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Invited review

From academic to applied: Operationalising resilience in river systems

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A R T I C L E I N F O

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A B S T R A C T

The concept of resilience acknowledges the ability of societies to live and develop with dynamic environments. Given the recognition of the need to prepare for anticipated and unanticipated shocks, applications of resilience are increasing as the guiding principle of public policy and programs in areas such as disaster management, urban planning, natural resource management, and climate change adaptation. River science is an area in which the adoption of resilience is increasing, leading to the proposition that resilience may become a guiding principle of river policy and programs. Debate about the role of resilience in rivers is part of the scientific method, but disciplinary disunity about the ways to approach resilience application in policy and programs may leave river science out of the policy process. We propose six elements that need to be considered in the design and implementation of resilience-based river policy and programs: rivers as social-ecological systems; the science-policy interface; principles, capacities, and characteristics of resilience; cogeneration of knowledge; adaptive management; and the state of the science of resilience.

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1. Introduction

Resilience has variously been described as the word of the year (Walsh, 2013), a concept with the potential to become a vacuous buzzword (Rose, 2007), a powerful lens through which to view major issues (Zolli and Healy, 2012), a systems approach to understanding change (Biggs et al., 2015), an organizing concept for radical change (Brown, 2014), and an academic bandwagon (Thorp et al., 2010). Despite, or even because of, these interpretations, total scientific publications on resilience have increased from 250 to 6000 over the last 15 years (Folke, 2016). Resilience is given attention in the fields of ecology, geomorphology, natural resource management, economics, social science, international development, psychology, and natural hazard management (e.g., Rose, 2007; Downes et al., 2013; Brown, 2014, 2016; Brown and Williams, 2015; Quinlan et al., 2015; Folke, 2016). Government and other organizations are also increasingly developing policies, programs, and communications using a resilience framework or philosophy (Brown, 2016). The concept of resilience is here to stay.

Translating ideas of resilience from a body of scientific thought to adoption and application in government policy and programs is not without its challenges. Managing systems for resilience represents a paradigm shift away from stability and equilibrium, yet the legislation under which an agency operates is often aligned with a stability mandate (Benson and Garmestani, 2011). Managing systems for resilience requires an interdisciplinary consideration of the biophysical and social

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influences on ecosystems, yet agencies and their responsibilities are often divided along disciplinary boundaries (Parsons et al., 2017). The inclusion of biophysical and social influences under a resilience approach also introduces challenges of multiple values in decision making and the tradeoffs necessary to attain a desired ecosystem state (Parsons et al., 2017). Scale awareness is a key component of resilience-based approaches to ecosystem management yet a mismatch often occurs between the evidence used in policy development and the processes being managed (Benson and Garmestani, 2011; Parsons et al., 2017). Despite these challenges, government agencies are often at the forefront of applying resilience because policy and program development occurs at shorter timescales than research (Cutter et al., 2010). Congruence with the foundations of resilience should be maintained as the application of resilience advances to ensure that the foundational principles are not diluted. At the same time, findings from the applications of resilience in policy and programs can be used to review the foundational principles of resilience as it develops from concept to practice.

River science is an area in which the adoption of resilience is increasing. River science, and its component disciplines, are asking questions about many aspects of resilience in river systems including adaptive cycles (Thapa et al., 2016), alternative states (Colloff and Baldwin, 2010), and social-ecological systems (Cumming, 2011). Resilience has also been examined in relation to river management (Green et al., 2013; Parsons et al., 2016a; Petersen-Perlman, 2016), disturbance (Casanova, 2015; Mouthon and Daufresne, 2015), and flow regimes (Botter et al., 2013). While these studies advance our understanding of river system resilience from an academic perspective, resilience concepts may be adopted into river policy and programs in the future. Major pollution incidents, fisheries collapses, water shortages, natural disasters, water resource development, catchment development, litigation, loss of recreational opportunity, or social and demographic pressures on water use might catalyse the adoption of a resilience-based approach to river policy and programs. At the start of a policy cycle, an issue emerges with demand for government action (Althaus et al., 2007). These issues can emerge from public concern, political mandates and policy agendas, evaluation of existing policy, media attention, or scientific (including economic, social, and environmental) evidence (Althaus et al., 2007). Scientists have windows of opportunity through the policy cycle to influence the direction and content of policy (Parsons et al., 2017). Thus, how will the discipline of river science respond when asked to help operationalise resilience in government policy and programs? Will the discipline retreat into further testing of the fundamental tenets of river resilience, insisting that solutions cannot be found until we know more, or will it take up the challenge to translate the many aspects of resilience thinking into policy and programmatic directions using techniques of learning by doing?

This paper outlines the elements that should be considered in the operationalisation of resilience into river policy and programs. These elements serve two purposes. First, they are a heuristic approach for the application of resilience thinking in river systems. Second, they are preparation for an uncertain future where resilience-based solutions to river sustainability may be called for.

2. Resilience: concept and application

Society faces unprecedented and accelerated change in its natural, social, political, and economic systems (Steffen et al., 2015). In essence, resilience is an approach to living with, managing, and adapting to change, complexity, and uncertainty. In this section we briefly overview the fundamentals of the concept of resilience. The resilience literature is vast, and it is not our intention here to review the literature. Rather, we point out key components of resilience related to the understanding of system dynamics in coupled human-environment systems. We then show how a resilience approach is increasingly being applied in public policy and strategies across a range of disciplines and identify emergent properties arising from the adoption of resilience-based approaches in public policy and programs.

2.1. The concept of resilience

The concept of resilience has been developing for several decades. Groundbreaking at the time, Buzz Holling developed the theoretical basis of resilience from studies of ecosystem dynamics conducted in the 1960s and 1970s. His discovery of multiple basins of attraction in ecosystem dynamics challenged the stable-equilibrium view of ecosystems dominant at the time (Folke, 2006). Failure to acknowledge the complexity and dynamics of ecosystems precipitated the growth of the resilience approach in natural resource management (Desjardins et al., 2015). In many production ecosystems (including lakes, forests, and rangelands), increasing focus on efficiency in resource use ignored the complexity and dynamics of the ecosystem and optimized for single uses. This 'command and control' type of ecosystem management reduces variation in system behaviour, reduces natural resilience, and can lead to resource collapses, crises, and surprises (Holling and Meffe, 1996). The formation of a group of scholars with interests in ecosystem dynamics advanced the theory and practice of resilience as an alternative to the stability and command and control resource management paradigms (Folke, 2016). This group is today known as the Resilience Alliance.

The concept of resilience acknowledges the ability of people, communities, societies, and cultures to live and develop with dynamic environments (Folke, 2016). Resilience relates to the capacity to persist in the face of gradual and abrupt change and the ability to transform or adapt along new development pathways (Folke, 2016). Classically, resilience is defined as the amount of change a system can undergo (its capacity to absorb disturbance) and remain within the same regime – essentially retaining the same function, structure, and feedbacks (Walker and Salt, 2012). Central to resilience is the idea of social-ecological systems: that people are embedded in the biosphere and interact with it in multiple ways to shape ecosystems at local to global scales (Berkes and Folke, 1998). Social-ecological systems behave as complex adaptive systems because they can self-organize, are characterized by nonlinear dynamics, and can learn or adapt in response to changing conditions (Gunderson and Holling, 2002). Change is therefore an inherent characteristic of social-ecological systems and a key tenet of resilience (Biggs et al., 2015). This is particularly relevant with increased rates of change in human and environmental systems associated with the Anthropocene (Steffen et al., 2015).

The concept of resilience comprises several components that describe the dynamics of social-ecological systems: feedbacks, controlling variables, thresholds, regime shifts, and adaptive cycles. Much of the empirical basis of resilience is generated from studies of these components. In complex adaptive systems, changes in a particular variable, process, or signal because of a perturbation can lead to changes that create feedbacks to the original variable (Scheffer, 2009). Feedbacks can be amplifying (positive feedbacks) or dampening (negative feedbacks). The dynamics of a social-ecological system depend on the behaviour of feedbacks in response to the types and frequencies of perturbation (Chapin et al., 2009). The controlling variables involved in feedbacks can occur at different spatial and temporal scales. Slow variables influence system dynamics over years to decades. Fast variables respond quickly at daily, seasonal, or interannual timescales. Controlling variables set bounds on the possible configurations of a social-ecological system; and resilient systems are able to absorb perturbations and maintain structure, function, and feedbacks and therefore remain in the same state (Scheffer, 2009; Biggs et al., 2015). If a system becomes unable to absorb perturbations, a threshold (or tipping point) may be reached. Close to a threshold, perturbations that the system was once able to absorb may now push the ecosystem over a threshold to an alternative configuration, or state, with a different structure, function, and feedbacks (Scheffer, 2009).

System dynamics also depend on the changes that occur during critical phases of cycles of change (Chapin et al., 2009; Thapa et al., 2016). Adaptive cycles describe change as a cyclic process with four phases: exploitation, conservation, release, and reorganization (Gunderson and Holling, 2002). In the exploitation phase, the system is engaged in rapid growth to exploit available resources. Through the conservation phase, biomass gradually builds with energy and materials accumulating in the system. The release phase is triggered by an internal or external disturbance. In the release phase the biomass, energy, and materials stored in the system are released, providing a template for the reorganization phase. In the reorganization phase the ecosystem reorganizes into the same state or into a new configuration via an exit cycle. Cross-scale linkages occur among adaptive cycles, and adaptive cycles at different scales interact to form a panarchy (Gunderson and Holling, 2002). The cyclic movement of an ecosystem through the adaptive loop is linked to resilience, where a resilient system has the structural and functional diversity to move through cycles of release and reorganization without transforming to an alternative state (Gunderson and Holling, 2002).

Social-ecological systems do not respond passively to perturbation, feedbacks, and changes in controlling variables (Biggs et al., 2015). Adaptability is the capacity of human actors within a system to influence resilience, while transformability is the capacity to create a new system when changed conditions make the existing system untenable. In a contemporary industrialized world, many feedbacks between humans and their environment are negative, in that human actions cause reduced environmental integrity. Assuming that reductions in environmental integrity are considered undesirable, adaptability and transformability are the mechanisms of human behaviour available to influence ecosystem integrity (Brown and Westaway, 2011). Once a system has changed state into a new basin of attraction, it is difficult to return it to its previous basin of attraction (Chapin et al., 2009). However, the adaptability of actors in the system can help to maintain resilience in a system and prevent it from changing to an undesirable state. The transformability of actors can also promote change toward a more desirable state, either before or after state change.

Failure of technocratic command and control style resource management and the need to live within dynamic social-ecological systems has also incubated several resilience-based philosophies of natural resource management. These philosophies are sympathetic to complex adaptive systems and to the central role of human actors to adapt and transform to influence resilience. Adaptive management emphasises learning by doing and situates management activities as an ongoing, adaptive, and experimental process based on incremental learning (single-, double-, and triple-loop) and decision making, coupled with strategic monitoring of the impacts and outcomes of decisions (Holling, 1978; McLoughlin and Thoms, 2015). Variants of adaptive management include strategic adaptive management that seeks sustainability through a strategic and predictive process of learning and experimentation involving multiple stakeholders (Roux and Foxcroft, 2011) and adaptive comanagement that seeks sustainability through a multiscale and collaborative process of intentionally learning from experience (Chapin et al., 2009). The role of governance and institutions is also key to resilience because it supports society to adapt, shape change, and create new systems when existing conditions are untenable. Variants of governance include adaptive governance that involves active experimentation with institutional and political frameworks designed for change (Chapin et al., 2009) and polycentric governance in which multiple governing authorities organize across different levels of the policy process to deliberate and make decisions about common pool resources (Ostrom, 2010). Calls have also been made for transformative governance in which an agenda is framed collectively by stakeholders who then work toward achieving state change in social-ecological systems (Chaffin et al., 2016).

An important distinction must also be made between resilience as an approach and resilience as a property of systems (Fig. 1). As an approach, resilience is an overarching way of thinking about sustainability and stewardship — resilience thinking — which seeks to understand the world as a complex social-ecological system characterized by change and uncertainty. As a property, resilience is the capacity of a specific social-ecological system to continuously self-organize and adapt so as to withstand a regime shift (Folke, 2006; Scheffer, 2009; Standish et al., 2014). These capacities include mechanisms such as resistance, thresholds, drivers, feedbacks, diversity, and redundancy. Both meanings are often used interchangeably, although the former tends to apply in policy settings, while the latter is the basis for empirical studies of resilience.

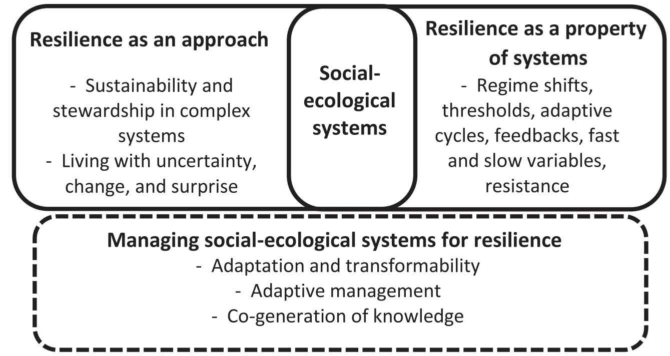

Fig. 1. Resilience as an approach versus resilience as a property of social-ecological systems. Resilience as an approach is about living in a world characterized by uncertainty, change, and surprise. Resilience as a property is about the mechanisms that allow a system to absorb disturbance without changing state. Managing for resilience in social-ecological systems requires actors to adapt and transform using learning-based, cooperative schemas.

2.2. Resilience applications

Resilience science is about the complexity of systems and their resilience, adaptation, and transformability in an uncertain and changing world. Many applications of resilience science exist, none of which are prescriptive, but all of which attempt to develop resilience-led solutions to a range of problems characterized by complexity, uncertainty, and multiple actors. In their book *Resilience Practice*, Walker and Salt (2012) neatly group the activities undertaken as part of resilience practice into three broad steps. First, describing the system involves bringing together stakeholders to determine the components that make up the system and how they are connected. Second, assessing resilience investigates the dynamics of the system by evaluating specified resilience (alternative states and thresholds), general resilience (diversity, modularity, feedbacks, openness, and capital), and transformability (options for change). Third, managing for resilience involves the development of an adaptive management and adaptive policy program in which interventions are considered as experiments. The book complements a set of workbooks to guide resilience assessment (Resilience Alliance, 2010).

Several case studies of resilience practice in natural resource management are outlined in Walker and Salt (2012). In Taos (New Mexico) and Bali (Indonesia), farming is supported by traditional, community-run canals (acequias) and terraced irrigation systems respectively. Population growth, urbanization, and globalization are changing this way of life. Understanding the resilience of these systems involves understanding their modular structure, governance, and cross-scale impacts (Walker and Salt, 2012). In Australia, the Namoi Catchment Management Authority adopted a resilience approach for land and water planning. Planning examined ecological, community, and farm viability thresholds and devised actions for managing water to stay above these thresholds (Walker and Salt, 2012). Understanding land and water planning through a resilience lens involved leadership, commitment, and time to bring stakeholders together to plan, reflect, and conduct follow-up activities (Walker and Salt, 2012). Further, Parsons et al. (2016a) examined how river monitoring and assessment programs could be updated to adopt a resilience perspective in which rivers are viewed as social-ecological systems, using indicators of adaptation, transformability, and thresholds.

Although the focus of *Resilience Practice* was on natural resource management, many other public policy and program areas are being developed through a resilience lens. One of the most prominent of these is disaster resilience. With genesis in the social sciences, rather than ecology, disaster resilience is interpreted as the ability of social systems to respond to and recover from disasters and to reorganize, change, and learn in response to a threat (Cutter et al., 2008). Disaster resilience is a dynamic process in which characteristics of communities and individuals (e.g., social capital, economic capital, governance, well-being) influence capacities for response, recovery, reorganization, and change (Norris et al., 2008). Resilience underpins approaches to disaster management in many jurisdictions worldwide. For example, Australia's National Strategy for Disaster Resilience (COAG, 2011) acknowledges the need to build resilience to natural hazards as a shared responsibility between individuals, governments, businesses, and communities. In the United States, the Strategic Foresight Initiative (FEMA, 2012) seeks to help the emergency management sector prepare for an uncertain future and acknowledges the centrality of fostering disaster resilient communities (NAS, 2012). The United Kingdom's National Security Strategy (UK Government, 2010) asserts how resilience is important for national prosperity in an age of uncertainty that includes natural disasters. Approaches are also being developed to assess and measure disaster resilience in the U.S. (Cutter et al., 2010; FEMA, 2016) and Australia (Parsons et al., 2016b). At an international level, the Sendai Framework for Disaster Risk Reduction aims to prevent new, and reduce existing, disaster risk (UNISDR, 2015). One of the goals of the framework is to invest in disaster risk reduction for resilience through structural and nonstructural measures because these are essential to enhance the economic, social, health, and cultural resilience of persons, communities, countries and their assets, as well as the environment (UNISDR, 2015).

Climate change adaptation is another area in which resilience is being adopted into policy and programs. Australia's National Climate Resilience and Adaptation Policy (Australian Government, 2015) proposes that a climate-resilient Australia supports prosperity and well-being by building the resilience of communities, the economy, and the environment to a variable and changing climate. The European Union Strategy on Adaptation to Climate Change (Climate-Adapt, 2017) ensures that adaptation is addressed in all relevant EU policies. The strategy addresses the need to incorporate climate resilience into health and social policies, agriculture and forests, biodiversity, ecosystems and water, coastal and marine areas, production systems, and physical infrastructure (Commission of the European Communities, 2009). Developing countries are also aligning resilience and climate change adaptation. For example, the Philippines established a Climate Change Commission to build countrywide climate change resilience (Philippines Climate Change Commission, 2017), and South Africa has developed an adaptation strategy with an aspirational goal to build resilience and adaptive capacity to respond to climate change risk and vulnerability (Government of the Republic of South Africa, 2016). Recognizing the disruptive influences that external shocks can have on food production, several countries have developed agricultural resilience research projects or government strategies including Myanmar, India, Vietnam, Nigeria, and Costa Rica (CCAFS, 2016).

Resilience is also emerging as a prominent goal of international development policy. In this field, resilience is being discussed or planned into frameworks, bureaucratic reforms, and programs to measure resilience (Brown, 2016). Resilience strategies have been adopted in developing countries subject to recent conflict or enduring poverty including South Sudan (FAO, 2016), Somalia (Somalia Joint Resilience Strategy, 2012), and Bangladesh (Staskiewicz and Khan, 2013). International development organizations, such as the Red Cross, also frame many approaches to development from a resilience perspective (IFRC, 2014).

Given that 54% of the world's population reside in urban areas, resilience has been applied as the guiding concept in urban planning and critical infrastructure protection. Resilience is part of the New Urban Agenda of the UN-Habitat Medellin Declaration on equity as a foundation of sustainable urban development (UN-Habitat, 2014). The privately- funded '100 Resilient Cities' program helps cities around the world become more resilient to the physical, social, and economic challenges that are a growing part of the twenty-first century. Central to the program is the appointment of Chief Resilience Officers (CROs) by participating cities. The CROs report to the city's chief executive but work across government departments and a wide array of stakeholders to lead the development of the city's resilience strategy and to ensure that a resilience lens is applied to the city's activities. A similar United Nations campaign called 'Making Cities Resilient: My City is Getting Ready' is focused on disaster resilience and is aligned with the implementation of the Sendai Framework for Disaster Risk Reduction (2015–2030) at the local level. Cities sign up to the program and use a toolkit of critical and independent steps to build and maintain resilience. The 10 steps are: organize for disaster resilience; identify, understand, and use current and future risk scenarios; strengthen financial capacity for resilience; pursue resilient urban development and design; safeguard natural buffers to enhance ecosystems' protective functions; strengthen institutional capacity for resilience; understand and strengthen societal capacity for resilience; increase infrastructure resilience; ensure effective disaster response; and expedite recovery and build back better. Thousands of cities have joined this program worldwide. Resilience is also used to guide critical infrastructure protection for public assets such as utilities (e.g., Victorian Government, 2016) and technological systems (e.g., The Scottish Government, 2015).

These examples of resilience application demonstrate how the resilience approach is being used in different contexts to live with, manage, and adapt to change, complexity, and uncertainty. These examples are not exhaustive and a resilience approach is also applied in other areas, including education (Victorian Government, 2017), human development and psychology (Masten and Obradovic, 2008), and economics and business (Fiksel, 2015). However, from these examples we make six general observations about the type, depth, and purpose of resilience emerging from these applications. First, applications of resilience occur across a wide range of disciplines, including natural resource management, disaster management, international development, and urban planning. Different sectors are applying resilience, including governments, businesses, and NGOs. Second, development of policy and programs with a resilience lens can occur in response to, or in preparation for, shocks such as natural disasters, climate change, or economic uncertainty. Third, resilience is applied using a range of paradigms— from the social science views applied in disaster management and international development to the social-ecological views applied in natural resource management. Fourth, resilience is applied into policy and programs at different depths — from perfunctory use of the word *resilience* to resilience as the central philosophy for all goals and activities. Fifth, the application of resilience into public policies and programs is new, emerging over the last decade. Sixth, as the adoption of resilience into public policy and programs is new, it is also innovative and requires understanding and commitment to the concept by different roles, including stakeholders, politicians, executives, policy makers, scientists, and agency staff. The uptake of resilience may be championed by individuals acting as boundary spanners or integrators across multiple stakeholders. Given the increasing recognition of the need to prepare for anticipated and unanticipated shocks, we predict that the adoption of resilience into public policy and programs will continue to grow over the next decade. Such growth raises questions about the conceptual cohesiveness of resilience in different policy and program settings and how applications of resilience can enhance understanding of complex systems and uncertainty. In the next section we discuss how the adoption of resilience might occur in river policy and programs and the factors that need to be considered to adopt robust resilience-based practice.

3. From concept to practice of resilience in river systems

3.1. The political economy of environmental science – a cautionary tale

We start this section with a cautionary tale about the uptake of science into public policy and programs. Many readers will be familiar with the so-called 'Rosgen Wars'. The field of stream restoration has expanded substantially in the U.S. in response to environmental legislation enacted in the 1960s and 1970s, with subsequent public demand and the emergence of a market for stream restoration (Lave, 2012). With no clear source for the basic knowledge, applications, and training needed to support the demand, Dave Rosgen's Natural Channel Design (NCD) emerged as the preferred approach to stream restoration (Lave, 2012). Natural channel design uses a classification system and reach-scale structures to design channels that align with fluvial geometries that are stable (Lave, 2012).

Restoring river ecosystems degraded by human activities is big business, worth billions of dollars annually. The market looks to NCD for its theory, applications, and training. Many stream restoration projects mandate the use of NCD and NCD-trained practitioners (Lave, 2012; Doyle, 2013). However, as NCD was becoming installed as the preferred approach to stream restoration in the U.S., a group of academics, agency scientists, and university-trained practitioners criticised Rosgen's work, arguing that his knowledge claims had 'no scientific basis, that he does not follow the norms of scientific practice, and that, far from restoring streams, his approach instead does considerable environmental damage' (Lave, 2012, p. 2). These criticisms were made in peer-reviewed journals, short courses, conferences, workshops, and design guidelines (Lave, 2012), but academic researchers were 'unable to move fast enough or communicate clearly enough to shape the practice of restoration and were left behind kicking and screaming in the pages of journal articles' (Doyle, 2013, p. 92).

The success of Rosgen's NCD approach within the stream restoration market was 'a symptomatic and early manifestation of the profound restructuring of scientific production under neoliberalism' (Lave, 2012, p. 3). Resonance between the NCD approach and the commercialization and privatization of knowledge under neoliberalism resulted in the success of the product and the collective fury of scientific opposition in 'profoundly relational ways' (Lave, 2012, p. 118). Instead of the conventional model of science being produced by scientists then circulated and applied by laypeople, the adoption of the NCD approach was reversed: science was produced, circulated, and applied outside of academia in a commercialized environment and then fed back into it to cause a shift in science practice toward applied work (Lave, 2012). Rebecca Lave portends that the 'Rosgen Wars' are not a fluke but 'presage a larger shift in the political economy of environmental science as a result of the intersection of the [United States'] increasingly neoliberal regime of science management and the particular character of environmental science itself' (Lave, 2012, p. 125). Examples from other science disciplines support her observations of the shifting position of scientific knowledge production and organization (Lave et al., 2010).

Readers interested in the issues of the political economy of environmental science are referred to Rebecca Lave's book *Fields and Streams* (Lave, 2012) and the special issue of Social Studies of Science (Lave et al., 2010). In the context of this paper, Lave's compelling analysis of stream restoration practice in the U.S. highlights the changing landscape of scientific legitimacy. Academic practice, traditionally held within universities and research institutes is being required —particularly in applied disciplines such as environmental science— to participate in an evolving and interdisciplinary knowledge system comprised of multiple legitimate users and producers of knowledge. Post-normal science is an approach for the use of science in issues where the facts are uncertain, values are in dispute, stakes are high, and decisions are urgent (Funtowicz and Ravetz, 1993). Post-normal science contends that the puzzle-solving exercises of normal science are no longer appropriate for the resolution of policy issues of risk and the environment (Funtowicz and Ravetz, 1993). While post-normal science has been adopted in various forms for decades (e.g., Pickett et al., 2007; Rogers et al., 2013), for others it is unfamiliar and threatening because in post-normal science 'hard' scientific inputs become inverted within a context where value commitments determine the success of environmental policies (Funtowicz and Ravetz, 1993). Post-normal science is applicable to most instances where the use of evidence is contested because of different norms and values. Thus, post-normal science resonates with problems encountered in applying resilience in river management: that of high system uncertainties and decision stakes with conflicting values.

3.2. Preparation meets opportunity – operationalising resilience in river systems

Rivers are extensively modified and are degraded because of various human activities, including flow modification, land use change, and pollution (Carpenter et al., 2011a). However, there is growing impetus for restoring rivers and recognition of the need to manage rivers as social-ecological systems (Poff, 2014; Parsons et al., 2017). The interaction between people and rivers in a social-ecological system also highlights elements of the complexity and uncertainty associated with river dynamics. The abundance of resilience-related public policy and programs outlined above supports the notion that resilience will form the basis of future river policies and programs. Associated with this future may be a marketization of elements of resilience science such as resilience assessment and monitoring, adaptive management, and multistakeholder river governance. Given this possible future scenario, how would the discipline of river science respond to a call for the adoption of resilience science into public policy and programs? Are there lessons that can be learned from the 'Rosgen Wars' about the legitimacy of different forms of knowledge and the model of post-normal science? In this section we offer six elements that need to be considered when designing and implementing resilience-based policy and programs in rivers (Fig. 2). These are presented in no particular order, and all carry equal weight in implementing resilience-based policy in rivers.

The first element to consider is that rivers are social-ecological systems. Sustainability is based on the principle that humans are part of ecosystems, giving rise to the term social-ecological systems (Berkes and Folke, 1998; Folke, 2006). Rivers are social-ecological systems because people depend on the resources provided by rivers, while river systems are influenced, to varying degrees, by human activities (Parsons et al., 2017). The social and ecological parts of river systems are linked through feedback mechanisms whereby actions in one part of the system can cause other parts of the system to adjust or adapt to changing conditions. Thinking about rivers as social-ecological systems challenges river science to see humans as embedded within river systems rather than external drivers of system processes (Ashmore, 2015). Social-ecological notions of working rivers, ecosystem services, adaptability, transformability, and the desirable state of rivers require consideration of human values, invoking a relativist paradigm in which knowledge exists in relation to society, culture, and experience (Ford, 2000). Many scientists, however, are trained and comfortable in a realist paradigm in which science seeks to find out about the real world and theorize truth (Ford, 2000). The framework of post-normal science (Funtowicz and Ravetz, 1993) can help river science to bridge the gap between realism and relativism.

Thinking about rivers as social-ecological systems also challenges river science to work closely with social science and the humanities in an interdisciplinary setting. While interdisciplinarity is an acquired skill, it is imperative that scientists do not make naïve interpretations of social systems nor that social scientists make naïve interpretations of biophysical systems. The social and natural sciences use different approaches, lexicons, and scholarship styles that influence the interpretation of resilience elements such as adaptation and feedbacks (Chapin et al., 2009; Downes et al., 2013; Olsson et al., 2015). However, there

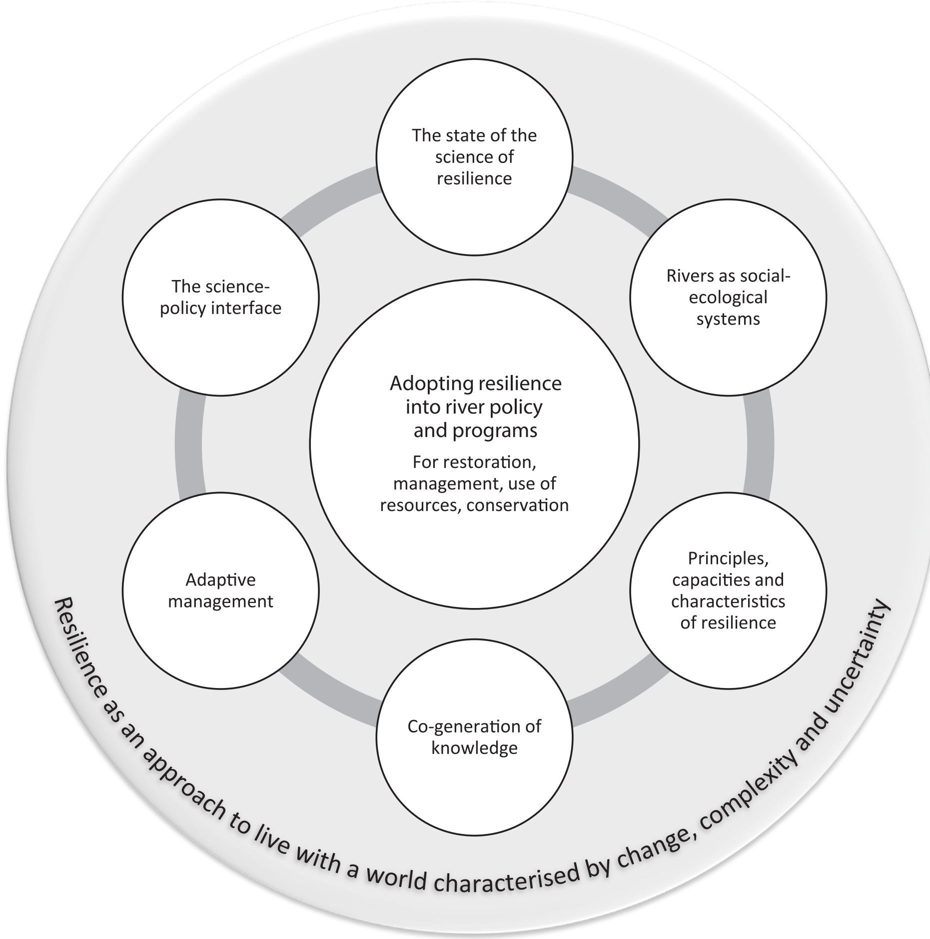

Fig. 2. Elements of resilience practice to consider when designing and implementing resilience-based policy and programs in rivers.

are also similarities between the social and natural sciences in objectivity, measurability, and exactness (Machlup, 1998). Thoughtful treatises for integrating social and natural science within a resilience context (e.g., Ostrom, 2007; Castree et al., 2014; Stone-Jovicich, 2015) can be used in river science to advance understanding of rivers as social-ecological systems.

The second element to consider when designing and implementing resilience-based policy and programs in rivers is the science-policy interface. Policy is implemented in the public domain through the functions and responsibilities of agencies, directed by relevant legislation or regulation. Despite policy makers and scientists working toward the same national interest —often one of sustainable rivers— both operate within a culture of differing philosophies, motivations, and rewards. Policy makers carry out the work of government by developing policies and programs that advance mandated issues, often under tight and unrealistic time constraints and in an environment of uncertainty (Gibbons et al., 2008). Policy makers must consider multiple stakeholders, identify policy options and the risks of those policy options, and minimize the criticisms of decisions and decision makers (Briggs, 2006). In contrast, scientists work to develop new knowledge, using established scientific principles of observation, testing, model development, and critical debate to maximize the certainty of their findings. Scientists may work alone on problems of their own choosing or may collaborate with others. While policy makers are rewarded for achieving policy outcomes, scientists are rewarded for achieving academic outputs such as peer-reviewed publications and student graduations (Briggs, 2006). As a result of such cultural differences, scientists often complain that policy makers make poorly informed decisions, and policy makers complain that scientists are out of touch (Gibbons et al., 2008). The implementation of resilience-based river policy and programs will require close collaboration between scientists (including natural and social scientists) and policy makers in navigating the policy process. However, scientists may not have familiarity with the processes of policy making, and policy makers may not have familiarity with river science or the science of resilience.

Effective communication, clear messaging, and relationship building can help bridge the river-science river-policy gap (Briggs, 2006). However, policy development and policy change processes are inherently complex and involve political, institutional, stakeholder, and community dimensions (Orach and Schlüter, 2016). Selecting and applying policy process frameworks to understand political decision-making is a first step in understanding the link between policy processes and the governance of social-ecological systems (Orach and Schlüter, 2016). Scientists also need to understand the policy cycle and the points at which interaction with the policy cycle can be most effective (Parsons et al., 2017). For example, scientists can have greatest input and influence during the evaluation, issue identification, policy analysis, and consultation phases of the policy cycle. Input is limited during the coordination, decision, and implementation phases of the policy cycle because these are largely parliamentary or congressional processes (Parsons et al., 2017).

The third element to consider in resilience for river policy and programs is the framing of principles, capacities, and characteristics of resilience. Resilience is a way of thinking about change in social-ecological systems and also a property that enables systems to persist (Biggs et al., 2015). The latter case is supported by a vast, and growing, literature about the components of resilience and the ways that these act in social-ecological systems to influence dynamics, persistence, and sustainability. Very few people could hope to be expert in all components of resilience across all disciplines. However, experts have been brought together to summarize the insights from the literature and identify principles for building resilience. Most recently, Biggs et al. (2015) identified seven principles for enhancing the capacity of social-ecological systems to produce desired sets of ecosystem services in the face of disturbance and change: maintain diversity and redundancy; manage connectivity; manage slow variables and feedbacks; foster complex adaptive systems thinking; encourage learning; broaden participation; and promote polycentric governance. Similarly, Folke et al. (2003) proposed four characteristics important in promoting resilience in social-ecological systems: learning to live with change and uncertainty; nurturing diversity for reorganization and renewal; combining different types of knowledge for learning; and creating opportunity for self-organization. In social systems, resilience is a dynamic process involving sets of capacities rather than an endpoint that a person or community achieves (Norris et al., 2008). In such systems, resilience may be summarized according to the characteristics or capacities within resilient communities. For example, disaster resilient communities can function under stress, are able to successfully adapt, and have self-reliance and social capital (COAG, 2011). Resilience cannot be captured by a single metric; however, the plural characteristics that make some systems more resilient than others can often be assessed (Hodgson et al., 2015; Quinlan et al., 2015).

These examples show how the theoretical and empirical evidence base of resilience (which is always progressing) can be distilled through the identification of key principles, characteristics, or capacities that contribute to system resilience. Identifying these gives policy and programs a schema which can be used to guide activities, assessments, research, communication, evaluation, and impact. It also allows the adoption of resilience approaches to proceed while the theoretical and empirical evidence develops: principles, characteristics, or capacities can be seen as working hypotheses that are tested through application in various policy and program settings. In river systems, it is likely that the seven principles identified by Biggs et al. (2015) for sustaining ecosystem services will be suitable for river policy and programs. However, the mechanisms of, for example, diversity, connectivity, slow and fast variables, and polycentric governance in river systems would need to be examined when applying these principles to rivers.

The fourth element to consider in resilience for river policy and programs is cogeneration of knowledge. This moves beyond the interdisciplinary research model in which disparate river-science disciplines cooperate (e.g., Gilvear et al., 2016). The production of knowledge in society is transforming between two modes. Mode 1 knowledge production is largely cognitive. Problems are proposed by a specific discipline and solved by disciplinary experts who disseminate information back into the discipline through hierarchical structures of peer review (Gibbons et al., 1994). In contrast, mode 2 emphasises the production of knowledge in a network of diverse actors from different disciplines, organized as a heterarchy, with problems proposed and resolved in the context of applications (Gibbons et al., 1994). The emergence of mode 2 knowledge production has coincided with the growth of complexity and uncertainty in society (Nowotny et al., 2001), the very dialogue that resilience thinking also seeks to address. Mode 2 science is contextualized by multiple participants, production of socially robust knowledge in which the public 'speaks back to science', and a changed, more fragmented, role of scientific and technical expertise (Nowotny et al., 2001). The 'Rosgen Wars', described earlier, mimic the turbulent transition from mode 1 to mode 2 science. Such a scenario needs to be avoided if river scientists are asked to input into resilience-based river policy and programs.

Participation is key to facilitating the collective action and knowledge required to live and develop with dynamic environments under a resilience perspective (Walker et al., 2002). Participation can range from information sharing, to stakeholder engagement, to complete devolution of power (Leitch et al., 2015). The socially robust knowledge production required under mode 2 can be addressed in river science through the use of participatory approaches that legitimize different types of knowledge. For example, action research is a reflective inquiry process that balances problem solving with collaboration. Action researchers partner directly with stakeholders, including communities, to embed and internalize resilience (Rogers et al., 2013). Participatory approaches can bridge indigenous and Western knowledge systems, provided issues of power and equity are addressed (Leitch et al., 2015; Johnson et al., 2016), and may also bridge academic boundaries between the arts, sciences, social sciences, and humanities. Social learning is another important element of the coproduction of knowledge because it facilitates the social mechanisms of knowledge production, regardless of the identity of participants (Chapin et al., 2009).

The fifth element to consider in resilience for river policy and programs is the applicability of adaptive management. The learning by doing basis of adaptive management is suited to complex systems because it acknowledges the uncertainties arising from system dynamics and the incompleteness of scientific knowledge (Chapin et al., 2009). Adaptive management adjusts to these constraints by applying management processes focused on reflexivity, experimentation, prediction, collaboration, and structured learning. In essence, adaptive management 'is about learning-by-doing in a scientific way, adapting behaviour and overall direction as new information becomes available' (Roux and Foxcroft, 2011, p. 1). Effective adaptive management occurs in cycles of activation, completion, and regeneration, facilitated by reflexive learning (McLoughlin and Thoms, 2015). Outcomes generated in these cycles also progress through single, double, and triple learning loops, facilitated by social and reflexive learning (McLoughlin and Thoms, 2015).

Although resilience is an approach to living with dynamic social-ecological systems, it does not have a strong operational and implementation procedure. Innovation, experimentation, and social learning are core processes of resilience and adaptation to change (Chapin et al., 2009). Adaptive management addresses these core processes and provides a method to implement resilience-based policy and programs in river systems. Doing adaptive management well is not easy, and there are major challenges in changing governance, organizational cultures, and institutional beliefs about knowledge production to be able to continuously refine how they operate within an adaptive management system (Fazey and Schultz, 2009). However, variants of adaptive management have been applied in river settings in South Africa (Pollard et al., 2011), Australia (Allan et al., 2009), and the U.S. (Hughes et al., 2007), suggesting that adaptive management should be an important consideration for the adoption of resilience into river policy and programs.

The sixth and final element to consider in resilience for river policy and programs is the state of the empirical science of resilience. Knowledge of the component parts of resilience in riverine or lake environments including thresholds (Schumm, 1979), adaptive cycles (Thapa et al., 2016), diversity and redundancy, and state changes (Carpenter et al., 2011b) is expanding. This suggests that empirical knowledge of river resilience undertaken at different scales can be used to progress resilience-based river policy and programs, particularly if combined with knowledge from other ecosystems as characteristics or principles (e.g., Biggs et al., 2015).

River science, and its component biophysical disciplines of hydrology, geomorphology, and ecology, is comfortable in the empirical domain of resilience. One of the potential pitfalls should there be a call to introduce resilience-based river policy and programs will be the tendency to revert to the empirical focus on systems data and evidence. There may be cries of 'we don't know enough about river system thresholds/feedbacks/disturbance/adaptive cycles/cross-scale linkages to advise with any confidence.' However, experience from policy development in other settings suggests that resilience-based policy will develop regardless of the state of the science. The challenge for river science will be to participate in the implementation of resilience into policy and programs while undertaking complementary research that adds to the empirical understanding of river resilience. Elements of adaptive management and cogeneration of knowledge support this duality because they engender principles of learning, experimentation, and continual knowledge review. Working alongside social scientists to understand rivers as social-ecological systems will also engender alternatives to the positivist practice of river science.

3.3. Operationalising the resilience approach in floodplain management

The concept of resilience resonates with the profound relationships humans have with river landscapes and provides a way to study, live with, manage, and adapt to global and local changes in these landscapes. We started this section with the cautionary 'Rosgen Wars' tale to demonstrate the complexities inherent in post-normal, mode 2 science. While we can only hypothesise what might occur in the operationalisation of a resilience approach to river policy and programs, the discipline of river science can prepare and, in doing so, avoid further 'Rosgen Wars' scenarios developing. In this section we provide a brief example of how the resilience approach might be operationalised in the specific area of floodplain management.

Floodplains are dynamic biophysical systems. The topography of floodplain surfaces is complex, arising from the presence of diverse physical features spatially arrayed in a multitude of patterns that may change over time (Thoms and Parsons, 2016). The environmental drivers of this surface complexity are poorly understood. However, the preliminary study of Scown et al. (2016) shows floodplain surface complexity to increase with increasing sediment yields but decline with increasing floodplain widths, irrespective of the scale of measurement. Inundation of floodplain surfaces creates a complex spatial and temporal mosaic of sediment, nutrients, vegetation, and other biota (Stanford et al., 2005; Southwell and Thoms, 2011). Floodplains exist in dry and wet states (Colloff and Baldwin, 2010; Thapa et al., 2016) and are associated with high productivity and biodiversity (Ward et al., 1999; Thapa et al., 2016). Floodplains are also highly valued for the provisioning, regulating, cultural, and supporting services they supply (Gren et al., 1995; Costanza et al., 1997; MEA, 2003). The intersection between the biophysical, utilitarian, and cultural values of floodplains also makes them centres of conflict because of the competing interests between using and conserving floodplain ecosystems. Worldwide, many floodplains are in decline in terms of their area, productivity, and ecosystem integrity (Tockner and Stanford, 2002; Nilsson et al., 2005) further exacerbating the conflict between competing floodplain management interests.

Crises in tradeoffs between competing interests may catalyse the adoption of resilience-based policy and programs for floodplain management. A well-developed resilience approach to floodplain management would encourage the adaptation and transformability required to manage dynamic floodplain landscapes toward a desired state that encapsulates multiple competing values and which maintains the properties important for resilience (Walker et al., 2002). The elements described earlier form a starting point for river science to engage with and contribute to the framing of resilience-based floodplain policy and programs. Under a resilience approach, floodplains should be considered as social-ecological systems with humans embedded as an intrinsic component of floodplains, not viewed as an external driver of floodplains.

Floodplain productivity supports economies and communities in many ways, but the extent to which the supply of ecosystem services can be traded against the environmental integrity that delivers those services is the subject of much debate (e.g., Rodrìguez and Beard, 2005). A resilience approach to floodplain policy would include mechanisms for cogeneration of knowledge among multiple disciplines, including social science, humanities, economics, politics, and the biophysical hydrology, geomorphology, and ecology disciplines of river science. Cogeneration of floodplain knowledge is not the sole domain of academic subject experts but should also legitimize the experiential floodplain knowledge of community groups, children, industries, and indigenous people. This type of socially robust ongoing knowledge cogeneration is required in resilience-based floodplain policy to ensure that decisions about floodplain resources do not privilege one demand at the expense of another, without consensus among all parties. Adaptive management provides a framework for experimenting with, and learning about, the trade-offs among competing floodplain uses (cf. Pahl-Wostl, 2009; McLoughlin and Thoms, 2015).

Empirical understanding of the biophysical properties of floodplain resilience would be a key contribution of river scientists in the development of resilience-based floodplain policy and programs. River science can provide knowledge about the capacity of floodplains to absorb disturbance without changing state and about the characteristics that confer resilience in floodplains. Data about thresholds, regime shifts, fast and slow drivers of change, and adaptive cycles will help to build the biophysical understanding of the capacities for floodplain resilience (cf. Thoms et al., 2017). Commensurately, other disciplines can build an evidence base of the social and economic capacities for resilience, thus completing the social-ecological picture.

4. Conclusions

This paper explored whether the discipline of river science would be ready to participate if, or when, resilience becomes a core premise of river policy and programs. The need to be unified has been demonstrated by responses to the marketization of stream restoration in the U.S. that resulted in winners and losers in knowledge production and application. While some river scientists are experienced and interested in mode 2 knowledge production and its characteristic interdisciplinarity, cogeneration of knowledge, and multiple values, others maintain a preference for mode 1 knowledge production. The adoption of resilience into public policy and programs privileges mode 2 knowledge production and the skills generated by working as a scientist in that domain. However, the empirical basis for resilience is somewhat better suited to mode 1 knowledge production. Both are necessary if resilience is to be adopted as an approach for river sustainability in the Anthropocene. Debate about resilience in rivers is part of the scientific method, but disciplinary disunity about the ways to approach resilience application in policy and programs may leave river scientists out of the policy process. Meanwhile, policy and programs using resilience approaches for sustainable futures will be developed and implemented by government and other agencies, regardless of the involvement of river scientists. River science needs to be prepared to argue and direct river resilience policy within the bounded reality of the science-policy interface.

The emergence of concepts of resilience in river science is in its infancy. In this paper we described six elements that should be considered in the operationalisation of resilience into river policy and programs (Fig. 2). None of these elements are new. They are drawn from the body of existing literature on resilience concepts and empirical analysis of those concepts. Each of these elements stands alone, but also have direct links between them so that in designing resilience-based river policy they should be thought of as a whole. Nonetheless, the elements represent a summary of considerations for river scientists —— either experienced or inexperienced in resilience to use as the basis for advising on policy and program direction and content. Given the unprecedented pressures on river systems, resilience concepts are an innovative approach to problems of river sustainability in the face of competing demands for water resources.

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