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Graeme S. Cumming
Percy FitzPatrick Institute, DST/NRF Centre of Excellence, University of Cape Town, Rondebosch, Cape Town, South Africa, 7701
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The resilience of big river basins

Graeme S. Cumming*

Percy FitzPatrick Institute, DST/NRF Centre of Excellence, University of Cape Town, Rondebosch, Cape Town, South Africa 7701

Big river basins are complex systems of people and nature. This article explores the resilience of nine case studies of big river basins. A system description and generic conceptual model suggests that resilience to changes in water quantity is critical. When water becomes limiting, the social-ecological system must adapt rapidly if key elements (for example, communities, biodiversity) are to be maintained. Water limitation imposes a water economy and alters political and institutional links between actors. Pro-active management for resilience demands politically acceptable participatory processes that use the best possible science and incorporate social, ecological and economic elements in problem definition and solution.

Keywords: complexity; sustainability; social–ecological system; ecosystem services; governance; poverty

Introduction

This paper explores the central issues relating to ecosystem services and human wellbeing in a set of 10 big river basins from around the world. Each basin has important social, economic and ecological elements; each can be considered a social–ecological system (SES), a linked system of people and nature. As the preceding papers make abundantly clear, the big river basins in this set of case studies are similar in some important ways and different in other, equally important ways. They all face big challenges in the future, including problems that are global in nature (such as climate change and human population expansion) and problems that are more localized (such as regional conflict or inequities). From both analytical and management perspectives, it is important to understand the ways in which what has happened in one basin can inform our understanding of other basins. Can we learn from comparisons between these basins whether, and how, they will be able to cope effectively with what the future holds for them? And more specifically, can analysis of their current strengths and weaknesses identify possible pitfalls or pro-active strategies through which additional coping ability could be built?

As with any comparative analysis, answering these questions requires a level of generalization. Generalization in turn requires reference to a set of underlying concepts that can be used to identify commonalities between systems that are superficially quite different. There are many different ways in which such an analysis could be framed,
and no single guide (aside from eventual utility) as to which framing is best. Traditional approaches to the problems of big river basins have tended to approach specific issues from a disciplinary perspective. For example, the allocation and efficiency of water use have been major themes in assessing the economics of river basin management (for example, Rosegrant et al. [2000]). While traditional approaches often provide essential information about individual aspects of a broader problem, they also make a large number of assumptions about the constancy of causal relationships, the prevalence of linear relationships, and the structure of the study system. The accuracy of standard scientific predictions is heavily contingent on things remaining as they are (Clark et al. 2001). In the context of river management, which includes high levels of uncertainty in many social and ecological parameters, conventional approaches to minimizing risks are quite likely to be sub-optimal (Clark 2002). Furthermore, the real world includes “messy” details like pushy stakeholders, political processes, technological change and feedbacks between science and human behaviour (Ludwig 2001, Stirling 2003, Waltner-Toews et al. 2003).

Big river basins are similar to many other systems of people and nature in that they involve a set of complex, “wicked” interactions and non-linear feedbacks. They are united by a shared biophysical component – water – which flows directionally along a well-defined gradient. Human societies have in many cases organized themselves around and along this gradient, with predictable variation in human-dominated components of the system (for example, income or city size) often occurring from headwaters to estuaries. The inescapable importance of environmental gradients, and the heavy reliance of human communities in a basin on a single resource (water), are probably the unique features of big river basins that distinguish them from other social–ecological systems.

A number of approaches to thinking about “wicked problems” in complex systems exist (e.g., Holling 2001, Norberg and Cumming 2008, Waltner-Toews et al. 2008, Ostrom 2009). The approach that I will take focuses on the idea of resilience (Holling 1973, Holling 2001), and particularly on the ability of key elements of the system to persist into the future (Cumming et al. 2005). I will first describe some elements of a general framework and then attempt to apply it in an integrative (if somewhat qualitative) analysis of the resilience of big river basins.

**Resilience thinking**

Resilience is used here as an emergent attribute of a social–ecological system. Resilience thinking (Walker and Salt 2006) has its roots in systems approaches, in which the world is perceived and described as a set of interacting “systems” (Checkland 2009). Systems are a form of model in that they are defined by the observer as a way of making sense of the complexities of the real world; they are intended to capture essential elements of a problem, rather than to describe accurately the full range of complexity that exists “out there”. Analysis of resilience focuses on understanding how the number and nature of current system components, and their interactions and broader context, influence the ability of important elements of that system to persist into the future.

Although the concept of resilience has become more widely used in recent years, some confusion still exists about the definition of resilience and some related terms. Some current definitions of resilience-related terminology as used in this paper are offered in Table 1.
Table 1. Definitions of some of the terms used in thinking about resilience.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>A cohesive entity consisting of key elements, interactions and a local environment; must show spatio-temporal continuity. An SES includes interactions between people and ecosystems.</td>
</tr>
<tr>
<td>Resilience</td>
<td>There are at least two complementary definitions of resilience that are currently used in the study of SESs. Carpenter et al. (2001) define resilience as: (1) the amount of change that a system can undergo and still maintain the same controls on function and structure; (2) the system’s ability to self-organize; and (3) the degree to which the system is capable of learning and adaptation. Second, based on Cumming et al. (2005), system identity depends on maintaining essential elements through space and time. Resilience can thus be viewed as the ability of the system to maintain its identity in the face of internal change and external perturbations. Note that these definitions offer slightly different perspectives on the same concept; they are not in competition with each other.</td>
</tr>
<tr>
<td>Robustness</td>
<td>Anderies et al. (2004) cite an engineering definition (Carlson and Doyle 2002) focusing on “maintenance of system performance either when subjected to external, unpredictable perturbations, or when there is uncertainty about the values of internal design parameters”. Levin and Lubchenco (2008) equate robustness and resilience, stating that both “mean much the same thing: the capacity of systems to keep functioning even when disturbed”. Maintenance of function is a different criterion from maintenance of identity (unless identity is defined purely in terms of function, which is not usually the case) and this functional emphasis appears, as best I can tell, to be the primary distinguishing feature of “robustness”.</td>
</tr>
<tr>
<td>Vulnerability</td>
<td>Vulnerability is a measure of the extent to which a community, structure, service or geographical area is likely to be damaged or disrupted, on account of its nature or location, by the impact of a particular disaster hazard (Organisation for Economic Co-operation and Development [OECD] Glossary). A more resilience-oriented definition is offered by Adger (2006); “Vulnerability is the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt.”</td>
</tr>
<tr>
<td>Sustainability</td>
<td>First introduced to the policy arena by the Bruntland Report (WECD 1987) which defined sustainable development as development that “meets the needs of the present generation without compromising the ability of future generations to meet their needs”. Also defined as “the equitable, ethical, and efficient use of natural resources” (Norberg and Cumming 2008). Inclusion of “efficiency” is contentious in some circles.</td>
</tr>
<tr>
<td>Regime, regime shift</td>
<td>A locally stable or self-reinforcing set of conditions that cause a system to vary around a local attractor; the dominant set of drivers and feedbacks that lead to system behaviour; a “basin of attraction”. For ecosystems, a regime shift is “a rapid modification of ecosystem organization and dynamics, with prolonged consequences” (Carpenter 2003, chapter 1).</td>
</tr>
</tbody>
</table>
Table 1. (Continued)

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold</td>
<td>In non-linear relationships, the point at which a function (or a rate) changes sign; in state space, the location at which a system tends towards an alternative local equilibrium or new attractor; the combination of variables under which a system enters a new regime.</td>
</tr>
<tr>
<td>(Scheffer and Carpenter 2003; Scheffer 2009)</td>
<td></td>
</tr>
<tr>
<td>Feedback</td>
<td>Occurs when a change in system element A triggers changes in other system elements (B, C, and so on) that eventually influence element A. Feedbacks may be self-regulating (negative, homeostatic) or self-amplifying (positive). For example, in the human body, sweating is a self-regulating response that cools the body down, pushing it back towards an equilibrium temperature; while hyperthermia and convulsions in response to heat serve only to exacerbate the problem, moving the body further away from its preferred equilibrium point. Self-amplifying feedbacks are particularly important in social–ecological systems as they can push a system over a threshold and into a new regime.</td>
</tr>
<tr>
<td>(Norberg and Cumming 2008)</td>
<td></td>
</tr>
</tbody>
</table>

The references in the left-hand column offer a recent example of a peer-reviewed publication in which the term is used and/or defined. Note that in many cases, different research groups have been working with very similar concepts using different terminology; differences here tend to matter less than similarities. Terminological differences also reflect the plurality of complex systems (that is, most complex systems can be viewed from many different but equally “correct” perspectives). The table is modified from Cumming (2011).
In thinking about system resilience, it is necessary first to define the system of interest (with particular emphasis on its most important elements) and then to consider how the system is likely to respond to specified future changes. System definition entails many subjective elements (Checkland 1981, 2009) and should be approached in a systematic manner to avoid excessive bias on the part of the analyst. One approach to system description is to break down the basic elements of a system into structural, spatial and temporal categories. These categories can be considered as axes, in the sense that each system element has a structure or nature, a location in space, and a location in time. A similar conceptual framework has been applied by Agarwal et al. (2002) to compare models of land use and land-cover change. As proposed by Cumming et al. (2005) and Norberg and Cumming (2008), structural elements in SESs include system components, internal interactions, and other system constituents that contribute to continuity, information processing and adaptation. The system interacts with its environment through input and output functions; and the environment provides a set of “givens” (for example, geographic location) as well as being a potential source of perturbations. The elements that are included in the structural axis should in theory be those that are considered to be most central to the system’s identity (see detailed discussion in Cumming et al. [2005]). Examples of each element in the system description are given in Table 2.

The spatial axis captures spatial variation, hierarchical system arrangements in space, and spatial interactions and connections at multiple scales. Spatial variation is relevant over at least three scales; internally within the system (“local”), and externally at the scale of the immediate context (“regional”), and the larger (“global”) set of social–ecological systems that impact the SES. Outside the boundaries of the focal SES, the primary spatial elements of interest include context (spatial surroundings, defined at the scale of analysis); connectivity; and spatial dynamics that are driven by connections or system inputs, such as spatially driven feedbacks and spatial subsidies (Polis et al. 1997, Polis et al. 2004). Both internal and external spatial elements of an SES must be considered in relation to the structural aspects of the system, including (as outlined above) the number and nature of components and interactions, the ability of the system to undergo change while maintaining its identity, system memory, and the potential inherent in the system for adaptation and learning. Note that despite its temporal role, memory is treated as a structural aspect of an SES because it requires a structure (for example, a brain, an archive, or a long-lived individual) that records change in time.

The temporal axis captures temporal variation, rates and temporal hierarchies, and the temporal location of a system within a set of processes or along a trajectory. Many of the aspects of temporal variation can be broken down in the same way as spatial elements, by considering local, regional and global dynamics and the relevance of sets of fast and slow variables. In addition, key aspects of this component of the framework include the diagnosis or assessment of the location of the system within a broader state-space, particularly in regard to its proximity to a potential threshold or regime shift; its location within an adaptive cycle (if the adaptive cycle is deemed to fit the system of interest), including whether key elements of the SES are growing, collapsing, or reorganizing; and assessment of the degree to which the system’s history has created path dependence in its current and future dynamics (see Martin and Sunley [2006], for example).

Slow variables are considered to be particularly important in SES theory because of their role in creating regime shifts and alternative stable states. For example, soil fertility may be a slowly changing variable in an agricultural system (Issaka et al. 1997). If crop rotation times and types are insufficient to allow the restoration of soil nutrients, and if communities lack the means to generate or purchase fertilizer, changes in soil nutrients
Table 2. Summary of elements of a generic big basin SES.

<table>
<thead>
<tr>
<th>System attribute</th>
<th>Generic elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Structural axis</td>
<td></td>
</tr>
<tr>
<td>SES components</td>
<td>Actors: farmers, fishers, household users, management agencies, local and international non-governmental organizations (NGOs), researchers, different ethnic or racial groups, mining companies, civil society groups, hydroelectric power producers, bridging groups or fora that connect different stakeholders. Biophysical components: water, vegetation, crops, livestock, fish. Built components: impoundments, roads, canals, cities. Institutions: laws, policies, regulations.</td>
</tr>
<tr>
<td>SES interactions</td>
<td>Implementation of land tenure and water rights; negotiations over water withdrawals; upstream–downstream user interactions; transboundary politics.</td>
</tr>
<tr>
<td>SES continuity and memory</td>
<td>Provided by long-term policies, laws and conventions; long-standing management agencies; and knowledgeable individuals.</td>
</tr>
<tr>
<td>SES information processing</td>
<td>Refers to information availability, decision making and response capacity. Although research is typically undertaken by universities and NGOs, information processing is often undertaken by individuals (for example, farmers may respond to predictions of drought by storing excess water) and by organizations.</td>
</tr>
<tr>
<td>SES adaptation</td>
<td>Related to research and local innovations; may also occur through the action of selection on diversity, although high social diversity may inhibit collective action.</td>
</tr>
<tr>
<td>Environment (context for SES):</td>
<td></td>
</tr>
<tr>
<td>Inputs and outputs to SES</td>
<td>External drivers, such as rainfall and global market demands for local produce; international and national influences such as resettlement schemes, economic incentives, flood compensation and others. Outputs include water, food and information.</td>
</tr>
<tr>
<td>Perturbations</td>
<td>Floods, droughts, climate change, economic shocks, politics (for example, governmental changes).</td>
</tr>
<tr>
<td>Asymmetries</td>
<td>Gradients exist along each case study from headwaters to foothills. These include biophysical gradients (elevation, river size, water quality, and so on) and socioeconomic gradients in household income and production systems as one moves from highlands to lowlands.</td>
</tr>
<tr>
<td>2. Spatial axis</td>
<td></td>
</tr>
<tr>
<td>Connectivity</td>
<td>Human communities in big river basins are connected by the water that flows through them and by networks of roads and waterways. Downstream ecosystems depend on upstream water production. Social networks provide an additional kind of spatial connectivity.</td>
</tr>
</tbody>
</table>
3. Temporal axis

| Subsidies | Many large downstream towns are to some extent subsidised by the opportunity costs incurred by upstream communities (for example, salinity outputs from irrigated agriculture are capped in the Goulburn-Broken catchment of the Murray-Darling system in Australia, in part to keep water drinkable for Adelaide (Anderies 2004). Similarly, the inhabitants of a river basin may produce or import their food; dependence on external sources can alter system resilience. |

| Slow variables | Groundwater extraction, soil fertility, human population increase, changes in attitudes of local community. |
| Evolution/selection | As the system changes through time, elements (such as farming systems or organizations) are lost and gained. |
| Path dependence | In some case studies the role of history is an important determinant of current patterns in such things as tenure, land use, soil fertility and equity. |
| Phase of adaptive cycle | Is the system increasing in one or more capitals, reaching a ceiling, in a state of collapse, and/or just emerging from a collapse? |

This list is not intended to be exhaustive; its focus is on identifying the most important elements that are present in a large catchment. This table provides both a simplified inventory for thinking about any individual case study and a generalised inventory for thinking about between-case comparisons. In this chapter it represented the starting point from which to select elements to include in a simple systems model.
can become a slow variable that ultimately limits the faster dynamics of crop planting and harvesting, with significant consequences for human wellbeing and social dynamics. In the social realm, a similar problem exists in regard to climate change; the supposedly “fast” political and social processes that should be reducing “slow” increases in carbon dioxide emissions to the atmosphere are currently operating at too slow a rate to prevent global climate change.

Achieving a working system description, with a focus on the most important dynamics, is the first step towards assessing system resilience. It is not possible to think constructively about system dynamics without an understanding of what constitutes the system and its primary elements. The next step towards assessing resilience is to pull together selectively the pieces of the system description into a more unified whole, using models. It is often particularly useful to think through some of the ways that a particular kind of system may respond to specified perturbations. This may be done formally, with quantitative models, or in a more qualitative manner as I have adopted here.

**Resilience of big river basins**

One entry point for thinking about the resilience of big river basins in this case study set is to take the primary elements identified in the case study description and use some of them to construct a simple generic system model (that is, one that captures important elements that are common to nearly all of the case studies). In order to build a generic system model we first need to have a clear idea of what the purpose of the model is; that is, to clarify in our own minds the aim of the analytical exercise and the kinds of outcome that we will consider important. As Carpenter *et al.* (2001) point out, resilience is contextual; in applying these concepts it is always necessary to ask “resilience of what to what?” To assist in determining a suitable focus for the analysis, I asked each case study team to rank a set of potential focal problems on a scale from one to five. I summarized the data in two different ways (Figure 1). First, I designated problems that were rated over 2.5 as being “important” for a given case study to obtain a chart that shows the number of catchments for which a given issue is important. I also calculated the total number of “votes” that each issue received by summing the scores given to each. The second plot gives an indication of the relative importance of each issue.

According to this simple survey, the most important concerns that this set of big river basins shares are water quantity, the demands and consequences of irrigated agriculture and poverty. Institutional issues, population growth, and land-cover change also appear to be important in most of the case study catchments. For the subsequent analysis I have therefore focused on the resilience of these big river basin SESs to changes in water quantity as driven by irrigation, land-cover change and climate change. Of course, these issues are strongly interrelated. Questions of institutional arrangements and equity can be seen both as important influences on the primary drivers and as important outcomes from changes in them.

Table 2 suggests a common set of system elements that occur in most of the case studies. Big river basins share a common set of biophysical elements, such as headwaters, tributaries, river deltas and reliance on rainfall. The human elements of individual systems show more variation, although in many cases these are variations along a relatively small set of common themes (Table 3).
Figure 1. (a) Salience of issues; (b) The total score for each issue, as obtained by the survey. Note: (a) The number of catchments, from a total of nine, for which a given issue was considered “important”. Water quantity was the only single issue that was considered important in all basins; (b) Since issues were rated from one to five across nine catchments, the maximum possible score was 45. Note the importance of irrigated agriculture in big river basins. LCC, land cover change.

Table 3 suggests some fundamental differences between different basins. In particular, there is considerable variation between big river basins in the degree to which agriculture is large-scale and commercial versus small-scale and subsistence-oriented. For example, water use in the Limpopo Basin is dominated by mining companies and commercial irrigation farmers, with small-scale farmers constituting a relatively marginalized voice; whereas in the Indus–Ganges basins, the number of small-scale cultivators is enormous and
Table 3. Important human system elements in each of the eight BFP big river basin case studies.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Local</th>
<th>National</th>
<th>International</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limpopo, Southern Africa</td>
<td>Mining and large-scale agriculture; Rural poor, often small-scale farmers; NGOs such as World Vision, Working for Water, and the Kalahari Conservation Society.</td>
<td>National governments of Botswana, Zimbabwe, South Africa, and Mozambique. Different ministries, often planning in isolation from one another. DWAF (Department of Water Affairs, South Africa) ARA-SuL (Administração Regional de Águas do Sul, Mozambique) ZINWA (Zimbabwe National Water Authority) Botswana Water Affairs</td>
<td>LIMCOM (Limpopo Basin Commission), an emerging bridging organization</td>
</tr>
<tr>
<td>Karkeh, Iran</td>
<td>Provincial governments, farmers; poverty-alleviation organizations such as the Red Crescent Society and the Emam Khomeini Relief Committee.</td>
<td>Power ministry offices, which determine water allocations Ministry of Energy, Ministry of Jihad-e-Agriculture and the Ministry of Jihad-e-Sazandagi (watershed management and rural development)</td>
<td>Not directly relevant since basin is internal to Iran.</td>
</tr>
<tr>
<td>Nile, North and East Africa</td>
<td>Commercial agriculture, small-scale farmers, fisheries.</td>
<td>National governments and ministries of bordering nations.</td>
<td>The Nile Basin Initiative (NBI) is the primary organization in the basin that works towards confidence, trust and capacity building among the riparian countries. The ultimate goal of the NBI is to facilitate the formation of a river basin commission and enabling environment for integrated water resources management. The Eastern Nile Technical and Regional Organization (ENTRO) is a subsidiary action programme of the NBI that works on the joint multi-purpose investment projects among Egypt, Sudan and Ethiopia. A similar subsidiary action programme exists for the Nile Equatorial Lakes (NELSAP) region. There are also legal institutions in the Nile Equatorial Lakes region, such as the Lake Victoria Basin Commission for the East African Community.</td>
</tr>
<tr>
<td>Region</td>
<td>Key Issues</td>
<td>Relevant Authorities</td>
<td></td>
</tr>
<tr>
<td>--------------------------------</td>
<td>---------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Volta, West Africa</td>
<td>Agriculture, almost entirely small-scale farmers</td>
<td>Governments of Burkina Faso and Ghana, including relevant ministries. The Volta River Authority, which is in charge of producing electricity.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>The Volta BASIN Authority, a multinational bridging organization.</td>
<td></td>
</tr>
<tr>
<td>Niger, West Africa</td>
<td>Agriculture, almost entirely small-scale farmers; nomadic herd; Office du Niger in Mali; Sub-basin agencies (Bani, Liptako Gourma); NGOs; Traditional governance and farming systems, including fadama/irrigation projects in Northern Nigeria. The Inner Delta in Mali is an important Ramsar site (3 M ha) and ecological/environmental interests in conserving this resource are also important.</td>
<td>National ministries of water and agriculture.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECOWAS (West African EU) at the regional level. Niger Basin Authority (which currently seems unable to fulfil its difficult role).</td>
<td></td>
</tr>
<tr>
<td>Yellow River, China</td>
<td>Irrigated agriculture, Industry, rural poor; agricultural research centres, stations and policy. Provincial-level governments and water resource bureaux (provinces control tributary flows within their boundaries). Some environmental NGOs are having growing impacts. Water-use rights transfer pilot projects to conserve water without adverse impacts on irrigation benefits, seen by many as a way to address the water crisis.</td>
<td>Ministry of Water Resources Ministry of Agriculture Ministry of Environmental Protection Yellow River Conservancy Commission (YRCC), under the Chinese Ministry of Water Resources, which has the mandate for allocating flows in the downstream part of the basin. The Yellow River Water Allocation Scheme, established and issued by the State Council of China in 1987, set a cap on abstraction at 37 km³ per year and quotas for each province tied to average runoff of 58 km³. 2002 Water Law (focus on river basin management, water savings, and many other topics)—highest-level legislation, but Not directly relevant.</td>
<td></td>
</tr>
</tbody>
</table>
Table 3. (Continued)

<table>
<thead>
<tr>
<th>Basin</th>
<th>Local</th>
<th>National</th>
<th>International</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indus-Ganges Basins,</td>
<td>Regulations on flow and water quality at controlling points along the river.</td>
<td>becomes only effective if supporting regulations are both developed and implemented.</td>
<td>Lacking international bridging organizations.</td>
</tr>
<tr>
<td>(Non-metric) India and Pakistan</td>
<td>Farmers’ organizations – formal and informal – who push to get water services at nominal or free costs. These organizations also impact the energy policies of the state for keeping the energy tariffs low or zero (for groundwater pumping).</td>
<td>Federal governments/ ministries of the water resources of the four major riparian countries: Pakistan, India, Nepal, Bangladesh.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non-governmental/ civil society organizations/ donors/ other voice groups who clamour to strike a balance between development and environment, inclusiveness of the poor and marginalized and long-term sustainability.</td>
<td>State/ provincial governments and irrigation bureaucracies in each of the states in the country (since water is considered a state subject, there is perpetual conflict between the federal and the state governments).</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Industries and domestic supplies are regulated to some extent, but irrigation supplies remain largely unregulated. One of the main reasons is the sheer number of small cultivators, which defies any governance mechanism.</td>
<td>Institutional basis under which water resources are not public/national; any person having land rights also has the right over water resources as an adjunct to the land.</td>
<td></td>
</tr>
<tr>
<td>Region</td>
<td>Key Stakeholders</td>
<td></td>
<td></td>
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<tr>
<td>------------</td>
<td>----------------------------------------------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mekong, Asia</td>
<td>Local inhabitants, especially farmers and fishers.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Governments of the riparian countries: China, Myanmar, Lao PDR, Thailand, Cambodia, Vietnam. Relevant ministries and departments in each country (including agriculture, fisheries, forestry, water resources and hydropower). National Mekong Committees.</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Mekong River Commission (MRC); relationship between MRC and China and Myanmar (two upstream countries), particularly relationship between China and MRC, as most of the developments such as construction of dams are in the upper part of the basin in China; bilateral relationship and interactions between the MRC countries such Cambodia–Thailand and Cambodia–Vietnam relationship.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Andes, South America</td>
<td>Farmers, communities, industrialists, dam operators for hydroelectric power and irrigation, mining companies, urban water companies.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>National governments and ministries; regional and national policy institutes.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>International environment, agriculture and development donors, international conservation NGOs</td>
<td></td>
<td></td>
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</tbody>
</table>

Table 2 provides a generic listing of case study elements; this table provides specific details of the human elements considered as important by participating case study teams. I have broken them down according to their scale of action. Note that this list is intended to provide supporting information, rather than an exhaustive inventory.
although some powerful organizations exist, there is no single channel through which they
can all be negotiated with. This makes small-scale farmers difficult to include in water-use
debates and equally hard to govern.

Some kinds of system element are particularly relevant to big river basins. A num-
ber of big river basins in this set of case studies have some form of bridging organization
that attempts to coordinate and integrate management across different sectors and between
upstream and downstream water users. Examples from the case studies in the BFPs include
the Limpopo Basin Commission (LIMCOM); the Mekong River Commission (MRC); the
Nile Basin Initiative (NBI); the Volta BASIN authority; and the Yellow River Conservancy
Commission (YRCC). The commonness of bridging organizations in big river basins, and
the importance accorded to such organizations in the resilience literature (Hahn et al. 2006,
Olsson et al. 2004, 2007), suggests that basins without bridging organizations (or where
they exist but are dysfunctional) may be less capable of responding effectively to environ-
mental change, and hence less resilient. Bridging organizations have also been proposed by
Ernstson et al. (in press) as potentially important contributors to the resolution of scale mis-
match situations, which occur when the scale of management is not appropriately aligned
to the scale at which ecological and social processes occur (Cumming et al. 2006).

Drawing on the summaries in Tables 2 and 3 and the issues considered to be of central
importance by case study teams, a simplified generic model of a big river basin case study
might look something like Figure 2.

As Tables 2 and 3 and Figure 2 suggest, big river basins have the potential for many
different kinds of feedback. To make Figure 2 a little more specific, consider a downstream
system that is in an economic growth phase and currently experiencing a beneficial climate
(Figure 3).

Tracing some possible feedback through Figures 2 and 3, for example, considering what
happens if rainfall is reduced or if agricultural demands for water increase, suggests that
the potential for both self-regulating and self-amplifying feedbacks increases hugely when
water is scarce. Once water becomes limiting, small changes in either water availability or
production systems will inevitably influence actors and land cover, which in turn will influ-
ence water and production systems. For example, when water demand from irrigated farm
land starts to approach the limit that rainfall in an average year can support, water availabil-
ity for other sectors (for example, fisheries, hydroelectric power companies, or downstream
ecosystems) is reduced, depriving the associated actors of resources and leading to conflict.
Similarly, excessive land clearing for agriculture (or the planting of water-hungry timber
plantations in place of native shrubs) can reduce the total amount of water entering the
basin, leading to reductions in crop and livestock production, increasing poverty, additional
land clearing, and a downward spiral that includes further environmental degradation and
a decrease in human wellbeing.

The point at which the demand for water approaches or exceeds the supply of water is
possibly the single most important tipping point for many of the big river basins considered
in the BFPs. Once it is exceeded, a number of initially dormant or potential interactions
between actors, production systems and land cover start to become increasingly impor-
tant. Given that the focus here is on the resilience of big river basin SESs to changes
in water quantity as driven by irrigation, land-cover change and climate change, water
quantity thresholds offer a convenient entry point for thinking about basin resilience.

Water scarcity may occur as a consequence of a number of different factors. There are
many routes to crisis and collapse. Some of the most important driving factors in the case
studies in BFPs include expansion of domestic demand (Indus–Ganges, Yellow); increas-
ing water demands for irrigation or mining (common to all case study systems); excessive
Figure 2. A generic model of a big river basin. Spatial dynamics are represented by a simple upstream–downstream divide; in reality the spatial distinctions between river sections will often include three or more recognisably different use-zones, corresponding to the headwaters, mid-sections and river delta, and some elements of the system may differ between zones. Upstream and downstream zones are connected by water, often with a delay via impoundments. Bridging organizations connect actors across different zones and/or at different scales. In each zone, local actors and production systems use and are influenced by water, and a variety of important interactions and feedbacks occur within both of these boxes. Climate (for example, via snowmelt or evaporation) determines water quantity, while also influencing land cover; and feedbacks from land cover (for example, vegetation via evapotranspiration, urban heat islands, or other albedo-altering effects) influence local rainfall. Production systems include different sectors (for example agriculture, mining, power generation and household users) and may directly influence land cover. Although actors may of course influence land cover directly for non-productive uses, I have chosen to focus on the interaction that has most impact (that is, LCC caused by production systems). Production systems respond to and influence water quantity and quality by such activities as extraction, alterations to runoff, and pollution. Land cover influences infiltration and runoff rates, with effects on water quantity and quality. Actors generate information, which may influence water use. Lastly, institutional interventions or guidelines, denoted in this diagram by “I”, can influence some but not all interactions within the system.

groundwater extraction (Karkheh, Indus–Ganges); climate change (a pending concern in all case studies); and more insidiously, reductions of water quality to the point where water becomes virtually unusable by one or more production systems or sectors (Yellow, Indus–Ganges).

What makes a big river basin more or less resilient to water scarcity? Once a point of water scarcity is reached, the social system is forced to reorganize and adapt to the
Figure 3. Generic system diagram. Derived from the model in Figure 2, indicating the strongest interactions (and whether increasing or decreasing) in the downstream component during a period when agriculture is expanding and rainfall is reliable. In this instance, households and other actors are withdrawing water; production systems are using water; and land-cover change is further reducing the amount of water available. Provided that there is sufficient rainfall (that is, the positive influence of climate on water quantity is large enough), there will be sufficient water for the net effect of water on production systems to remain positive. The system can remain in its current regime (and keep growing) as long as the magnitudes of the interactions indicated by pluses and minuses complement one another sufficiently well for excess water to remain in the system. However, if the demands on water become excessive (whether by direct or indirect pathways), water scarcity will limit production and create a crisis in the social–ecological system. The ability of the system to navigate this crisis while keeping essential system elements intact (for example, particular social groups, human wellbeing, ecosystems, food production systems, and/or culture and ways of life) represents its resilience.

new regime that now dominates the system. The way in which this reorganization occurs, and the management trajectory that the system subsequently follows, can be expected to have a large influence on the overall resilience of the system. Resolution of management problems in many real-world situations is hindered by ineffective institutions, corruption and incompetence within key organizations. Substantial delays can occur between crossing the water quantity threshold and the implementation of an effective management response, particularly in systems where social networks and management institutions are weak and actors have little history of communicating with one another or coordinating their use of water at an appropriate scale.

In some of the case studies in the BFPS, such as the Yellow River, the point at which water scarcity becomes important has long since been passed. The persistence of desirable social and ecological elements in these systems depends on reaching a successful two-pronged solution that: (1) creates a socio-politically acceptable compromise under current conditions; and (2) in the longer term, addresses the slow variables of reductions in water quantity and increasing demands on resources.

In other large-basin SESs, such as the Andes, water scarcity looms as a possible future shock to the system. In cases where a threshold of water scarcity has not yet been reached, it should be possible to attempt to build resilience to water scarcity into the social system, through such activities as building stronger social networks, developing a better understanding of the limits on production systems, and working towards more effective integrated management over the entire basin.

From a resilience-oriented perspective, crossing the threshold into water scarcity can occur in a number of different ways. Although some of these pathways may ultimately be beneficial for the long-term resilience of the case study basin to climate change (for
example, if crisis leads to better integration of different management actions), entering into water scarcity can easily push a large-basin SES into one or more problem situations from which escape can be difficult.

For example, a common management syndrome, termed “fixes that fail” (Senge 1990), occurs when a solution that is effective in the short term has unforeseen longer-term consequences. This is very similar to the typical complex systems dynamic in which changes in a slow variable (often one which is considered unimportant by decision makers) gradually undermine attempts to manage a faster variable (Carpenter and Turner 2000). A big river basin of the kind discussed here can become trapped in this dynamic through attempts to alleviate poverty. Poor households are often perceived as being trapped by circumstances that make it difficult to raise the starter capital that is needed to create the means to provide a steady income (Yunnus 1998). Being able to afford a vehicle with which to transport produce to market, for instance, can make a huge difference to a farmer’s earning potential. One plausible solution to getting households out of the poverty trap is for actors in the system, such as governmental agencies and non-governmental organizations (NGOs), to provide arable land, technical support and training to would-be farmers. The logic of this solution appears sound: that financially poor households will then be able to both feed themselves and sell their surplus, gradually lifting themselves out of poverty and ultimately becoming self-sustaining. In practice such programmes are often accompanied by, or part of, resettlement schemes such as those in the Amazon Basin (Imbernon 1999).

If the human population is large, however, fostering additional farming activities without appropriate zoning and enforcement of good farming practices can result in widespread clearing of native vegetation and increasing demand for water (Figure 4). This in turn sets in place a series of slower environmental changes, such as reductions in infiltration.

Figure 4. An example of how attempts to reduce poverty in a complex social–ecological system can have unintended side-effects. Gains in poverty alleviation achieved by increased food production may be offset by declines in human wellbeing resulting from worsening water quality and quantity. This figure also ignores the potential human population increase that may follow from increased food production. In the worst-case scenario, poorly conceived poverty reduction programmes may actually worsen the problem that they are attempting to solve.
rates, increased erosion of topsoil, and increases in pesticide and fertilizer use. These changes can gradually accumulate until a point is reached at which agricultural production becomes heavily dependent on external inputs. In the worst cases, water quality and quantity are reduced, water storage is difficult because of high sedimentation rates, landslides and floods become commoner, and soil fertility is considerably lower. The net outcome of naïve policies aimed at agricultural expansion can thus be to leave poor households worse off than before, while creating significant environmental problems that may take decades to fix.

At some point this kind of dynamic will also create difficulties for the agencies concerned, requiring a complete rethinking of current policies and an attempt to push the system on to a new trajectory. Whether or not a feasible solution can be achieved is path dependent, in the sense that it will depend heavily on the degree to which other options remain open within the system. If the number of people who have been allocated farmland in the basin is too high for the river basin to cope with, the entire river basin SES may enter a long-lasting poverty trap. Escaping this predicament requires altering the current regime, focusing policies on different goals, and possibly transforming the system by reducing the resilience of some attributes and enhancing the resilience of others. For example, introducing policies that focus on urban job creation may attract people into towns, reducing the pressure on soil and water resources. On the island of Puerto Rico, for instance, expansion of the pharmaceutical industry following tax reductions ultimately led to a forest cover increase from 4% of the island’s area to over 40%, with corresponding improvements in water quality and quantity (Gonzalez 2001, Lugo and Helmer 2004).

Agricultural activities can create situations in which different biophysical regimes exist in at least three different areas: soils, hydrology and the atmosphere (Gordon et al. 2008). Gordon et al. (2008) review 10 different agriculturally linked regimes that can lead to alternate stable states in big river basins. Shifts between some of these regimes can be extremely difficult to reverse. For example, once soils are high in nutrients, they can continue to release reactive nitrogen for a long period, even in the absence of further fertilizer application.

Pro-active management in big river basins with substantial agricultural demands will aim to develop and enforce policies that recognize the longer-term and slower variables in the system, particularly those on which farming activities depend. This level of policy development requires both a holistic perspective on what constitutes the system (for example, appreciating that water quality and quantity are closely linked to ecosystems) and the generation and availability of sufficient high-quality information on which to base decisions.

It is important to recognize that each case study will be resilient to water scarcity in some ways and not in others; the aim of cross-case resilience analysis is not to label one case study resilient and another vulnerable, but rather to draw out and explore potential shared pitfalls and traps, while attempting to identify and test general guiding principles that advance the theory and practice of social-ecological research.

I next examine some more detailed examples from different case studies from the perspective of the preceding analysis.

Case study resilience

A first basic separation of the nine case studies can be made on the basis of water quantity. In two catchments, the Yellow River and the western half of the Indus–Ganges, the SES is
well over the water scarcity threshold. The Yellow River in particular has run dry on several occasions, with a set of resulting problems. The Limpopo, the Karkheh and the Nile are relatively close to the water scarcity tipping point but are not necessarily there yet, except perhaps in drought years. The Niger, the Volta, the Mekong and the Andes are systems in which water scarcity is not currently considered a major issue, although it may of course become so in the future.

Although water is the first and most important identity criterion for a big river basin, other important elements (see Tables 2 and 3) typically include long-term residents of the catchment; commercial, large-scale players who contribute to national food security and economic growth; unique ecosystems, such as mangroves and wetlands; and a range of ecosystem services that are integral to the wellbeing of people living in the basin. If these elements are lost, the system can be said to have not been resilient.

Each basin has one or more “burning issues” that may eventually lead to the system entering crisis mode (if it is not there already) and ultimately to the loss of one or more important aspects of system identity. These issues are thus the areas in which basin resilience can be considered weakest. They are summarized for each of the eight case studies in Table 4.

As Table 4 shows, there is a wide range of complex dynamics in progress in each of the case study systems. The most fundamental common problem is probably the role of increasing demand for water from large-scale users, who include industry, irrigation farmers and cities. As demand increases, these systems must develop ways of reducing environmental impacts, allocating water equitably, and leaving some leeway in the system for periods of reduced flow. In fundamental terms, net population expansion must be slowed and water use efficiencies in industry and agriculture will need to be built in at an early stage. Once a large basin system has crossed the water scarcity threshold, with numerous water-demanding actors already in place, corrective action becomes increasingly difficult.

One of the most important concerns from a management perspective is that attempts to manipulate the system should not create further problems. As discussed previously, one of the greatest dangers is that naïve policies and unfettered, unregulated development may ultimately make worse the very problems (poverty, food production, slow economic growth) that they are trying to resolve. People have a tendency to see solutions through their own expert lenses. For example, development agencies often see the root problems in big river basins as institutional; scientists may see them as being driven by water flows, deteriorating soil quality, or other biophysical components of the system; and demographers may blame population growth. In many cases disciplinary experts assume that implementing “fixes” in their own area of expertise will solve the problems. Economists demand better pricing and incentive structures; development agencies want greater institutional accountability; and ecologists want restored riparian buffers and ecological flows. In each of these cases, remedial actions offer only partial solutions. While each may have some desirable outcomes, none on their own is adequate to solve the broader problem. Long-term sustainability in nearly every case will require the implementation of a set of carefully negotiated tradeoffs between different actors in the system, including not only human needs but also minimal flows that will keep relevant ecosystems functioning and diverse (see Zwarts et al. [2006] for example). Diversity in both the human and the ecological realm offers an important buffer against future change (Yachi and Loreau 1999, Norberg et al. 2008);
<table>
<thead>
<tr>
<th>Question</th>
<th>Burning issues in the basin</th>
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<tr>
<td><strong>Limpopo, Southern Africa</strong></td>
<td>Natural resource-based economic development plans have been scaled up in each of the four riparian states. Infrastructure development has lagged behind, and previous investments are not optimized. Limpopo Basin stakeholders include large groups of rural poor who rely on natural resource-based livelihoods for survival. Major threats include: (1) An already overcommitted river basin where new water resources development is being planned and implemented. This increases pressure on ecologically sensitive areas, such as wetland ecosystems; (2) Competing uses including extremely high-value commodities (platinum and others); large-scale commercial irrigated agriculture; poorly resourced smallholder agriculture; tourism—much of it in areas with unsecured land and water rights; (3) The likelihood that climate change will further reduce available water and increase already unpredictable water events (floods, drought, rainy seasons—onset, duration, accumulation, and so on); (4) Limited institutional function in water governance despite numerous structures and policies toward that end.</td>
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<tr>
<td><strong>Karkeh, Iran</strong></td>
<td>There is growing competition for water among different sectors in the basin, which is already closed. Increasing demand for water in industrial and domestic sectors will reduce water available for agriculture and the environment. At the same time, food demand is rising due to population growth. In addition, the current rate of ground water extraction in the basin is much more than the aquifer's capacity. As a result, the groundwater table is dropping by about one metre every year. Lastly, existence of the Ramsar “Hoor-al Azim” swamp is in danger, partly due to low inflow from Karkheh River to the wetland.</td>
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<td><strong>Nile, North and East Africa</strong></td>
<td>The Nile Basin supplies water to about five million ha of irrigated agriculture. The present irrigation demand consumes about two-thirds of the Nile River flow. Potential future problems include expansion of irrigation, climate change and unilateral approaches to basin development and management. The irrigation demand is expected to double in the near future to feed the rapidly growing population in the basin. The Nile Basin is not managed in an integrated and sustainable manner; rather the riparian countries are independently developing and managing their own parts of the basin, creating a major challenge for efficient and sustainable utilization of the Nile Basin water resources.</td>
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<td><strong>Volta, West Africa</strong></td>
<td>The basin contains some of the world's poorest countries, and most are getting poorer. Increases in food production are well behind demographic increase, mainly as a result of poor soils, lack of inputs and production means (oxen and tools), bad access to markets, poor infrastructure, lack of education and health care, and so on. Institutions are midway between traditional hierarchies and modern state laws and hence are frequently dysfunctional.</td>
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<td><strong>Niger, West Africa</strong></td>
<td>The major threats in the Niger Basin revolve around environmental variability and institutional weaknesses. The population suffers from high ambient poverty levels (economy, health, education, infrastructure, and so on) and is affected by regular disasters (drought, flooding, and cholera outbreaks to name a few). The basin also suffers from insecurity issues (ethnic tensions in the North with the Touareg in Niger and Mali, and religious tensions in northern Nigeria and widespread insecurity in southern Nigeria), as well as from corruption and inefficient governance. Additional pressure is mounting due to extreme population growth, climate change, land appropriation, rising fuel and food prices, and uncontrolled development (land-use changes, pollution, dam development and so on). The lack of established and effective institutions also has a detrimental impact on integrated water resource management at the basin scale, as several dam developments are planned, which are likely to increase the strain on blue water resources and downstream (often transboundary) users. Agriculture is predominantly subsistence agriculture and rained, exposing it to variations in climate. Yields are low and currently rely on land extension (rather than yield increases) to feed a growing population.</td>
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</table>
Yellow River, China

The Yellow River basin is faced with absolute water scarcity and poor water quality and little improvement is expected for the future. The basin faces severe competition between irrigation water uses mid-stream and partially downstream and rapid urban-industrial development downstream. No additional irrigation expansion is planned, but the government policy of food-self sufficiency in key grains will continue to put pressure on the basin's water resources. The river has been running dry; no flow was recorded at the downstream station, for five to 226 days during 1972–99. After 1999, the Yellow River Conservancy Commission was given the task to ensure that some flow reaches the river mouth. Despite this, the small downstream wetland area remains threatened from canalization, oil development and rapid urbanization. Its area declined by 50% over the last 20 years.

Other urgent issues include population growth, further urban–industrial development, climate change and high sediment deposition rates.

Water allocation between regions is still based on an allocation plan issued in 1987, which has not been revised to reflect the change in water demand.

Water quality in the river is very poor, due to a lack of treatment stations and limited enforcement of existing environmental regulations in the basin. The silt content of the water is very high. New policies of silt flushing have helped reduce the risk of downstream flooding, but are a further drain on water availability for irrigation.

Indus-Ganges Basins, India and Pakistan

These basins are facing two entirely different kind of crisis. The western part of the Ganges and the Indus are witnessing an over-exploitation of the groundwater resources and a continuous decline in the water table making the dependent agriculture hydrologically/financially unsustainable. This region is considered the global hotspot for groundwater over-use. The eastern part of the Ganges has a lot of surplus water but lacks human, financial and technical capital to make good use of the available water, keeping millions of the population in poverty and low productivity. Climate change is the major threat to the basins which will seriously alter the flow regime and intensity and frequency of the extreme events: floods and droughts and temperature changes.

Related issues include low productivity in a large part of the basin; a high concentration of poverty, especially the eastern section; deterioration of public irrigation systems (canals) and unsustainability of ever-increasing groundwater irrigation; and the transboundary nature of the basin in the volatile South Asian context.

Mekong Basin, Asia

The key issues in the Mekong Basin stem from rising pressure on the natural resource base. The growing population needs hydropower and food. The population of the Lower Mekong Basin is expected to increase from the current 65 million to about 90 million by 2050, and the proportion of urban dwellers from about 20% to about 40% or about 36 million. Economic growth is around 4.5% per annum. Total food demand will increase at a rate greater than that of population alone, due to rising incomes and changing diet preferences consequent upon urbanization. A further threat to food supplies comes from climate change. Projections suggest that the current rate of growth in agricultural production will meet future demands; but capture fisheries will probably fail to meet rising demand, since production is unlikely to go up and impoundments may lead to declines.

There is widespread poverty in the Lower Mekong region. The people in Cambodia and Lao PDR are among the poorest in the world, and in the northeastern part of Thailand and the provinces of Vietnam that are part of the basin, many people suffer from severe poverty. Poverty is closely related to access to water and cultivable land, as well as to fish.

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<table>
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<th>Question</th>
<th>Burning issues in the basin</th>
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<td></td>
<td>Although water availability is not considered a huge concern in the Mekong Basin (except in certain areas, such as northeast Thailand, during the dry season), alterations to flow regimes by impoundments and irrigation diversions are impacting river ecology, fish production, access to water, and food security. Changes in the natural flow regime may alter the environment of fisheries in the Tonle Sap and elsewhere. Altered low flows may lead to salinity intrusion into the Mekong Delta, thus altering the balance of rice and shrimp production, which in turn may affect food security and incomes.</td>
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<tr>
<td>Andes, South America</td>
<td>Areas of stress are usually associated with degradation of the natural environment and its impact on the quality and quantity of water supply; increasing demands for water and energy from increasingly large, urbanized populations; and the juxtaposition of water-demanding activities with others (such as mining, wastewater, oil and gas) which can spoil water for downstream uses. Climate change is an emerging threat, particularly to sensitive headwater ecosystems such as cloud forests and paramos. Areas relying on snowmelt may suffer. Access to water is also important in this system and may lead to conflict. Land and water legislation and policy are variable and sometimes poorly developed in Andean countries and this can seriously undermine the sustainability of common resources.</td>
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This table summarizes some of the problems that seem most likely to move individual river basins in this set of case studies into a new social–ecological regime. Note that for obvious reasons, this list largely excludes unexpected perturbations and surprises.
change imposes selective pressure on social-ecological systems, and it is more likely that important system elements will be able to persist into the future if a range of potential solutions is available. Similarly, it is important that managers in SESs think carefully through the implications of capital in all its forms (ecological, social, financial, human and physical) for resilience (Pretty 2008). Capital can play an important enabling function during times of change (Adger 2003, Deutsch et al. 2003, Brand 2009) and conversion of capital from one form to another, such as from ecological to financial, may alter system resilience to future perturbations.

Ecosystem services are fundamental to the wellbeing of human populations living in big river basins, and development often requires tradeoffs between different ecosystem services (Rodriguez et al. 2006, Mainuddin et al. 2009). I asked individual case study teams to identify key tradeoffs and compromises, as well as important actions that would be relevant in different basins for the sustainable management of ecosystem services. These responses, together with some of my own interpretations of individual basin reports, are summarized in Table 5.

As these responses indicate, there are a number of apparent needs that are integral to the long-term resilience of most of the case studies. Chief among these is the need to develop more effective ways of integrating water resource management such that it bridges the gaps between upstream and downstream users, and between different sectors, more effectively. Effective management will require effective enforcement of regulations, another major problem.

Table 5 suggests some possible pathways to greater resilience, but it does not offer a comprehensive route to resilience for any single river basin. Resilience to climate change at present appears to be higher in basins that are not yet water limited. Most big river basins are experiencing high population growth, however, and increasing demand for food (and hence, agricultural expansion). Building resilience to climate change in each of these systems will require proactive, forward-looking management and regulation. It is also important to note that resilience is not always desirable (dysfunctional management systems being a case in point). Resilience will need to be built in some system components and reduced in others; and in some case studies, such as the Yellow River, transformation of the SES (with the loss of some or all of its current “key” elements, for good or for bad) seems virtually inevitable. Olsson et al. (2004), based on their study of a successful transformation of a wetland SES (Kristianstad) in southern Sweden, suggest three key steps towards social transformation: preparing the system for change, seizing a window of opportunity, and building social-ecological resilience of the new desired state. Transformation in Kristianstad was facilitated by the creation of a new bridging organization which was able to bring together key actors.

Managers and water users in many cases are aware of many of the issues and possibilities listed in Table 5. Awareness of solutions, however, does not always translate into solutions; action occurs at the end of a political process in which different needs and values are considered and alternative solutions are negotiated (Cronon 2000). The development and implementation of more effective management strategies in most case study basins is currently being hindered by a wide range of political variables, including historical incompatibilities, power struggles, a lack of trust and overlapping (and sometimes contradicting) legislation. For example, in some of the BFP case studies, different water management districts refuse to share their water flow data to provide a comprehensive picture of basin-wide flows. There is also a paucity of relevant science-based information on which appropriate legislation can be based. Some of the major uncertainties and information gaps in the case study basins are summarized in Table 6.
Table 5. Tradeoffs and other compromises perceived by basin case study teams as needed for improving the sustainability of big river basins; and suggestions for necessary changes to enhance resilience in each basin.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Compromises or tradeoffs with relevance for sustainability</th>
<th>Pathways proposed to lead to greater resilience</th>
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<tbody>
<tr>
<td>Limpopo, Southern Africa</td>
<td>Economic vs. natural capital: sustainable management of ecosystem services, and particularly reductions in water use, will have to be paid for.</td>
<td>Improve equity, reduce marginalization of rural poor by education and building local capacity and institutions. Introduce more effective policing and enforcement of existing regulations. Improve pricing and prioritization structures for smallholder water use. Develop more effective ways for different countries in the basin to interact and co-manage water resources, through strengthening LIMCOM. Planning being done now must be based on best available climate forecasts under the assumption that there will be less water, more major weather-related events, and increased temperatures.</td>
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<td>Short-term vs. long-term benefits: rural households will have to be compensated for the loss of economic opportunity that they face when conserving the resource base.</td>
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<td></td>
<td>Tradeoffs between sectors: industry, particularly mining and agriculture, will have to balance their needs with those of rural communities.</td>
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<tr>
<td>Karkeh, Iran</td>
<td>Anthropogenic vs. ecosystem needs: ecosystems need reduced groundwater usage and incorporation of environmental flows into decision making.</td>
<td>Extend trade networks to meet future food demand. Develop a larger set of non-agricultural ways of generating income. Need to improve water management and allocation processes. Improve water use efficiency of irrigated agriculture. Map water production to identify opportunities for increasing water quantity.</td>
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<tr>
<td></td>
<td>Upstream vs. downstream tradeoffs: downstream water laws need to be revised.</td>
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<td></td>
<td>High vs. low economic value activities: possibility to shift water away from (lower-value) food production and towards hydropower and urban uses. Specifically, difficult tradeoffs expected between hydropower and irrigation needs.</td>
<td></td>
</tr>
<tr>
<td>Nile, North and East Africa</td>
<td>Upstream vs. downstream tradeoffs: differences in water access, demand and management must be resolved. Water quantity available to humans vs. water for ecosystems (including wildlife and grazers) on floodplains in the Sudd area (Jonglei Canal debate). Consumptive vs. non-consumptive uses (for example, hydropower vs. irrigation).</td>
<td>Create enabling environment (basin-wide institution with law-enforcement capacity, water management policy, strategies and regulation). Improve productivity of farmland and agricultural water management. Reduce water waste/loss and increase availability Consider climate change and environmental impact assessment during project planning and design.</td>
</tr>
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Multivariate tradeoffs between different, potentially conflicting uses of water (for example, irrigation, fishing, hydropower, drinking, washing, transport, repository for waste).

Volta, West Africa

- Few explicit tradeoffs at present because water volume not limiting, although rainfall is highly variable and soils are poor.
- Future tradeoffs between storage and irrigation and cropping vs. ranching systems seem likely.

Attract investment funds (economic capital).
- Resolve political differences between nations, particularly Egypt and other water users.
- Build management capabilities of agricultural and ranching communities.

Introduce better management for grasslands, particularly for livestock with access to water and use of crop residues (livestock perceived as only possible use of grasslands in the northern drier part of the basin).
- Develop reforestation programmes, reduce deforestation rate.
- Soil use currently unsustainable; introduce small-scale irrigation and better farming practices.
- Possibly regulate fisheries and limit expansion of rice production into small inland valleys.

Niger, West Africa

- Impoundments to support hydropower and irrigation during low-flow periods vs. downstream river flow for herders, fishermen and rice cultivators.
- Livestock ranching of nomadic herds vs. agriculture (which restricts water access and cattle movements).
- Tradeoffs between different crops with different values and water demands (for example, rice vs. market gardens).
- Customary laws vs. governmental legal system (effectiveness of different systems for water management differs; plurality can create tenure insecurity and negatively impact development).

Improved agricultural productivity.
- Improved water productivity and/or more effective water management (ground water extraction, dam construction, and so on).
- Inclusion of marginalised sectors, such as fishers and nomadic pastoralists, in decision-making and planning processes.
- Conflict resolution between nomads and farmers.
- Resolution of land tenure issues stemming from legal pluralism (traditional vs. legal systems).
- Improved education and access to clean water.

Yellow River, China

- As a closed basin, use of water by any sector almost inevitably entails a tradeoff with other sectors.
- Irrigated agriculture in middle and upper sections of basin vs. industrial, domestic and ecosystem demands downstream.
- Transboundary (province) water diversion vs. water demand, particularly in downstream areas within the basin;

Enforce water quality regulations to ensure that less industrial waste and domestic sewage enters the river.
- Eliminate fertilizer subsidies, which lead to nutrient runoff and poor water quality.
- Find new ways to compensate provinces for using less water, particularly upstream provinces where benefit per unit of water used is lower (however, given the reuse of flows within the basin, the potential for saving is also limited).

(Continued)
Table 5. (Continued)

<table>
<thead>
<tr>
<th>Basin</th>
<th>Compromises or tradeoffs with relevance for sustainability</th>
<th>Pathways proposed to lead to greater resilience</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Waste removal vs. other water quality-related services (wastewater discharge high in upper and middle sections).</td>
<td>Enhanced cooperation between the ministries of agriculture (MOA) and water resources, as the MOA’s policies tend to increase pressure on water resources without taking these into account in their decision-making processes. Reduce agricultural water use, depending on how much water use efficiency has been increased.</td>
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<td></td>
<td>Fertiliser use for food production vs. downstream water quality.</td>
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<td></td>
<td>Flood control vs. water storage.</td>
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<td></td>
<td>Poverty alleviation (via irrigated agriculture) vs. ecosystem integrity.</td>
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<td></td>
<td>Decentralization of water rights vs. central control.</td>
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<tr>
<td>Indus-Ganges Basins, India</td>
<td>Investing for rural labour expansion in agriculture vs. investing in non-agricultural job creation.</td>
<td></td>
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<tr>
<td>and Pakistan</td>
<td>In the Indus, a closed basin, use of water by any sector almost inevitably entails a tradeoff with other sectors.</td>
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<tr>
<td></td>
<td>Upstream vs. downstream uses.</td>
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<td></td>
<td>Tradeoffs between economic returns on different crops and on monoculture vs. diverse cropping systems.</td>
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<td></td>
<td>Reliance on formal vs. informal institutions (tradeoffs in flexibility, responsiveness, enforcement, and adherence to rules).</td>
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<td></td>
<td>Policies to encourage groundwater pumping (short-term gains) vs. groundwater recharge (long-term sustainability).</td>
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<td></td>
<td>Improve food security for the region, especially the poor population.</td>
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<td></td>
<td>Develop new cropping patterns in response to climate change.</td>
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<td></td>
<td>Create sufficient attractive off-farm employment (involve farmers in other sectors).</td>
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<td></td>
<td>Manage extreme events better (improve contingency preparedness) and reduce vulnerability of the population.</td>
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<td></td>
<td>Provide energy security to the rural population through alternative fuels.</td>
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<tr>
<td></td>
<td>Improve markets and infrastructure.</td>
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<tr>
<td></td>
<td>Empower poor people, especially women.</td>
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<tr>
<td>Mekong, Asia</td>
<td>Development of hydropower dams vs. downstream water use and ecosystem function (including production of fish for capture).</td>
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<td></td>
<td>Improve tenure and access rights of the poor to natural resources; give marginalised communities a voice.</td>
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<td></td>
<td>Maintain sufficiently good downstream water quality and quantity to support fisheries.</td>
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<tr>
<td>Andes, South America</td>
<td>Upstream vs. downstream activities and impacts (for example, mining vs. domestic water use).</td>
<td>Improve current institutions (for example, strengthen Mekong River Commission) and develop a more holistic institutional perspective (that is, not only focused on growth and development).</td>
</tr>
<tr>
<td></td>
<td>Local vs. national benefits, increase investment in water treatment for urban centres, with local costs but national benefits.</td>
<td>Improve local and regional governance; develop ways to prevent national political interests (for example, indebtedness to China for aid) from becoming too dominant in decision making.</td>
</tr>
<tr>
<td></td>
<td>Economic benefits vs. ecological integrity (poor environmental record of agriculture in the region).</td>
<td>Manage land use more carefully (for example, deforestation impacts on water and sediment inputs to hydropower dams; or agricultural impacts on water quality).</td>
</tr>
<tr>
<td></td>
<td>Tradeoffs between competing land uses in steep areas (for example, agricultural production systems, major dam projects, inter-basin transfers, mining).</td>
<td>Improve management of wastewater and effluents from cities and industry.</td>
</tr>
<tr>
<td></td>
<td>Downstream irrigation vs. water supply to major cities.</td>
<td>Improve political stability, reduce rural violence, implement better governance.</td>
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<td></td>
<td></td>
<td>Develop ways of including currently marginalised groups in decision-making processes in their own regions.</td>
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</tbody>
</table>

This table combines responses to a questionnaire and my own interpretations of information presented in case study reports.
Table 6. Major information needs in eight big river basins, as identified by case study teams.

<table>
<thead>
<tr>
<th>Question</th>
<th>Major information needs identified by case study teams</th>
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</thead>
<tbody>
<tr>
<td><strong>Limpopo, Southern Africa</strong></td>
<td>Actual water use, by sector, per country is still difficult to pinpoint. Better data from Botswana. The changing, unpredictable political situation in Zimbabwe and potentially South Africa make generational planning and assessment difficult. Political priorities may change quickly, thereby realigning the economic landscape and placing pressure on natural resources. These dynamics are poorly understood. Likely impacts of climate change.</td>
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<tr>
<td><strong>Karkeh, Iran</strong></td>
<td>Better hydrological data, both for flows in basins and groundwater–surfacewater interaction. Understanding how to develop and implement groundwater policy. Better understanding of linkages between water and poverty in the basin. Relationships between production systems not typically included in basin water assessments (for example, ranching, forestry, fisheries) and water supply and demand. Likely climate change impacts on freshwater availability in basin. Impacts of Iranian government’s decision to remove subsidies on energy and agricultural inputs.</td>
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<tr>
<td><strong>Nile, North and East Africa</strong></td>
<td>Little data available on water requirements of wetland ecosystems. In addition, contributions made to the Nile by the Sudd wetland system (one of the largest in the world), and possible impacts on the Sudd of the Jonglei Canal, are poorly understood. The relationships between biophysical variables and ecological indicators are poorly understood. Climatic and hydrologic monitoring data are weak; lack of basin-wide monitoring strategy; water quality information lacking; climate change projections uncertain.</td>
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<tr>
<td><strong>Volta, West Africa</strong></td>
<td>Quality/reliability of published data from state agencies is often not known (for example, agriculture production, livestock, cultivated area, fine-scale poverty data). Data gaps from countries that have only a small part of the basin. Large gaps in hydrological (river discharge) data. Similarly, groundwater resources poorly understood. Climate projections uncertain. Sustainability of fisheries on Lake Volta unclear.</td>
</tr>
<tr>
<td><strong>Niger, West Africa</strong></td>
<td>Population growth data. Impacts of climate change uncertain. Need to research to determine how to improve agricultural output in local conditions. Ways to improve uptake of agricultural productivity interventions. Ways to improve governance and integrated water resource management.</td>
</tr>
</tbody>
</table>
Yellow River, China
Need monitoring, information and awareness generation on water quality situation in the basin.
Information exchange needs between ministries of agriculture and water to assess impacts of agricultural policies on water availability.
Key uncertainties need to be resolved: cost of poor water quality to the public and the country; cost of continuing business as usual; cost of rigid water allocation planning (for example, province-level quota systems).
Approaches to drought management (lack of policies given past focus on flood control).
Impacts of climate change on both surface and groundwater supply.
How much water use efficiency can be increased in agricultural sector, and likely impacts of adopting agricultural water-saving technologies on local and basin-level water use.
Irrigated and rainfed area by crop is unknown.
Crop evapotranspiration (ET) by month by county (or better resolution).
Water requirements for downstream ecosystems (estimates from the various sources are very different).

Indus-Ganges Basins, India and Pakistan
Due to transboundary nature and low trust level among the riparian countries, water resources data for basin-level analysis are unavailable. A similar situation also exists for groundwater/flood data (and other resources).
Impact of climate change upon Himalayan water resources is not well understood and there are conflicting scientific evidence.
Poor knowledge of use by sector and revenues generated for water services.
Impact of water resources development on local ecology, biodiversity, livelihoods, displacements and other costs.

Mekong, Asia
Impact of dams, new irrigation systems and upstream development on the lower part of the basin, on the capture fisheries and on the environment and ecology.
Understanding relationships between food security and poverty reduction.
Impact of climate change on flows, agricultural productivity, fisheries ecology, environment and sea level rise.

Andes, South America
Better integrated modelling and research that is capable of moving beyond single issues to looking at multiple issues and unforeseen consequences.
Bridging science and policy to provide policy support.
Better measurement and monitoring of some of the fundamentals (for example, rainfall and distribution of water treatment plants).
Better information on the role of poverty in determining water access.
Better measures of livelihoods and wellbeing, beyond purely economic measures.

Further details on these needs are available in individual chapters of *Water International* 35 (5) (2010).
Addressing these information needs would presumably make the case study basins more resilient, in the sense that the facts that are needed for informed decision making would be more readily available. It is, however, a mistake to assume that simply getting the science or even the number and nature of institutions right will solve the problems; the focus in most cases will need to be on process, and in particular on developing flexible, transparent, inclusive political approaches to dealing with and resolving water allocation issues.

One of the hardest questions to answer in the context of assessing the resilience of big river basins is that of whether pro-active managers are thinking about (and preparing for) the right future. Surprise is an integral element of complex systems and it is quite possible that new, unexpected threats to the integrity of big river basins will emerge from unexpected quarters (see, for example, the discussion in Gordon et al. 2008). For example, none of the BFP case studies has considered the possible implications for basin sustainability of such possible future trends as increased production of biofuels (de Fraiture et al. 2008), outsourcing of agricultural production from wealthier countries to Africa (Daviron and Gibbon 2002), or the potential for anthropogenic influences to create “unhealthy landscapes” that are susceptible to novel forms of water-borne or water-associated pathogens (Patz et al. 2004).

The future will not necessarily conform to the present. Building resilience to surprise is more a case of building adaptive capacity (for example, through developing monitoring schemes with feedback loops to management, setting in place appropriate decision-making processes, building capital stocks, maintaining diversity and redundancy, and ensuring that some “slack” remains in key components of the system) than of managing for a specific outcome or goal. Managing for resilience inevitably comes at a cost, and many complex systems will (whether intentionally or not) tend to reduce adaptive capacity by shifting towards greater efficiency during periods of relative stability when diversity, redundancy, and under-utilization are seen as wasteful (Holling and Meffe 1996). One of the central challenges for big river basin management is thus to put in place the structures (institutions, policies, expertise) that are needed to cope with times of change, and to retain them through periods of relative constancy when their direct relevance may be less obvious.

Concluding comments

This brief analysis of the resilience of big river basin SESs in this set of case studies has raised some important questions and recommendations in two realms: (1) conceptual and scientific understanding; and (2) practical recommendations for managing these systems towards greater resilience in desired characteristics.

In the conceptual and scientific realm, standard approaches to river basin management (including most development and water allocation programmes) have yet to fully grapple with the questions that are raised by scientific uncertainty and system complexity. All of the case studies face potentially large uncertainties in the estimation and prediction of a wide range of important variables, ranging from likely future rainfall and runoff through to more diffuse variables such as changes in water demand and the future role of technology in water-use efficiency. Uncertainty exists not only in the estimation of such variables, but also in our understanding of the nature of the relationships between variables. Lake eutrophication offers a good example of a well-studied, non-linear relationship in freshwater systems (Carpenter 2003), but a wide range of other relationships are likely to show significant non-linearities and complex behaviours, particularly if climate change or water extraction push key variables beyond their normal range of variation (Holling and Meffe
Understanding and incorporating such uncertainties into models and decision-making tools remains an important goal for research in many big river basins.

In the practical realm, a number of general and specific suggestions emerge from the preceding discussion. Complex systems theory highlights the value of maintaining diversity, redundancy, and capital within a given system as well as of fostering learning, innovation and adaptive capacity where possible (Holling and Meffe 1996, Norberg and Cumming 2008). The temptation to blame problems on a single cause or driver (such as population growth or institutional failure), and build expectations around working towards a single overarching solution or “panacea”, must be avoided (Ostrom 2007). Big river basins are complex systems that are composed of multiple interacting variables, which change at different speeds and occupy different hierarchical levels. System manipulations, even of biophysical components of the system that are supposedly well understood, may have unintended consequences (Patten et al. 2001). Pro-active management will be most effective (and most capable of making necessary mistakes, and learning from them) if it occurs via politically acceptable and participatory processes (Adger and Jordan 2009), uses the best possible science, and takes a holistic perspective that seeks to incorporate social, ecological, and economic elements in problem definition and solution.

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I am grateful to Simon Cook for inviting me to contribute this paper and to the nine contributing BFP project teams for their willingness to respond to my questions and provide me with relevant materials. Most of the text in Tables 2 to 6 was generated by the case study authors, although I may have subsequently introduced errors. I would particularly like to thank Amy Sullivan (Limpopo); Poolad Karimi (Karkheh); David Molden, Seleshi B. Awulachew and Solomon S. Demissie (Nile); Jacques Lemolle (Volta); Andrew Ogilvie and Jean-Charles Clanet (Niger); Claudia Ringler, Jinxia Wang and Ximing Cai (Yellow); Bharat Sharma (Indus-Gangetic); Mac Kirby and Mohammed Mainuddin (Mekong) and Mark Mulligan (Andes). Simon Cook, Tassilo Tiemann and an anonymous reviewer provided useful comments on earlier versions of this paper.

Note
1. Ludwig (2001) defines “wicked” problems as those that include not only multiple disciplines, stakeholders and epistemologies, but also that cannot be separated from issues of values, equity and social justice.

References


