



Synthesis

Resilience, Adaptability, and Transformability in the Goulburn-Broken Catchment, Australia

*Brian H. Walker*¹, *Nick Abel*¹, *John M. Anderies*², and *Paul Ryan*¹

ABSTRACT. We present a resilience-based approach for assessing sustainability in a sub-catchment of the Murray-Darling Basin in southeast Australia. We define the regional system and identify the main issues, drivers, and potential shocks, then assess both specified and general resilience. The current state of the system is a consequence of changes in resource use. We identify ten known or possible biophysical, economic, and social thresholds operating at different scales, with possible knock-on effects between them. Crossing those thresholds may result in irreversible changes in goods and services generated by the region. Changes in resilience, in general, reflect a pattern of past losses with some signs of recent improvements. Interventions in the system for managing resilience are constrained by current governance, and attention needs to be paid to the roles and capacities of the various institutions. An overview of the current state of the system and likely future trends suggests that transformational change in the region be seriously considered.

Key Words: *integrated assessment of regional resilience; interventions to support specific and general resilience; threshold interactions and cascades*

INTRODUCTION

This paper is a case study of regional resilience assessment—to the best of our knowledge the first comprehensive such assessment. It presents a resilience-based approach for assessing sustainability in the Goulburn-Broken (henceforth referred to as the GB) region, a sub-catchment of the Murray-Darling Basin in southeast Australia (Fig. 1).

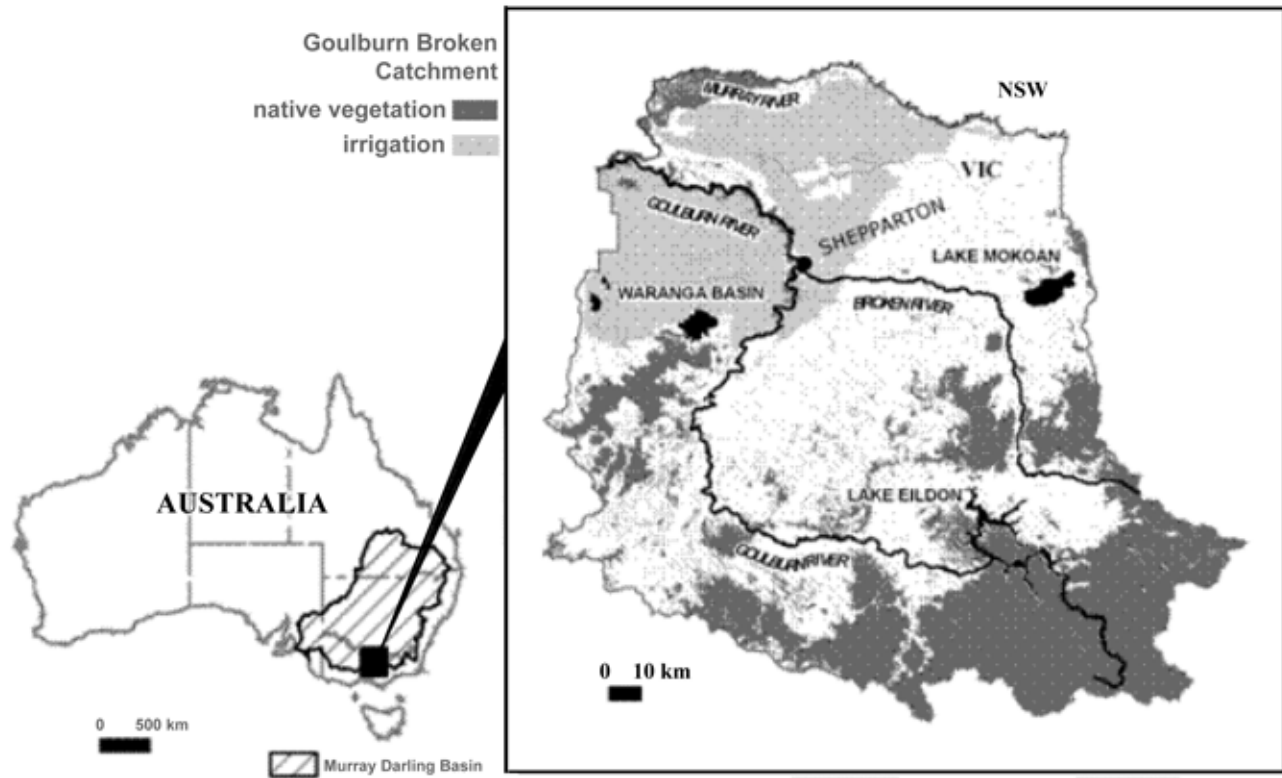
Resilience is a measure of a system's capacity to cope with shocks and undergo change while retaining essentially the same structure and function. As resilience declines, it takes progressively smaller disturbances to push the system into a different regime, or "basin of attraction" (Scheffer and Carpenter 2003), in which its structure and function are substantially different. Within a regime, the system tends toward an equilibrium composition, within limits bounded by the basin of attraction. Beyond those limits (the edge of the basin), due to changes in feedbacks, the system tends toward a different long-run configuration. The resulting differences in structure and function can have important consequences for

society, and so some system regimes are deemed more desirable than others.

A resilience approach treats biophysical, social, and economic elements of a region as components of a single social-ecological system (SES). It emphasizes the capacity of a SES to continue delivering goods and services to people, and the trade-offs associated with being in different regimes. Without the possibility of regime shifts (Scheffer and Carpenter 2003), there is no fundamental problem of choice because changes in the system are always smoothly reversible (albeit at some cost); that is, the system has a single basin of attraction—a single homeostatic regime—and decisions are about what might be the best part of the basin (the best state) to be in. If a mistake is made, or if values change, there is no great difficulty in moving to another state of the system. However, where there are alternate regimes, the hysteretic effects involved make a shift from one to the other difficult or even impossible to reverse. Resilience, therefore, emphasizes the possibility of alternate system regimes and the thresholds between them. The ability to manage resilience—to avoid regime

¹CSIRO Sustainable Ecosystems, ²School of Human Evolution and Social Change and School of Sustainability, Arizona State University

Fig. 1. Location of the Goulburn-Broken Catchment and subregions.



shifts and to become more (or less) resilient—is referred to as adaptability, or adaptive capacity (Walker et al. 2004). A related concept is transformability—what to do when it appears that a shift into an undesired regime is either inevitable, or has already occurred and is irreversible (Walker et al. 2004). We explore these concepts in the context of the GB SES, drawing on information from farmers, citizens, researchers, public servants, and publications from both within and outside the region.

ANALYTICAL FRAMEWORK

Earlier developments in applying resilience theory include an account of what is needed to take the concept “from metaphor to measurement” (Carpenter et al. 2001) and a suggested framework for assessing resilience (Walker et al. 2002). In this paper, in the process of assessing resilience in the GB catchment, our aim is also to develop an

approach that might be useful in other regional-scale SESs. We use ideas from the workbooks of the Resilience Alliance (http://www.resalliance.org/file/s/1183512442_workbook_for_scientists_june-12-07_2.pdf) and, adding to the earlier framework, we deal with balancing the need to address both specified (targeted) resilience and general resilience. The analytical framework is reflected in the structure of the paper, as follows.

First we characterize the region as a system by defining the key subsystems, identifying the main issues, drivers, and potential shocks (including changes in drivers). We then assess the capacity of the system to deal with these shocks based on the major benefits currently generated by the region and the biophysical, economic, and social sub-systems that underpin their continued supply.

Next we assess the resilience of the region. We begin by examining past changes in resilience, using the adaptive cycle metaphor (Gunderson and Holling

2002) to interpret the pattern of change. Adaptive cycles consist of an initial stage of rapid growth that is followed by a ‘conservation’ phase in which resources are progressively locked up and resilience declines. The system becomes progressively vulnerable to disturbances and enters a short “release” phase in which resources are freed for reallocation during the reorganization phase that follows, leading to a new growth phase, and the cycle begins anew.

Our resilience assessment considers:

1. specified resilience (resilience of what, to what)—the resilience of what is considered to be of value in the region to the identified shocks and other changes. The focus here is on the possibility of alternate stability regimes and involves identifying possible threshold effects in controlling variables, how they might interact, and the attributes that determine where these thresholds are.
2. general resilience—here, we identify attributes of the GB system that may determine its capacity to cope, generally, with unidentified shocks.

The resilience assessment is followed by a discussion of interventions for managing resilience, and the paper ends with our conclusions concerning future options for the GB.

RESILIENCE ASSESSMENT

Part 1. Characterizing the System: Problems, Values, and Potential Shocks

Defining the social–ecological system

The region and its problems

The GB catchment covers 2.1 million hectares in the Murray-Darling Basin (Fig. 1). Aboriginal people lived in the catchment for millennia before colonization around 1830. The current population is 190 000 people (3% indigenous). The upper, mountainous or hilly catchment (900 000 ha) is more than 50% forested. The mid catchment (1 million ha) of riverine plains, low slopes and foothills has less than 20% of native vegetation cover, which is highly fragmented, and the rest is

used for dryland cropping and grazing. The Shepparton irrigation region is on riverine plains adjacent to the Goulburn and Murray Rivers in the lower catchment (about 500 000 ha) with about 2% native vegetation cover and 300 000 ha used for irrigated dairy and fruit production. It is a very productive region, and a major contributor to the economy of the state and the nation.

The main issues in the region are:

- Past clearing of native vegetation has caused saline water tables to rise, threatening crop production. Groundwater pumping is necessary but leads to discharging salt into the Murray River at levels that can be unacceptable to downstream users. The recent drought has reduced the immediate threat of rising water tables, but resulted in insufficient water for irrigation. Climate change threatens the future viability of irrigation.
- Water storage, together with unseasonal releases of water for irrigation, is degrading the ecological functions of river channels, floodplains, and wetlands, and reducing their values to humans.
- Application of nitrogenous fertilizer and leguminous plants are lowering soil pH to the extent that soil health is declining in some areas.
- Native dryland vegetation is sparse, fragmented, and in poor condition, and many native species are threatened.
- Energy costs are an important driver in the system. If carbon emissions are capped or taxed, the intensive agricultural sectors may become economically unviable. Similarly, salinity outputs from the region to the Murray River are already capped, but salinity control through pumping into evaporation basins is also energy intensive.

System boundaries, drivers, controlling (slow) variables, and outcomes

Resilience theory emphasizes the importance of managing “slow” variables that may cross critical

threshold levels and induce regime shifts in SESs (Carpenter et al. 2001). Because of cross-scale interactions, a slow variable at, say, a regional scale, may drive other slow variables at landscape or farm scale. Figure 2 shows the categories of slow variables, relevant scales, and exogenous drivers.

Values held by Australians and participants in overseas markets are major drivers of the regional system, influencing demands for products and services. Values operate through the political system to affect what for brevity we label rules and investments—that is, public and private investments, and the laws, regulations, incentives, and informal norms and rules that mediate interactions among humans and between humans and their environment. Current patterns of land and water use are the consequence of rules and investments made in the past, and these were themselves formed under the influence of past values. Formal rules established in the constitution or in property rights tend to be very stable because of respect for the law and support from those who benefit (Table 1). Major infrastructure also tends to remain in operation for long periods, partly because of the costs of changing it. Changes in values could, though, by changing rules and investments, change patterns of land and water use, and the functioning of the region's biophysical systems in the long term. Current trends suggest a shift in the balance of values between production and nature conservation. These are proximate outcomes. The ultimate outcome is the values delivered. These outcomes might be secured by maintaining the resilience of the current regime, or through a shift into an alternate regime of the system, or transformation to a different kind of system (Walker et al. 2004)

The focal scale for this paper is the region, but with strong awareness of the scale below (farms and other businesses, households etc), and the scales above—the State of Victoria, the Murray-Darling Basin in which the GB catchment is set, and the Australian Federation.

Values and their determinants

The level of output and mix of values generated by the region are a measure of the desirability of a particular system regime. We classify the types of values following Pearce and Turner (1990) (Table 1): use (e.g., agricultural products, recreational use of a river) and non-use values (e.g., existence, option, or bequest (value based on knowledge that

a species, an ecological community, a landscape exists, might be used in the future, or left to posterity)). In the case of the GB, the total marketed use value for the region was A\$8.71 billion in the year 2000–2001, and it produces around one quarter of the State of Victoria's export earnings. The contributions of the top 16 sectors are in Fig. 3. There are no formal statistics for use and non-use values that are not marketed. Surveys by Stone (1992), Bennett et al. (2007) and Kragt et al. (2007) indicate substantial values, but because they were related to specific wetlands or riverine components, and because they estimated consumers' surplus, not prices, they are not comparable with the marketed values.

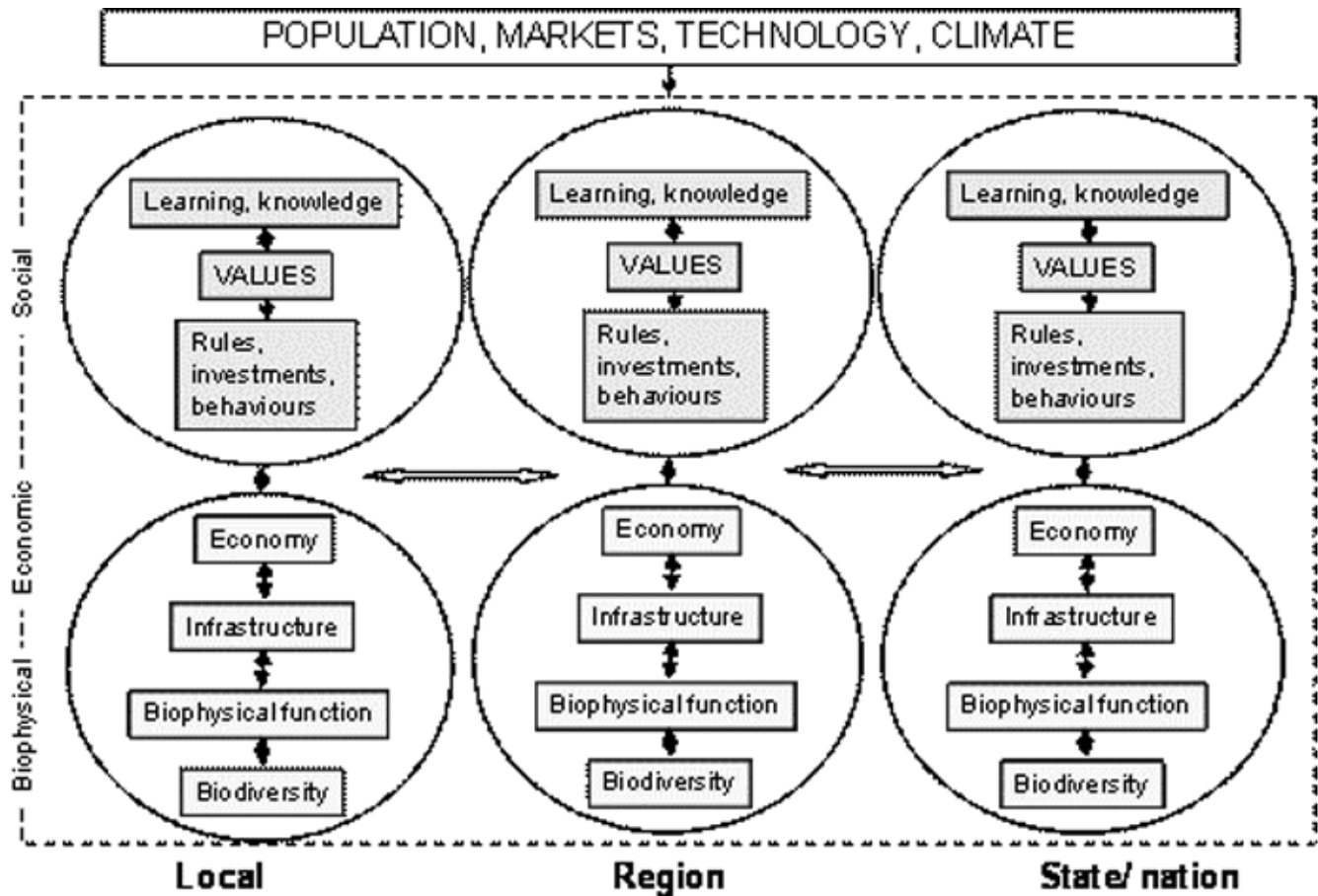
The regional biophysical subsystem

The GB catchment is one of the few Australian non-coastal regions in which the population and economy continue to grow, largely because of its water for irrigation (Goulburn Broken Catchment Management Authority (GBCMA) 2003). The major elements of the biophysical subsystem that support the flow of goods and services are as follows.

Surface hydrology and climatic change.—Capture of water for irrigation has transformed the volumes and the seasonal patterns of natural flooding, with adverse effects on the condition of river channels, wetlands, and floodplains (GBCMA 2003), with consequent impacts on both use and non-use values (see below). However, water for irrigation is scarce. If the climate experienced between 1997 and 2006 were to continue, average surface water availability would be reduced by 41%, the volume of water diverted for use within the region would be reduced by 25%, and the flow of the Goulburn River near its junction with the Murray would decrease by 22%. Under the most likely climate-change scenario, by 2030, average surface water availability would fall by 14% (the best to worst case range is 2% to 44%), the volume of water diverted for use within the region would decrease by 6% (best case 1%, worst 29%), and the flow of the Goulburn River into the Murray would decrease by 22% (best to worst case range 5% to 62%) (Commonwealth Scientific and Industrial Research Organisation (CSIRO) 2008).

Groundwater.—Clearing of native vegetation for agropastoralism soon after settlement initiated a rise in water tables, and consequent salinization of streams and plant root zones. The values generated

Fig. 2. Conceptual framework for regional change, showing categories of slow variables affecting the resilience of the region.



by irrigated and dryland agriculture, wetlands, and river channels are all threatened by this process.

Dryland native vegetation.—Native vegetation supports intrinsic, option, and use values by providing habitat for native biota and shade and shelter for stock. About 30% of the catchment is still covered with native vegetation, patchily distributed. Most of the remaining patches in the mid and lower catchment are small and isolated (GBCMA 2003), and many native species have declined and remain vulnerable as a consequence.

River channels, wetlands, and floodplains.—Less than 2% of the total length of the region's rivers and streams were classified by the GBCMA as ecologically healthy in 2003 (GBCMA 2003), but

its 2006–2007 report indicates an improvement and increased resilience of the rivers through remedial actions taken in the intervening years. High nutrient loads with associated outbreaks of blue-green algae are a key driver on investment in river management. The region contains one wetland of international significance, 10 of national significance, and 113 of bioregional significance. Some 68% of the pre-European area of wetlands is affected by changes in water regimes (GBCMA 2003). Floodplains have been similarly affected.

The economic subsystem

The main sectors of the regional economy and the annual output they generated in 2000–2001 are listed in Fig. 3 (Plant et al. 2003).

Table 1. Ability of proponents of particular values to influence changes in rules and investments to favor their interests.

Value	Political influence of proponents	Consequences for rules and investment
Marketed irrigation use values	Generally very strong because of lobbying power of sectors and voting power of employees and associated social networks, but varies across sectors.	Very strong property rights and secure access to water resources and infrastructure
Non-marketed use values	Strong for recreation because of number of voters enjoying recreation. Indigenous groups lobby separately to secure control over traditional lands, so far without significant gains.	Public provision of parks and reserves, with secure formal allocation of water, but it is probably inadequate to maintain the ecological processes that generate these values, and it is subordinate to irrigation allocations in times of drought.
Intrinsic values	Strong because of lobbying power of non-governmental conservation organizations, and power of urban votes. Lobbying by Indigenous groups is also aimed at maintaining intrinsic values.	
Bequest values	Negligible because beneficiaries are under age or unborn.	As above, with additional protection from heritage laws and regulations.
Option values	Negligible because no current use.	No explicit protection now.

Primary production ranks low in the list, with dairying the highest in this set, but processing of milk, fruit, and vegetables are important sectors, as they have an important multiplier effect, discussed later.

The social subsystem

The social subsystem embodies the governance system, the social networks, organizations, and human capital that manage the economic and biophysical subsystems. Changes in the resilience of the social system are discussed in the next section.

Part 2. Resilience Assessment

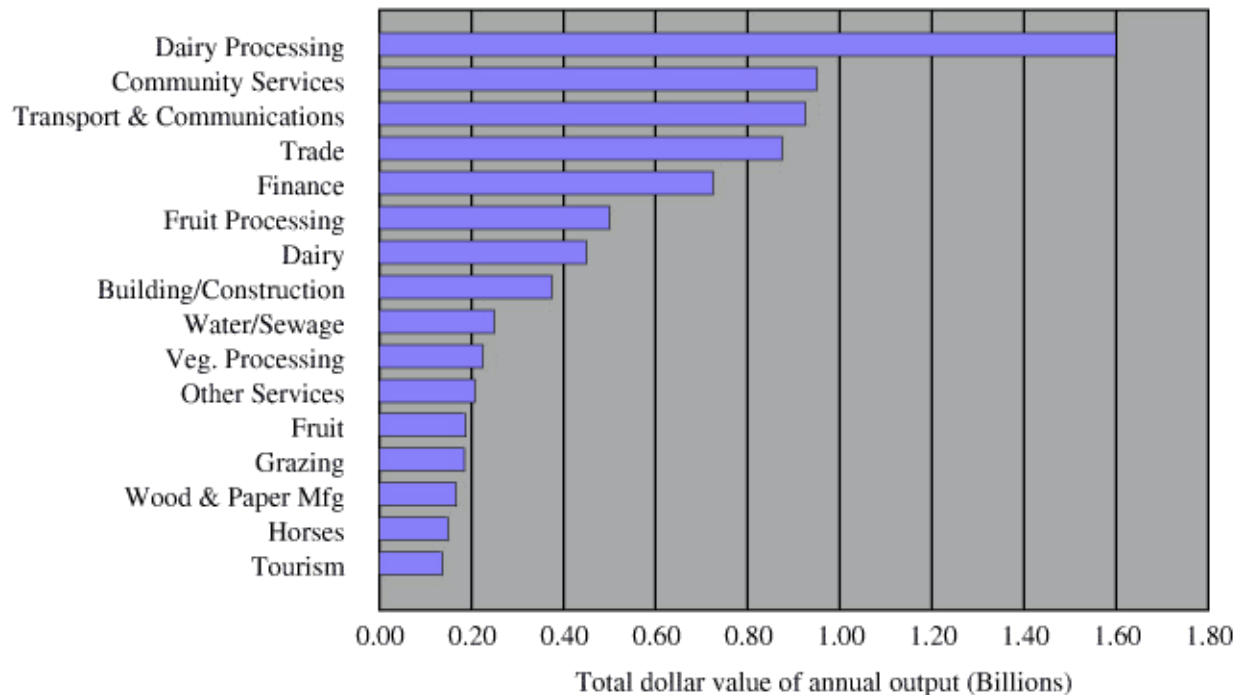
Losses of resilience during the growth and conservation phases of the region

Gibson et al. (1999) note the strong social resilience of the GB region, and its adaptation to major changes in economic drivers by diversifying its economy away from primary production. Overall, however, in keeping with agricultural development worldwide, its resilience has declined since colonization, especially biophysically. Early development of irrigation in the region constituted

a typical growth (r) phase in an adaptive cycle, driven by widely shared values that favored development and resource exploitation (Reeve et al. 2002). At the outset, native vegetation regulated water-table depth; soils were at their natural pH levels; nutrient cycles were self-maintaining; river channel, wetlands, and floodplains were maintained by alternating natural floods and low flows; and the indigenous fire-management regime maintained a mosaic of woodland and grassland supporting a high biodiversity. Following colonization, indigenous peoples were dispossessed, native trees and shrubs that encroached with the cessation of indigenous fire regimes were cleared, connectivity was lost, riverine systems were degraded by changes in flow regimes caused by river regulation and diversion for irrigation, and biodiversity declined.

At the time of colonization, many options lay open, but the assignment of property rights, demarcation of properties, and building of roads and irrigation infrastructure reduced those options and set subsequent development on the path that led to the tightly constrained modern system. Rights to water were given to private landholders and to irrigation groups as part of their land tenures. Water trading, to enable adaptation to changing circumstances and movement of water to where it produced its highest

Fig. 3. Contributions of the 10 largest sectors to total dollar value of output (Source: model built by Plant et al. 2003).



returns, was prevented by tying water to land title. Also, there was no incentive to allocate water efficiently because its price was set bureaucratically at a level that did not reflect its value in production. Provision of water below cost (Tisdell et al. 2002) resulted in profligate use and provided no incentive to innovate. Over-irrigation hastened the rise of water tables and consequent loss of resilience (Anderies 2005). These seemingly unwise decisions may be attributable to ignorance, but they were also in accordance with values at that time, which favored rapid development of land and water resources for the production of marketed use values (Table 1).

Changes in the GB catchment mirror the degradation of the whole Murray-Darling Basin. Economic (Davidson 1969) and environmental arguments against irrigation began to appear in the 1960s, marking the beginning of the conservation, or K phase, of the adaptive cycle in which increasingly complex rules, investments (Fig. 2), and organizational structures were deployed to

address problems initiated during the growth phase. The interstate Murray-Darling Basin Ministerial Council, and the Murray-Darling Basin Commission (MDBC) were established in 1985, and catchment management authorities (CMAs; under another name) in 1994, reflecting a shift in social values toward economic efficiency and environmental management (Reeve et al. 2002, Tisdell et al. 2002). The CMAs were expected to foster the integrated management of catchments to maintain and supply a broader range of use and non-use, market and non-market values. Water reforms have recently separated water titles from land titles, enabling water trading. Abstraction is capped and, in theory, some water is left for “environmental flows.” In practice, towns and irrigation take priority during dry periods, and as a consequence of the recent run of dry years, wetlands and floodplains along the Murray and at its mouth have probably shifted irreversibly to new regimes.

As southeastern Australia and the GB Catchment strive to cope with a prolonged drought, under the

longer-term threats of climate change and energy-cost increases, the multi-level, multi-interest system is making decisions that attempt to shore up the current water-use regime with major investment in improved water-distribution infrastructure plus some purchase by governments of water for environmental flows. The complexity of governance has increased as each new problem has emerged. We judge that the GB region and the Murray-Darling Basin as a whole are now in a late conservation (K) phase in which state and federal institutions, politicians, lobbyists for different values, voters, and bureaucrats interact in a political-bureaucratic network of microdecisions, to which the new arrangements are being added to form a “churning cauldron of consultation” (Connell et al. 2005:12). We follow Tainter (1988) in seeing this institutional complexity as dysfunctional and prone to collapse. Given the economic, social, and ecological precariousness of the Murray-Darling Basin and the complexity of its rules and irrigation infrastructure, resilience theory would anticipate a release phase and either a regime shift or (more likely) a transformation.

The current resilience of the system

Given these historical changes in resilience we now assess the current resilience of the biophysical, economic, and social subsystems of the region in terms of the critical thresholds affecting the delivery of benefits, and the feedback loops that control the proximity of the system to those thresholds. Before proceeding, we note that in its 2006–2007 annual report, the GBCMA assessed changes in the resilience of the catchment between 1990 and 2007. It assigned degrees of confidence to assessments of the resilience of some of its subsystems, and also changes in resilience with respect to some kinds of shocks (GBCMA 2007). This is the first such assessment by a regional organization. It is a measure of increasing awareness of the resilience concept. We have presented their assessments (as GBCMA) in the relevant sections.

Specified resilience (the resilience of what, to what)

In this section, we identify the set of controlling (mostly slowly changing) variables with threshold effects that might lead to regional-scale regime shifts. It is the core of a resilience analysis and the most difficult part, because we are dealing with inadequate data and understanding and, hence, much uncertainty. Accordingly, in the assessment

that follows, we present the thresholds in three categories along the lines of the Intergovernmental Panel on Climate Change (IPCC) assessments: (1) known—known to exist or fairly certain, (2) strongly suspected, and (3) possible—those with a fair degree of uncertainty.

Thresholds and resilience in the biophysical subsystem

Agricultural system thresholds

(1) Known

(i) Cover of woody vegetation required to maintain an equilibrium groundwater table below the surface. Around 85% of the native woodland and forest cover has been removed from the mid catchment, and 98% from the lower catchment (GBCMA 2003). Anderies et al. (2006b) estimate that the cover of woody vegetation was reduced to below the threshold level needed to maintain the water table below the surface about a decade after clearing began. This threshold is estimated at about 80% vegetation cover in the mid catchment (groundwater in the upper catchment appears not to be connected to water tables in the mid and lower catchment). Because of a strong hysteresis effect (tree roots do not function well in saturated soil, so it takes more trees than in unsaturated soil to achieve the same amount of transpiration), more than 80% needs to be revegetated to change the trajectory of the system such that the equilibrium water-table depth is below the root zone. As this would affect large areas of dryland farms, pumping is needed in addition to revegetation—the less revegetation, the more pumping (see Anderies et al. 2006b). A constraint is the large volumes of saline water produced. Almost twice as much saline water needs to be pumped if there is no revegetation, which would violate the current salt discharge cap. Revegetation and pumping are both costly.

(ii) Depth to water table. Related to (i), as water tables rise, there is a critical threshold at around 2 m below the surface (depending on soil texture). When the water table rises above this, capillary action draws water to the surface. The height of the water table determines the area salinized because of topographic variation, so area salinized and water-table depth are treated as a single threshold.

The GBCMA assessment: Between 1990 and 2007 the GBCMA judges that resilience in the irrigation area to changes in water tables and salinity has increased from low to satisfactory, due to

investment in water-use efficiency (less irrigation = less added to water table). (We assert that the current drought has also contributed to this increase in resilience.) For dryland agriculture, its assessment is negligible change and low resilience, with the comment that “if there is a run of wet years the appropriate response is now considered to be to ‘live with salt’ (adjust to a transformed system).”

(iii) Soil acidity. A critical threshold in acidity occurs around pH 5.0 (measured in calcium chloride solution). Below that level, there is a sudden, marked drop in soil fertility and crop production. Economic viability demands that crops (dryland and irrigated) be fertilized with nitrogen, which lowers pH, and so soil pH continues to be a slow declining variable. It is estimated that somewhere around 750 000 ha in the catchment are prone to this threshold, and avoiding it will require costly additions of lime.

Dryland biodiversity thresholds

(1) Known

The two hydrologically determined thresholds that affect agricultural regime shifts (numbers (i) and (ii) above) also affect biodiversity in native habitats, and so will soil pH.

(2) Strongly suspected

(iv) Dryland vegetation cover, connectivity, and condition. Key variables for the conservation of dryland native biota are assumed to be the condition relative to the presumed presettlement state, patch size, connectivity, and percent cover by vegetation type (Langston et al. 2003). In the mid and lower catchment, native vegetation condition is rated generally poor, and most patches are small and isolated from other areas of native vegetation (GBCMA 2003). These attributes will interact and will affect different biota in different ways, so there is unlikely to be a general threshold for biodiversity. The current convention for cover is based on generic species area curves (Turner 2005) and modeling of woodland bird species occurrences (Radford et al. 2005) which suggest precipitous declines in species diversity once vegetation cover decreases below 30%. Many vegetation types in the mid and lower catchment are currently below this (GBCMA 2003). Climate change may magnify the losses.

The GBCMA assessment: Low resilience, negligible change, owing to continued threats from habitat loss and fragmentation.

Aquatic / wetland biodiversity thresholds

(1) Known

(v) There are thresholds for nutrient (N, P) levels in water bodies, that lead to eutrophic states. The estimated annual cost of algal blooms in rivers, irrigation, and farm storages in the GBC is approximately \$5 million (Atech Group 1999). Although most algal blooms are from benign algae, outbreaks of toxic *Cyanobacteria* have periodically threatened urban and industry water supplies, temporarily closed rivers and water storages to recreation, and restricted use of irrigation water. Major sources of nutrients to waterways in the catchment include run-off from irrigated and dryland agricultural areas, urban stormwater and treatment plants, and industries such as fish farming (Goulburn Broken River Environment and Water Quality Committee (GBREWQC) 1997). What is not known is the threshold load from all these sources that drives the water bodies across the threshold nutrient concentrations into the eutrophic state (see Carpenter and Lathrap (2008) for a discussion of how this can be estimated in a northern hemisphere lake).

(2) Strongly suspected

(vi) River flow regime. As described earlier, the region has a legacy of degrading riverine, wetland, and floodplain ecosystems because of changes in the seasonality and quantities of water flows. Climatic change is likely to exacerbate the effects. Each species of riverine plant or animal has a characteristic, but unknown, response threshold. Departure of any flow attribute (depth, duration, frequency, seasonality) from the pre-irrigation flow regime likely has a negative effect on rivers, streams, wetlands, and floodplains, but we are unable to either estimate the magnitude of these effects or specify thresholds that trigger major adverse changes. Water allocations control these attributes. Simplified alternate states of these systems are:

- perennial river channels
 - a. current flow regime—used as irrigation conduits, native fish replaced by exotics;
 - b. some native fish and foodwebs persist, flows managed for multiple values;
 - c. native fish and foodwebs intact, flows managed for conservation, tourism, and recreation.

– wetland

- a. current regime of higher water levels in spring

and summer as irrigation water released for downstream use, with changed species composition, including exotic species;

b. original flow regime and species composition

– floodplains

a. existing regime of no winter floods and excessive summer flooding, with different species composition;

b. original flood regime and associated species.

There is a feedback from the condition and trend of these riverine ecosystems through values delivered, to the governance arrangements, hence to water allocations (Fig. 2). It is strongly modified by pressure from the conservation and irrigation lobbies (conflicting ones) and by political perceptions of public preferences.

The GBCMA assessment: the resilience of riparian and in-stream habitats and water quality in rivers and streams, have increased since 1990 from low and very low to satisfactory, whereas the resilience of water supply and environmental flows has decreased from low to very low (due to the stress of a decade-long dry period).

Thresholds and resilience in the economic subsystem.

The kinds of thresholds we have identified in the economic subsystem are different to those in the biophysical system. There is nothing surprising or new about them. They are more in the nature of tipping points resulting from cost–benefit effects, and as the input costs and the product prices change, the tipping point changes accordingly. At any time, however, biophysical shocks (like droughts), exacerbated by the loss of resilience in the biophysical subsystem, can push farms over these points.

(1) Known (nil)

(2) Strongly suspected

(vii) Farm income:debt ratios. The viability of a farm will change according to the proportion salinized, the availability of water (if irrigated), the costs of capital and inputs, and product prices. The recent drought has lessened concern about salinity, but it remains a problem in the event of a wet period. The cost of water will be affected by the amount allocated to the irrigation sector, because of its effect on supply to the water market. Paradoxically, if climatic change lowers the equilibrium level of the water table below the root zone, it is also likely to

reduce catchment water yield and raise water costs. Increased cost is expected to enhance on-farm innovation and water-use efficiency, but it will require increased capital investment. Farm economic viability is captured by the ratio of income to debt. Figure 4 shows trends in profit and debt for Victorian dairy farms. Farm debt is a slow variable in the region, and growing debt increases the vulnerability of farms to droughts and interest rate rises. We propose that there is a threshold in the ratio of debt to income above which an increase in water cost, or a rise in water table, would bankrupt a high proportion of farms and reduce supply to the processing industries.

There are links from farm viability through land use to the processing sectors, hence to the regional economy and values delivered, with a feedback loop to governance and investment.

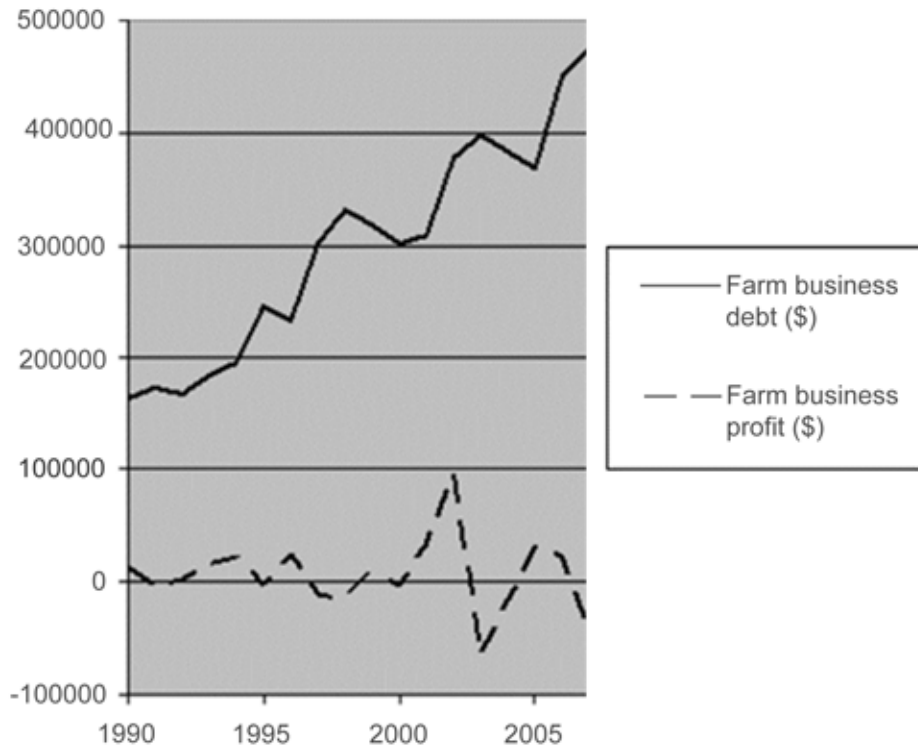
(viii) State of infrastructure. The current irrigation infrastructure is leaky (it contributes to the rise in water tables), evaporation losses are unnecessarily high, and it is deteriorating. To maintain the irrigation system in its current regime, reinvestment is necessary and is now happening. The economic threshold is the minimum level of reinvestment required to maintain the system for, say, the next 30 years. Given the uncertainties of climatic change, and the absence of comprehensive economic analyses, we do not know what this investment threshold would be and whether investment is worthwhile. The pumping and storage of saline groundwater is energy intensive, and if energy costs rise, it may make reinvestment unattractive. As already argued, the original decisions to invest public funds in infrastructure were driven by society's values at the time, rather than economic criteria, and this may be the case again.

(3) Possible

(ix) Presence/absence of high-multiplier economic sectors. The closure of a sector that is linked to many others in a regional economy through buying and selling of inputs and services has a major flow-on impact, because of their high multiplier effects. The top five multipliers for output and employment for the regional economy (Plant et al. 2003) are given in Fig. 5a, b.

Dependence on local production is different in each sector. Milk, vegetables, and fruit, because of their perishability, are best produced locally. Lack of local production would probably drive processors

Fig. 4. Trends in profit and debt on Victorian dairy farms. Source: Australian Bureau of Agricultural and Resource Economics.



from the region, with severe consequences for the economy. This has been demonstrated in the past when individual processing businesses have closed (Gibson et al. 1999). The impact of closing a sector would of course be much more severe. Milk, vegetables, and fruit production are all vulnerable to salinization and water logging. The threshold of potential concern is the departure of the agricultural processing sectors from the region caused by the inability of the region to produce sufficient fresh agricultural products as a result of water-table rise or high water costs. Depth to water table (thus area salinized) (i above), and farm income:debt ratios (vii above) are closely linked thresholds.

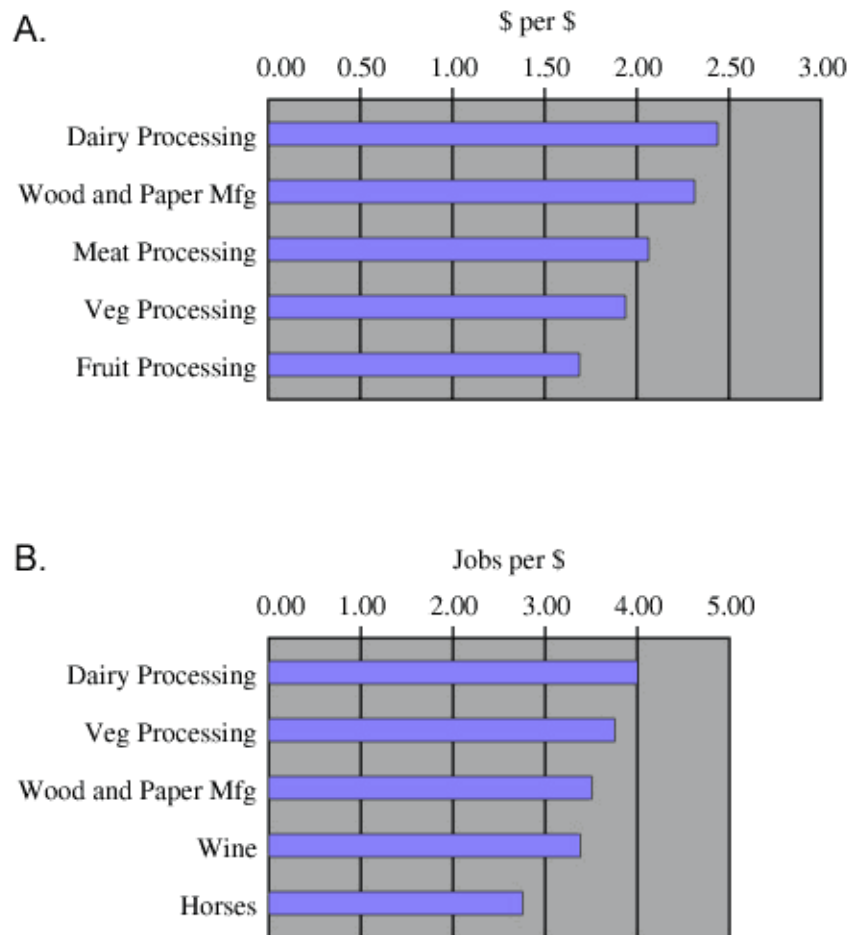
Thresholds, resilience, and adaptive capacity of the social subsystem.

- (1) Known (nil)
- (2) Strongly suspected

(x) Balance among values held. Although thresholds can be crossed in the mind of an individual, feedbacks from peers, news media that encourage uniformity of thought, sunk cost effects, and the innate conservatism of humans' mental models tend to maintain values over long periods (Kelly 1955, Abel et al. 1998). Changes in values are, therefore, likely to take place as significant tipping points, usually in response to events. The current societal shift toward valuing the environment is a slow variable with a possible tipping point. Table 1, which is about values at all scales in the panarchy, summarizes our understanding of the relative political significance of the different value sets influencing this point.

The balance is influenced by both the values held within and outside the region. Irrigation use values are strong within the region but a shift favoring environmental water allocations over irrigation

Fig. 5. a. Top five regional output multipliers. For example, each extra dollar of output from the dairy industry results in A\$2.45 of extra output in the rest of the economy. b. Top five regional employment multipliers. For example, each extra job in dairy processing leads to four extra jobs in other sectors in the regional economy. (Source: Plant et al 2003.)



would be driven by urban interests, not regional ones.

The GBCMA assessment: The GBCMA has judged that its corporate and statutory operations, its people, its planning and response, and its knowledge have all got satisfactory levels of resilience, and have mostly gone up from low to satisfactory. It has a concern that in terms of relationships, partnerships, and community capacity, resilience is low and has not changed, and the GBCMA identifies rapid turnover of staff and loss of corporate memory as a factor.

The set of interacting thresholds in the Goulburn Broken catchment SES.

The analysis of resilience has identified 10 slow variables with thresholds. The nature of the thresholds differs. Following Scheffer (2009), some are sharp transitions or step changes, such as the changes in infrastructure (no. viii) and others are catastrophe folds, with alternate stable states, such as the salinity threshold (no. ii). Both types are important, although the latter have more profound effects. Figure 6 shows how these thresholds interact and some of the shocks and other changes

in exogenous drivers that could result in thresholds being crossed. We have not made a comprehensive list of all possible shocks and other changes in exogenous drivers.

The significance of Fig. 6 is that it defines the thresholds of potential concern (TPCs; cf. Biggs and Rogers 2003) at the focal scale of interest that need to be encompassed by management and governance. Concentrating on the resilience of any one of the spatial scales or subsystem domains in Fig. 6 is likely to mask thresholds of potential concern driven by cross-scale effects. This focal scale system is, furthermore, subject to the consequences of threshold effects at higher scales. Such higher-scale threshold effects need to be considered in terms of their impacts, although they are not subject to the management and governance actions at the catchment scale.

Even though the SES may be very close to one of the 10 thresholds, the kind of shock experienced may not affect it, and instead may result in one of the other thresholds being crossed. Crossing any one threshold can have a cascading effect, causing other thresholds to be crossed (Kinzig et al. 2006) (e.g., crossing threshold (ii) can lead to crossing threshold (vii)), or it may reduce the likelihood of another being crossed (e.g., crossing threshold (x) could reduce the chances of crossing thresholds (i), (ii), (iv) and (v)).

Considering the set of thresholds in relation to changes occurring in the SES highlights a distinction between thresholds that are fixed and those that can be changed. The water-table depth threshold (ii), for example, is determined by the physical structure of the soil and, in practical terms, is fixed. The vegetation cover and biodiversity threshold (iv), on the other hand, is influenced by the condition of the vegetation and its pattern (size distribution of remaining patches and their connectivity), and occurs at a higher percentage cover if the remaining patches of native ecosystems are degraded and less connected. The potential threshold in social values (x) can be influenced by communication, as has happened in the climatic-change debate. Some of the thresholds can, therefore, be influenced by management or policy and some cannot.

General resilience

Because of uncertainty about the specified thresholds, regions must be prepared for a wide

range of disturbances. By building targeted resilience, regions may inadvertently be reducing other kinds of resilience. It is well known that in feedback systems (of which social-ecological systems are an example) increasing robustness to disturbances at a particular frequency range may reduce robustness to disturbances at another range. It was shown long ago that this is necessarily the case for linear, time-invariant systems (Bode 1945). This idea has been extended to more complex systems recently. For example, Carlson and Doyle (2000) illustrate that biophysical systems that become robust to frequent disturbances become necessarily less resilient to those that are very infrequent. Anderies et al. (2007) have applied these ideas to simple, nonlinear, renewable-resource management problems and illustrated fundamental robustness trade-offs to different types of disturbances. It is, therefore, sensible to consider, in addition to resilience to specified thresholds, whether general resilience is declining.

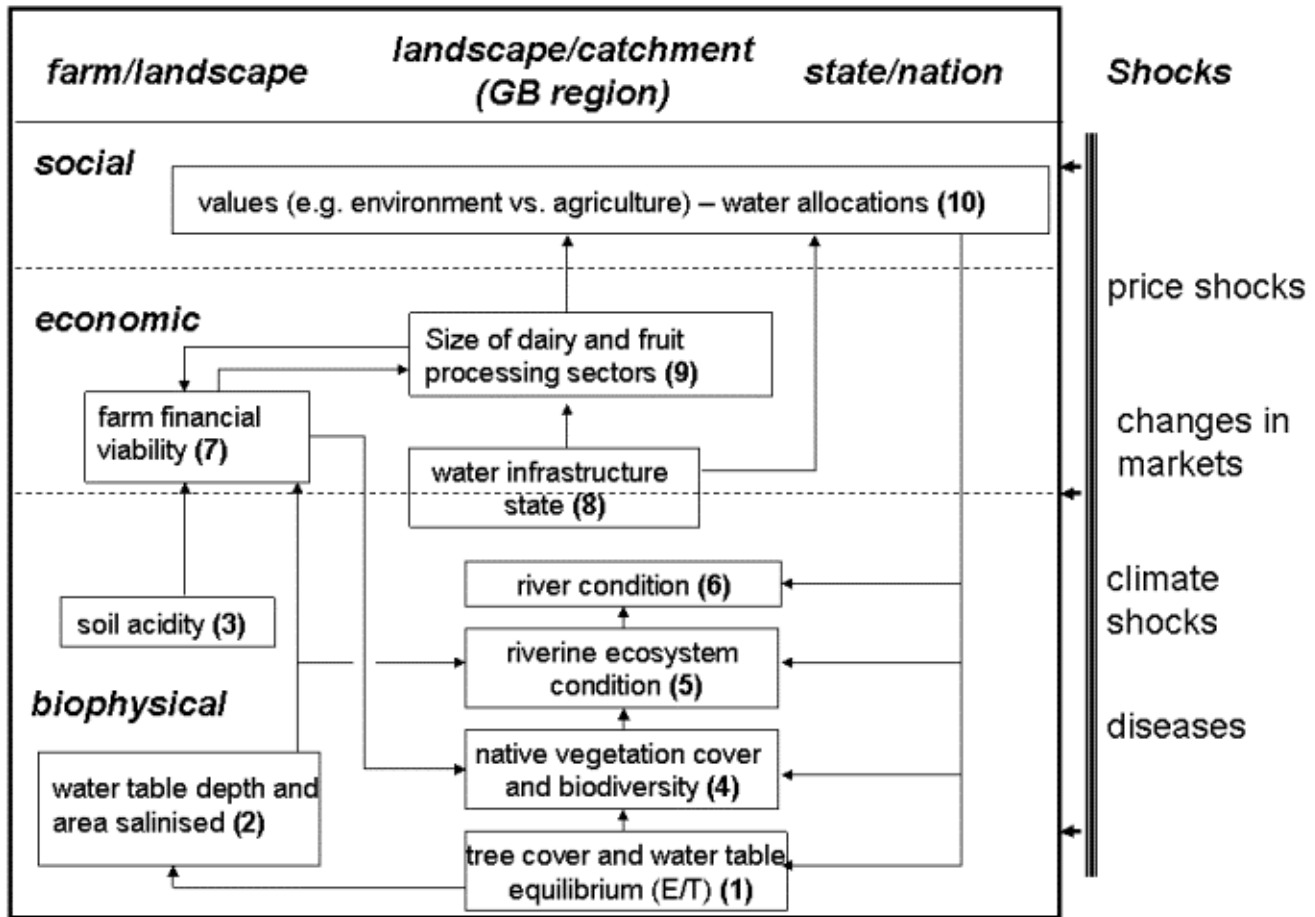
Depending on the circumstances, general resilience could be increased (Walker et al. 2006) by: building and deploying human and social capital (including political influence); fostering experimentation and learning; investing in response diversity (“redundancy”) and reserves of resources; maintaining or increasing options; and increasing spatial heterogeneity and ecological connectivity. We consider each in turn, below.

Building resilience comes at a cost and so involves choices about how much “insurance” (one aspect of resilience) to invest in. Given that the regime shifts are not specified for general resilience, neither the likelihood nor the cost can be specified, which probably explains the widespread pattern of declining general resilience.

Building and deploying human and social capital.

—According to the GBCMA’s (subjective) assessment, human capital in the GB is reasonably high, and based on the networks and leadership we have encountered over the past 10 years of research with stakeholders in the region, we suggest social capital is also fairly strong. There are, however, aspects of social inequity and lack of participation that call for a better, quantitative assessment of social capital. Given the likelihood of future shocks and ongoing disputes over allocation of resources such as water and access to public land, a resilient GB region may require levels of human capital (e.g., levels and diversity of skills or expertise, labor) and social capital that exceed those currently

Fig. 6. Ten slow variables with identified thresholds in the panarchy that constitutes the Goulburn-Broken Region. The arrows between boxes indicate possible cascading threshold effects.



available across all scales and all segments of society.

Regions compete to attract human, financial, and physical capital. Regional leaders are well aware that becoming politically unimportant will likely lead to an overall decline in welfare through reductions in investment in public infrastructure and human capital. This may reduce some pressures on ecosystems associated with agricultural and grazing activities, and may increase intrinsic, option, and bequest values, so is not necessarily undesirable. Obviously, dealing with conflict is critical in the political domain. In the GB, proponents of irrigation, recreation, tourism, and conservation (Table 1) require different and often incompatible river-flow regimes and land-cover patterns to

support their values, and the state and federal governments attempt to reconcile these. Historically, the political power of and social support for the irrigation industry has dominated political discourse through extensive lobbying efforts. Proponents of the status quo will, in the future, be competing with proponents of change to secure policies and investments that favor their interests. In similar regions elsewhere in the world, the existence of so-called bridging organizations has played a key role in achieving mutually acceptable outcomes (Olsson et al. 2004), and the GBCMA comes close to the role of such an organization.

Learning, monitoring and experimentation.—An adaptive approach to dealing with uncertainty requires a strong emphasis on learning. Historical

analysis (learning from the past) makes an important contribution to understanding the current configuration of a social–ecological system, the reasons for it, and how it is believed to function. The development of a suite of conceptual and other models of how the system responds to disturbances (part of the resilience of what, to what assessment), coupled with monitoring the effects of management and shocks to the system, is also a key part of this. Evaluation brings with it the concept of double-loop learning (Argyris 1982), in which the objectives are systematically revisited and questioned, and the monitoring system redesigned if necessary. It goes without saying that an iterative approach to refining a developing model of how the GB system works is an essential part of a general adaptive approach. Although it does not have a particular set of such evolving, heuristic models, the GBCMA has been engaged in an ongoing series of such exercises.

Monitoring is limited in its capacity to distinguish between causes of change from correlations, and to identify the shape of response functions when there are no treatments and controls. In regard to policies on learning, it is important to distinguish between research to enhance the efficiency of resource use (which has been plentiful through Australia's development history) and research to enhance the resilience of the resource in response to use. In regard to water use, for example, investment in ecological research along the Murray has been very small, given the high intrinsic, bequest, and non-market values of the declining native ecological communities along the river. For the Barmah Forest, an internationally important wetland and Ramsar site ([Ramsar List of Wetlands of International Importance](#)) in the GB suffering ecologically through changes in its hydrological regime, Roberts (2006) found just three published references on which to base water allocations to the Forest. They are the sole basis for management other than the experiential knowledge of skilled managers.

Overall, learning and innovation have been unevenly distributed in the catchment. The drylands region appears not to exhibit high levels of either, but experimentation and learning in the irrigation region have been strong, although focused in particular areas such as pollution control from dairy into waterways, and in dairy and horticultural production systems. However, learning in the catchment as a whole has all been directed to staying in the same system regime. The levels of monitoring are difficult to judge, and a more explicit form of

Adaptive Environmental Assessment and Management (AEAM) (Holling 1978) would address this limitation on learning.

Economic efficiency innovation permeates the thinking of agencies and resource users in the region, and the powerful drive toward economic efficiency from open markets is a reality to many producers. It requires maximization of net benefits through production of optimum amounts and mixes of outputs with the least cost combination of inputs. This way of thinking has become a structural problem, encouraging resource users to run systems close to thresholds of degradation (Anderies et al. 2006a, Walker and Salt 2006), which may be irreversible (Fernandez et al. 2002). We return to innovation in a later section on transformational change.

Building and maintaining reserves, options, and redundancies.—Keeping resource reserves is a widespread strategy in both nature and across human cultures, and is related to the point made in the preceding paragraph. In terms of natural capital, the GB region has few reserves—stocks that could be readily brought into use if needed, or easily diverted from current uses. As mentioned earlier, the GBCMA's assessment of its social and economic capital reserves is that they are in good condition. Given its importance, however, this requires a quantified, preferably independent, assessment.

In the social domain, investments in trust funds for the future and for unexpected needs, the maintenance of resources with option values despite the pressures of current demands, deliberate over-investment (in static economic efficiency terms) in leadership and education, investment in multiple energy sources and duplicate infrastructure and other fail-safe strategies and the deliberate fostering of diversity in social, economic, and ecological subsystems are areas that are wanting in the GB, in terms of general resilience.

Heterogeneity and connectivity.—Many of the region's landscapes have become homogenized in time and space as a result of agricultural development. Crops have become more genetically uniform, and rotational cropping has declined, thus providing the uniformity of habitat in which pests, weeds, and diseases thrive. The dairy cattle of the GB region are also very uniform genetically, which further raises the risk of a disease spreading.

There has been a concomitant decrease in the connectivity of native vegetation, raising the risk of extinctions caused by reduced mobility of biota. The forecast climate changes in the region will require increased mobility and habitat options for native species, and in this regard the region, therefore, has low general resilience.

With this assessment of its specified and general resilience, we are in a position to consider changes in policy and management of the GB region.

Part 3. Interventions for Managing Resilience

Our challenge is to test whether the Regional Catchment Strategy would be written differently if it were based on resilience thinking.

The vision of the GBCMA is of:

A catchment recognised locally, nationally and internationally for quality agricultural produce and where community values contribute to the benefits of abundant and well maintained environmental assets used for tourism and recreational activities. The environmental footprint of irrigation and dryland farming will be significantly reduced, with farmers occupying less land and using less water whilst managing their resources more sustainably. New opportunities will arise for increasing the ecosystem services provided by the land retired from agriculture and by improved environmental flows. The region's economy will be robust, with much of the agricultural produce processed within the region, generating employment and wealth creation opportunities for a regional community actively engaging in natural resource management programs.

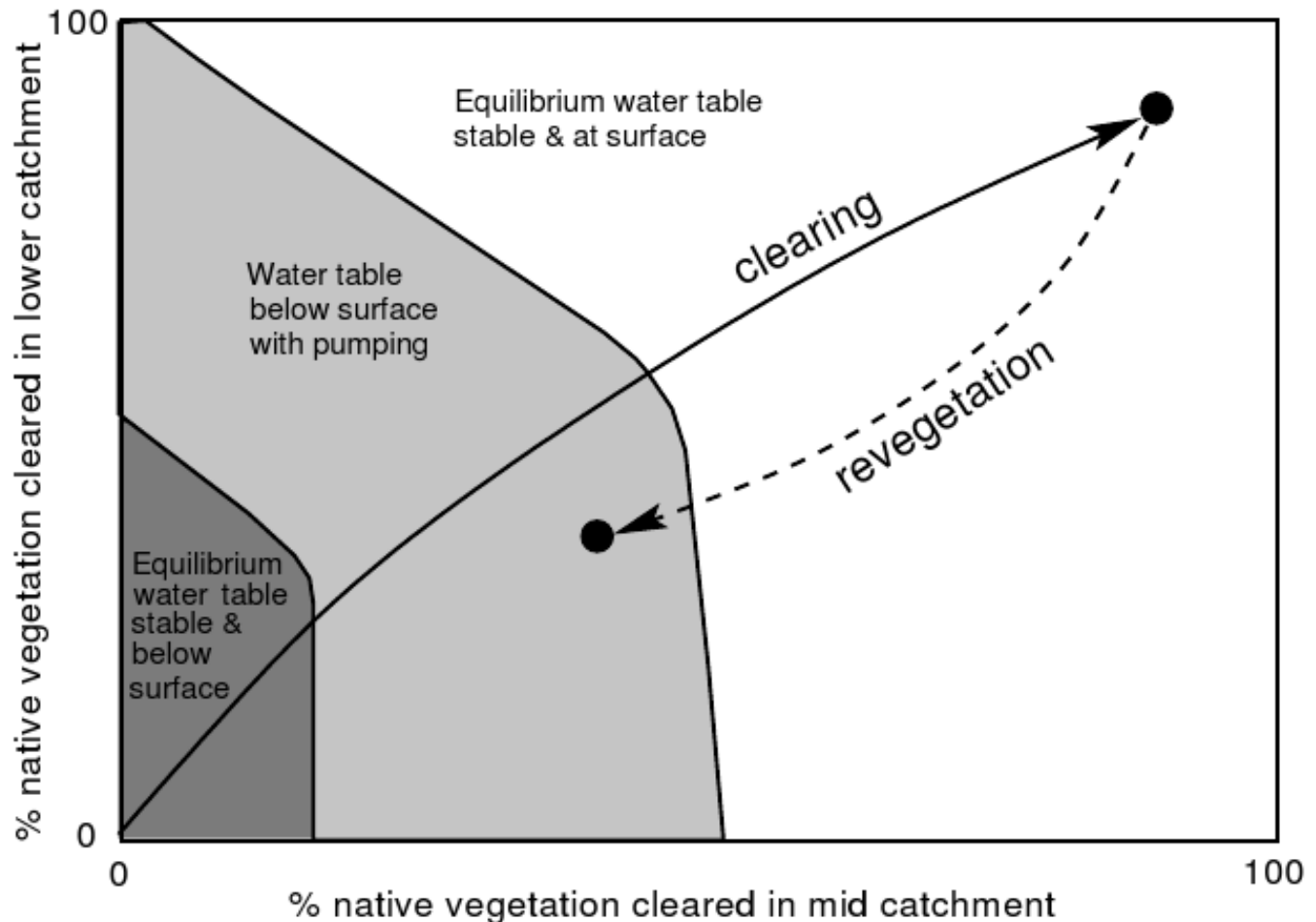
The Regional Catchment Strategy addresses problems of (i) water tables, (ii) salinity, (iii) nutrient loads, (iv) degradation of river channels, floodplains, and wetlands, and (v) the loss of cover and fragmentation of native dryland vegetation, all of which reduce values delivered by the region. The strategy is aimed at keeping the regional system within its current regime. The feasibility of achieving this requires that the following seven conditions be met.

1. a) Drying of the climate reduces the equilibrium level of the regional water table to more than 2 m below the surface over an area sufficiently large to support irrigated agriculture, or
b) Pumping can continue to keep the water table below 2 m from the surface (rising energy costs are a problem here, and there is also a limit to public tolerance for salt storage and number of suitable sites in which to store the salt), or
c) Native vegetation cover in the mid catchment increases from its current level of <15% to 80% in time to prevent the water table reaching the surface. This is unlikely in the view of Anderies et al. (2006b)—Fig. 7 below), or
d) Some combination of partial revegetation (perhaps about 50%) and pumping will allow the system to reach a point (Fig. 7) where the equilibrium water table is below the surface.
2. There is sufficient water for irrigation, taking into account climatic change.
3. The investment in improving irrigation infrastructure that began recently (A\$10 billion for the Murray-Darling Basin) reduces leakages to the water table and other transmission losses.
4. Processing industries remain in the region.
5. Demand for agricultural produce remains strong.
6. Regional biodiversity is maintained.
7. The ecological functions of riverine systems are maintained through environmental flows, despite intensifying competition for water and climatic change.

Growth in tourism could help reduce the current reliance on agriculture. The catchment is a “fine food and wine” region, has good upland scenery, and attracts some tourists. The region already has significant water-based recreation and tourism, but these are as vulnerable to climate change as is agriculture.

Even if climate change results in a drying trend, wet phases will likely still occur. Point 1d emphasizes

Fig. 7. Equilibrium states of water-table depth for different combinations of vegetation cover, including current levels of groundwater pumping. Avoiding water tables reaching the surface equilibrium condition will require a trajectory of revegetation something like that depicted, in combination with continued pumping. A reduction in average rainfall (over a prolonged period) would alter this picture. (After Anderies et al. 2006). [Erratum \(added 31 March 2009\)](#)



that to avoid being overwhelmed by a very wet period (when the water table may rise above 2 m long enough to induce irreversible surface salinity), a combination of pumping and revegetation may be needed. Even so, it would be a race against time to shift the system into a position where the water table is stable below the surface, with pumping, such as depicted by the dashed arrow in Fig. 7, before such a wet period occurs. If climatic change means that wet periods no longer threaten, the problem then becomes sufficiency of water for irrigation and for environmental flows.

The strategy's aim to keep the catchment in its present regime focuses on desirable levels of water,

salinity, river and floodplain condition, and biodiversity, and identifies the problems to be tackled. A resilience perspective would focus on how much these variables can be changed before they can no longer recover. Therefore, it would pay attention to the thresholds in Fig. 6, and in particular to the "slow" variables on which they occur, and how they interact. The strategy would be about identifying just where these threshold positions are and devising interventions that either keep the slow variables concerned below (or above) these threshold amounts, or working out how to change the positions of the thresholds (where that is possible) so as to increase the resilience of the current regime.

The resilience of the GB is strongly influenced by its cross-scale connections. We have already noted that the GBCMA has only a small influence on the key slow variables because it is local, state, and federal governments, not the CMA, that control land and water use and investments in infrastructure. The current governance of water leaves the region highly vulnerable to both climatic variation and to long-term change. Because the region is part of the Murray Basin, its future depends on changes at state and federal as well as regional scales. However, the ability of governments to influence the direction of change in this capitalist democracy is itself limited by the need to accommodate multiple conflicting values (Table 1). Political lobbying, information, public and private investments, and the laws, regulations, incentives, and informal norms and rules are the main influences that maintain the region, precariously, in the current regime. Governmental interventions and the GBCMA's strategy are aimed at maintaining this regime. Changes at the scale of the Murray-Darling Basin and the region that could increase the likelihood of success include:

- Increase efficiency of water use through trading, especially the removal of barriers to inter-state trading (Qureshi et al. 2006, Young and McColl 2008), genetic modification of crops, and improved water, soil, and crop management. Khan and Abbas (2007) estimate that feasible on-farm efficiency increases in two irrigation areas on the Murrumbidgee River floodplain, a tributary of the Murray, could lead to a decreased water use that is between 16% and 33% of the current (small, but so far unrealized) allocation to environmental flows in the Murray River (500 GL/year). However, the tendency to expand the irrigated area to use the water savings would need to be countered.
- Eliminate incentives to farmers who reduce resilience. Response to historic droughts has been to build more storage and distribution infrastructure. The result has been to increase the dependency of the system on irrigation and bring it closer to critical water supply and water-table thresholds (Fig. 6). If the current and proposed A\$10 billion investments in water infrastructure are used to increase storage rather than reduce leakages, resilience will be further reduced. Drought

relief policy has had a similar effect to water storages and is currently under review.

- Increase incentives to farmers who enhance resilience. Market-based measures for improving off-farm water quality, conserving wetlands and maintaining on-farm biodiversity are already operating at a small scale, with the potential for expansion limited by public reluctance to place environmental priorities on a par with human health and current prosperity.
- Develop dynamic rules that accommodate rainfall and other trends and fluctuations. The aim is to promote conservation, and land- and water-use decisions that are matched to prevailing circumstances. For example, Young and McColl (2008) advocate an entitlement and allocation system that matches inflows to use during floods and droughts, and under climatic change, giving environmental flows an entitlement to water that has precedence, along with urban water, over irrigation entitlements. Entitlements are secure rights, but the actual allocations vary with water availability.
- Develop dynamic incentives. An example is to vary conservation payments to farmers so that when rainfall is plentiful incentive levels fall, but payments increase during droughts, when native ecosystems are under pressure from both moisture stress and grazing. Farmers would benefit from the alternative source of income in dry times.
- Redress the conflicting connectivity problems (described under "general resilience"). It may be useful to reduce the connectivity of agriculture and enhance that of native vegetation by addressing both on the same landscape. A range of instruments have been developed and tested and small amounts of public funding deployed to run competitive auctions to increase the area planted to native vegetation.
- Make adequate public investments in maintaining long-term resilience. Incentive payments for environmental management are budgeted for a few years at a time and are driven by public preferences, the electoral cycle, and economic trends and fluctuations.

The ensuing uncertainty discourages commitment and long-term environmental management. Trust funds dedicated to environmental management and under the control of an autonomous commission are a potential solution.

- Promote, through information, rules, and incentives, a shift in mental models from maintaining an unachievable stability, to resilience thinking. Implementing the thresholds-of-potential-concern approach of Biggs and Rogers (2003) could be a practical way of promoting it. It could be applied at each level in the panarchy, but it could be implemented most easily and soonest in the Goulburn Broken region.
- Devolve resources and authority to the requisite scale (polycentric governance—Ostrom et al. (1999), Marshall (2005)), which would run counter to the centralizing agendas of past and present federal governments.

Enhancing resilience, promoting a regime shift, or initiating a transformation?

To this point, we have been concerned with how the current regime of the GB system could be maintained, but that is not necessarily desirable, or feasible. Promoting a regime shift, or transforming to a different kind of system, would require at least the following conditions:

- Clear evidence that the current regime is untenable and that a better alternative regime exists. If the current regime cannot continue and there is no desirable alternate regime that is possible, then transformation is necessary. In other words, it is necessary to “jump” to a new kind of basin, not shift to an alternate basin of the same system.
- Given the above, recognition by sufficient numbers of sufficiently influential people that change is necessary. The state-of-denial phase is difficult to overcome.
- Effective leadership, strong social networks, and a high level of trust (Olsson et al. 2006).
- A process for negotiating a vision of the new regime. This is inherently difficult given

disparate societal sector views. Also, because it is unwise to be too specific (what seems “ideal” now can change with changing external conditions), it may be best to proceed by gaining agreement on regimes that are not wanted and allowing some self-organization among those that are deemed acceptable, rather than trying to pick the “optimal” one.

- Strategic disinvestment in infrastructure, drought relief, or other subsidies or incentives that promote the maintenance of the current regime. This is politically difficult, which is why SESs commonly remain in a regime long after it ceases to be worthwhile (Abel et al. 2006).
- Support for those who will lose from the regime change or transformation. Support might include compensation, retirement, retraining, and relocation.
- Political ability to change property rights and other institutions. Such institutions are usually at the ideological heart of a society, and form the foundations of its social structure and economy. It is possible though—changes to water entitlements have already been implemented.
- Investment in social and human capital, new infrastructure, and technology.

Achieving the above would, we submit, be more likely under a decentralized, polycentric system of governance (Ostrom et al. 1999, Marshall 2005), and we suggest deeper thought needs to be given to which of the two options for the future role of CMAs (regional government vs. bridging organization) would be the better. Such a change would itself constitute part of a transformational change in the region.

CONCLUSIONS

The development path of the GB region has been marked by increasing investment in infrastructure and growing reliance on agricultural processing sectors that are vulnerable to a rising water table. This has reduced the intrinsic value of biodiversity. Irrigated agriculture produces very high levels of market values, in line with current social preferences. Diversions of water for irrigation

reduced the resilience and compromised the intrinsic and other values of riverine ecosystems. Development has reduced options for the region and, therefore, its resilience. We propose that the current level of resilience depends on interactions among slow variables at state/federal, catchment, and farm/landscape scales. Those we have identified are:

- Values. We propose there is a possible tipping point between market values vs. preferences for non-market, intrinsic, and option values.
- Size of the dairy- and fruit-processing sectors. Contraction below some threshold level leads to loss of jobs and consequent decline of social networks.
- Financial viability of farms, which depends mainly on water allocations and price (for irrigated farms), and the area of the farm salinized; if too many farms go bankrupt, the processing sectors will leave.
- The condition of irrigation and water-pumping infrastructure. A tipping-point effect exists in terms of costs and benefits from maintenance investment. It will influence the ability to distribute water to irrigators and to control the consequent water-table rise and salinity discharge.
- Tree cover, which affects water-table depth. It also affects native biodiversity although the location and abundance of trees for this is different than that required for water-table control.
- Water-table depth and area salinized, which depend on rainfall, thus climate, water allocations, energy cost, infrastructure, and tree cover.
- Soil acidity, which increases through application of fertilizer and use of legumes.
- The condition and functioning of the riverine ecosystems that support a range of non-agricultural values. This depends on water allocations.

A key point is that this interacting set of thresholds on controlling (slowly changing) variables, at three

scales and in three subsystems (ecological, economic, and social) of the GB SES, constitutes the “system” that policy and management need to encompass. Measures addressing any one, or a few, of the problems associated with these critical changes, or acting at a single scale, are bound to fail.

To keep the region in the current regime (if that is the aim), the seven conditions identified in the interventions section would need to be met. The GBCMA has very limited capacity to manage the slow variables and meet these conditions. Social preferences at state and national scales are critically important but are outside the influence of the CMA. Resources for investment in revegetation, irrigation infrastructure, and water-table pumping are controlled from outside the region. Water allocations to irrigation and to environmental flows are also made externally (with due regard to the region). Investment and location decisions of the critically important fruit- and dairy-processing sectors are made by executives and boards under the influence of shareholders. We did not identify, in the GB Regional Catchment Management Strategy, significant options for enhancing regional resilience. Therefore, we explored the potential for enhancing regional resilience through changes in governance to a polycentric system that aligns the governance arrangements with the panarchic structure of this SES.

At the regional scale, we see two options for the CMA: (i) devolving more resources, responsibilities, and authority to the CMAs. This is expected to increase adaptive capacity by matching the scale of governance better to the scale of ecological and social processes; (ii) becoming a more effective bridging organization, operating across scales and sectors.

At the scale of the Murray Basin, water sharing and coordination across state boundaries already occurs through the intergovernmental MDBC. Interstate and national initiatives have established a water-trading system coupled with a system of catchment-scale regulatory water plans. If this system proves to be more-or-less self-organizing, encourages innovation and adaptation, and reduces salinity and water-table rise, it should enhance resilience. However, inter-state barriers to trade need to be removed. Also, the basin-scale water-planning and allocation system needs to be radically changed so that: sufficient water is allocated to towns, and to flush the river to the sea; so that allocations are matched to inflows during floods and droughts and

under climatic change; and so that the environment has an entitlement to water (Young and McColl 2008).

Other changes at the scale of the Murray-Darling Basin to enhance the resilience of the region include:

- removal of incentives, such as excessive water storage and drought relief, that reduce resilience;
- increasing incentives to farmers that enhance resilience, such as payments for improving off-farm water quality, conserving wetlands, and maintaining on-farm biodiversity;
- developing incentives that vary dynamically with circumstances, especially rainfall;
- establishing trust funds dedicated to environmental management that are insulated from the political electoral cycle;
- promoting resilience thinking, for example by implementing the thresholds of potential concern approach across the panarchy, beginning with regions.

So far, our conclusions have addressed resilience that is specific to foreseeable threats. There are key attributes of systems that confer general resilience, and these can also be built into the development strategy of the region. They include recommendations to build human and social capital, learn from the past, monitor the present and experiment, scan the future and navigate its thresholds rather than aiming for some hazardous optimum, build reserves, options, and redundancy, increase spatial heterogeneity and connectivity, and build political capital.

Given that maintaining the region in its current basin of attraction may not be either feasible or desirable, what might be included in a strategy for promoting transformation? Its elements should include:

- clear evidence that transformation is needed
- acceptance that change is necessary
- leadership, strong social networks, and trust

- a negotiation process
- strategic disinvestment in infrastructure, subsidies, or incentives that maintain the current regime
- support for those who will lose from the transformation
- political ability to implement structural changes
- strategic new investments in social and human capital, infrastructure, and technology.

Our analysis of the thresholds defining the current regime suggests that transformation of the catchment is needed.

Responses to this article can be read online at:
<http://www.ecologyandsociety.org/vol14/iss1/art12/responses/>

Acknowledgments:

The members of the Goulburn-Broken Catchment Management Authority, and in particular their CEO, Bill O’Kane, provided valuable input during this analysis of their region. We thank Doug Cocks, Sarah Ryan, and the reviewers for their constructive comments. Roel Plant has given useful advice on the use and limitations of input–output modeling in general, and of his particular model. We thank Art Langston for producing the regional map, and Sonja Heyenga for editing the paper. The authors also gratefully acknowledge financial support for this work under National Science Foundation grant BCS-0527744.

LITERATURE CITED

- Abel, N., H. Ross, and P. Walker.** 1998. Mental models in rangeland research, communication and management. *Rangelands Journal* 20:77–91.
- Abel, N., D. H. M. Cumming, and J. M. Anderies.** 2006. Collapse and reorganization in social–

ecological systems: questions, some ideas, and policy implications. *Ecology and Society* 11(1): 17. [online] URL: <http://www.ecologyandsociety.org/vol11/iss1/art17/>.

Anderies, J. M. 2005. Minimal models and agroecological policy at the regional scale: an application to salinity problems in south-eastern Australia. *Regional Environmental Change* 5:1–17.

Anderies, J. M., B. H. Walker, and A. P. Kinzig. 2006a. Fifteen weddings and a funeral: case studies and resilience-based management. *Ecology and Society* 11(1): 21. [online] URL: <http://www.ecologyandsociety.org/vol11/iss1/art21/>.

Anderies, J. M., P. Ryan, and B. H. Walker. 2006b. Loss of resilience, crisis, and institutional change: lessons from an intensive agricultural system in south-eastern Australia. *Ecosystems* 9:865–878.

Anderies J. M., A. A. Rodriguez, and M. A. Janssen. 2007. Panaceas, uncertainty, and the robust control framework in sustainability science. *Proceedings of the National Academy of Sciences of the United States of America* 104(39):15194–15199.

Argyris, C. 1982. *Reasoning, learning and action: individual and organizational.* Jossey-Bass, San Francisco, California, USA.

Atech Group. 1999. *Cost of algal blooms.* Occasional Paper 26/99. Land and Water Resources Research and Development Corporation, Canberra, Australia.

Australian Bureau of Agricultural and Resource Economics. 2008. *AgSurf.* Canberra. Online database. [online] URL: <http://www.abareconomics.com/ame/agsurf/agsurf.asp>.

Bennett, J., R. Dumsday, C. Lloyd, and M. Kragt. 2007. *Non-use values of Victorian public land: case studies of River Red Gum and East Gippsland forests.* Victorian Environmental Assessment Council, Melbourne. [online] URL: <http://www.vea.c.vic.gov.au/eefea.htm#top>.

Biggs, H. C., and K. H. Rogers. 2003. An adaptive system to link science, monitoring, and management in practice. Pages 59–80 in J. T. du Toit, K. H. Rogers, and H. C. Biggs, editors. *The*

Kruger experience: ecology and management of savanna heterogeneity. Island Press, Washington, D.C., USA.

Bode, H. W. 1945. *Network analysis and feedback amplifier design.* D. Van Nostrand, Princeton, New Jersey, USA.

Carlson, J. M., and J. Doyle. 2000. Highly optimized tolerance: robustness and design in complex systems. *Physical Review Letters* 84:2529–2532.

Carpenter, S. R., M. Walker, J. M. Anderies, and N. Abel. 2001. From metaphor to measurement: resilience of what to what? *Ecosystems* 4:765–781.

Carpenter, S. R., and R. C. Lathrap. 2008. Probabilistic estimates of a threshold for eutrophication. *Ecosystems* 11:601–613.

Connell, D., S. Dovers, and Q. Grafton. 2005. A critical analysis of the National Water Initiative. *Australasian Journal of Natural Resources Law and Policy* 10(1):81–107.

Commonwealth Scientific and Industrial Research Organisation (CSIRO). 2008. *Water availability in the Goulburn Broken.* A Report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Canberra, Australia.

Davidson, B. 1969. *Australia wet or dry?: The physical and economic limits to the expansion of irrigation.* Melbourne University Press, Carlton, Australia.

Elmqvist, T., C. Folke, M. Nystrom, G. Peterson, J. Bengston, B. Walker, and J. Norberg. 2003. Response diversity, ecosystem change and resilience. *Frontiers in Ecology and Environment* 1:488–494.

Fernandez, R. J., E. R. M. Archer, A. J. Ash, H. Dowlatabadi, P. H. Y. Hiernaux, J. F. Reynolds, C. H. Vogel, B. H. Walker, and T. Wiegand. 2002. Degradation and recovery in socio-ecological systems: a view from the household/farm level. Pages 297–323 in J. F. Reynolds, and D. M. Stafford Smith, editors. *Global desertification: do humans cause deserts?* Dahlem University Press, Berlin, Germany.

- Gibson, K., J. Cameron, and A. Veno.** 1999. *Negotiating restructuring: a study of regional communities experiencing rapid social and economic change*. Australian Housing and Urban Research Institute Working Paper No. 11. Department of Geography and Environmental Science, and School of Humanities and Public Policy, Monash University, Australia.
- Goulburn Broken Catchment Management Authority (GBCMA).** 2003. *Goulburn Broken regional catchment strategy*. GBCMA, Shepparton, Victoria, Australia.
- GBCMA.** 2007. *2006-07 annual report*. GBCMA, Shepparton, Victoria, Australia.
- Goulburn Broken River Environment and Water Quality Committee (GBREWQC).** 1997. *Goulburn Broken catchment water quality strategy—a component of the Goulburn Broken regional catchment strategy*. Goulburn Broken Catchment Management Authority (GBCMA), Shepparton, Victoria, Australia.
- Gunderson, L., and C. S. Holling, editors.** 2002. *Panarchy: understanding transformations in human and natural systems*. Island Press, Washington, D.C., USA.
- Holling, C. S.** 1978. *Adaptive environmental assessment and management*. Wiley, London, UK.
- Kelly, G. A.** 1955. *The psychology of personal constructs*. W. W. Norton, New York, New York, USA.
- Khan, S., and A. Abbas.** 2007. Upscaling water savings from farm to irrigation system level using GIS-based agro-hydrological modelling. *Irrigation and Drainage* 56:29–42.
- Kinzig, A. P., P. Ryan, M. Etienne, H. Allyson, T. Elmqvist, and B. H. Walker.** 2006. Resilience and regime shifts: assessing cascading effects. *Ecology and Society* 11(1): 20. [online] URL: <http://www.ecologyandsociety.org/vol11/iss1/art20/>.
- Kragt, M., J. Bennett, C. Lloyd, and R. Dumsday.** 2007. *Comparing choice models of river health improvement for the Goulburn River*. 51st Conference of the Agricultural and Resource Economics Society, 13–16 February 2007, Queenstown, New Zealand.
- Langston, A., P. Ryan, and J. Langridge.** 2003. Ecosystem services from a dryland sub-catchment. Pages 54–82 in N. Abel, S. Cork, and R. Goddard, editors. *Natural values: exploring options for enhancing ecosystem services in the Goulburn Broken Catchment*. CSIRO, Canberra, Australia.
- Marshall, G. R.** 2005. *Economics for collaborative environmental management: renegotiating the commons*. Earthscan, London, UK.
- Olsson, P., C. Folke, and F. Berkes.** 2004. Adaptive co-management for building social–ecological resilience. *Environmental Management* 34:75–90.
- Olsson, P., L. H. Gunderson, S. R. Carpenter, P. Ryan, L. Lebel, C. Folke, and C. S. Holling.** 2006. Shooting the rapids: navigating transitions to adaptive governance of social–ecological systems. Pages 97–118 in B. H. Walker, J. M. Anderies, A. P. Kinzig, and P. Ryan, editors. *Exploring resilience in social–ecological systems*. CSIRO Publishing, Collingwood, Australia.
- Ostrom, E., J. Bugar, R. B. Norgaard, and D. Policansky.** 1999. Revisiting the commons: local lessons, global challenges. *Science* 284: 278–282.
- Pearce, D. W., and R. K. Turner.** 1990. *Economics of natural resources and the environment*. Harvester Wheatsheaf, Hemel Hempstead, UK.
- Plant, R., J. Robinson, P. Ryan, and N. Abel.** 2003. *Water inputs and nutrient outputs from the Goulburn Broken economy*. Chapter 11 in N. Abel, S. Cork, R. Goddard, J. Langridge, A. Langston, R. Plant, W. Proctor, P. Ryan, D. Shelton, B. Walker, and M. Yialeloglou, editors. *Natural values: exploring options for enhancing ecosystem services in the Goulburn Broken Catchment*. CSIRO Sustainable Ecosystems, Canberra, Australia.
- Qureshi, M. E., W. L. Proctor, and J. M. Kirby.** 2006. *Economic assessment of water trade restrictions in the Murray Darling Basin*. Regional and Urban Modelling Conference, 1–2 June 2006, Brussels, Belgium.
- Radford, J. Q., A. F. Bennett, and G. J. Cheers.** 2005. Landscape-level thresholds of habitat cover for woodland-dependent birds. *Biological Conservation* 124:317–337.

Reeve, I, L. Frost, W. Musgrave, and R. Stayner. 2002. *Agriculture and natural resource management in the Murray-Darling Basin: a policy history and analysis*. Report to the Murray Darling Basin Commission. Institute for Rural Futures, University of New England, Armidale, Australia.

Roberts, J. 2006. Floodplain vegetation responses to water regime, grazing and fire. Chapter 6 in N. Abel, J. Roberts, J. Reid, I. Overton, D. O'Connell, J. Harvey, and S. Bickford, editors. *Barmah Forest: a review of its values, management objectives and knowledge base*. Report to the Goulburn Broken Catchment Management Authority. CSIRO, Canberra, Australia.

Scheffer, M. 2009. *Critical transitions in nature and society*. Princeton University Press, Princeton, New Jersey, USA.

Scheffer, M., and S. R. Carpenter. 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends in Ecology and Evolution* 12:648–656.

Stone, A. 1992. Contingent valuation of the Barmah Wetlands, Victoria. Pages 47–70 in M. Lockwood and T. de Lacy, editors. *Valuing natural areas: applications and problems of the contingent valuation method*. The Johnstone Centre of Parks and Heritage, Charles Sturt University, Albury, New South Wales, Australia.

Tainter, J. A. 1988. *The collapse of complex societies*. Cambridge University Press, Cambridge, UK.

Tisdell, J., J. Ward, and T. Grudzinski. 2002. *The development of water reform in Australia*. Technical Report 02/05. The Cooperative Research Centre for Catchment Hydrology, Griffith University, Brisbane, Australia.

Turner, M. G. 2005. Landscape ecology: what is the state of the science? *Annual Review of Ecology Evolution and Systematics* 36:319–344.

Walker, B. H., S. R. Carpenter, J. M. Anderies, N. Abel, G. C. Cumming, M. Janssen, L. Lebel, J. Norberg, G. D. Peterson, and R. Pritchard. 2002. Resilience management in social–ecological systems: a working hypothesis for a participatory approach. *Conservation Ecology* 6(1): 14. [online] URL: <http://www.consecol.org/vol6/iss1/art14>.

Walker, B. H., C. S. Holling, S. R. Carpenter, and A. P. Kinzig. 2004. Resilience, adaptability and transformability. *Ecology and Society* 9(2): 3. [online] URL: <http://www.ecologyandsociety.org/vol9/iss2/art5>.

Walker, B. H., L. Gunderson, A. P. Kinzig, C. Folke, S. R. Carpenter, and L. Schultz. 2006. A handful of heuristics and some propositions for understanding resilience in social–ecological systems. *Ecology and Society* 11(1): 13. [online] URL: <http://www.ecologyandsociety.org/vol11/iss1/art13/>.

Walker, B. H., and D. Salt. 2006. *Resilience thinking: sustaining ecosystems and people in a changing world*. Island Press, Washington, D.C., USA.

Young, M., and J. McColl. 2008. *A future-proofed basin: a new water management regime for the Murray-Darling Basin*. Droplet 13. University of Adelaide, Australia. [online] URL: <http://www.myoung.net.au/water/droplets.php>.