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Realizing resilience for decision-making

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Researchers and decision-makers lack a shared understanding of resilience, and practical applications in environmental resource management are rare. Here, we define social-ecological resilience as a property of social-ecological systems that includes at least three main characteristics — resistance, recovery and robustness (the 'three Rs'). We define socio-economic resilience management as planning, adaptation and transformational actions that may influence these system characteristics. We integrate the three Rs into a heuristic for resilience management that we apply in multiple management contexts to offer practical, systematic guidance about how to realize resilience.

Resilience is factored into many socio-economic decisions, including public health[1], risk management in the private sector[2], and development and finance investments[3]. Resilience has been incorporated into the stated management objectives of influential multilateral and United Nations agencies (for example, FAO (Food and Agriculture Organization); World Bank) and is also included in several Sustainable Development Goals (SDGs): SDG 1 (no poverty); SDG 2 (zero hunger); SDG 9 (industry, innovation and infrastructure); SDG 11 (sustainable cities and communities); SDG 13 (climate action); and SDG 14 (life below water)[4]. Further, resilience is a foundational concept for the 2005–2015 Hyogo Framework and the 2015–2030 Sendai Framework for international disaster policy[5]. It is also included in the nationally determined contributions of the Paris Agreement from the United Nations Framework Convention on Climate Change.

The increasing popularity and use of resilience contrasts with a lack of clarity over how to implement it in practice[6], especially in the broader context of social-ecological systems. Even after decades of research and policy engagement to advance understanding of resilience[7–10] and calls for better inclusion into decision-making[11], resilience management of social-ecological systems is still not widely practiced.

We attribute the difficulty of operationalizing resilience to two key challenges. First, 'resilience thinking'[12] is hampered by the proliferation of different, sometimes overlapping, and possibly conflicting definitions and interpretations of resilience[13–15]. The resilience-related concept of stability has also been applied in a range of different ways in different schools of research[8,9,12,16–19]. Consequently, differences in understanding, and even confusion, limit the applied value of resilience in the research–policy–practice interface[20]. Second, what to manage and what to manage for, in relation to resilience, are highly context-dependent and this constrains the practical value, especially in the near absence of social-economic guidance about how it can be operationalized.

We respond to the ongoing problem of realizing resilience in social-ecological systems from an interdisciplinary perspective and with a socio-economic decision-making focus by: reviewing how resilience is conceptualized and measured; developing a socio-economic resilience heuristic for resilience management of social-ecological systems; contextualizing this heuristic in a mathematical example of an aquifer subject to saline intrusion and also with an illustration in relation to marine fisheries; and applying this heuristic (Table 1) in three resilience-management contexts (surface water flows, emergency management and marine wild-capture fisheries).

Conceptualizing social-ecological resilience

Definitions of resilience differ by discipline and application (Box 1). For instance, a psychologist can define resilience in terms of an individual's state of mind and body as a: "stable trajectory of healthy functioning after a highly adverse event"[21]. By contrast, in water resources engineering, resilience refers to how quickly a system recovers after a loss of system function[22].

In ecology, resilience is used in two distinct ways. The first refers to how quickly, or the speed at which, an ecosystem returns to an equilibrium state following a temporary disturbance[9,19,23]. Holling[8] called this 'stability', but it has been variously called 'resiliency'[22] and 'elasticity'[24]. We call this 'recovery time'. The second definition also comes from Holling[8]. He defined resilience in relation to systems,

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Table 1 | Three management contexts using a socio-economic resilience heuristic

Management steps	Resilience for surface water flows	Resilience for emergency management of communities	Resilience for marine wild-capture fisheries
System definition, boundaries and drivers	Water catchment. Catchment dynamics are affected by both human activity and by natural fluctuations.	Small community (~2–3,000) well-defined spatially. Residents' activities include farming and timber extraction, and social interactions.	Multi-species fishery. Dynamics of the system depend on natural mechanisms (for example, growth and recruitment), fishing activities and environmental drivers.
Stakeholders	Farmers, tourists, water agencies and NGOs.	Community residents.	Fishers, consumers, regulating agencies and NGOs.
Metrics identification	Water quality and quantity, the net economic return of water users, and environmental quality scores.	Employment, production, and consumption/food security, and ecosystem services.	Biomass estimates and indicators of fishing production and profitability.
Viability goals and metrics	Positive net returns for farmers, guaranteed stream flows, cultural needs and safe thresholds.	Human safety, maintaining infrastructures, water and electricity supply, and economic activities.	Stock thresholds, such as precautionary limits, and also minimum profit levels for the harvesting sector.
Adverse events	Droughts or floods.	Wildfires.	Recruitment failures.
Quantification of the three Rs	Resistance: measures of ecosystem health (species diversity) or habitat functionality (vegetation cover). Recovery: recovery time for population of key species. Robustness: probability of 'normal' water inflows.	Resistance: safety margins for multiple metrics (environmental, economic, heath and social). Recovery: magnitude, type and scale of resources post-disaster. Robustness: probability of not having wildfires.	Resistance: population viability analysis of key fish stocks. Recovery: responses to annual recruitment variability, regime shift, climate change and socio-economic shocks. Robustness: probability of fish stocks, catches or fisher profits not falling below pre-defined thresholds.
Resilience-management actions and benefits	Construction of infrastructure for inter-basin transfers, storage (surface and aquifer), water extraction and policies that affect land-use and vegetation type.	For wildfire risk management, prescribed burning and fuel treatment.	Modern fisheries management includes active adaptive management as a response to large, and frequently unpredictable, adverse events and also uncertainty over fisher responses.

and to relationships within systems, as their ability to absorb change and persist while maintaining core structural and functional attributes (for example, biodiversity, biomass or ecosystem service provision). In the tradition of Holling[8], Cumming and Collier[25] emphasized system 'identity', which persists when key components, interactions and spatiotemporal continuity are maintained; if they do not, a system's identity is lost, and the system is not resilient.

Our focus is on social-ecological resilience (as defined by Holling[8]) and actions related to its 'how, when and why', rather than 'what should be', for an individual, population, subsystem or system; and its ability to bounce back, or to retain its identity, following (an) adverse event(s). These actions include: actively maintaining a diversity of functions and homeostatic feedbacks; steering systems away from thresholds of potential concern; increasing the ability of the system to maintain its identity by increasing the size of its 'attractor basin'[26]; increasing the capacity of the system to cope with change through learning and adaptation[27]; and active assessment of scaling and cross-scale effects using a systems approach[28].

Biggs et al.[29,30] proposed seven generic actions to enhance the resilience of ecosystem services. These include: (1) maintain diversity and redundancy; (2) manage connectivity; (3) manage slow variables and feedbacks; (4) foster understanding of complex adaptive systems; (5) encourage learning and experimentation; (6) broaden participation; and (7) promote polycentric governance systems. Building on these actions, we define resilience management as the planning, adaptation and transformation actions intended to influence the resistance, recovery and robustness (the three Rs) of the social-ecological system under consideration. Improvements in the three Rs may (or may not) be desirable from the perspective of a given stakeholder or for society at large, are not necessarily independent, and can be influenced by human actions and other drivers.

We illustrate the three Rs in Fig. 1. Hereafter, we specify dimensionless (normalized) units (from zero to one) for resistance and recovery while robustness is measured as a probability. A higher value of our dimensionless measure of resistance, recovery, and also robustness, represents a greater level of social-ecological resilience. Resistance is a system's ability to actively change while retaining its identity, or to passively maintain system performance, following one or more adverse events[31,32]. Recovery is a normalization of recovery time that converges to zero when the time it takes for a system to recover to a value in the neighbourhood of its previous level of performance approaches infinity, and equals one when the system remains unchanged following an adverse event. Robustness is the probability that a system stays functional, maintains its identity and does not cross an undesirable (and possibly irreversible) threshold following one or more adverse events[33,34].

Measuring social-ecological resilience

Our three measures of social-ecological resilience of a system (the three Rs) build on a multidisciplinary literature. We also observe that resilience includes a tension between persistence and change; in particular, resistance embodies system persistence to maintain identity while also including essential changes to maintain the system.

The recovery time measure of resilience was used by Hashimoto et al.[22] to measure how fast a system can recover after a failure, and later by Pimm[9,10] for individual populations in relation to ecosystem effects. Recovery time has been applied by various researchers[34–36] while Bruneau et al.[37] proposed that resilience be measured by a system's performance loss over the recovery period.

Engineers, typically, measure resilience in terms of probability of failures, or the reliability of systems. In the context of networks,

Box 1 | Key terms

Adverse event: a consequence that has a negative impact on system performance.

Recovery: a normalized (dimensionless) measure of recovery time bounded by 0 and with a maximum value of 1 where a higher value indicates a shorter recovery time.

Recovery time: the time it takes for a system's performance to recover to a desired functionality or viability following one or more adverse events.

Resilience management (socio-economic): the planning, adaptation and transformation actions of decision-makers intended to influence key system characteristics (for example, resistance, recovery and robustness) for specified goals.

Resistance: in general, a system's ability to actively change while retaining its identity or to passively maintain system performance following one or more adverse events.

Robustness: the probability of a system to maintain its identity and not cross an undesirable (possibly irreversible) threshold following one or more adverse events.

Social-ecological resilience: an overarching concept commonly understood to be the characteristics of a system that allow it to recover or bounce back in terms of system performance or functionality following one or more adverse events.

Social-ecological systems: complex systems that include social (for example, culture and institutions), economic (for example, technologies and preferences) and environmental and ecological (for example, climate and habitat) components that interact in multiple ways, including with both positive and negative feedbacks.

Stability: the concept that either a system or components of a system will, over time, converge back to a given state following an adverse event.

Threshold: an exogenous or endogenous limit beyond which system performance deteriorates to a level whereby it is impossible, very costly, or unacceptable to cross or to recover from to achieve a desired level of system performance.

Ganin et al.[38] measure resilience by the 'critical functionality' of a network, for example, the percentage of nodes functioning under adverse events and their relative importance. These are proxies of robustness.

System measurements are required for effective management. To assign causality from an adverse event to its consequences on system performance (of what and over what time period) demands an empirically and statistically valid causal inference operationalized through statistical approaches such as difference-in-differences, matching and propensity scoring, and Bayesian methods[39]. It also requires understanding that the adverse event(s) might arise from the randomness or the unpredictable behaviour of systems and/or individuals[40], or from imperfect knowledge, as well as an understanding of who the persons of interest are.

Socio-economic resilience management

Building on the insights of Carpenter et al.[18], Helfgott[41] highlights that social-ecological resilience needs to be operationalized, and therefore managed, by identifying: for whom (those affected by adverse events and outcomes of management actions); of what (aspects of system performance of interest, including system boundaries); to what (adverse events that affect system performance); and over what time frame (short versus long-run, time to recover, and so on).

Figure 1 highlights possible policy implications of the three Rs for resilience management. System performance is measured on the vertical axis while the horizontal axis is time (T). System performance varies over time, within some desirable or acceptable range, prior to T_0 when a pulse or one-off adverse event occurs, but we observe that adversity may also include ongoing and long-term influences (presses) on system performance[19,42].

The threshold in Fig. 1 represents a single and static critical transition[26,43] point beyond which the system may move to an irreversible state where previously desirable and attainable levels of system performance (defined by M) cannot be restored. Thresholds may not always exist; but, when they do, they may be exogenous or endogenous such as the requirement that profits always be positive, as determined by stakeholders or decision-makers.

For illustrative purposes only, Fig. 1 includes three possible scenarios after T_0. Scenario one is represented by the green trajectory where no adverse event is assumed to occur and, thus, there is no observable impact on system performance. In this case, social-ecological resilience is characterized by: resistance, such that there is no observable decline in system performance; recovery as system performance remains at M and recovery time is zero; and robustness is unchanged, with the probability $0 < p1 < 1.0$ of not crossing the threshold.

Scenario two is represented by the yellow trajectory where a moderate adverse event is assumed to occur with a modest impact on system performance. Social-ecological resilience is characterized by: decreased resistance from its previous level at M by the loss of system performance K; decreased recovery compared to the green trajectory because the time it takes for system performance to recover its previous level at M is strictly positive ($T_3 - T_0 >> 0$); and lower robustness, as the probability $p2$ of not crossing the threshold is less than with the green trajectory, namely $0 < p2 < p1$.

Scenario three is represented by the red trajectory where an adverse event is assumed to occur with a low probability but with a potentially large impact on system performance. Social-ecological resilience is characterized by: decreased resistance as system performance declines from its previous level at M by the loss of system performance $2K$; recovery is not possible and is bounded by 0 because recovery time is infinite, such that system performance never returns to its previous level at M; and robustness, the probability of not crossing the threshold, is 0.

We note that: an increase in one characteristic (such as improved resistance) is not always associated with improvement in another (such as increased robustness); the connectivity, diversity, variability and state of a social-ecological system influence its characteristics[17]; systems exhibit hysteresis and path dependence, such that their previous states and past shocks, as well as human choices about trade-offs (for example, between different ecosystem services), can permanently affect system performance and identity[44]; and adaptation and transformation of system performance, through resilience management, may occur before, during or after an adverse event.

Like others before us[12,45], we seek to bridge the gap between resilience theory/principles and actual practice. We do so in relation to social-ecological resilience and, specifically, realize resilience by including social and economic dimensions.

A socio-economic resilience heuristic

Management actions are part of social-ecological systems and should be made with an understanding of a system's context, including questions about who bears the burdens(s) of changes in system performance and management costs around resilience[46]. For example, a watershed managed for resilience to drought (to what) might have very different management actions if performance (resilience of what) were defined by financial metrics (such as profitability

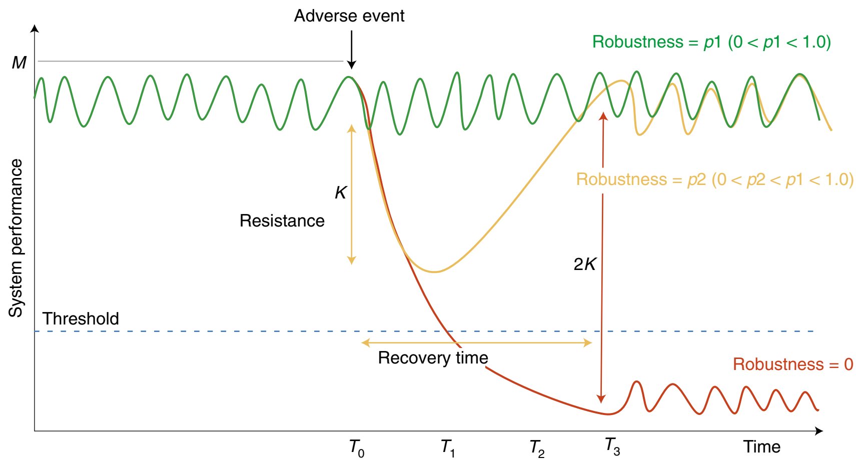

Fig. 1 | Possible effects of an adverse event on resistance, recovery and robustness. M is system performance prior to T_0, K (yellow trajectory) and $2K$ (red trajectory) represent two different declines in system performance, $p1$ is the probability of the green trajectory not crossing the threshold when at T_0, $p2$ is the probability of the yellow trajectory not crossing the threshold when at T_0, and T_3 is the time point when the yellow trajectory returns to a level in the neighbourhood of its previous level (M) following an adverse event at T_0. Dimensionless (normalized) resistance is defined in the interval [0, 1] and can be measured by $(M - N)/M$ where M is observed system performance at T_0 and N ($N = K$ for the yellow trajectory and $N = 2K$ for the red trajectory) is the consequential reduction in system performance following an adverse event at T_0. Dimensionless (normalized) recovery is defined in the interval (0, 1] and can be measured by $1/(T_L - T_0 + 1)$ where T_L is the finite time period (recovery approaches 0 as T_L approaches infinity) when system performance returns to a level close to its previous level (M) before the adverse event at T_0 ($T_L = 3$ for yellow trajectory). Robustness is defined in the interval [0, 1] and is the probability of system performance not crossing the defined threshold when at T_0. A higher value of dimensionless resistance, dimensionless recovery and robustness indicate a greater level of social-ecological resilience. Figure adapted from ref. [58], Wiley.

from additional water use) compared to environmental metrics (such as end-of-system flows) or by indigenous community metrics (such as socio-cultural benefits).

Our proposed social-economic resilience heuristic encompasses seven questions or steps in relation to a social-ecological system (and its boundaries):

(1) Resilience of what objects (system, system component or interaction) is being managed?
(2) For whom (stakeholders) is resilience being managed?
(3) What are the metrics of system performance for the identified stakeholders?
(4) What are the viability (or safety) goals of the stakeholders (and associated metrics) for key system variables that allow a system to retain its identity?
(5) What adverse events or causes, in relation to resilience, are being considered?
(6) How are the three Rs measured in relation to system performance and in response to adverse events?
(7) What are the expected net benefits, currently and over time and space, of resilience-management actions?

Several, but not all, of the seven questions are similar to the framing questions and/or figures developed by Cumming[45], Helfgott[41], Li et al.[47], Walker et al.[48], Waltner-Toews and Kay[49], and Ulrich[50], among others. The questions are also influenced by the 'diamond schematic' of Waltner-Toews and Kay's[49] that begins, first, with a detailed social-ecological system description and then links understandings of this system to the choices of decision-makers.

Each of the seven resilience-management steps corresponds to an individual question in our heuristic. For each step, we provide a qualitative description of how our heuristic could be used in the context of modern fisheries management.

System boundaries and drivers. To answer the question 'Resilience of what objects is being managed?', specify the system boundaries, states, and key natural and anthropogenic drivers including spatial and temporal patterns, and flow relationships between them[51]. For instance, understanding how key management variables affect the system and the possible dynamics, or how the system might change over time, provides an important reference mode for decision-makers. It is also important to recognize that 'of what' includes a system's past; and the development of explicit timelines may be helpful in understanding hysteresis and path dependence. Thus, if the system being managed is a fish population then a key state of the system could be its population or biomass, perhaps measured by different age structures, while a key control variable could be the current fish harvest rate. The system's dynamics could be specified by biological recruitment and mortality (or migration) mechanisms of fish populations, and also by the level of the fish harvest.

Stakeholders' key issues. To answer the question 'For whom is resilience being managed?', specify the stakeholders, the inputs of stakeholders as well as the nature and challenges of decision-making. Thus, if the system being managed is a harvested marine fish population, then the potential stakeholders could include the fishers and their communities, the seafood consumers, the regulating agencies, and relevant NGOs (non-governmental organizations).

Metrics identification. To address 'What are the metrics of system performance for the identified stakeholders?', criteria, metrics, scores, and other measures in relation to ecological, economic and social system performance and management performance must be identified. These metrics do not necessarily need to be measured in a common unit of account, such as dollars. Nevertheless, by including monetary and non-monetary values, multi-criteria approaches should facilitate comparisons and ranking when evaluating decisions across alternative management actions while respecting the diversity of involved stakeholders. Ideally, these metrics should be useful to both managers as well as stakeholders and would include who bears the costs (and benefits) and their magnitude. In the context of fisheries management, possible metrics could be the level of overall profitability in the fishing sector, the level (in volume and value) and quality (selectivity) of catches and supply for consumers, and the fish stock size (population biomass, spawning stock biomass, or number and types of fish).

Viability goals and metrics. In relation to 'What are the viability goals of stakeholders for these metrics?', targets, thresholds, tipping points and constraints need to be identified. For fisheries, goals can include positive net returns, employment, food security in terms of fish supplies, and ensuring the fish stock size is above a desirable ecological threshold.

Adverse events. This corresponds to the question 'What adverse events or causes, in relation to resilience, are being considered?' Adverse events may be exogenous to the system, such as changes in sea surface temperatures, or may be related to unintended consequences of fishing activity, such as habitat degradation.

Quantification of the three Rs. This responds to the question, 'How are the three Rs measured in relation to system performance?' Where possible, decision-makers should empirically evaluate the expected effects of the adverse events on the selected measures of system and management performance in the context of resistance, recovery and robustness. Examples of such methods include quasi-experimental methods, causal inference and other statistical approaches. This should also include an evaluation of the 'for whom' in relation to who bears the loss or costs of the adverse event(s). In the fisheries context, and in relation to the goal of fisher profitability, resistance could be measured by the profit decline from a change in the current fishery stock. Recovery could be calculated by the time it takes to rebuild profits until they become positive following an adverse event. Robustness could be the probability of not incurring fisher losses due to adverse events on fish stocks or market prices.

Across all the three Rs, additional attention must be paid to the system's capacity to adapt and respond to change. For example, the high resistance of crocodilian populations to overhunting is related to temperature-dependent sex determination. This sex determination allows adults to more effectively respond to change and ensure their hatchlings are better adapted to local conditions[52]. Similarly, redundancy in engineering control systems is a common strategy to build robustness[33]. Theory suggests that system-level properties such as diversity, redundancy and compartmentalization can be important for all three Rs[53].

Resilience-management actions and benefits. This responds to the question; 'What are the expected net benefits, currently and over time and space, of resilience-management actions?'. Where possible, decision-makers should select — and actively adapt with new information — priority management actions, such as adaptation and possibly transformation or mitigation of possible adverse events, in relation to expected effects on system performances in the context of resistance, recovery and robustness. In the fisheries context, management strategies following an abrupt decline in fish stocks could include reduced harvesting to allow stocks to recover which would reduce recovery time[54]. For robustness, diversification in terms of fish catches and fishing gears might emerge as a resilient strategy. Enhancing adaptive capacity by building diversity and redundancy may incur additional costs or reduce efficiency but could ensure the system remains more resilient. Thus, building resilience may involve trade-offs over different time frames.

Management actions can be 'top-down' or 'bottom-up' using, for instance, participatory approaches and meaningful engagement with stakeholders[29,55]. Top-down control is, typically, expert-driven and quicker. However, a number of considerations are important for top-down control, it may: marginalize some stakeholders[56]; fail to fully utilize the available information and understanding of systems by stakeholders; inadequately reflect stakeholders' values; and delegitimize resilience management from the perspective of some stakeholders.

Contextualizing a resilience heuristic

How a socio-economic resilience heuristic is used and what guidance it provides to decision-makers depends on what is being managed, and for what goals. Table 1 illustrates our socio-economic resilience heuristic in relation to three contexts: (1) surface water flows within a catchment; (2) emergency management for communities; and (3) marine wild-capture fisheries. For each, the seven decision steps of the socio-economic resilience heuristic are described, noting that these steps are not necessarily implemented consecutively.

Insights from the three cases include: the flexibility in how our socio-economic resilience heuristic can be used for different social-ecological systems; the critical need to elicit system dynamics and processes to effectively implement resilience management; the importance of identifying, and quantifying where possible, the potential adverse events, vulnerabilities and risks; and the possible gains of resilience management in terms of planning, adaptation and transformation actions to achieve defined management goals. While resilience management may add further complexity to decision-making, much of the information needed to apply our socio-economic resilience heuristic should already be collected and be available for an actively managed system (Table 1).

To illustrate how our social-economic resilience heuristic might be quantified, for each step we also include a mathematical illustration of a representative freshwater aquifer subject to irreversible saline intrusion[57].

System boundaries and drivers.

$$x(t+1) = x(t) + r(x(t)) - u(t) \quad (1)$$

$$y(t+1) = y(t)q(x(t)) \quad (2)$$

where $x(t)$ is the stock of freshwater in the aquifer, $y(t)$ is the salinity of water, $u(t)$ is the control variable that relates to the overall extraction rate, $r(x(t))$ is the natural recharge rate of water into the aquifer, and $q(x(t))$ represents whether or not saline intrusion has occurred (takes the value of 0 when saline intrusion has occurred and the value of 1 when it has not).

Two states characterize the system's dynamic behaviour: the size or volume of freshwater in the aquifer given by $x(t)$, and the water quality (saline or not) given by $y(t)$. Prior to resilience management, resource managers can only influence the extraction rate, $u(t)$.

Stakeholders. Stakeholders and their related variables of interest: farmers, $u(t)$ and $y(t)$; urban consumers, $u(t)$; water regulation agencies, $x(t)$, $y(t)$ and $u(t)$; and environmental NGOs, $x(t)$ and $y(t)$.

Metrics.

$$\text{Net economic return} = \text{NER}(t) = au(t)^b y(t) - cu(t) \quad (3)$$

where water quality is $y(t)$; $a > 0$, $c > 0$ are, respectively, revenue and cost parameters; and $b < 1$ indicates that revenues are increasing at a decreasing rate with respect to the level of water extractions. The term, $cu(t)$, is the cost of extracting water from the aquifer.

Viability goals.

$$\text{Positive net economic return} = \text{NER}(t) > 0 \quad (4)$$

Revenues are positive only when $y(t) > 0$, or when there is no saline intrusion.

Adverse events.

$$P(q(x(t)) = 0) = e^{-\beta x(t)} \text{ with } \beta > 0 \quad (5)$$

$$P(q(x(t)) = 1) = 1 - e^{-\beta x(t)} \quad (6)$$

where the probability of the adverse event, or when $q(x) = 0$, is, in part, determined by the volume of freshwater in the aquifer that is influenced by the cumulative rate of recharge and rate of extraction. The greater the volume of freshwater, the lower the probability of an adverse shock of saline intrusion.

Quantification of the three Rs. Resistance (normalized) can be measured in relation by base-level (positive) net economic return $\mathrm{NER_{base}}$ as:

$$e^{-(\mathrm{NER_{base}} - \mathrm{NER(t)})^{+}} \quad (7)$$

where $\mathrm{NER}(t)$ is the current net economic return as in equation (3) and where function z^{+}, defined by $z^{+} = \max(z, 0)$ considers the positive value of any z. Thus, when $\mathrm{NER}(t) = \mathrm{NER_{base}}$, then $(\mathrm{NER_{base}} - \mathrm{NER}(t))^{+} = 0$ and resistance equals 1. By contrast, when $\mathrm{NER}(t) \ll \mathrm{NER_{base}}$, which occurs in particular after an adverse event $q(x(t)) = 0$ which means water salinity $y(t)=0$ and a negative economic return $\mathrm{NER}(t) = -cu(t) < 0$, then $(\mathrm{NER_{base}} - \mathrm{NER}(t))^{+} = \mathrm{NER_{base}} - \mathrm{NER}(t) \gg 0$ and resistance is closer to 0.

Another option is to evaluate resistance by considering the viability constraint (equation (4)) in relation to positive net economic return and the following normalized value:

$$1 - e^{-\mathrm{NER(t)}^{+}} \quad (8)$$

Recovery (normalized) is bounded by 0 if $y(t) = 0$ because saline intrusion cannot be reversed and, thus, recovery time is infinite, that is, it is not possible to ever to return to the previous level of water quality (non-saline). Otherwise, recovery is 1, if $y(t) = 1$. Robustness = $1 - e^{-\beta x(t)}$; this is the probability of not crossing the freshwater–saline interface, which is when the aquifer becomes saline. Thus, the larger the volume of freshwater, the greater the system's robustness.

Resilience-management actions. Resistance: through a control of the rate of freshwater extraction $u(t)$, resistance for net economic return $au(t)^{b}y(t) - cu(t)$ can be enhanced. In particular, the myopic optimization $\max \mathrm{NER}(u)$ when $y(t) = 1$ yields a level of economic resistance that is optimal when $u_{*} = [(ab)/c]^{1/(1-b)}$. If the extraction u_{*} corresponds to a decrease with respect to current extraction $u(t)$, such a strategy can also benefit robustness indirectly and might emerge as a 'win–win' situation (resistance-robustness) for resilience.

Robustness: first, increase the freshwater stock $x(t)$ through a decrease of the rate of freshwater extraction $u(t)$; this increases robustness given by $1 - e^{-\beta x(t)}$, and then reduces the probability of crossing the freshwater–saline threshold. Second, increase the freshwater stock $x(t)$ through an increase of recharge $r(x(t))$; this increases robustness by reducing the probability of crossing the freshwater–saline threshold.

The recharge rate includes natural recharge, but this might be augmented by pumping used water back into the aquifer such that recharge becomes $r(x(t), v(t))$ with $v(t)$ the new control variable for the rate that water is pumped back into the aquifer. A higher recharge rate increases robustness, but the direct and indirect costs of undertaking additional recharge should be considered. Thus, with recharge:

$$\mathrm{NER}(t) = au(t)^{b}y(t) - cu(t) - dv(t) \text{ (with } d > 0) \quad (9)$$

Conclusions

We conclude that the 'how, what, whom, why and when' of social-ecological resilience, in practice, is always context-dependent. Decision-makers must, therefore, actively adapt their actions to their own circumstances. Nevertheless, we contend that: (1) the measurement of three distinct, but related, characteristics of social-ecological resilience and (2) a socio-economic resilience heuristic that includes seven questions linked to complementary management steps, together provide practical guidance to those who manage system performance in an uncertain world.

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Author contributions

R.Q.G initiated and led the collaborative work, co-conceptualized the approach, co-developed the resilience heuristic, co-wrote and revised the text. L.D. co-conceptualized the approach, co-developed the resilience heuristic, co-wrote and revised the text. Alphabetically, C.B., G.S.C., S.D., A.H., P.K., L.R.L. and P.R.W., co-developed the resilience heuristic and co-wrote and revised the text. Alphabetically, E.B., K.B., J.D., D.G., Q.J., T.K., N.M., C.R., D.S., S.V., S.W., and J.W. co-wrote and revised the text. Authorship is alphabetical following R.Q.G. and L.D.

Competing interests

The authors declare no competing interests.

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