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# Incorporating Resilience in the Assessment of Inclusive Wealth: An Example from South East Australia

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**Abstract** This paper explores the consequences of changes in a system's resilience on the sustainability of resource allocation decisions, as measured by Inclusive Wealth (IW) (Arrow et al. in Environ Resour Econ 26:647–685, 2003). We incorporate an estimate of resilience in IW by taking account of known or suspected thresholds that can lead to irreversible (or practically irreversible) changes in the productivity and value of assets and hence social welfare. These thresholds allow us to identify policies or projects that may be leading to an increased risk of decline in capital stocks (the wealth of the region). Such risks are not reflected through usual measures of current system performance, e.g. agricultural production. We use the Goulburn-Broken Catchment in south-eastern Australia as a case study to explore the significance and practicality of including resilience in inclusive wealth estimates.

**Keywords** Inclusive wealth · Resilience · Shadow prices · Sustainable development

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## 1 Introduction

Of the many challenges in assessing whether or not a country or region is embarked on a sustainable development pathway, two are particularly important; (1) how to develop an acceptable, integrated measure that allows the inevitable trade-offs to be evaluated, and (2) how to take into account changes in the risks that significant losses in wealth may occur. The first is addressed by using an integrated stock-based approach such as the 'inclusive wealth' measure (Arrow et al. 2003).

The second issue, changes in risk, has been outlined in Maler (2008) but not yet applied, and forms the basis for this paper. We follow Maler's approach of using the concept of resilience to deal with risk. Resilience is the capacity of a system to remain in a given configuration of states—a system "regime"—in systems where multiple regimes are possible. By definition (Holling 1973; Walker et al. 2004), the more resilient a system is the larger the shock (disturbance) it can absorb without shifting into an alternate system regime. If changes along some forecast development path increase the risk of a shift from one regime to another, then sustainability analyses should take these increases in risk into account in some quantifiable way. Perrings (1998), for example, identifies two different concerns in the analysis of the environmental consequences of economic change; the concern that desirable states or processes may not be 'sustainable', balanced by the concern that individuals and societies may get 'locked-in' to undesirable states or processes. Incorporating this into empirical sustainability assessments raises the problem of "how to measure changes in state given…the lack of physical measures of relevant changes in environmental variables" (Perrings 1998, p. 513).

In considering how resilience can be incorporated into an operational measure of sustainable development, we refer to the resilience of a "preferred state" of the system. This preferred state is in reference to our case study. However, as the cases of desirable and undesirable states are perfectly symmetric both can be used in the conceptual part of the paper. A decline in resilience should therefore be reflected as a decline in wealth. If the system is already in a non-preferred state (low productivity/ low value), the reverse is true.

Various strands of earlier work by Ciriacy-Wantrup (1952), Bishop (1978), Smith and Krutilla (1979) and others have pursued issues of valuing and managing thresholds, and catastrophic and irreversible events. Dasgupta and Maler (2003) have highlighted work addressing the integration of non-convex ecosystems into economics in a dedicated journal issue on the topic, and more recently Dasgupta (2008) has followed this up with another issue on 'Nature in Economics'. Specific applications of resilience thinking include work by Serrão et al. (1996) that discusses sustainability and resilience informally in the context of the Amazonian upland ecosystems. They make reference to the idea of environmental criticality, "a state of nature in which the extent and/or rate of environmental degradation passes a threshold beyond which current human use systems or levels of social welfare may not be supported, given a society's ability to respond" (p. 7). This idea of a critical threshold is central to quantifying resilience, as considered in this paper. Trosper (2002) shows how the ways in which institutions function in Northwest coast indigenous American communities (including property rights and penalties for trespass) can provide resilience in managing fisheries and other resources. Norton (1995) stresses the interpretation of resilience as the value of holding options open (which presumes the current state is the preferred state).[1]

[1] The concept of option value in the face of major events and irreversibilities has a long history in economics, going back at least to Arrow and Fisher (1974) and Henry (1974), recently updated by Narain et al. (2007). Norton is distinctive in this context in relating options explicitly to resilience.

Using a more formal approach Perrings and Walker (1997) examine resilience effects in optimal management of fire-driven rangelands. They simulate choices of optimal grazing (the control variable) in circumstances where fire events can result in a change in the state of the rangeland. Perrings and Stern (2000) attempt to quantify a variable they call resilience, based on the long run productive potential of a semi-arid rangelands system, which they model in terms of carrying capacity. Their approach is econometric, generating measures of changes in resilience with parsimonious data.

The objective of this paper is to examine the practicality of incorporating resilience as a quantifiable variable in the measurement of sustainability, using change in Inclusive Wealth as that measure. We begin with a brief account of the capital-theoretic approach used for measuring "Inclusive Wealth" (IW), described by Arrow et al. (2003)(Sect. 2). Section 3 explains ecological resilience and the roles of hysteresis and irreversibility. Section 4 shows how treating resilience as another "capital stock" allows it to be measured and priced in empirical assessments of IW. Section 5 presents an example from a current sustainability assessment project in Australia to illustrate the significant impact that a change in ecological resilience can have on an estimate of IW. Finally, Sect. 6 discusses the impact of including resilience in a measure of sustainability.

## 2 Brief Introduction to Inclusive Wealth

Standard aggregate sustainability analyses have been flow-based, with the sustainability condition taking the form of some constraint on total consumption (see Harris and Fraser 2002). The inclusive wealth (IW) approach, as the name suggests, switches the focus from flows to stocks, and accordingly imposes a sustainability condition based on present values of consumption flows. It neither assumes nor requires any assumptions of optimality or even optimising behaviour. Therefore, issues of efficiency and sustainably are separate and can be interrogated independently. This de-coupling is explained in Arrow et al. (2004).

The key theoretical elements of the model are given in Arrow et al. (2003). An aggregate inter-temporal social welfare function is defined on a vector of consumption flows (goods and services). The instantaneous utility function is assumed to have the conventional properties (monotonically increasing, strictly concave) and welfare $W_t$ is subject to a positive and constant utility discount rate, $\delta$.

$$W_t = \int_t^\infty U(C_\tau)e^{-\delta(\tau - t)}\mathrm{d}\tau \tag{1}$$

With this definition of social welfare, we define sustainable development as non-decreasing social welfare $W_t$. What this means intuitively is that the present value of the future utilities must be maintained over time. This allows in principle for short term declines in instantaneous consumption, though such declines must be offset by future increases sufficient to prevent declines in the present value of utility of consumption (Dasgupta and Maler 2001).

To make this definition of sustainable development operational, an innovation of the IW approach is to avoid any assumption of optimisation by, instead, specifying a "resource allocation mechanism" ($\alpha$) which predicts consumption flows $C$, given the present capital stocks and knowledge on the future functioning of the economy (including technology). Social welfare can then be expressed as a function of the initial capital stocks and the resource allocation mechanism ($\alpha$);

$$W_t \equiv V(\boldsymbol{K}_t, \alpha, t) \tag{2}$$

Equation 2 can be represented as $V(\boldsymbol{K}_t, \alpha, t) = V_t$, which means that, instead of having to measure welfare in terms of future consumption (through utility), there is an equivalent in the form of wealth, the value of capital stocks at time $t$.

Value or wealth is now in principle an observable magnitude, measured by the quantity of the current stocks multiplied by their shadow prices. Assuming $V$ is differentiable in $K$, and $K_i$ is the $i$th capital stock, we can define the shadow price of the $i$th capital stock at time $t$ as

$$p_{it} = \frac{\partial V V(\boldsymbol{K}t, \alpha, t)}{\partial K_{it}} \equiv \frac{\partial V_t}{\partial K_{it}} \tag{3}$$

The shadow price of a capital asset today is the present discounted value of the perturbation to utility (U) that would arise from a marginal change in the quantity of the asset today. Note that an important proviso in this "inclusive" wealth model is that wealth must indeed be inclusively defined. For example, the value people put on the existence of nature conservation in some landscape needs to be included in the estimation of the shadow price of that landscape. A market price that reflects only its agricultural value is inadequate as a shadow price.

A local-in-time change in welfare from a point in time, i.e. a change in welfare over an infinitesimal period of time, is equivalent to the change in the capital stocks (valued by shadow prices)

$$\frac{dV_t}{dt} = \sum_i p_{it} dK_{it}/dt + \partial V_t/\partial t \tag{4}$$

The term $\partial V_t/\partial t$ represents the exogenous ("inevitable") effects of the passing of time on wealth. They are inevitable in the sense that they are not alterable by any actions taken by members of the population whose wealth is being considered. This term, variously referred to in the literature as the "value of time" or the "drift term", is zero, by definition, with an autonomous resource allocation mechanism.

As shown above, over an infinitesimal time period, we can use constant local accounting prices to evaluate the welfare effect of changes in capital stocks. For welfare comparisons over a longer time period, however, we have to take into account the effect of changes in the accounting prices. Following Arrow et al. (2003), the welfare change in this latter case is given by

$$V_T - V_0 = \sum_i [p_{iT} K_{iT} - p_{i0} K_{i0}] - \int_0^T \left[ \sum_i \frac{dp_{i\tau}}{d\tau} K_{i\tau} \right] \mathrm{d}\tau \tag{5}$$

where the second part of the equation is the 'capital gains' term and deducts the endogenous price changes. Estimating IW at two points in time allows for an assessment of sustainable development, based on the assumption that the resource allocation pattern over this period is sustainable. If IW is non-declining over the period, ie. $V_T - V_0 \geq 0$, then the development can be said to be sustainable.

This paper focuses on the likelihood of a change in underlying variables that determine the state of a capital stock $K_i$, which leads to a change in the likelihood that the state of $K_i$ itself will change, with an associated change in its value to society. If $Ki$ does not change between two times it suggests there has been no change in IW. However, if the *risk* that $K_i$ will change has increased this should somehow be included and reflected as a change in real wealth.

## 3 Resilience and Vulnerability

The formal definition of resilience is the capacity of a system to undergo change while still maintaining the same structure, functions and feedbacks, and therefore identity (Walker et al. 2004). This definition follows the original paper on the subject by Holling (1973), and places emphasis on the ability of a system to recover from a disturbance-induced change. We are concerned about what happens when a system exceeds its capacity for recovery.

A wide range of examples suggests that many ecological and social-ecological systems can exist in two or more "regimes" (configurations of states), separated by thresholds that occur on controlling (usually slowly changing) variables (Scheffer et al. 2001; Walker and Meyers 2004). The flows of goods and services from capital stocks in the different regimes of the system can differ markedly. While the flows generated by a capital stock over time may show no change (because the state of the stock has remained within the same regime), an underlying control variable that determines the dynamics of the stock might be approaching a critical threshold. When the critical threshold level of this underlying variable is passed the structure and function of the capital stock abruptly changes (the stock moves into a new regime) with associated changes in the levels of flows. Therefore, as the threshold is approached, the risk of disruptions to the future supply of the goods and services increases. Of course any changes in the riskiness of stocks results in a value change, and does not always imply an approaching threshold. This paper focuses on the risks associated with irreversible, or at least hysteretic, change in the capacity of a system, due to a loss of resilience with respect to a particular set of environmental shocks (see Fig. 1).

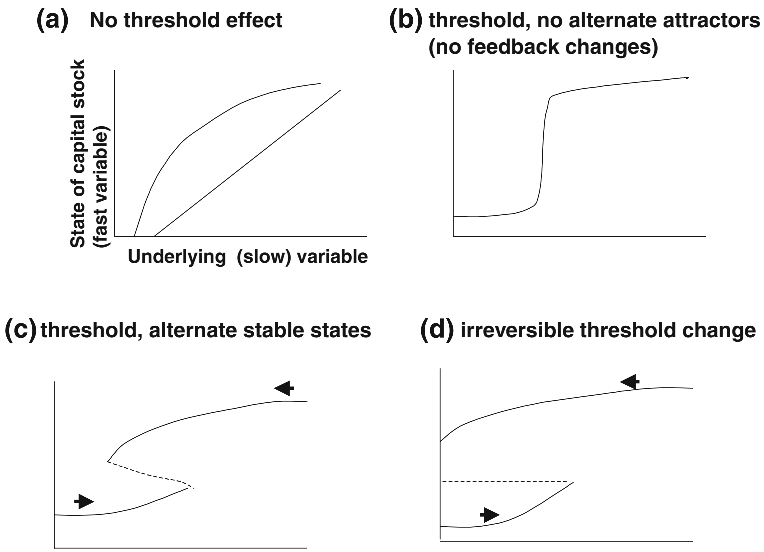


**Fig. 1** Relationships between the state of a capital stock and the underlying variable that determines its dynamics. In **a** there is no discontinuity and the nature (and value) of the capital stock varies continuously with a change in the underlying (often slowly changing) variable. In **b** there is a very sharp (sometimes discontinuous) change in the capital stock, but it is reversible. In **c** there is a discontinuous change that is reversible but with a hysteretic return path, and in **d** the change is irreversible. The *arrows* indicate the direction of change in the underlying (slow) variable

From a sustainable development perspective it is important to know how far the system is from such critical thresholds, and how likely it is that it might cross the threshold. Using the ball-in-a-basin analogy of a system's stability properties, resilience of a system at any one scale has three components; latitude (the width of the basin), resistance (the steepness of the basin—how much force is needed to change the system) and precariousness (the current position and trajectory of the system in the basin; Walker et al. 2004). The edge of the basin marks an unstable equilibrium, a threshold, between two system regimes. The general measure of resilience, used in this paper, is the distance in the underlying variable from the initial state to the unstable threshold (sometimes referred to as instantaneous resilience). We infer distance here to mean the probability of the system transitioning to another state (regime), although a more specific and quantifiable measure of "distance" is offered in the next section, and interpreted as a "stock of resilience". This measure does not take into account the amount of force needed to change the position of the system in the basin (resistance); this is something that might be added later. For our purposes, the closer to the threshold, the lower the stock of resilience, and the higher is the probability that the system will flip to the alternate regime. The real value (shadow price) of the stock changes as the likelihood of crossing the threshold into the alternate regime increases.

Relationships between the capital stocks of a system that determine welfare and the underlying controlling variables of those stocks fall into four main types (Fig. 1). Most of them (fortunately) are likely to be of type (a) with no threshold effects, i.e., where changes in the underlying control variable are reflected by continuous changes in the stock. Stocks with patterns of dynamics of types (b), (c) and (d) need to be identified because they can exhibit sudden and dramatic changes. Changes in stocks of type (b) are fully reversible. In type (c) systems, when the controlling (slow) variable exceeds the critical threshold level, feedbacks in the system change and the trajectory of the system changes direction towards a new attractor (Walker and Meyers 2004). Recovery of the system to the original regime is difficult, following a hysteretic path. Type (d) systems are an extension of (c) where the hysteretic return path intercepts the $Y$ axis, and makes recovery impossible if change in the slow variable is the only option. The relative value of a regime change (reflected in the shadow price of resilience, in effect) is directly affected by its reversibility. Thus the value (or cost) associated with such a change will be greatest in stocks of type (d) followed by (c), then (b).

## 4 Including Resilience in the Inclusive Wealth Model

The challenge before us is to move from qualitative descriptions of resilience, to identifying resilience as a variable that can be quantified and priced, in order to be incorporated in measures of wealth. Inclusion of resilience in the IW model is discussed, though not resolved, by Arrow et al. (2003). They use a shallow lake example (Scheffer et al. 2001) to illustrate that IW (and hence Genuine Investment) can be employed in non-convex systems (ecological and economic systems) as well as convex systems, neither requiring an assumption of economic optimality. Additionally they demonstrate that it is possible to extend the IW model to an uncertain world. However, they did not address the question of determining the shadow price of resilience. On the other hand, Maler (2008) (based on Maler et al. 2007; Walker et al. 2007) has developed a general formula for such a price (Maler et al. 2007), but does not specify *how* the resilience variable is to be quantified. This paper adds to these general frameworks by explicitly quantifying the "distance to threshold" concept of resilience, and measuring the shadow price of resilience using the most general formulation of the possible time of a flip. Such expressions are detailed below and estimates of their significance are provided in Sect. 5.

Maler (2008) proposes adding to the IW model a resilience stock that is a measure of how close the system is to a shift. To incorporate resilience in this way we have to be clear about the "resilience of what, to what", and in our case this means the resilience of crop production in the catchment to variations in the water table. In this way, resilience can be regarded as an insurance against rises in the water table. The shadow price of the resilience stock reflects the expected change in future social welfare from a marginal change in resilience today. Estimating the price of resilience separately enables us to determine its significance in policy and management decisions and therefore how much attention it warrants. For each underlying variable (such as depth to the water table) that has a threshold effect resulting in a discontinuous change in the state of one or more capital stocks, we define a resilience stock $X$, equal to the current distance from the threshold. In the examples discussed in this paper, our attention is confined to situations of a threshold on a single controlling variable. Most systems will likely have more than one controlling variable with a threshold, and the effects of interactions amongst the controlling variables on the various resilience stocks is an area for future research.

For the depth to water table threshold, in practice this means that a water table 5 m below the surface would be 3 m below the threshold, meaning that there is 30 dm "worth of resilience", which we would count as a stock at a point in time. We discuss other examples of such resilience stocks later.

Let $F(X_0, t)$ be the cumulative probability distribution of a flip up to time $t$ if the initial resilience is $X_0$. We assume that the flip is irreversible. It is quite easy to extend the analysis to the reversible case, but that is not needed for the application in this paper. In order to simplify formulae, we introduce the survival function $S(X_0, t) = 1 - F(X_0, t)$, which gives the probability that the system has not flipped before time $t$.

Assume that $U_1(t)$ is the net benefit at time $t$ if the system has not bifurcated at that time and let $U_2(t)$ be the net benefit if the system has bifurcated before (or at) $t$. Then one can show that expected welfare is (see Maler 2008)

$$E(W(X_0)) = \int_0^\infty [S(X_0, t)U_1(t) + F(X_0, t)U_2(t)]e^{-\delta t}\mathrm{d}t \tag{6}$$

The price ($q$) of one more unit of resilience is estimated by marginally perturbing a generalised form of Eq. 6 by a small amount of the stock of resilience $X_0$, that is, the stock of resilience at time 0

$$q(0) = \frac{\partial E(W_0)}{\partial X_0} = \int_0^\infty \frac{\partial S(X_0, t)}{\partial X_0} [U_1(t) - U_2(t)]\, e^{-\delta t}\mathrm{d}t \tag{7}$$

We now introduce three more stocks; capital stock $Y$ that affects the probability of a bifurcation (for example the stock of pumps that are used to control the water flow), the land area sensitive to salinisation, $L^{\mathrm{sen}}$, and the land area not sensitive to salinisation, $L^{\mathrm{un}}$. We assume that these two areas will not change over time. The benefits in the two states in sensitive land before a flip is given by $U_1(L^{\mathrm{sen}}, \mathrm{s})$ and after a flip $U_2(L^{\mathrm{sen}}, \mathrm{s})$ when the flip to the alternate regime occurs in time period $s$. Finally, let the benefit for non-sensitive land be $U_3$ $(L^{\mathrm{un}}, \mathrm{s})$.

It is easily seen that expected welfare is now

$$E(W) = E(W(X, Y, L^{\text{sen}}, L^{\text{un}})) = \int_{s=0}^{\infty} [S(X, Y, s)U_1(Y, L^{\text{sen}}, s) + F(X, Y, s)U_2(Y, L^{\text{sen}}, s) + U_s(L^{\text{un}}, s)]e^{-\delta s}\mathrm{d}s$$

The accounting prices are respectively

$$q_X(0) = \int_0^{\infty} \left[\frac{\partial S(X, Y, s)}{\partial X}U_1 + \frac{\partial F(X, Y, s)}{\partial X}U_2\right] e^{-rs}ds$$

$$q_Y(0) = \int_0^{\infty} \left[\frac{\partial S(X, Y, s)}{\partial Y}U_1 + \frac{\partial F(X, Y, s)}{\partial Y}U_2\right] e^{-rs}ds$$

$$q_{L^{\text{sen}}}(0) = \int_0^{\infty} \left[S(X, Y, s)\frac{\partial U_1}{\partial L^{\text{sen}}} + F(X, Y, s)\frac{\partial U_2}{\partial L^{\text{sen}}}\right] e^{-rs}ds$$

$$q_{L^{\text{un}}}(0) = \int_0^{\infty} \frac{\partial U_3}{\partial L^{\text{un}}} e^{-rs}ds \tag{8}$$

As long as the area of the two types of land does not change during the period under study, the two last shadow prices are not interesting. We will in the sequel assume this is the case. On the other hand, the first two are crucial for a study of wealth changes.

The estimation of the streams of benefits, $U_1$ and $U_2$, are conventional. For each year estimate the value of sales and subtract the costs including capital costs. It might be thought that the current land prices would be appropriate. However, that is not the case. Assume that land is bought and sold on perfect markets for land. The current price on land would then be a possible estimator. However, if the market actors have the same information and forecasts as "we" have, the market price would be the accounting price of sensitive land, as given by the third equation. However, that is not sufficient information to calculate the interesting shadow prices $q_X$ and $q_Y$. On the other hand, if the actors on the land market are completely myopic and do not take the possibility of a future flip into account when they make their decisions on buying and selling land, the current land price $q_{\text{sen}}(0)$ would reflect their present value of future net benefits, and the land price could be used to evaluate the correct shadow price of resilience and "pumps". In the absence of a defence of such an assumption, we need to estimate explicitly the benefit streams. If land becomes completely unproductive for ever after salinisation, then presumably $U_2$ is zero. $U_1$ is estimated by looking at the net revenues of the farmers under present conditions, assuming that there are no forecasted future changes in prices and technology and no externalities.

Next, we need to know the cumulative probability distribution of a bifurcation. The easiest way would be if the probability distribution for a flip is constant over time, say $\theta e^{-\eta X_0}$, where $X_0$ denotes the initial resilience stock. Note that $\theta$ denotes a hypothetical benchmark probability for a flip if the initial resilience stock $X_0$ would be zero, and $\eta$ is a parameter measuring how fast the flip probability decreases as the resilience stock increases. To simplify, let us assume discrete time. Then the cumulative distribution, that is the probability that there has been a flip before or up to period $t$ is $F(X_0, t) = 1 - (1 - \theta e^{-\eta X_0})^t$, and the corresponding survival function becomes

$$S(X_0, t) = (1 - \theta e^{-\eta X_0})^t \tag{9}$$

Under these simplifying assumptions, the accounting prices are

$$q_X(0) = (U_1 - U_2) \sum_{t=0}^{m=100} \left( \frac{\Delta S(X_0 t)}{\Delta X_0} \frac{1}{(1+\delta)^t} \right) \tag{10}$$

provided that $U_1$ and $U_2$ are constants. Similarly, we can also derive the shadow price on the stock $Y$.

In empirical work, it is necessary to replace the infinite time horizon with a finite horizon. In addition, in empirical applications, the flip probability at a future point in time may need to be calculated according to the predicted resilience level at the time instead of the constant initial level. With $X_0$ as a starting point, if we predict the resilience stock to be $X_t$ at a future date $t$, the flip probability at that date will be $\theta e^{-\eta X}$.

## 5 An Example: Including Resilience in Estimating IW in a Catchment in SE Australia

The Goulburn-Broken Catchment (GBC) in South East Australia is one of the country's most important agricultural regions. The lower third of the catchment (300,000 ha) is used for irrigation, 80% of it for dairy pastures. In addition to agricultural production, nature conservation has been identified as a significant flow to regional welfare. A trade-off exists between the two flows since declines in the native vegetation cover associated with agricultural expansion have resulted in the disappearance of many species and reductions in other species.

To estimate IW for the GBC we identified all the significant flows to regional welfare and then measured all the constituent capital stocks. For the purposes of this paper we used only a subset of these stocks. To include resilience we also identified any underlying (controlling) variables that cause threshold effects in these capital asset stocks. Three such variables were identified: (a) a rising ground water table in irrigated agricultural land, (b) vegetation connectivity in regard to nature conservation, and (c) the condition of irrigation infrastructure.

### 5.1 Groundwater and Salinity Dynamics in Agricultural Land

Removal of native vegetation to allow for cultivation has led to rising water tables and associated salinity; a looming problem that has put this system at risk (Anderies et al. 2006). Tree clearing in the upper catchment reduced transpiration, allowing more rainfall to penetrate through to the groundwater. The addition of irrigation water in the lower catchment, imported mostly from dams in the upper catchment but also from the Murray River outside the catchment, exacerbates the problem. Rising water tables mobilise salt deposits in the soil profile and when the water tables reach c.2 m below the surface, the water (with the dissolved salt) is drawn to the surface by capillary action. The salt can be flushed back down through the soil profile by irrigation or rain, but this again adds to the height of the water table. Half the GBC irrigation region is estimated to be at risk of high groundwater tables and salinity. Salinity and waterlogging have important, independent impacts on agriculture. We consider here only the impacts of salinity as it has a strong threshold effect.

Two episodes of high rainfall years, in the 1950s and the early 1970s, caused significant crop losses in several areas. The response to these episodes was the installation of a system of some 500 pumps that keep the water table below 2 m, discharging the pumped water via drainage channels into the Murray River. When the 'cap' on the allowable amount of exported

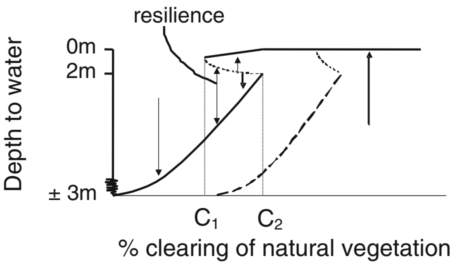


**Fig. 2** Equilibrium levels of water table depth in the Goulburn-Broken Catchment in relation to natural vegetation cover, with (*dashed line*) and without (*solid line*) pumping. The stable equilibrium represented by the *dashed line* occurs under significantly less natural vegetation cover (significant higher clearing) owing to the effects of pumping (equivalent to mechanical trees). C1 and C2 are the critical levels of clearing that lead to threshold changes in the equilibrium level of the water table in the direction of clearing (C2) and re-vegetation (C1)

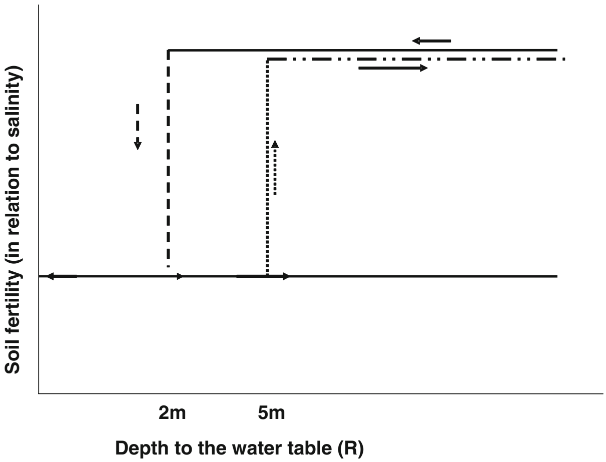


**Fig. 3** Dynamics of soil fertility (due to salinity) in relation to depth to the water table. The *solid lines* depict the equilibrium levels of salt over the short term (c.20 year) with *downward dashed line* being the unstable threshold at around 2 m depth. The broken (*dash-dot*) line represents the longer term (multi-decadal) equilibrium with the c.5m unstable threshold in the return direction (i.e., declining water table)

salt into the Murray river has been reached, the water is pumped into evaporation basins. This results in two relationships between rainfall and water table depth: a historical one when the water table was rising, and a current one that includes the effect of pumping. It is the latter we have used in our analysis.

Horticultural crops are more sensitive to salinity than pastures and the consequences of exceeding the 2 m threshold are therefore more severe. Some (periodic) production is possible with pastures when water tables are within 2 m of the surface, and so the shadow price for dairy in the two regimes differs less than for horticulture.

When the water table was 20 m below the surface the state of the "stock" of soil that produces pasture (basically the top 1 m of the soil) was the same as it is when the water table had risen to 3 m below. However, once the water table rises above 2 m the stock of soil is radically changed; it shifts into a different regime—degraded, salinised soil. In terms of IW, when the water table is 3 m below the surface, although current agricultural production hasn't changed, the real value of the capital stock of soil is less than when the water table was at 20 m, because the risk of salinisation has increased.

The dynamics of the water and salt in terms of their twofold effect on agriculture are shown in Figs. 2 and 3. The alternate regimes for water are reversible (Fig. 2), with a hysteretic effect. Our analysis in this paper has focussed on resilience at the farm scale and the controlling (slow) variable at that scale is the depth of the water table. At the scale of the catchment, the controlling variable for water table depth is the amount of native vegetation (presented as the percent of original vegetation that is cleared). The hysteresis effect is due to the fact that growth and transpiration of trees are affected by salinity and water logging in the upper soil, so in the re-vegetation direction (as opposed to the de-vegetation, or clearing direction) more trees are needed to effect the same amount of water uptake that occurs via trees in non-salinised soil. The smaller hysteresis in the case with pumping is due to the fact that water uptake is due to both trees (which are affected by waterlogging and salinity) and pumps (which are not).

Figure 3 represents the soil fertility change due to salt dynamics in relation to changes in water table depth on a time scale of one or two decades. Salt disperses clay particles leading to reduced infiltration and poor plant growth conditions and these changes in the soil structure and fertility mean that, on a decadal time scale, the regime shift is, in practical terms, irreversible. Over much longer time scales, multi-decadal to century, *if* trees can be maintained or technology can fix the problem, the salt will eventually be flushed down. The broken line in Fig. 3 indicates that this long-term return to a fertile (low salt) top soil will only take place when the water table is considerably lower than the 2 m depth. This hysteresis effect is due to inter-annual fluctuations in rainfall. As long as the 2 m threshold is within range of a wet period "spike", salt will again be drawn up to the surface.

Resilience at any one time in this system is measured by the distance from the water table to the 2 m threshold. We include the measure in the estimate of inclusive wealth by estimating the probability that the system will shift from the non-saline to the saline regime. A particular feature of the GBC's recent climatic history that complicates the following story about changes in inclusive wealth is that the region has been gripped by an unusual drought for more than a decade. The result has been a slight lowering of the water table and therefore (in contrast to the general trend over the previous 80 years) an increase in resilience with respect to salinity.

## 5.2 Incorporating Resilience with Regard to Salinity in a Measure of IW

An estimate of IW at a single point in time has no real meaning. It is the *change* in IW that matters, since it is the change over time that allows us to assess the sustainability of particular projects or policies. There are two ways in which change in IW is of interest: (i) The difference in IW between two points in time, as a monitoring procedure to detect if the resource allocation in effect at time 1 was sustainable. (ii) The difference between two resource allocation options (eg, proposed policy options), as a comparative procedure to determine the difference in IW that will result from the two options.

To determine changes in IW under either (i) or (ii) a forecast of how the various stocks will change into the future is required in order to calculate the shadow prices.

### *5.2.1 Forecasts*

Measuring IW relies on economic and stock quantity forecasts to derive shadow prices. We have defined two forecasts for the period 2001–2030. Both relate to climatic conditions in the Goulburn-Broken Catchment, which we assume affects only the depth of the groundwater table. For the purpose of this analysis, we ignore any direct affects of climatic changes on dairy and horticultural production. Both forecasts share the same history of groundwater table movement between 1991 and 2001, decreasing from 3 to just above 3.5 m. We assume linear changes in the groundwater table between 2001 and 2030. The two forecasts are:

(I) Re-establishment of the Normal Climate Conditions, which produce average rainfall and evaporation, resulting in a rising water table that is assumed to reach 3 m below the surface by 2030.
(II) Continuation of the current, unusual Dry Climatic Conditions, which have resulted in the lowering of the water table between 1991 and 2001. Based on current trends, we assume that the water table falls to 5 m below the surface by 2030. (We note that there is a view in the region, based on predictions from climate change models, that the current dry conditions may in fact become the norm.)

### *5.2.2 Shadow Prices*

We have identified four stock categories in all, three of which have entered into the analysis and have associated shadow prices:

(I) Stocks of dairy and horticultural land not subject to a regime shift (non-salinisable, see Table 1 for price and quantity data),
(II) Stocks of dairy and horticultural land which are subject to a regime shift (salinisable, see Table 1), and
(III) Stocks of resilience. Our single measure of salinity-resilience is the distance from the water table to the 2 m threshold, a distance that we treat as a stock, as described in Section
(IV) As we describe later, however, there may be more than one kind of resilience stock.

The salinisable and non-salinisable lands should in reality have different shadow prices, and the numbers presented in Table 1 are therefore not, strictly speaking, shadow prices. They are more "ideal shadow prices" conditional on no future regime shifts (as the lands are equally valued in all other aspects except the regime shift risks). These prices will be used for calculating the monthly-equivalent loss due to a flip from the normal to the disturbed state.

The fourth stock is the stock of pumps used to lower the water table, and therefore to enhance resilience. For this assessment, it does not change, and we do not therefore include it. We discuss it again later, when changing the stock of pumps becomes a policy alternative.

**Table 1** Stock quantities and prices in 1991 and 2001 for dairy and horticultural land

| Stock characteristics | Quantity (ha) | Price ($/ha) | | | |
|---|---|---|---|---|---|
| | | 1991 | | 2001 | |
| | | Current regime | Alternate regime | Current regime | Alternate regime |
| Dairy land non-salinisable | 48, 000 | $448.29 | NA | $385.85 | NA |
| Dairy land subject to salinity | 192, 000 | $448.29 | $44.83 | $385.85 | $38.59 |
| Horticultural land non-salinisable | 4, 800 | $723.00 | NA | $677.16 | NA |
| Horticultural land subject to salinity | 19, 200 | $723.00 | $7.23 | $677.16 | $6.77 |

*NA* Not applicable to this stock as it is not subject to a regime change

To demonstrate the impact of resilience on an IW assessment, we make the simplifying assumption that all capital stock quantities are held constant ($K_{i,t} = K_{i,t+\Delta t}$) and only the stock of resilience ($X_j$) changes.

Market prices are used as a proxy for ideal shadow prices in the current regime.[2] There are significant problems with using market prices as shadow prices and some of these are listed in the discussion. However, this paper is focused on how to incorporate resilience in IW, not the calculation of IW per se, and the prices are therefore used only to illustrate the method. Accordingly, the 1999 shadow price for the stock of salinisable dairy land in the current regime is, for instance, taken at the market price of $448.29 per ha ($P$), with an estimated price of dairy land in the alternate regime as $44.83 per ha ($P$; 10% of current value). The greater reduction in value of horticultural land when it shifts into the salinised regime is based on the lower sensitivity of pastures to water tables in the upper 2 m compared to fruit trees. The estimated price of salinised land in Table 1 (i.e., 10 or 1% of current land value for dairy and horticultural land, respectively) is broadly in line with other investigations of the land value of salinity to farmers, which generally claim that saline land has minimal commercial value (e.g., Whish-Wilson and Shafron 1997).

### 5.3 Including the Value of Resilience in IW at a Point in Time

There are three steps to including resilience to salinity in estimates of IW. The first is to estimate the cumulative probability $F(X_0, t)$ of the stock crossing the threshold at a future time $t$. We used the data for monthly water table depths since 1974 from a central site in the region to derive the probability of a rise in the water table of a particular magnitude within any one year. We did this using a best fit function to the relative frequency of magnitudes of monthly rises in the water table. As explained earlier, this relationship includes pumping activities.

For a given initial resilience stock, $X_0$, i.e. the distance between the actual water table and the threshold of 2 m below the surface, we make forecasts about the future trends of water tables and calculate the expected resilience level $X_t$ for all time $t > 0$. Since we use discrete time in this empirical illustration, we may refer to a future "time" $t$ as a future month $t$, $t = 1, 2, \ldots, m$. Conditional on no flips in previous months, the probability of a flip in month $t$ can thus be expressed by $\theta e^{-\eta X_t}$. Based on monthly observations from the GBC region, the parameters were estimated to be $\theta = 0.4583$ and $\eta = 2.75$, where the initial water table was about 3 m below. Thus, the survival probability up to month $t$ becomes

$$S(X_0, t) = \prod_{t=1}^{m} \left(1 - 0.4583e^{-2.75X_t}\right) \tag{11}$$

The corresponding cumulative flip probability is $F(X_0, t) = 1 - S(X_0, t)$. Note that the trend of expected future resilience levels $X_t$ depends on the initial level $X_0$ according to a certain stochastic process. Following the scenario of the "normal" climatic conditions, the water table would rise from the 2001 level of 3.5 m below surface to 3 m, implying a loss in resilience stock of 5 dm. If the "dry" climatic conditions are assumed, then the water table would fall further to 5 m resulting in an increase in the resilience stock of 15 dm.

[2] Both dairy and horticultural land price data are derived from net present value calculations of land rent based on ABS (2001) and ABS (1998) collated for the GBC.

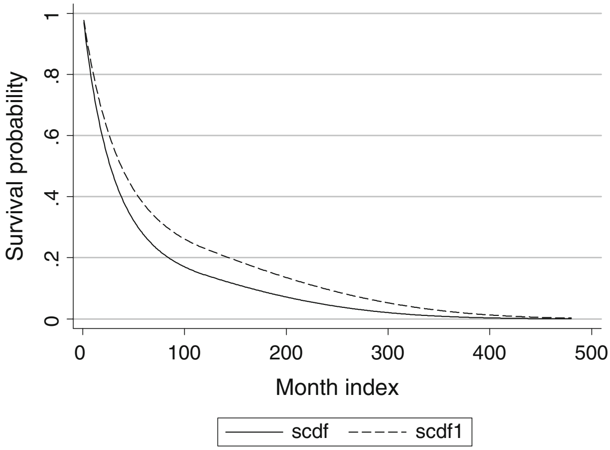


**Fig. 4** Survival curves conditional on different initial resilience levels for a 1 dm increase in the resilience stock. With initial resilience starting stocks of 10 dm (*scdf*) and 11 dm (*scdf1*)

In the second step, we calculate the marginal price of the resilience stock per decimetre at our initial year 1991 by

$$q(0) = \sum_{t=0}^{480} \frac{\Delta S(X_0, t)(U_1 - U_2)}{(1+\delta)^t} \tag{12}$$

where $\Delta S(X_0, t)$ denotes the increase in survival probability at month $t$ due to a hypothetical increase[3] in the initial resilience stock (i.e. a fall in the water table) by 1 dm (decimetre). There is a $\Delta X_0 = 1$ in the denominator which has not been displayed. The monthly-equivalent loss.[4] caused by a flip is calculated by $U_1 - U_2 = (0.04/12) \times (0.90 \times 192000 \times 448.29 + 0.99 \times 19200 \times 723.00)$, where we use an annual discount rate of 4% (about $\delta = 0.04/12 \approx 0.33\%$ monthly rate of discount). The expression within the second parentheses on the right-hand-side is the total loss in present value caused by a flip. As touched upon in the theory section, we use a finite time bound ($m = 480$ months) which reflects the horizon used for 'long term' planning and infrastructure development projects in the catchment.

Based on the "normal" climate scenario, we calculated the change in survival probabilities due to a 1 dm increase in the resilience stock, as depicted in Fig. 4. While the lower curve *scdf* depicts the survival curve conditional on an initial resilience stock of 10 dm, the upper one shows the survival curve from a counterfactual initial resilience stock of 11 dm, as of the first month in 1991. It is seen that with higher initial (and subsequent) resilience levels, the survival probability is higher at each future point in time. Applying the formula in Eq. 12, we obtain the 1991 resilience price per decimetre as $4,570,530. The GBC's 1991 inclusive wealth thus becomes

[3] We assume that the expected future resilience stocks would improve by the same amount. This is a different assumption as compared to Maler et al. (2007), when the effect of a change in the initial water table diminishes over time.

[4] In this paper, we treat utility and its monetary value with no distinction. In other words, we assume a linear-in-income-utility function with marginal utility normalized to unity.

**Table 2** Change in inclusive wealth between 1991 and 2001 using constant prices

| Forecast<br>Forecast | Change in wealth not<br>including resilience | Change in IW<br>including resilience | |
|---|---|---|---|
| Normal climatic conditions | \$0 | \$22,852,650 | 7.0% |
| Dry climatic conditions | \$0 | \$28,558,360 | 8.4% |

$$\begin{aligned}\omega_{1991} &= \sum_i p_{it} K_{it} + \sum_j q_{jt} X_{jt} \\ &= (448.29 + 723.00) \times 1{,}92{,}000 + (448.29 + 723.00) \times 48{,}000 + 45{,}70{,}530 \times 10 \\ &= \$326{,}814{,}900 \qquad (13)\end{aligned}$$

i.e. about \$327 million, where the last term in the middle line represents the value of resilience stock being 10 dm. The corresponding 1991 resilience price following the "dry" scenario is calculated to be \$5,711,672, and the inclusive wealth turns out to be \$338,226,300, about \$338 million. Although the wealth numbers are informative for the scale of the economy, they have no real meaning on their own for welfare comparisons. It is the change in IW that matters, which we come to in the following two sections.

## 5.4 Resilience and Change in IW Over Time

Change in IW can be calculated at constant prices for small changes in the resilience stock. For larger changes, however, the effect of price movement should also be taken into account as shown in Eq. 5 in order to make more precise welfare comparisons. In this section, we study the welfare changes between 1991 and 2001 based on constant 1991 prices. Over the time period concerned, the resilience stock increased by 5 dm due to a water table fall from 3 to 3.5 m. Using the constant price at the initial year 1991, i.e. \$4,570,530 per dm for the "normal climate" scenario, the corresponding change in IW is calculated to be 4,570,530 × 5 = \$22,852,650, about \$23 million. This corresponds to about 7.0% of the total wealth in 1991. For the "dry climate" scenario, where $X_t$ linearly declines from just above 3.5 to 5 m over the time period, the increase in IW is \$28,558,360, i.e. about 8.4% of the 1991 inclusive wealth. Stated another way, if we expect the resilience stock to continue increasing in the future (dry conditions), the 0.5 m change between 1991 and 2001 is valued at \$28.5 million. On the other hand, if we expect the resilience stock to decrease again in future (normal conditions) the 0.5 m change between 1991 and 2001 is valued at \$23 million.

From Table 2, it is seen that the growth in wealth not including resilience does not change between forecasts because we have held all other stocks constant (i.e., $K_i$ and $K_h$). Including the effect of resilience, we find the 2001 IW is higher than that in 1991 (ex-post), meaning that the inter-temporal welfare has been improved during the period. These intuitive results support the importance of forecasts in wealth estimates and highlight the important role that the resilience stock plays in estimating wealth.

## 5.5 Resilience and Change in IW to Assess Policy Options

The calculation in the previous section is based on the assumption of the business-as-usual pumping activities. From a policy point of view, it is interesting to study the value of an Enhanced Pumping (EP) policy, with increased pumping capacity. The pumping operation is assumed to control water flows so as to (deterministically and "costlessly") regulate the water table. As shown by Arrow et al. (2003), the accounting prices can be used both for welfare comparisons over time and project evaluations of alternative states along the time line.

For simplicity, let us suppose that the water table in 1991 could be instantly decreased through EP by 1 m (10 dm) from the actual 3 m level. Following the path from the initial resilience stock of 3 m, the maximum inter-temporal wealth is as derived earlier to be about \$300 million. The question here is how the welfare measure would increase if the water table was, instead, 4 m. As a first-order approximation, this increase can be calculated by multiplying the constant 1991 resilience price with the decrease in water table. This turns out to be

$$q_Y(0)dY_0 = q_X(0)dX_0 = 4,570,530 * 10 = \$45,705,300$$

i.e. about \$46 million, for the "normal climate condition", where $q_y(0)$ denotes the accounting price per unit of EP capacity and $dY_0$ the increase in the EP stock. With this simple model, the value of the enhanced pumping capacity is exactly equal to the value of enhanced resilience enabled by the EP. For the "dry climate" scenario, we have

$$q_Y(0)dY_0 = q_X(0)dX_0 = 57,11,672 * 10 = \$57,116,720$$

i.e. about \$57 million. Applying the cost-benefit rule, it may be claimed that if the cost of EP to reduce the initial water table by 1 m was less than the value(s) above, then it is socially profitable to adopt the enhanced pumping, otherwise not.

The 'correct' estimate of IW (either \$46 or \$57 million) will depend on expectations of the future. Current climatic conditions in the region indicate that for the foreseeable future a 'dry' climate is expected, and as such the higher value is correct. The value of this analysis is in showing the significance and impact of forecasts on empirical IW estimates.

It is worth mentioning that the calculations above are based on an instant change in the pumping capital with an immediate effect on resilience enhancement. In reality, it could take years to install the pumps and build drainage water channels. In this case, it is obvious that the costs and benefits during this transition period should be better accounted for. As our aim with this exercise is to illustrate the use of the IW theory for evaluating projects in an ideal setting, we avoid such complications.

### 5.6 Sensitivity Analysis

Our analysis above is based on the cumulative probability function Eq. 11 where the monthly probability of a flip is equal to $0.4583e^{-2.75\times1.0} \approx 0.029$ given that the "normal" resilience stock is 1.0 m (a water table of 3.0 m below surface). To generate such a monthly flip probability, however, there are many other parameter pairs $(\theta, \eta)$ that satisfy $\theta e^{-\eta X} = 0.029$ with the same resilience stock, such as $(\theta, \eta) = (0.25, 2.15)$ and $(\theta, \eta) = (0.125, 1.45)$.

Although the different pairs generate the same flip probability for the "normal" resilience stock of 1 m, they may result in rather different flip probabilities for alternative resilience stock levels. Thus, the choice of a parameter pair may imply very different resilience prices. In Table 3, we show that calculated price per decimetre resilience stock at the reference year 1991 for the different sets of parameters. It is seen that the results are sensitive to the choice of parameters describing the flip probability function. The larger the "speed parameter" $\eta$, the more sensitive the flip probability is to a change in the initial resilience stock, and thus

**Table 3** Sensitivity analysis with different parameter pairs

| Parameter pair $(\theta, \eta)$ | Forecast | The 1991 resilience price per decimetre |
|---|---|---|
| (0.4583, 2.75) | Normal | $4,570,530 |
| | Dry | $5,711,672 |
| (0.25, 2.15) | Normal | $3,144,708 |
| | Dry | $3,852,056 |
| (0.125, 1.45) | Normal | $1,770,415 |
| | Dry | $2,012,951 |

the larger the resilience price per meter is. This implies that the resilience prices should be interpreted with caution due to possible uncertainties involved in the flip probability model.

## 6 Discussion of Including Resilience in Inclusive Wealth

The GBC example shows that including resilience can make a significant difference to the estimate of changes in IW when multiple regimes may exist, as hypothesised in Maler (2008). The change in IW over the period 1991–2001, incorporating the resilience measure, indicated that the sustainability of using the system over that period depended on the climate forecast expected in the future. Our analysis is, however, partial as we have assessed only a limited number of stocks and suppressed all changes in those stocks in order to focus on the effects of including resilience.

Had normal climatic conditions prevailed during the period 1991–2001, the likely outcome would have been rising water tables, a lowering of resilience and a decrease in IW. The unusual dry conditions during the decade actually led to an increase in IW, especially so under the forecast of continuing dry conditions. Under both policy options (current and Enhanced Pumping, in our partial analysis) the system has not actually moved into the saline regime, but it is more likely to do so under current pumping.

We note the following limitations of our analyses:

(1) The results are constrained by available data and cannot be used in any real world sense. In particular, the relationship between rainfall variation and the probability of crossing the 2 m water table threshold needs to be refined. Its present formulation (derived from sparse data) leads to sensitive and quite spectacular differences between the normal and dry climatic forecasts. The sensitivity analysis results in Table 3 show clearly that it is important to get a model for water table changes that will stand up to scrutiny before any recommendations could be made, for example in regard to policy options for enhanced pumping.

(2) Market prices and proxies have been used for shadow prices. This requires a number of assumptions to be made about how the land market operates (e.g., perfect competition, the extent to which non-agricultural services such as nature conservation are included) and how the catchment operates now and during the forecast period (e.g., saline land has no/ minimal productive capacity). Currently the GBC land market “believes” that salinity is controlled and hence salinity does not significantly influence the prices. This is why we have used the same price for land that is non-salinisable and for the current regime of land that is salinisable. Obtaining credible estimates for shadow prices remains a major hurdle in the wider application of the inclusive wealth approach.

(3) We have assumed that once the threshold is crossed there is no return within the forecast period. In the case of the GBC this is a reasonable assumption. It will not be so in all cases, and this could be handled by either adding consecutive time period analyses to the base equation for inclusive wealth (Eq. 10) or including a terminal or scrap value to the resource which would reflect the reversibility of salinization.

The salinity example has outlined the process for including the stock of resilience of a single regime shift. As mentioned earlier, in reality most social-ecological systems have more than one possible regime shift and each of these shifts affects a number of different stocks. As an illustration, we briefly outline two additional possible regime shifts in the GBC.

*Nature conservation*. Native vegetation determines the diversity and abundance of animal species, with a threshold effect. There are three aspects of native vegetation that determine its nature conservation value: the total extent of native vegetation, its condition (whether heavily grazed by livestock, harvested, burned, etc.) and its connectivity. Several studies (e.g., Andren 1994; Bennett and Ford 1997) have shown that, combining the total extent and connectivity, there is a marked threshold effect of the type in Fig. 1b when vegetation cover reaches around 30%. It is not a step function, but it is a steeply changing relationship. In terms of biodiversity the region can be considered as having alternate regimes, above and below a vegetation cover of 30%. The slow, controlling variable is the cover of native vegetation. Response types of this nature are quite different from the salinity example or Fig. 1c. However, from the point of view of estimating IW it is convenient to consider the probability of crossing the threshold as a resilience stock that influences the likelihood of a regime shift.[5]

*Irrigation infrastructure*: A third kind of state change has been suggested in the GBC for one of the built capital stocks— irrigation canals. They were originally built and maintained by State and Federal agencies but are now owned by a privatised body that includes the irrigators. The canals need regular, costly repairs which can only be paid for out of profits when excess water is available for sale beyond the annual growers' entitlements. However, because the region has been in a drought for several years, maintenance requirements have been mounting. It is mooted that canal repair costs will be higher than the expected returns from the dairy operations they serve. In the context of our assessment, the "flip" does not involve any complex dynamics (as in Fig. 1d or e). But it does involve a flip in terms of economic decisions, a point of no return regarding the economic viability of the canals, i.e., it is a "tipping point". If there were significant changes in prices of crops, or in canal repair technology, the situation could be reversed and it could be economically viable to repair the canals (the threshold would have changed). From the perspective of estimating IW this example shows we have built capital thresholds at the farm (sub-regional) level that need to be incorporated in to the regional assessment (ie. thresholds nested by scale).

These examples of multiple thresholds and their impacts on the stocks (natural and built) within a region like the GBC will result in a matrix of capital stocks impacted by possible regime shifts and a number of resilience stocks. The consequence of multiple thresholds and associated resilience stocks is very complex, and we have not attempted to address them in this paper. Finally, changes in the underlying controlling variables will in some cases have a direct effect on the on the current benefits flowing from the ecosystem in question, such as in the nature conservation example just mentioned. Our analysis assumes the underlying variable—the resilience stock—only affects the chance of a state flip. When changes in the one variable affect both the risk of a system flipping *and* the immediate benefits flowing from that

[5] The vegetation example is one in which changes in the resilience stock have (potentially) immediate impacts on Vt (through associated changes in ecosystem services) separate to the probabilistic effects through changes in distance-to-threshold.

system, using our terminology it plays the role of a K stock and an X stock simultaneously, and its shadow price will need to reflect both those contributions.

## 7 Conclusion

Resilience is a necessary inclusion in any comprehensive measure of sustainable development as argued in Dasgupta and Maler (2003) and Maler (2008) and evaluated in this paper. It is difficult to incorporate because of uncertainties about the positions of thresholds and threshold effects, but our analysis has shown that even if accurate data are not available an initial assessment of the significance of resilience can be undertaken by answering three key questions:

1. Is there a known or suspected alternate regime in a stock's forecast?
2. If so, how will a shift into the alternate regime affect social wellbeing (including which other capital stocks it affects and by how much)?
3. What is the probability of the stock crossing the threshold? (which requires some estimate of the state of the stock, where the threshold might be, and therefore the "stock" of resilience)

The GBC example (acknowledging its limitations) has shown that the effect on IW of including a small change in the likelihood of a shift to a saline regime was large. This indicates in a pure cost-benefit manner the maximum expenditure for maintaining the current regime. Assessing the effects of resilience associated with a single potential regime shift on single stocks is substantially easier than the complex notion of multiple regime shifts affecting many stocks.

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