy industry: *Water has left the region…processors will close …farmers will want to keep farming or…move to other regions…Or they'll just exit…totally driven by water availability…The environment is getting enough water now and there's enough water left to sustain the industry… If it was to keep dropping, because more and more water was being diverted to the environment, the industry would keep falling* (F9). However, other interviewees (including those from industry) were supportive of constraints relaxation and believed it could deliver improved environmental outcomes without negative impacts on dairy and horticulture: *[We] need to recognise hydrological and environmental limits with the Goulburn…We have*

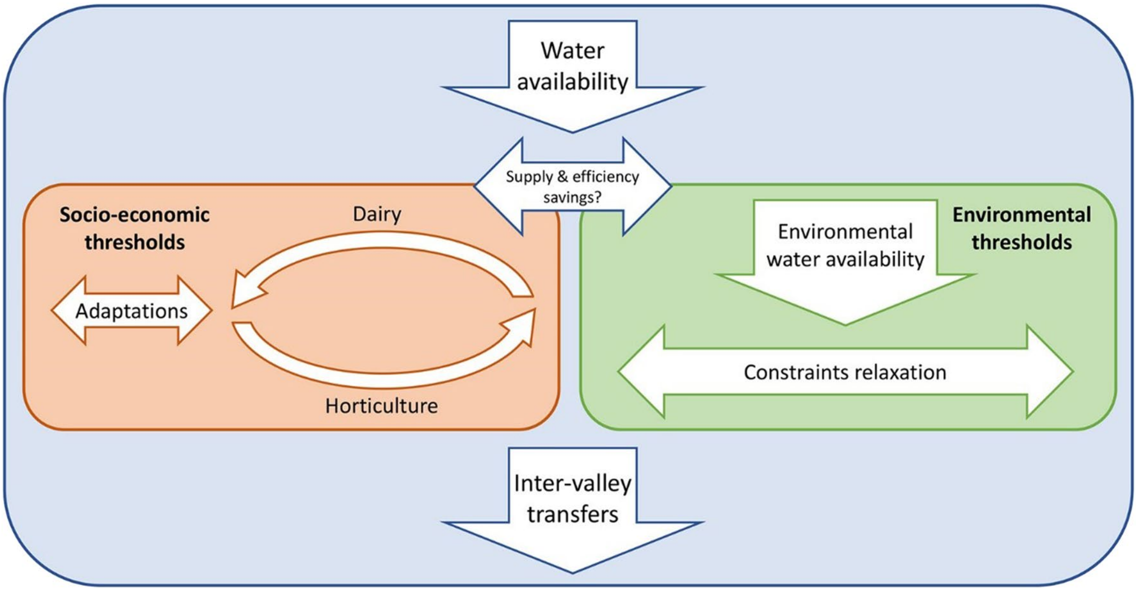

Fig. 6 Key issues identified in the Goulburn–Broken Catchment. Industries and the environment depend on water availability. Due to limited water, industries have a strong inter-relationship based on sharing water resources. If water availability declines, industries will need to adapt. The environment depends on constraints relaxation to spread water across the floodplain. Industries and the environment are affected by inter-valley transfers due to competition for channel capacity between irrigation water and environmental water and. Additional water is to be recovered through supply and efficiency projects, but target volumes have not been met

to optimise trade…maximising trade might mean destroying the Lower Goulburn River. Optimise means to manage… and allow trade within sound biophysical, hydrological, economic, and ecological [limits]…You've just got to make sure you stay within some sort of no-regrets zone (I10). Co-benefits to wetlands and private landholders can be delivered through overbank flooding (Kahan et al. 2021). An improved community understanding of ecosystem services and options for payments for services to landholders may ease institutional barriers to adaptation.

Adaptations for irrigation presented by interviewees were largely extensions of existing incremental approaches rather than transformative actions (Table 1). Future transformative adaptation may be limited if the community cannot imagine options beyond what currently exist. Nonetheless, transformative adaptations will be critical to avoid thresholds and maladaption.

The threatened closure of SPC Ardmona in 2014 indicates economic thresholds for the food processing sector relate to variability in supply of produce, prices, costs and market conditions (Table 1). Horticulture adapted to be less reliant on the food processing sector, reflecting changing market demands: *We've gone through a transformation of this region being predominantly processed fruit to more fresh fruit growers…the region [has] traditionally been very focused on volume growth, and [is] now having to shift towards more growing for quality for the fresh market* (F15). Closure of food processing businesses have been considered a threshold because of falling local milk production caused by projected increased salinisation of pastures (Walker et al. 2009). However, salinity has largely been managed, but dairy processors reduced vulnerability to low milk supplies by sourcing it from elsewhere, as well as product diversification and vertical integration: *as the milk supply started to drop, the company…bought the western Victorian site, … you can get milk from more areas…make your raw materials for your own company…Bega has diversified into spreads, juices, peanut butter…If they just stayed wholly and solely in dairy, you're beholding to the volatility of it…we pull the milk apart and send the components elsewhere…a lot of it's to do with the climate threat* (I17). Thresholds shift as businesses adapt: *We've got to have the ability now to turn things on and off, depending on the market…the water supply, milk supply…We'll try extract as much value as possible, rather than the old days where volume was king…We've had to become more efficient, but more adaptable, more flexible* (I17).

As farmers improve their adaptive capacity, limits to adaptation will continue to be challenged as industries transition to a new normal, including by developing inter-industry relationships such as that between dairy and horticulture (Figure 6). However, interviewees remain uncertain about the future viability of irrigated agriculture: *We're… sort of at those thresholds now…we can cope with consecutive dry years. But if we continue to shift more water out of the region, then I think…if dairy folded in the region, that would impact horticulture, horticulture wouldn't survive in this region…you'd end up with stranded irrigation assets* (I8).

The use by the dairy industry of feed substitutes during drought is a short-term adaptation to uncertainty about water access but creates a local dependency on other regions, broadening the risk base. It also lessens incentives to build capacity for adaptation and diversification for the long term. In the future, dairy, horticulture and irrigation operators may approach or exceed thresholds, by which time fewer options for adaptation will be available. Future water policy and management options could build on inter-industry relationships: *Setting up demonstration sites in the region to grow winter cereals and summer crops so that we can help lift the skills and capability of our dairy industry, around growing those crops for quality silage or fodder and to improve the relationship between those [horticultural] growers and the dairy industry because there's that constant trade between the two* (I8). A whole-of-industry approach to adaptation in the Goulburn–Broken will help mitigate thresholds being exceeded and avoidance of maladaptive pathways: *There is a clear opportunity for us to work as a regional community to better understand what the future does look like and planning for that together, as opposed to doing it through separate industries or organisations* (I8).

Although droughts threaten the viability of some farmers and industries, major decline is not evident, though it has been assumed that falling agricultural income is proportional to reduced water availability (RMCG 2016; Rendell 2019, p. 16). This assumption is incorrect. There was weak or no negative effect on farm income from selling water entitlements and reduced production was offset by income from water sales and reinvested on-farm or used to reduce debt (Wheeler et al. 2014, p. 1). During the Millennium Drought, there was a 67% decline in irrigation water use in the Basin but gross value of irrigated agricultural production fell by only 14%. Impacts of drought were offset by water trading, improving irrigation efficiencies, substituting crops and inputs and other measures, indicating a relatively high level of adaptive capacity (Kirby et al. 2014).

We are not aware of other water reform initiatives elsewhere in the world like the Murray–Darling Basin Plan where social-ecological systems have been assessed in relation to thresholds of change and water availability. However, our work builds on previous social-ecological systems and resilience research in the Goulburn–Broken Catchment. Successive management decisions were considered to have 'eroded the resilience of the system and reduced options for future change' (Anderies et al. 2006, p. 865). Thresholds were identified for rising saline groundwater, threatening crop production. Nearly 20 years on, the prediction by these authors that drastic actions were required to prevent water tables reaching the surface has proved unfounded.

Walker et al. (2009) identified ten known or possible thresholds in the Goulburn–Broken catchment, particularly relating to feedbacks between water availability, farm income, irrigation infrastructure and high interdependence of agriculture and food processing. They concluded reliance on agricultural products and processing was vulnerable to rising water tables and reduced water availability under climate change. Rising water tables have compromised riverine ecosystems and reduced the resilience and future options for the catchment. These conclusions accord with our findings.

Concluding remarks

We have undertaken a preliminary analysis using a conceptual framework based on social-ecological systems modelling using the Cultural Adaptation Template. The Goulburn–Broken Catchment was used as a case study to apply the concept of social-ecological thresholds in systems models to determine options for adaptation to less water under climate change, with lessons for water policy and management in the Murray–Darling Basin.

We focussed on three issues: (1) the current water-sharing context; (2) environmental and socio-economic thresholds and (3) options for adaptation. Regarding the water-sharing context, different water users, within and outside the catchment, have competing demands, values and needs, making water management a complex system of trade-offs. Currently, there is little evidence of competition between water for the environment and agriculture in the Goulburn–Broken. However, local dairy and horticultural industries may be threatened if inter-valley transfers to downstream users were to increase. Although dairy and horticulture depend on water, their interactive water trading relationship indicates they can endure severe droughts. There are major concerns from irrigators that the volume of inter-valley transfers is already too high and jeopardises their economic viability. However, subsequent changes in trade rules were aimed at protecting the environment by limiting high downstream flows rather than limiting downstream trades, though the impact was the same. This policy response potentially runs counter to the need to enable overbank flows to reach floodplain wetlands. Other options are needed to address this policy shortcoming.

In relation to thresholds of change, it is highly probable that environmental thresholds will be crossed if existing environmental water is not delivered overbank to the lower Goulburn–Broken floodplain. Relaxing constraints to allow water to be released as overbank flows to floodplain wetlands would have significant environmental benefits and needs re-consideration by policy-makers, in line with the Murray–Darling Basin Constraints Management Strategy (MDBA 2013), which all Basin states and territory have agreed to implement. Socio-economic thresholds of water availability for irrigation, costs of production, farm profitability and production to sustain food processing, may be crossed without adequate adaptation and diversification to lower water availability, higher irrigation infrastructure costs and higher prices for water and feed substitutes. Thresholds can shift, as farmers adapt their management, as evidenced by inter-relationships between dairy and horticulture around water trading. But this form of adaptation is only a symptomatic solution to the growing uncertainty about water access. Industries need to further adapt and diversify to ensure long-term viability.

Regarding options for adaptation, there are clear options to conserve ca. 12,000 ha of floodplain and provide co-benefits to irrigators, but these are constrained by values trade-offs, institutional and governance factors. Relaxing constraints and schemes for payments for ecosystem services need to overcome institutional barriers. Irrigation efficiency measures were identified as maladaptive, increasing dependence on irrigation water access. Investment in adaptation and diversification for farmers represent potential pathways out of irrigation water dependence. Interviewees identified more appropriate options for adaptation for irrigated agriculture which have not yet been implemented. To facilitate this transition, future policies can be co-produced with the local community that can assist farmers to adapt and diversify.

Our research provides insights that may be scaled up to assist water management in the broader Basin and beyond. These findings can help governments make better informed decisions about the vulnerabilities and trade-off options for managing diminishing water availability due to climate change. Thresholds are important in understanding environmental and socio-economic values and identifying ways to preserve them. However, thresholds are not simple but are complex and dynamic. This study highlights the need for water managers and users in the Basin and beyond to consider and identify adaptation pathways that provide for long-term adaptation co-benefits.

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