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Quantifying uncertainty and trade-offs in resilience assessments

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ABSTRACT. Several frameworks have been developed to assess the resilience of social-ecological systems, but most require substantial data inputs, time, and technical expertise. Stakeholders and practitioners often lack the resources for such intensive efforts. Furthermore, most end with problem framing and fail to explicitly address trade-offs and uncertainty. To remedy this gap, we developed a rapid survey assessment that compares the relative resilience of social-ecological systems with respect to a number of resilience properties. This approach generates large amounts of information relative to stakeholder inputs. We targeted four stakeholder categories: government (policy, regulation, management), end users (farmers, ranchers, landowners, industry), agency/public science (research, university, extension), and NGOs (environmental, citizen, social justice) in four North American watersheds, to assess social-ecological resilience through surveys. Conceptually, social-ecological systems are comprised of components ranging from strictly human to strictly ecological, but that relate directly or indirectly to one another. They have soft boundaries and several important dimensions or axes that together describe the nature of social-ecological interactions, e.g., variability, diversity, modularity, slow variables, feedbacks, capital, innovation, redundancy, and ecosystem services. There is no absolute measure of resilience, so our design takes advantage of cross-watershed comparisons and therefore focuses on relative resilience. Our approach quantifies and compares the relative resilience across watershed systems and potential trade-offs among different aspects of the social-ecological system, e.g., between social, economic, and ecological contributions. This approach permits explicit assessment of several types of uncertainty (e.g., self-assigned uncertainty for stakeholders; uncertainty across respondents, watersheds, and subsystems), and subjectivity in perceptions of resilience among key actors and decision makers and provides an efficient way to develop the mental models that inform our stakeholders and stakeholder categories.

Key Words: *coupled human-natural system; resilience assessment; social-ecological system; stressed watersheds*

INTRODUCTION

Resilience is a measure of the amount of perturbation or disturbance a system can withstand without crossing a critical threshold (Holling 1973). When such a threshold is exceeded, the system collapses and reorganizes. Reorganization can occur with the same driving variables and processes, in which case the original system renews, or the system can reorganize around a new set of variables and drivers in which case a new organization emerges, and quite often a very different system (Chaffin et al. 2016). When reorganization occurs around new drivers, the new system may be less desirable to humankind than the former system in terms of the provision of goods, services, and relative predictability. Therefore, it is often in managers and other stakeholders' interest to maintain systems in desirable states, avoid critical thresholds, and enhance resilience. Alternatively, when a system is undesirable, it may be necessary to erode resilience and purposely transform the system to a more desirable state (Chaffin et al. 2016). In either case, it is important to be able to assess, at least relatively, how resilient a system is, so that managers can either foster or erode resilience, depending upon the desirability of the current system state.

Resource managers often rely on the resilience, or the capacity, of a social-ecological system (SES) to absorb and respond to a disturbance while maintaining its essential structure and

functions (Holling 1973, Folke et al. 2002). A resilient system is useful to managers because it provides latitude in management options, and management is less likely to result in an unwanted regime change in a resilient, versus a nonresilient system. An improved understanding of the boundaries of resilience, i.e., the thresholds that separate one state of a system from alternative regimes, may help resource managers avoid or facilitate regime shifts so that desired ecosystem services are maintained or restored. Resilience in a complex system of people and nature has both ecological and social dimensions (Folke et al. 2002). Whereas ecological resilience is the magnitude of disturbance that an ecosystem can absorb before it shifts into a new regime, social resilience is the capacity of social systems to withstand and adapt to disturbances that result from social, political, or environmental changes (Adger 2000). Enhancing and maintaining resilience is increasingly identified as a management goal or strategy for projects focused on either ecosystems (e.g., Benson and Garmestani 2011, WWF 2012) or social systems (e.g., Godschalk 2003, Norris et al. 2008, Longstaff et al. 2010), but resilience is best understood as a product of both social and ecological, reinforcing, interactions. However, because of the different drivers in social and ecological systems, explicitly considering social versus ecological aspects of resilience can be useful and provide meaningful insight.

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Unfortunately, quantifying resilience is poorly developed (Angeler and Allen 2016). Many resilience assessment approaches are based on a gestalt regarding the resilience of the system, reliant on stakeholder inputs that envision the system of interest, dominant drivers, and a limited range of scales above and below the focal scale of interest (Angeler and Allen 2016, Quinlan et al. 2016), disregarding complex cross scale structure (Allen et al. 2014). With such approaches, quantitative assessments are difficult. However, advancing resilience science is important if the concept is to have utility and application for navigating a rapidly changing Anthropocene (Biggs et al. 2012, 2015).

Although several frameworks have been proposed for conducting resilience assessments (e.g., Walker et al. 2002, 2009, Resilience Alliance 2010, Biggs et al. 2015, Quinlan et al. 2016), the application of these techniques to real-world systems continues to be a challenge because of the highly dynamic and multidimensional nature of linked social-ecological systems (Berkel and Folke 1998, Walker et al. 2002). In addition, although some practitioners may find these or similar frameworks to be useful and appropriate (see Resilience Alliance 2013 for some case studies, <http://www.resalliance.org/resilience-analysis-practice>), others may want to conduct a resilience assessment but lack sufficient time or information to use the often detailed and time-consuming approaches inherent in existing frameworks. In addition, an important aspect missing from existing resilience assessments are measures of uncertainty, and measures that are useful to compare relative levels of resilience across similar systems. Assessing uncertainty will help understand the systems in question better and should improve management by identifying areas of knowledge deficit, allowing the design of adaptive interventions that can further enhance understanding of the system, enhance learning, and iteratively reduce key areas of uncertainty as revealed by analyses.

Uncertainty takes many forms (Williams 2001, 2011), as does its quantification and identifying key uncertainties through resilience assessments may provide insight into how assessments can be improved, how the system itself functions, and the potential for structured experimentation and learning, which in turn can reduce uncertainties (Allen et al. 2011, 2016a, Birge et al. 2016). Therefore, methods to assess uncertainty are critical for advancing resilience theory and for the application of resilience approaches to particular systems or challenges. We present and apply a simplified approach to resilience assessment that incorporates Walker and Salt's (2006) nine measures of resilience: ecological variability, diversity, modularity, acknowledgement of slow variables, tight feedbacks, social capital, innovation, overlap in governance, and ecosystem services.

An absolute measure of resilience has not been developed, is not likely to be developed, and may not be useful (Quinlan et al. 2016). Rather, there are two types of resilience assessments: the quantification of specific resilience, that is, the resilience of what, to what, and for whom (Carpenter et al. 2001), and general resilience of similar systems relative to one another (Nemec et al. 2013). We focus on the latter type of resilience assessment (relative resilience) to incorporate trade-offs and uncertainty. Quantitative approaches to resilience that also incorporate uncertainty, as we do, may provide new avenues to assess risk and vulnerability. Our empirical results are for illustrative uses only because our sample

sizes are small. Our analyses are not meant to capture the true resilience of these watershed-based systems, but are meant to illustrate the utility of the approach.

METHODS

Study area

River systems in water-stressed landscapes present some of the most challenging natural resource management issues facing the world today. Anthropogenic pressures have significantly altered river systems, affecting the provision of ecosystem services.

Our resilience assessment surveys were administered to stakeholders in the Anacostia, Columbia, Middle Rio Grande, and Platte River Basins, all located within the United States (U.S.), with the exception of the Columbia River Basin, which extends into Canada at its northern reaches. These watersheds were included in a SESYNC (National Socio-Environmental Synthesis Center) working group focused upon adaptive governance of stressed watersheds, and all share the basic similarities of being water stressed, greatly modified, the subject of intense management and frequent litigation, subject to adaptive management restoration efforts, and with unknown resilience.

The Anacostia River Basin encompasses 1140 km² of rural to urban land-cover types, including the District of Columbia, making it the most urban system of those assessed. Population density in the 1990 census was 2.66 persons/acre. As a result, questions surrounding the resilience of the Anacostia River Basin often focus on the social and ecological system's ability to withstand ongoing or increased pollution, runoff, and flooding. This is especially true in light of the complex institutional interactions that define the ability of social and ecological components to respond to disturbances related to water quality (Arnold et al. 2014).

The Columbia River Basin covers an area of roughly 670,000 km² and extends across large parts of Idaho, Washington, Oregon, British Columbia, and smaller parts of Wyoming, California, Nevada, and Utah. The basin includes largely rural landscapes, but also encompasses a handful of metropolitan areas including Portland, Oregon, Boise, Idaho, and Spokane, Washington, in which most of the Columbia Basin's six million human inhabitants reside (Cosens and Fremier 2014). In the Columbia River Basin, issues emerging from the intersection of climate change and water scarcity, characteristic of western river systems, include competition among hydropower, irrigation, flood control, ecological integrity, and other valuable social-ecological goods and services for dwindling water supplies (Cosens and Fremier 2014).

The Middle Rio Grande Basin encompasses roughly 8000 km² and is contained entirely in the U.S. state of New Mexico. Although sparsely populated through most of its extent, it contains the city of Albuquerque and a total population of 690,000 (Bartolino 2012). The resilience of the Middle Rio Grande River Basin generally concerns the ability of the social-ecological system to withstand ongoing human population growth and urbanization, biodiversity loss, and cyclical drought in the face of ongoing appropriation and climate change (Benson et al. 2014). Much like the other western water systems in our

Table 1. The nine properties of a resilient social-ecological system from Walker and Salt (2006), along with their definitions (adapted from Allen et al. 2016), and a survey question designed to address that property (asterisks represent definitions given to participants via hyperlinks).

Property	Definition	Example of Survey Question
1. Biological Diversity	The number and evenness of species, functional groups, and response to disturbance in the ecosystem	How would you assess the ecological diversity* of the basin?
2. Ecological Variability	Natural variability and fluctuations in ecological processes, structures, and populations	How would you assess the water flow variability of the basin?
3. Modularity	System components are connected to one another so that information is transferred effectively, but not so overly connected that shocks cause disproportionate damage	What would the impact be of a random loss of an institution on the basin as a whole?
4. Acknowledging Slow Variables	Incorporation of information about long-term outcomes that result from near-term decision making	How does the basin's governance acknowledge slow variables*?
5. Tight Feedbacks	Feedbacks among critical system components respond quickly allowing practitioners to avoid dangerous thresholds	How do decision makers in the basin understand information about the ecosystem?
6. Social Capital	It comprises the net sum of benefits generated from relationships among components in a system's social network	How would you assess trust among stakeholders in the basin?
7. Innovation	Degree of learning, experimentation, education, and locally developed rules to embrace change and creatively improve conditions	How would you assess grassroots governance efforts in the basin?
8. Overlap in Governance	Institutions have redundancy in their roles and responsibilities	How evenly is institutional power* distributed in the system?
9. Ecosystem Services	Essential and nonessential benefits people obtain from ecosystems	How would you assess the production of ecosystem services* from the basin?

study (Columbia and Platte), interstate water and/or energy compact obligations strongly interact with social-ecological components in the system.

The Platte River Basin drains an area of more than 23,000 km² extending across the U.S. states of Colorado, Nebraska, and Wyoming (Palmer 2006). In the Platte Basin, the population is disproportionately distributed among a few dozen medium (e.g., Kearney, Nebraska) to very large (e.g., Denver, Colorado) metropolitan areas, many of which are in the South Platte Basin, in which population is expected to double in the next 40 years, putting additional pressure on already over-appropriated water sources (CDLF 2010). Similar to other western basins, interstate water compacts and limited flows constrain the amount of water available for appropriation for endangered species, riverine wetlands, irrigation projects that generate power and recreation opportunities, downstream users entitled to flows, and other uses. Resilience in this system is therefore largely focused on the ability of the social-ecological system as a whole to withstand flow variability, specifically droughts, but also major floods, without any integral system component losing access to water and undermining the rest of the system (Birge et al. 2014).

Survey

We used a rapid prototyping approach (Nicolson et al. 2002) to score relative resilience by having stakeholders individually respond to a series of survey questions meant to probe different aspects of the social-ecological systems inferred to confer resilience, on a Likert scale of 1 to 5, with 1 being least resilient and 5 being most resilient (Table 1). Additionally, we rated the uncertainty of each resilience score on a scale of 1 to 5, i.e., low to high. The choice of metric for resilience assessment is important. We focus on social and ecological components, but incorporating components of critical infrastructure and explicitly incorporating economics may also be useful. Organizations such as the Resilience Alliance (<http://www.resalliance.org/>) have spent considerable time and resources in determining relevant aspects

of resilience. Although it would be appropriate for assessments to develop particular aspects, or axes, of resilience, we utilize a modification of those presented in Nemec et al. (2013), because they are both useful and illustrative. Our method is based on surveys of stakeholders in the social-ecological systems of interest and based on 26 questions focused on social and ecological aspects of resilience. The selection of particular variables (survey questions) is important and necessarily varies based on the systems of interest and the aspects of those systems that are important.

We surveyed government, researchers, end users, and NGOs within each of the four watersheds of interest to illustrate our methods for assessing relative resilience of the watersheds, trade-offs among social and ecological components of resilience, and uncertainty in the assessments. To identify participants, each of the basin research leads invited 40 people they identified as members of each of the 4 stakeholder groups (10 people per group) to participate in the survey using an institutional review board (IRB) approved email. When 10 people per group could not be identified, basin leads/the survey coordinators used search engines to locate additional participants. Potential participants were informed that they were identified as users belonging to certain groups by the basin leads, but that they could reassign themselves to other groups should they agree to participate. Names and email addresses of those who gave affirmative consent to participate were sent to the survey coordinator. Participants were then sent an email from the coordinators with informed consent, survey instructions, and an anonymous link to the survey, administered online using SNAP software.

In total, 200 (5 basins, 4 user groups each, 10 surveys per user group) surveys were administered, 30 were completed for a response rate of 15%. More than 30 responses were initiated with more than 1 question completed, but we only included fully completed surveys in our analyses.

Because we relied on interpersonal connections of academic researchers, there is bias toward participants who are already likely to engage with the material in the survey, and they may have lower uncertainty and stronger opinions than the population we hope our participants represent. Further, we used a search engine to identify NGO and end-user participants more than government and academic participants, potentially leading to a more random sampling of those groups. However, because our analyses were meant to explore a new methodology and not to draw inference regarding the user groups or the basins of interest *per se*, the bias in our participants does not affect the objective of our study.

Although social and ecological resilience are intertwined, we evaluated the properties for social and ecological resilience separately as well as in combination to provide a clearer assessment of the elements of resilience (Allen et al. 2003). Because not all of the properties applied to both kinds of resilience, we assessed eight with regard to social resilience and three for ecological resilience (Table 1). We concurred with Walker and Salt's (2006) creation of a property for ecological variability but not social variability because, as they defined it, variability refers to variability in the occurrence and magnitude of ecological phenomena, such as flooding and wildfire that do not have a social equivalent. Similar aspects of a system, such as social and cultural heterogeneity, are incorporated into the social diversity and social modularity variables. Likewise, the social properties of social capital, innovation, and overlapping governance do not have an ecological equivalent. We decided that slow ecological variables and tight ecological feedbacks are so closely related to ecological variability that these properties are encompassed by the ecological variability property, and ecosystem services are a social and not an ecological construct because they refer to the benefits that humans obtain from nature.

Within each of these 5 basins, we invited 40 survey participants that we identified as representatives of end users (farmer, rancher, and/or private citizen), state or federal government, nongovernment organizations, or research/extension stakeholder groups, but allowed respondents to reassign themselves at the outset of the survey to the stakeholder category with which they most closely identified. This, along with the survey hyperlink being nonspecific to user, and the collection of no identifiable information beyond stakeholder group and basin, assured that the anonymity of the participants was carefully preserved.

We sent consenting participants a hyperlink to an online questionnaire. The questions we included in the survey were designed to assess stakeholder perception and uncertainty concerning various aspects of their system's social-ecological resilience. Specifically, we designed our questionnaire to analyze stakeholders' assessments of Walker and Salt's (2006) nine properties of a resilient world, but within individual contexts (Table 1). We used a Likert scale of 5 points for the questionnaire, which included 25 content questions each followed by a question asking respondents to rank their level of certainty in their response to the previous question (see Appendix 1 for the full list of questions). Some definitions (e.g., modularity) were provided to respondents via hyperlinks embedded in the online survey (see Appendix 2 for definitions provided).

Our questions addressed both how different stakeholders from the five basins perceive the level of (1) biological (species,

response, and trait) diversity, (2) ecological variability, (3) modularity, (4) acknowledgement of slow variables, (5) feedback length, (6) social capital, (7) innovation, (8) overlap in critical social roles, and (9) ecosystem services provisioning in their social-ecological system. We asked stakeholders explicitly to assess these properties (i.e., "assess the ecological diversity in your system"), but also designed questions to address the properties for a stressed river basin context.

These nine resilience variables likely represent an incomplete and subjective list, but their use in prior assessments (e.g., Nemec et al. 2013, Allen et al. 2016b), ease of interpretation, and applicability across different systems lend them well to a rapid comparative approach and for uncertainty assessments, as we have done here. Practitioners should design their own survey questions based upon the context of their study.

Analysis

To assess resilience and uncertainty, we calculated the mean scores reported for each question by assigning values corresponding with the Likert score for each question (i.e., very high = 5, high = 4, moderate = 3, low = 2, very low = 1, etc.). To assess uncertainty, we calculated mean uncertainty across individual stakeholders as reported in the questionnaires (explicit uncertainty) as well as the degree of variance across both response to content questions and the explicit uncertainty (implicit uncertainty). Only completed surveys were included in our analysis.

Relative resilience is inferred from the total area under the curve in the radar plots of results (refer to Figs. 1-8), that is, by summing the individual axis scores. Ecological and social areas can be compared to assess trade-offs among different components of resilience. Relative resilience scores and degree of uncertainty can be compared among user groups and basins. Therefore, a suite of empirical results follows from our survey: relative resilience of each basin; the sum of the individual axis scores, and uncertainty therein; relative measures of resilience of individual axes, and uncertainty therein; relative resilience scores and their uncertainty for different user groups and for social versus ecological components; and trade-offs among axes of resilience, measured by the axes scores and in particular the relative strength of scores in relationship to one another. Additional measures are possible, as is the selection of different axes for measuring resilience.

RESULTS

We received completed responses ($n = 30$) from representatives of all four user groups and four watersheds (Figs. 1-9). Total resilience scores (the sum of average response to questions) was similar among NGO, end user, and government user groups, but markedly lower for research/extension respondents (Table 2.). Among river basins, respondents from the Anacostia reported the highest scores (Fig. 5), followed by Columbia, Platte, and Middle Rio Grande (Table 2).

No individual questions from the survey appeared to drive or diverge from total resilience trends across user groups, but research/extension respondents consistently reported lower average scores (Fig. 2). Variance in our assessment is meant as an index of implicit, group-level uncertainty. Although most user groups had relatively low variance relative to their mean resilience scores, there are departures from this trend for the end users in their responses to questions on flow variability, ecosystem services production, and trust among stakeholders. Spikes in variance

Fig. 1. Spider diagram showing average resilience scores for individual survey questions by user group.

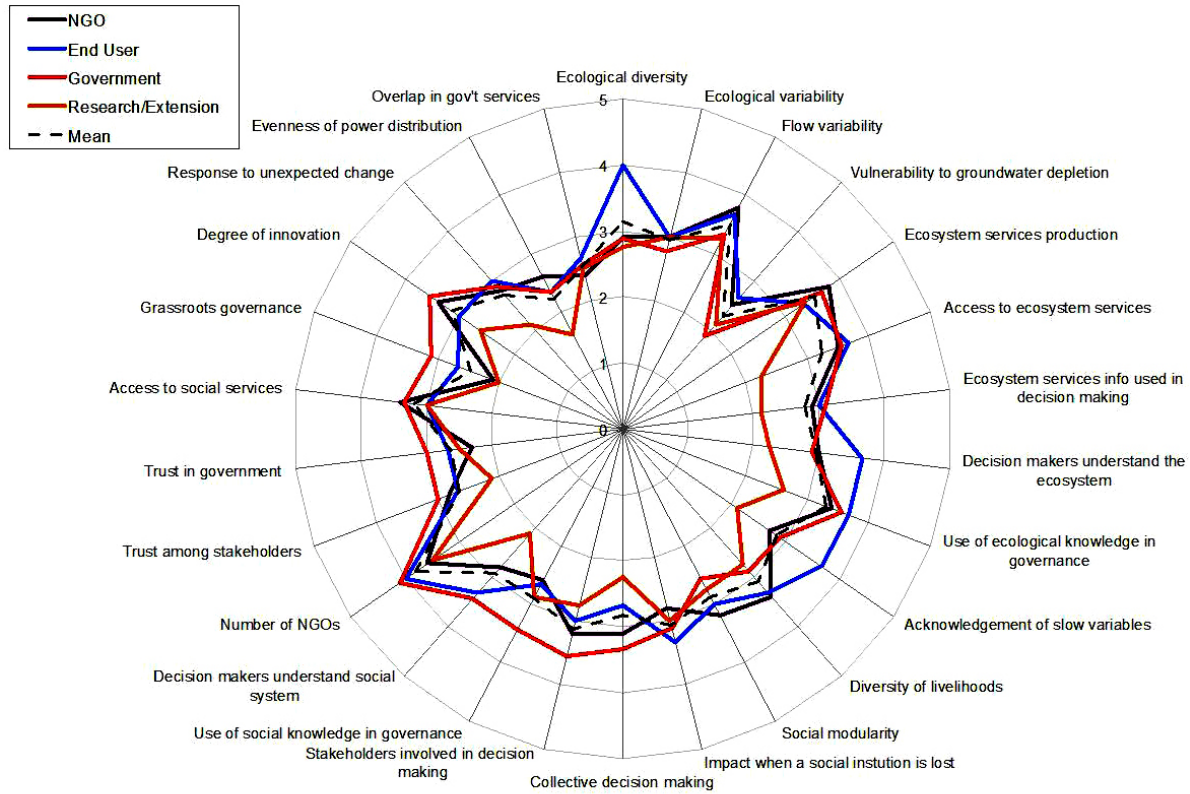


Fig. 2. Spider diagram showing variance in resilience scores for individual survey questions by user group.

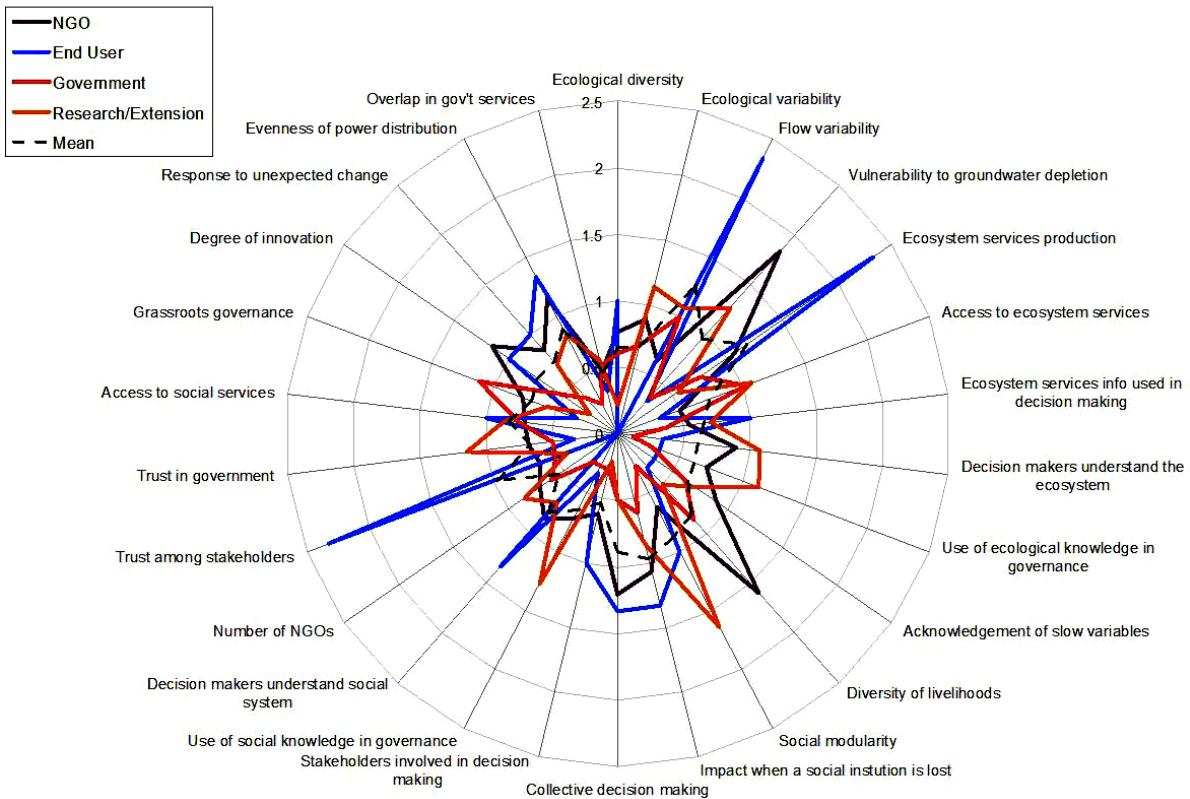


Fig. 3. Spider diagram showing average certainty in response for individual survey questions by user group.

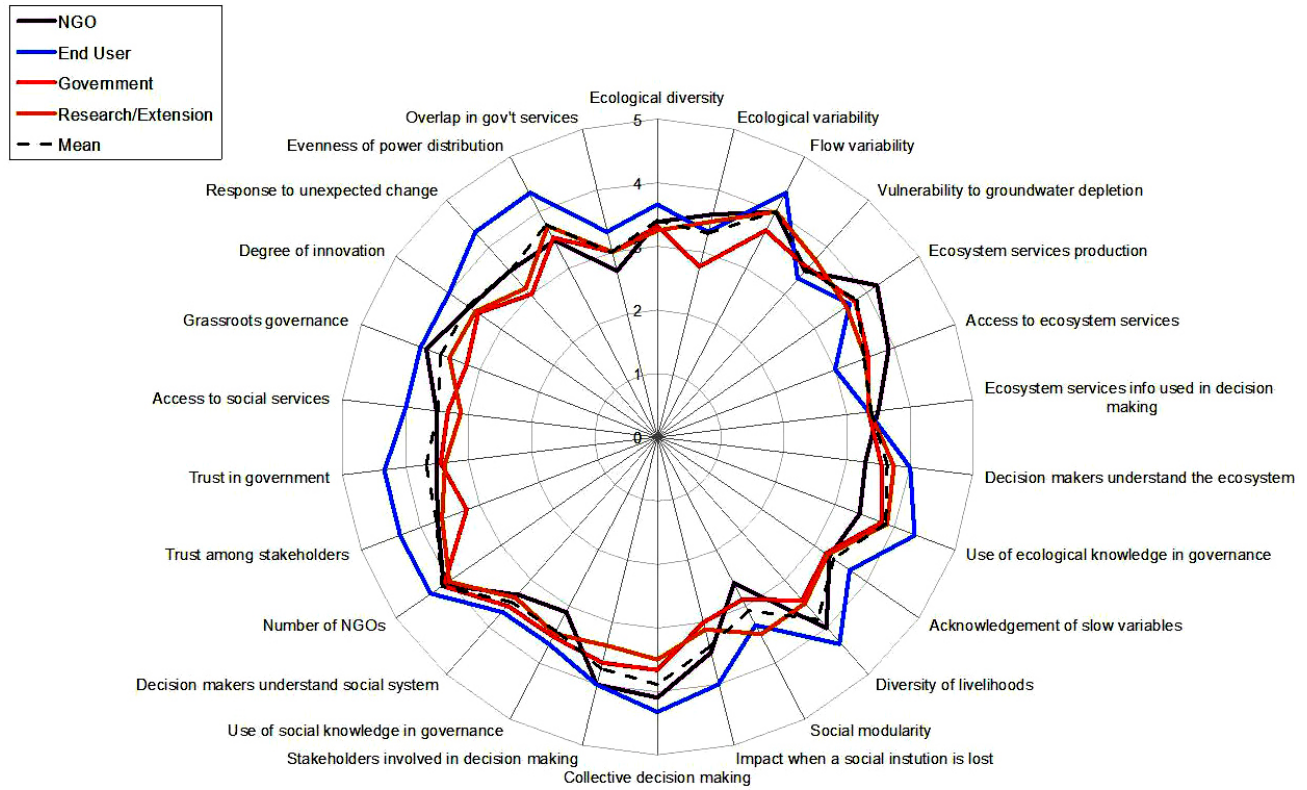


Fig. 4. Spider diagram showing variance in level of certainty for individual survey questions by user group.

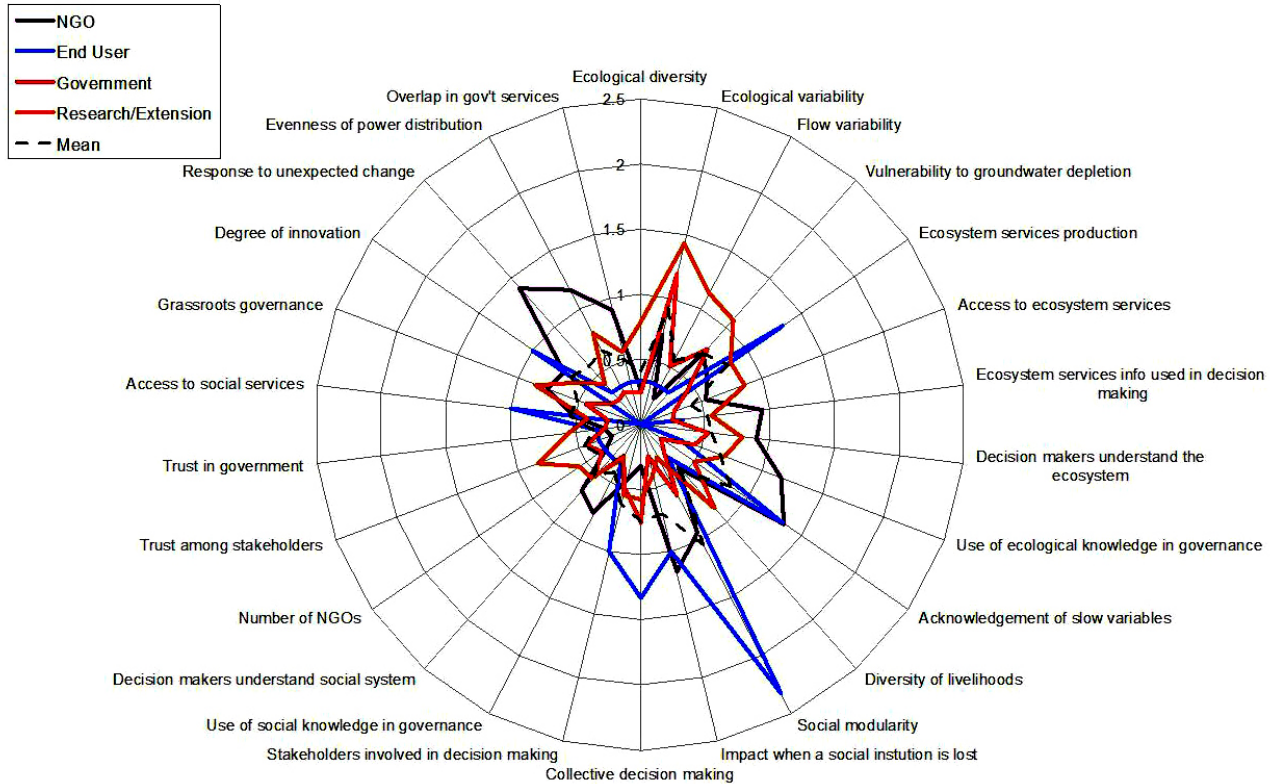


Fig. 5. Spider diagram showing average resilience scores for individual survey questions by watershed basin.

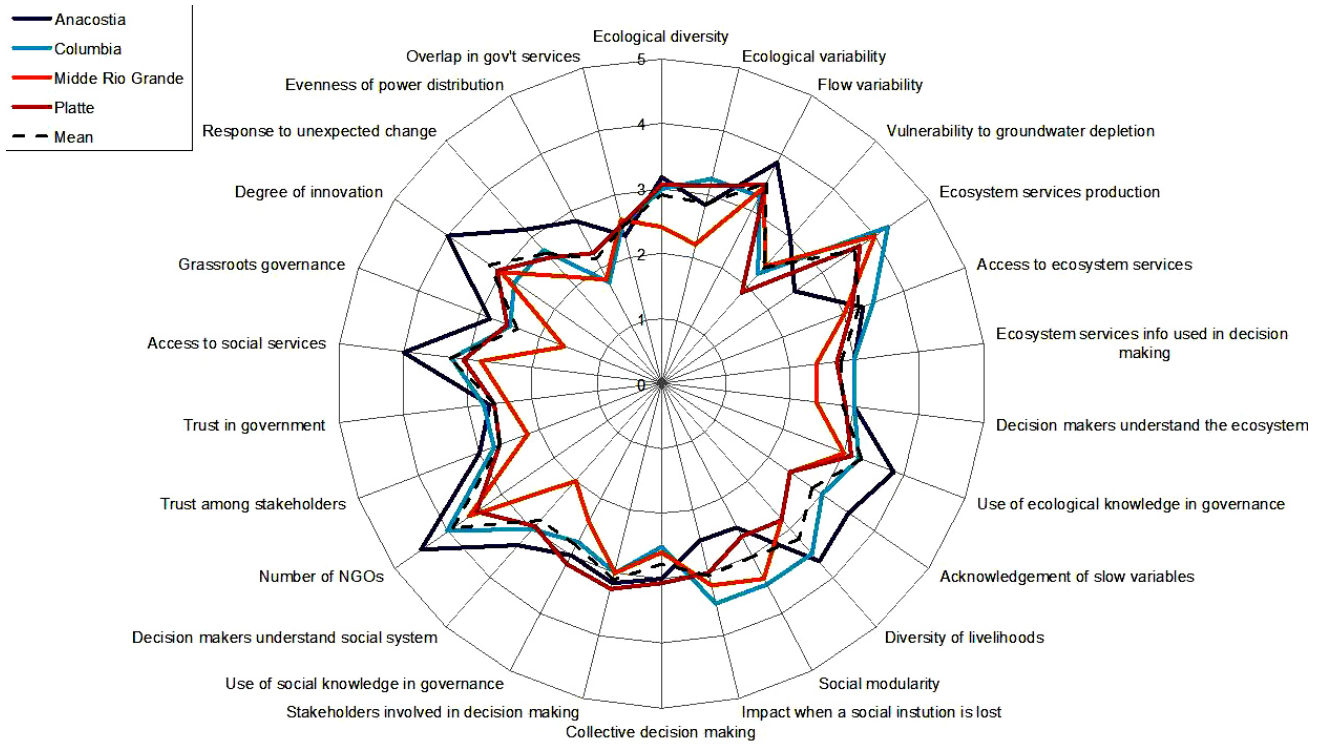


Fig. 6. Spider diagram showing variance in resilience scores for individual survey questions by watershed basin.

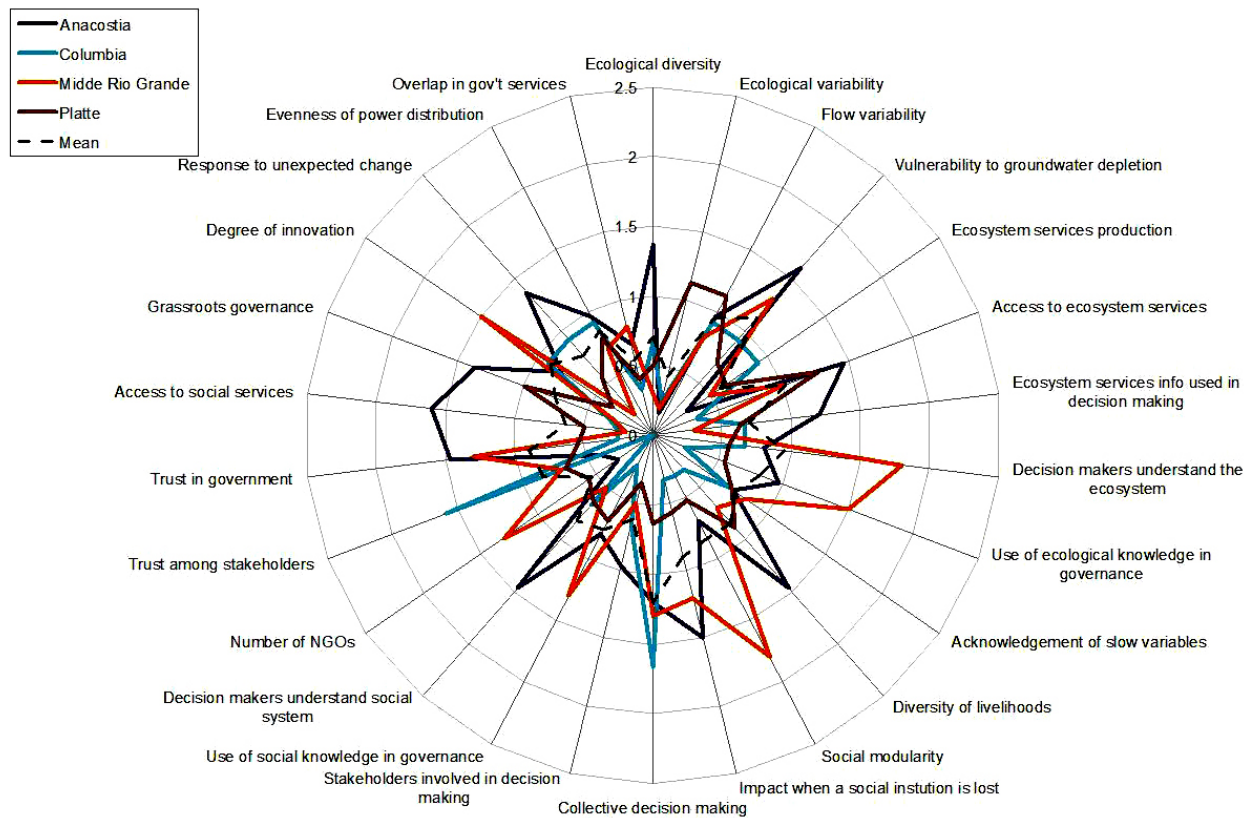


Fig. 7. Spider diagram showing average certainty in response for individual survey questions by watershed basin.

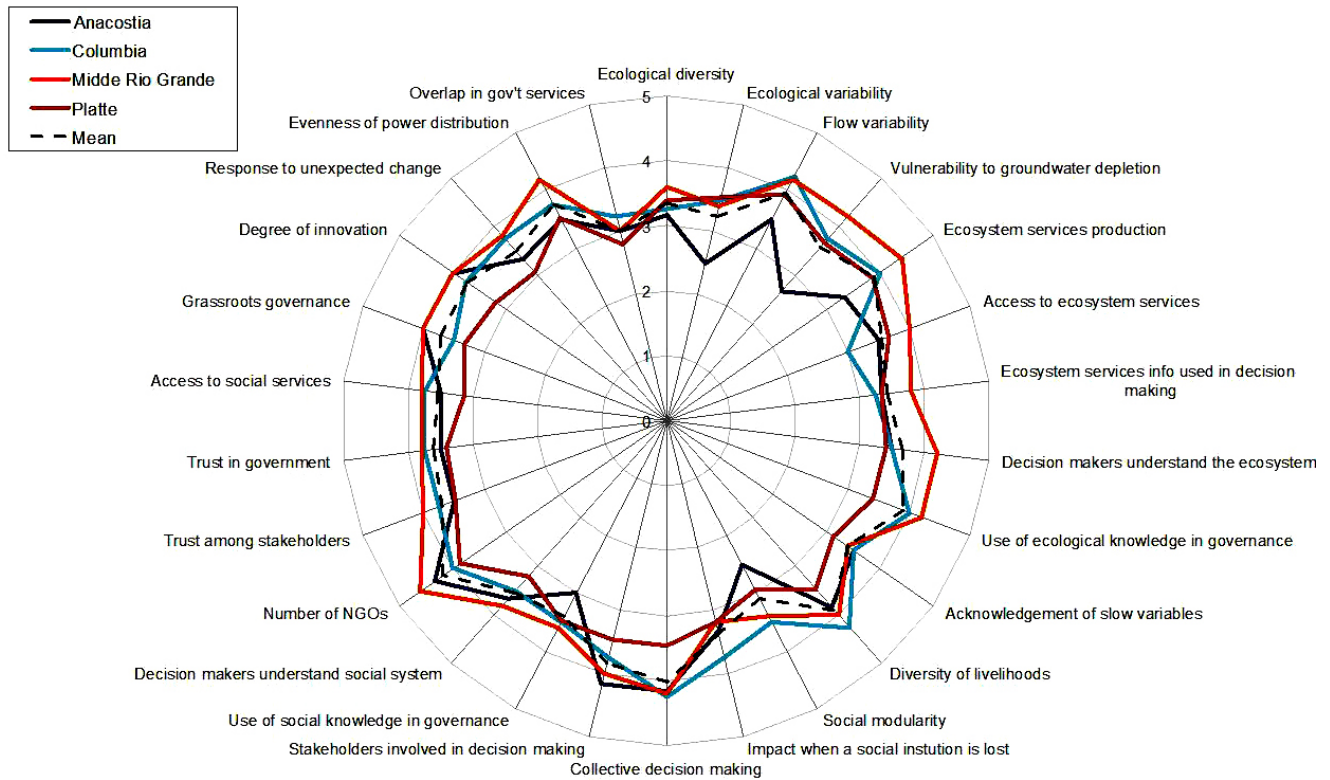
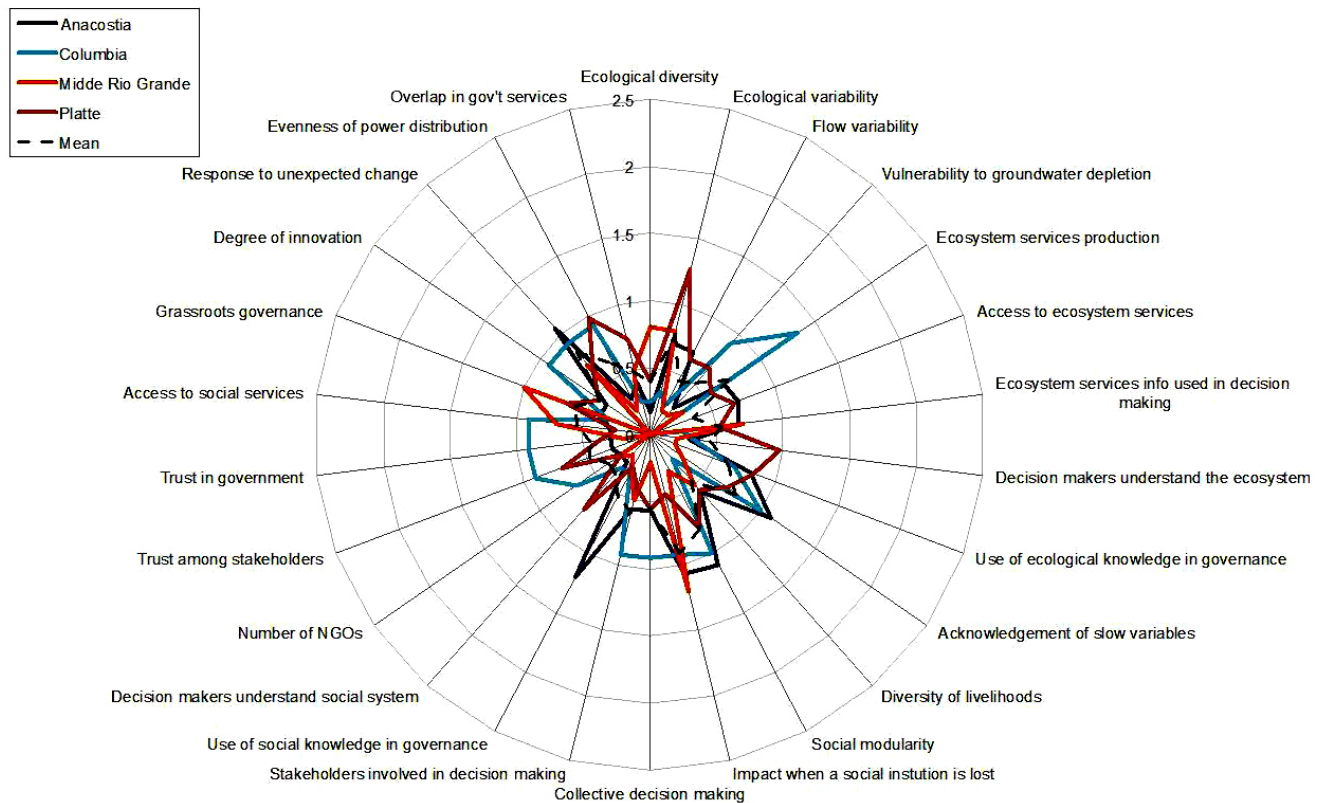


Fig. 8. Spider diagram showing variance in level of certainty for individual survey questions by watershed basin.



(Fig. 2) for some questions and user groups indicate uncertainty in those areas and opportunities for learning and further probing to determine the sources of uncertainty.

Fig. 9. Relationship between observed variance and user identified level of certainty.

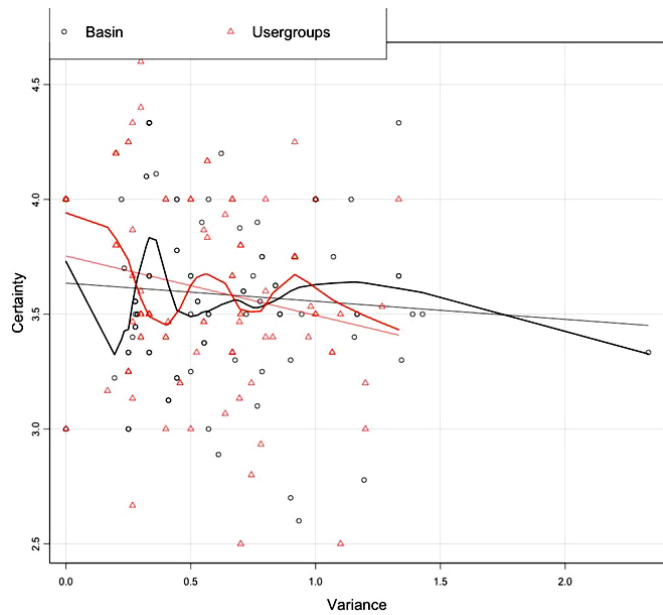


Table 2. Total resilience scores by user group and watershed.

	Total Resilience
Usergroup	
NGO	78
End User	81.7
Government	80.8
Research/Extension	66.5
Basin	
Anacostia	82.5
Columbia	78.5
Midle Rio Grande	69.2
Platte	75.2

In addition to this group level, implicit uncertainty (i.e., variance in responses), we asked respondents to report their self-assessed individual level of certainty in their responses (Fig. 3) as a second approach to quantify uncertainty. In our survey, self-assessed uncertainty varied relatively little and was moderate across all questions, although there appears to be more uncertainty in social and governance questions than for ecological questions. End users reported higher mean certainty in their responses; we also assessed variance in user identified uncertainty and found relatively low variance with interesting departures of high variance for some questions and user groups, particularly for social modularity among end users. (Fig. 4).

Resilience scores for each question across basins (Fig. 5) parallel total resilience scores (Table 2). However, it is noteworthy that the shape of the resilience scores in Figure 1 is rounder than that of

Figure 5, even though they draw from the same source data. This is perhaps reflected in the significantly higher variance, or implicit group level uncertainty in resilience scores across basins (Fig. 6). Individual uncertainty was also higher across basins (lower certainty scores; Fig. 7) than across user groups, but this difference is nominal and likely attributed to the redistribution of end users across basins in the former analysis. Similar to the pattern of variance across user groups, there was no discernible pattern of variance in level of response certainty by basin (Fig. 8).

When the variance of mean response to questions was plotted against certainty (i.e., group level uncertainty versus individual certainty), we expected a negative relationship. However, this relationship is weak (Fig. 9) and only significant ($P < 0.043$) when comparing variance versus certainty of user groups.

DISCUSSION

Quantifying absolute, general resilience of complex systems of people and nature is problematic, but assessing relative resilience and specific resilience (resilience of what to what) is a realistic goal that may provide useful tools for managers and policy makers, as well as other stakeholders. Furthermore, the search for better methods to quantify resilience will lead to greater understanding of the drivers of resilience in complex systems. We expanded upon the properties of resilience forwarded by Walker and Salt (2006) and modified by Nemec et al. (2013) to develop a straightforward survey of stakeholders in SES and approaches to quantify relative resilience (Nemec et al. 2013), trade-offs among social and ecological (or economic or infrastructure) components, and uncertainty. We addressed uncertainty in two ways: user self-assessment and analysis of variance within responses and across watersheds and user groups. Although we developed and implemented our survey simply to demonstrate the approach, with sufficient randomization and sample size, quantitative comparison of our metrics is straightforward, and amenable to analysis of variance or a number of similar approaches to determine if significant differences are present in responses, across basins or user groups.

It is clear that resilience in complex systems of people and nature encompasses both social and ecological components of the system. Furthermore, purely social components can be differentiated from economic components. Among social, ecological, and economic components, clear trade-offs are often apparent. For example, the Platte River Basin, encompassing nearly all of Nebraska and parts of Colorado and Wyoming, is a system that has been heavily altered by human activities (primarily agriculture), with extensive hydrological alteration of surface and groundwater in support of agriculture and development. In support of agriculture, and for other reasons including energy production, the Platte River itself has been dammed and hydrological variability greatly reduced. The riparian corridor has undergone a regime shift (Birge et al. 2014). Prior to damming, pulsing floods created bare sandbar habitat necessary for currently endangered least terns (*Sterna antillarum*) and piping plovers (*Charadrius melodus*). With damming, sandbars became vegetated and eventually armored by herbaceous and woody vegetation, and channels became reduced and incised. The riparian corridor, ecologically, is in an undesirable state with deep hysteresis. However, the social and economic aspects of the Platte Basin are highly desirable, and,

unconsciously at least, a decision has been made to sacrifice the ecological component in favor of the social and economic components (Birge et al. 2014). Such imbalance is likely to lessen overall resilience. Our described methods allow for assessing trade-offs in system subcomponents, which, in addition to social and ecological, could include economic and infrastructure components.

Identifying individual components of resilience that are weak or highly uncertain, either at high levels (ecological versus social, example above) or at the survey question (axis) level, should be beneficial for practitioners. Explicitly considering trade-offs and identifying the areas of highest uncertainty will allow for focus on those aspects or components in most need of intervention or further understanding. These types of results can also provide baseline information against which the success of interventions can be assessed over time. Time series data following interventions that affect resilience (e.g., Nemec et al. 2013) provides an especially valuable opportunity to assess trade-offs.

Resilience approaches are maturing, and better, objective, measures of resilience are being developed (Angeler and Allen 2016). It is critical that quantitative methods be developed to complement qualitative measures, especially given that the concept of resilience has expanded to mean many things to many people. Resilience can be considered a process (as in building resilience), a rate (as in return time following perturbation), or, most appropriately, as an emergent property of complex systems of people and nature. The latter definition avoids normative determinations and is appropriate for objective quantitative measures. Return time is also amendable to quantification, but return time is a stationary concept that also discounts the potential for thresholds to alternative regimes and is thus at best a partial measure of resilience (measuring transient behavior occurring below thresholds). Understanding sources of uncertainty is the first step in reducing that uncertainty over time, the ultimate goal for environmental management.

We presented a simplified approach for resilience assessment, which incorporates measures of resilience (Walker and Salt 2006). This approach was designed to reduce uncertainty in resilience assessments, as well as to compare the relative resilience of different, large-scale watersheds. We tested the approach on four watersheds in North America, using a rapid prototyping approach that generated responses from stakeholders in each of the respective watersheds. The results of the study are for illustrative purposes only, due to small sample sizes, but the results indicate that the approach has significant potential for assessing relative resilience, trade-offs, and uncertainty in complex systems of people and nature.

Responses to this article can be read online at:
<http://www.ecologyandsociety.org/issues/responses.php/9920>

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Resilience Questionnaire

Q1	To which stakeholder group do you most closely belong (please check only one)?	
	☐	Government (policy, regulation, management)
	☐	End User (farmer, rancher, private landowner, industry)
	☐	Agency/Public Service (research, university, extension)
	☐	NGO (environmental, citizen, social justice)

Q2	To which river basin do you belong?	
	☐	Anacostia
	☐	Columbia
	☐	Florida Everglades
	☐	Klamath
	☐	Middle Rio Grande
	☐	Platte

Q3a	How would you assess the ecological diversity of the basin?	
	☐	There is very low ecological diversity
	☐	There is low ecological diversity
	☐	There is moderate ecological diversity
	☐	There is high ecological diversity
	☐	There is very high ecological diversity

Q3b	How certain are you in your answer to question 3a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q4a	How would you assess the ecological variability in the basin?	
	☐	There is very low variability
	☐	There is low variability
	☐	There is moderate variability
	☐	There is high variability

	☐	There is very high variability
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Q4b	How certain are you in your answer to question 4a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q5a	How often are decisions made collectively in in the basin?	
	☐	Management decisions are never made collectively
	☐	Management decisions are rarely made collectively
	☐	Management decisions are sometimes made collectively
	☐	Management decisions are often made collectively
	☐	Management decisions are always made collectively

Q5b	How certain are you in your answer to question 5a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q6a	How would you assess stakeholder involvement in decision-making?	
	☐	No stakeholder interests/perspectives are incorporated into decision-making.
	☐	Few stakeholder interests/perspectives are incorporated into decision-making
	☐	Some stakeholder interests/perspectives are incorporated into decision-making.
	☐	Many stakeholder interests/perspectives are incorporated into decision-making
	☐	All stakeholder interests/perspectives are incorporated into decision-making

Q6b	How certain are you in your answer to question 6a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat Certain

	☐	Certain
	☐	Very Certain

Q7a	How would you assess the diversity of livelihoods in the basin?	
	☐	The social system has a very low diversity of livelihoods
	☐	The social system has a low diversity of livelihoods
	☐	The social system has a moderate diversity of livelihoods
	☐	The social system has a high diversity of livelihoods
	☐	The social system has a very high diversity of livelihoods

Q7b	How certain are you in your answer to question 7a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q8a	How would you assess the water flow variability of the rivers and wetlands in the basin?	
	☐	The rivers and wetlands in the basin have very low variability
	☐	The rivers and wetlands in the basin have low variability
	☐	The rivers and wetlands in the basin have moderate variability
	☐	The rivers and wetlands in the basin have high variability
	☐	The rivers and wetlands in the basin have very high variability

Q8b	How certain are you in your answer to question 8a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q9a	How would you assess the vulnerability of streams and wetlands to further groundwater depletion?	
	☐	Groundwater inputs to the streams and wetlands have very low vulnerability to groundwater depletion
	☐	Groundwater inputs to the streams and wetlands have low vulnerability to groundwater depletion
	☐	Groundwater inputs to the streams and wetlands have moderate vulnerability to groundwater depletion

	☐	Groundwater inputs to the streams and wetlands have high vulnerability to groundwater depletion
	☐	Groundwater inputs to the streams and wetlands have very high vulnerability to groundwater depletion

Q9b	How certain are you in your answer to question 9a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q10a	How would you assess the social <u>modularity</u> of the basin?	
	☐	Economic, political, and social institutions have very low modularity
	☐	Economic, political, and social institutions have low modularity
	☐	Economic, political, and social institutions have moderate modularity
	☐	Economic, political, and social institutions have high modularity
	☐	Economic, political, and social institutions have very high modularity

Q10b	How certain are you in your answer to question 10a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q11a	How would you assess the social impact on other institutions/the system as a whole when an institution is lost from the basin?	
	☐	The elimination of any one institution has a very low impact on other institutions and/or the system as a whole
	☐	The elimination of any one institution has a low impact on other institutions and/or the system as a whole
	☐	The elimination/impairment of any one institution has a moderate impact on other institutions and/or the system as a whole
	☐	The elimination/impairment of any one institution has a high impact on other institutions and/or the system as a whole
	☐	The elimination/impairment of any one institution has a very high impact on other institutions and/or the system as a whole

Q11b	How certain are you in your answer to question 11a?	
	☐	Very uncertain
	☐	Uncertain

	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q12a	Does the basin's governance acknowledge slow variables?	
	☐	Slow variables are never acknowledged in the governance of the system
	☐	Slow variables are rarely acknowledged in the governance of the system
	☐	Slow variables are sometimes acknowledged in the governance of the system
	☐	Slow variables are often acknowledged in the governance of the system
	☐	Slow variables are always acknowledged in the governance of the system

Q12b	How certain are you in your answer to question 12a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q13a	Is information about the ecosystem incorporated into the basin's governance?	
	☐	Information about the ecosystem is never incorporated into the basin's governance
	☐	Information about the ecosystem is rarely incorporated into the basin's governance
	☐	Information about the ecosystem is sometimes incorporated into the basin's governance
	☐	Information about the ecosystem is often incorporated into the basin's governance
	☐	Information about the ecosystem is always incorporated into the basin's governance

Q13b	How certain are you in your answer to question 13a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q14a	Do decision-makers in the basin understand information about the ecosystem?	
	☐	Decision-makers never understand ecosystem feedbacks, identify potential thresholds, or respond to change

	☐	Decision-makers rarely understand ecosystem feedbacks, identify potential thresholds, or respond to change
	☐	Decision-makers sometimes understand ecosystem feedbacks, identify potential thresholds, or respond to change
	☐	Decision-makers often understand ecosystem feedbacks, identify potential thresholds, or respond to change
	☐	Decision-makers always understand ecosystem feedbacks, identify potential thresholds, or respond to change

Q14b	How certain are you in your answer to question 14a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q15a	Is information about the social system incorporated into the basin's governance?	
	☐	Information about the social system is never incorporated into the governance of the system
	☐	Information about the social system is rarely incorporated into the governance of the system
	☐	Information about the social system is sometimes incorporated into the governance of the system
	☐	Information about the social system is often incorporated into the governance of the system
	☐	Information about the social system is always incorporated into the governance of the system

Q15b	How certain are you in your answer to question 15a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q16a	Do decision-makers understand social information in the basin?	
	☐	Decision-makers never understand social system feedbacks, identify potential thresholds, or respond to change.
	☐	Decision-makers rarely understand social system feedbacks, identify potential thresholds, or respond to change.
	☐	Decision-makers sometimes understand social system feedbacks, identify potential thresholds, or respond to change.
	☐	Decision-makers often understand social system feedbacks, identify potential thresholds, or respond to change.
	☐	Decision-makers always understand social system feedbacks, identify potential thresholds, or respond to change.

Q16b	How certain are you in your answer to question 16a?	
	☐	Very uncertain

	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q17a	How many non-governmental groups are there in the basin?	
	☐	Very few groups exist
	☐	Few groups exist
	☐	Some groups exist
	☐	Many groups exist
	☐	Very many groups exist

Q17b	How certain are you in your answer to question 17a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q18a	How would you assess trust among stakeholders in the basin?	
	☐	There is very little trust among stakeholders
	☐	There is little trust among stakeholders
	☐	There is moderate trust among stakeholders
	☐	There is high trust among stakeholders
	☐	There is very high trust among stakeholders

Q18b	How certain are you in your answer to question 18a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q19a	How would you assess trust in government institutions in the basin?	
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	☐	There is very little trust in government institutions
	☐	There is little trust in government institutions
	☐	There is moderate trust in government institutions
	☐	There is high trust in government institutions
	☐	There is very high trust in government institutions

Q19b	How certain are you in your answer to question 19a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q20a	How would you assess access to social services in the basin?	
	☐	A very small subset of society has access to social services
	☐	A small subset of society has access to social services
	☐	A moderate subset of society has access to social services
	☐	A large subset of society has access to social services
	☐	All of society has access to social services

Q20b	How certain are you in your answer to question 20a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q21a	How would you assess grassroots governance efforts in the basin?	
	☐	There is very little grassroots governance
	☐	There is little grassroots governance
	☐	There is moderate grassroots governance
	☐	There is high grassroots governance
	☐	There is very high grassroots governance

Q21b	How certain are you in your answer to question 21a?	
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	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q22a	How would you assess the degree of <u>innovation</u> in the basin?	
	☐	There is very little innovation
	☐	There is little innovation
	☐	There is moderate innovation
	☐	There is high innovation
	☐	There is very high innovation

Q22b	How certain are you in your answer to question 22a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q23a	How does the governance of the system respond to unexpected change in the basin?	
	☐	Change is never embraced
	☐	Change is infrequently embraced
	☐	Change is sometimes embraced
	☐	Change is often embraced
	☐	Change is very often embraced

Q23b	How certain are you in your answer to question 23a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q24a	How evenly is <u>institutional power</u> distributed in the system?	
	☐	Power is very unevenly distributed
	☐	Power is unevenly distributed
	☐	Power is moderately evenly distributed
	☐	Power is evenly distributed
	☐	Power is very evenly distributed

Q24b	How certain are you in your answer to question 24a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q25a	How would you assess overlap in essential government services?	
	☐	There is very little overlap in essential governance services
	☐	There is little overlap in essential governance services
	☐	There is moderate overlap in essential governance services
	☐	There is high overlap in essential governance services
	☐	There is very high overlap in essential governance services

Q25b	How certain are you in your answer to question 25a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q26a	How would you assess the production of ecosystem services from the basin?	
	☐	The river and the wetlands produce a very low amount of ecosystem services
	☐	The river and the wetlands produce a very low amount of ecosystem services
	☐	The river and the wetlands produce a moderate amount of ecosystem services
	☐	The river and the wetlands produce a high amount of ecosystem services
	☐	The river and the wetlands produce a very high amount of ecosystem services

Q26b	How certain are you in your answer to question 28a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Q27a	How often is the generation of ecosystem services incorporated into management decision?	
	☐	The generation of ecosystem services is never incorporated into management decisions
	☐	The generation of ecosystem services is rarely incorporated into management decisions
	☐	The generation of ecosystem services is sometimes incorporated into management decisions
	☐	The generation of ecosystem services is often incorporated into management decisions
	☐	The generation of ecosystem services is always incorporated into management decisions

Q27b	How certain are you in your answer to question 29a?	
	☐	Very uncertain
	☐	Uncertain
	☐	Somewhat uncertain
	☐	Somewhat certain
	☐	Certain
	☐	Very certain

Definitions guide

1. **Ecological Diversity:** The variety of species, functions, and interactions, e.g., the number of species in the ecosystem.
2. **Variability:** Fluctuations in space and time, e.g., the range of flow rates for the river.
3. **Groundwater depletion:** Long term declines in the level of groundwater due to sustained overuse
4. **Modularity:** The degree to which different parts of the river basin function independently, e.g., river flow rate is independent of deer population growth rate.
5. **Slow variables:** Parts of the watershed that change at a very low rate/over long time periods, e.g., soil health.
6. **Innovation:** The creation of new technology, ideas, institutions, and rules based on learning and experimentation, e.g., creation of new precision irrigation technology.
7. **Overlap in governance:** Multiple government institutions share responsibilities, e.g., federal and state agencies are both responsible for the management of endangered species.
8. **Ecosystem services:** Flows of goods and services from ecosystems that provide some (often unpriced) benefit to society, e.g., drinking water, recreation on rivers.