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FLEXIBILITY IN WATER RESOURCES MANAGEMENT: REVIEW OF CONCEPTS AND DEVELOPMENT OF ASSESSMENT MEASURES FOR FLOOD MANAGEMENT SYSTEMS[1]

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ABSTRACT: Discussions around adapting water management systems to climate change often express the need to increase system flexibility. Yet despite the frequent use of the term flexibility, very little work has examined what exactly it means to have a flexible water management system, what features of a system make it more flexible than another system, or when the costs to implement flexible options outweigh the benefits gained from increased flexibility. To define and operationalize the concept of flexibility in the field of water resources management, this article reviews and analyzes concepts of flexibility from the fields of information technology, manufacturing, management, and adaptive social-ecological systems. We identify five characteristics of flexible water resources systems, namely: slack, redundancy, connectivity, compatibility/coordination, and adjustability. We then operationalize the assessment of flexibility for flood management systems by proposing original flexibility metrics and discussing their application. We conclude with a discussion on the tradeoffs of increasing flexibility.

(KEY TERMS: flexibility; adaptive capacity; optimization; climate variability/change; risk assessment; flood management; water resources flexibility.)

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INTRODUCTION

Associated with a need to increase water resources systems' capacity to cope with and adapt to climate change, recent literature regarding water resources management increasingly includes recommendations for more flexible systems (Richter *et al.*, 2003; IPCC, 2007; Pahl-Wostl *et al.*, 2007; Johnson and Lilly, 2009; Huang *et al.*, 2010). The need for flexible systems is driven by uncertainty and changing conditions (Zhao and Tseng, 2003), which influence water resources systems in a number of critical ways. For example, standard risk analysis methods applied in water resources planning, design, operation, and maintenance require defining probability distributions on the basis of assuming hydrologic stationarity (U.S. Water Resources Council, 1983). This assumption has been heavily challenged due to land use and climate change (Frederick *et al.*, 1997; Milly *et al.*, 2008), leading to an increased emphasis on flexibility, robustness, and adaptive capacity in water resources planning (Lempert *et al.*, 2003). Furthermore, the utility and validity of optimization techniques, utilized in water resources planning studies since the 1960s for meeting multiple objectives (Wolman, 1962; Wurbs, 1991), declines as uncertainty increases (Lempert *et al.*, 2003) and the future is not constrained to the limited scenarios examined by optimization (Bonder, 1979). With water resources systems facing

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all of requirements for conditions of deep uncertainty (Lempert *et al.*, 2003), planning and analysis of water resources projects are shifting toward emphasis on adaptive and robust strategies that perform reasonably well over a wide range of uncertain, yet plausible future scenarios (Frederick *et al.*, 1997; Lempert *et al.*, 2003).

While it is acknowledged that increased emphasis on adaptive water resources systems can improve their robustness in the future, clarity is needed regarding how adaptive capacity can be integrated into water resource systems. The capacity to adapt has been variously defined in the literature on social-ecological systems (SESs) over time (Adger *et al.*, 2004, 2005a; Gallopín, 2006; Smit and Wandel, 2006; Engle, 2011) and generally converges on a definition that includes the processes, actions, or resources of a SES that facilitate adjusting to, coping with, and/or benefitting from a change or hazard (Adger *et al.*, 2005a; Carpenter and Brock, 2008). Adaptive capacity is determined by several system features, including financial, human, and social assets, governance and institutions, knowledge and information, and stakeholders (Adger *et al.*, 2004; Smit and Wandel, 2006; Jones *et al.*, 2011). Yet, the mere existence of these features does not lead to adaptive systems. Rather, certain traits exhibited by the features, such as the flexibility of governance and institutions (Folke *et al.*, 2002, 2005; Dietz *et al.*, 2003; Huitema *et al.*, 2009; Pahl-Wostl, 2009) and the engagement of stakeholders (Pettengell, 2010), increase adaptive capacity. As such, flexibility and adaptive capacity are positively related (Engle, 2011).

However, despite the importance and frequency of recommendations for flexibility in adaptive water resources systems, very little work has examined what exactly it means to have a flexible water management system and what makes one system more flexible than another. From the management perspective, the term lacks utility because it is unclear how to assess and compare the flexibility of proposed management actions. Furthermore, to our knowledge, no analysis has considered whether the costs to implement flexible options outweigh the benefits gained from increased flexibility. However, analysis of flexibility from the fields of information technology (IT) (Duncan, 1995; Byrd and Turner, 2000; Golden and Powell, 2000; Turner and Lankford, 2005), management (Fayol, 1916), manufacturing (Pyoun and Choi, 1994), planning (Pye, 1978), and adaptive SESs (Adger *et al.*, 2005a; Smit and Wandel, 2006) can offer insight on applying the concept of flexibility to the management of water resources systems.

Thus, the overarching goals of this study are to define the concept of flexibility in water management systems generally and then to operationalize the concept in the field of flood management more specifically. We review literature on flexibility in water management by first conducting a Google Scholar keyword search on "flexibility water management" and then expand our search to "flexible systems" to review the use of the term in other domains. We apply and modify the flexibility topology in the literature to define flexibility in water resources systems. We identify different characteristics of flexible systems and propose a set of metrics under each characteristic to assess the flexibility of flood management systems. We conclude with a discussion on the costs and unintended consequences of incorporating additional flexibility into water resources systems.

FLEXIBILITY IN WATER RESOURCES SYSTEMS

Definition and Features of Flexibility in Water Resources Systems

Despite the proliferation of flexibility recommendations in water resources management and other sectors, flexibility remains an ambiguous term due to the lack of a common, operational definition (Duncan, 1995; Golden and Powell, 2000). Few studies have been undertaken to directly assess the flexibility of adaptive systems (Engle, 2011). This ambiguity stems from the term's multidimensional and varied traits (Golden and Powell, 2000), making flexibility difficult to measure and integrate into the planning and decision-making processes (Duncan, 1995). Definitions of flexibility (or inflexibility) vary between sources and often depend on the target of the flexibility or the system being assessed (Table 1). We synthesize the definitions and features of flexibility from other domains to define flexibility in water resources as

> the inherent ability of the human and physical elements of a system to cope with, or adapt to, uncertain and changing conditions, in a timely and cost-effective manner.

This definition is based on three features of flexibility derived from the literature. First, flexibility supports the ability to cope (Gallopín, 2006) and adapt (Gallopín, 2006) to uncertain, changing conditions. The IT, management, and manufacturing literature on flexibility focuses on the need to meet new and growing demands (Fayol, 1916; Pyoun and Choi, 1994; Duncan, 1995; Golden and Powell, 2000; Turner and Lankford, 2005) under an uncertain future (Golden and Powell, 2000). Water resources flexibility relates to the capability to adapt to new or changes in both demands and supply (FAO, 1993; Gunderson and Holling, 2002; IPCC, 2007; Patel

TABLE 1. Definitions of Flexibility and Inflexibility.

Target System/Sector	Definition	References	Contribution to Water Resources' Flexibility
General	Characterized by a ready capability to adapt to new, different, or changing requirements	Merriam-Webster, Inc. (2003)	Relationship to adaptation
Information technology	Ability of a resource to be used for more than one end product; Degree to which (IT infrastructure's) resources are sharable and reusable	Duncan (1995)	Redundancy and connectivity characteristics
	"The capacity to adapt" across four dimensions, or areas within which flexibility can be achieved: temporal, range, intention, and focus	Golden and Powell (2000)	Relationship to adaptation; time component
	Represented by three dimensions or influences, defined as: (1) slack, the degree of excess capacity, underutilization, or salability; (2) adaptability, the degree of versatility, openness, robustness; and (3) intensity, the degree of repetitiveness and frequency of changes in a parameter	Turner and Lankford (2005)	Slack, adjustability, and redundancy characteristics
Management	Ability to be adapted to changing circumstances	Fayol (1916)	Relationship to adaptation
Management *(inflexibility)*	Physical resources of a firm are characterized by fixed capacity. Also, they are usually useful in a few very similar industries	Chatterjee and Wernerfelt (1991)	Slack, redundancy, and adjustability characteristics
Manufacturing	Capability of a manufacturing system to: increase or decrease its capacity when needed; produce new or improved parts; support interchange between stations or their tooling and functions when needed; and handle the system control software in the above cases	Pyoun and Choi (1994)	Slack, adjustability, and redundancy characteristics
Planning	The amount of uncertainty which the decision maker retains concerning the future choices he will make. . .Unforeseeable uncertainty can only be dealt with if the decision maker's response to nature's moves is not fixed in advance but is itself uncertain. Flexibility is then defined as the entropy of that uncertainty	Pye (1978)	Emphasis on uncertainty
Social-ecological systems	Degree to which a system is pliable or compliant (similar to adaptability, but more absolute than relative). Adaptability is defined as the ability, competency, or capacity of a system to adapt to (to alter to better suit) climatic stimuli (essentially synonymous with adaptive capacity)	IPCC (2007)	Relationship to adaptation; adjustability characteristic; absoluteness
Social-ecological systems *(inflexibility)*	Rigid social-ecological systems are those that are highly connected and self-reinforcing, with low potential for change	Gunderson and Holling (2002)	Adjustability characteristic
Water management	Allocations between users, uses, regions, and sectors can be changed at a low cost in relation to benefits; changes in demand are accommodated easily by reallocating water to higher-valued uses as they emerge; Certainty is also necessary: water-use rules must be easy to discover and to understand	FAO (1993)	Compatibility and adjustability characteristics; cost component
	Limited possibilities to introduce change based on new insight	Pahl-Wostl (2007)	Adjustability characteristic
	Ability to cope with uncertainties and . . . capability to adapt to new or changing requirements	Patel Center (2011)	Relationship to adaptation
	Ability to respond to uncertainties in the future	Suttinon and Nasu (2010)	Emphasis on uncertainty

Center, 2011). For example, water resources managers face challenges from increasing demands for residential water supply due to population growth (Holdren and Ehrlich, 1974; Falkenmark and Widstrand, 1992; Vörösmarty *et al.*, 2000), new demands and operational requirements for which the systems were not designed, such as providing environmental flow releases (Richter *et al.*, 2003; Arthington *et al.*, 2006; Richter and Thomas, 2007), and for protection from potentially larger and/or more frequent future floods under climate change (IPCC, 2007).

Second, several definitions of flexibility (Table 1), as well as further explanations in the IT and manufacturing literature, include economic and time benefits of flexibility (Pyoun and Choi, 1994; Duncan, 1995; Golden and Powell, 2000). Flexibility involves not only the ability to cope or adapt but also the ability to do so in a timely and cost-effective manner. For example, flexible IT systems provide a competitive advantage in their capability to quickly respond to customer demands and keep up with new innovations marketed by competitors (Duncan, 1995).

Third, the assessment of flexibility is an absolute characteristic of a system, rather than relative to a particular hazard or stressor (IPCC, 2007), presenting a snapshot of a single, specific system at a point in time. In contrast, adaptive capacity, vulnerability, and resilience are measured in terms of some specific type of disturbance or perturbation, requiring an answer to the question: Adaptation, vulnerability or resilience of what to what? (Carpenter *et al.*, 2001; Gallopín, 2006). Alternatively, flexibility is an inherent system characteristic that needs no qualifier. Thus in describing the flexibility of a system, we need not answer the question: Flexible to what? This makes it possible to assess the flexibility of a system without the need to fully characterize potential future conditions and uncertainties. However, although perturbation and uncertainty parameters do not enter into the process of measuring the flexibility of a system, they do influence the *value of flexibility* (Zhao and Tseng, 2003; Huang *et al.*, 2010). The value of flexibility increases with the degree of uncertainty and the projected magnitude of perturbations in future conditions, as further discussed later in this manuscript.

Characteristics of Flexible Water Resources Systems

Following a comprehensive review of the literature across scholarly databases and the references found therein, we find that in-depth assessments of flexibility and attempts to operationalize the term appear primarily in the field of IT, which maintains similarities with water resources management regarding uncertainty and growing demands. We thus apply concepts from the IT field as a foundation for operationalizing the concept of flexibility in flood management, along with relevant contributions from other fields. Researchers in the IT field (e.g., Duncan, 1995; Byrd and Turner, 2000; Golden and Powell, 2000; Turner and Lankford, 2005) propose assessing characteristics of flexible systems that relate to (1) the range of options that an organization has available and (2) how long it takes an organization to adapt. Along similar lines, we find that the characteristics found in the literature (e.g., efficiency, responsiveness, versatility, and robustness; Golden and Powell, 2000) relate to water system's (1) ability to cope and (2) ability to adapt. We use these characteristics as the foundation from which we operationalize the concept of flexibility in water resources systems (Figure 1). We find that the characteristics of slack, redundancy, connectivity, and compatibility/coordination, increase the range of available options, providing water systems with the flexibility to *cope* with changes. The ease of adjusting the aforementioned flexibility characteristics, adjustability, provides water systems with the flexibility to *adapt* to changes. Individually, each of the flexibility characteristics may be insufficient to fully represent the concept of flexibility, requiring some collective combination of dimensions to adequately characterize flexible systems (Turner and Lankford, 2005).

We integrate and modify the measureable characteristics of flexible systems provided by the IT literature to develop a framework for characterizing and assessing flexibility in water resources management (Figure 1). As a starting point to developing a full methodology to assess the flexibility of water systems, in the following section, we (1) identify and define five flexibility characteristics in water resources systems, namely: slack, redundancy, connectivity, compatibility/coordination, and adjustability; (2) propose a set of sample metrics within each of the characteristics for evaluating the degree of flexibility in flood management systems (Table 2); (3) give descriptive examples of actions that may increase flexibility for that characteristic; and (4) explain the contribution of each flexibility characteristic to increasing flexibility and informing management decisions.

Slack

Slack provides surplus capacity to cope with uncertain and changing conditions (Turner and Lankford, 2005). Intentionally embedding excess capacity into a system provides increased flexibility for future expansion, helping to ensure it can meet increased demands and/or changing objectives under a wider

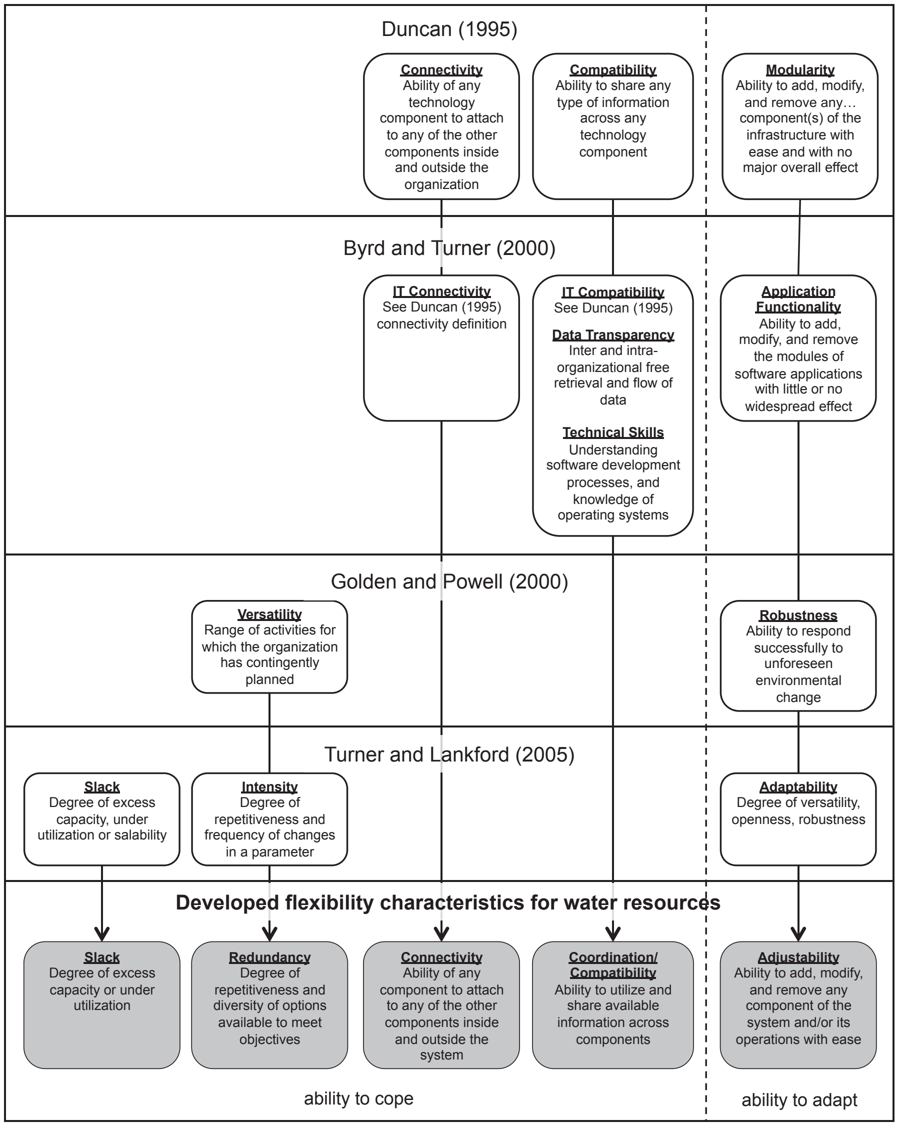

FIGURE 1. Flexibility Characteristic from Domains Outside Water Resources Used to Develop the Characteristics for Water Resources in the Bottom Row. The four left columns of characteristics ease the system's ability to cope with uncertainty and change, while adjustability on the bottom right eases the system's ability to adapt.

variety of conditions (Zhao and Tseng, 2003; Hall and Murphy, 2012). For example, Zhao and Tseng (2003) apply a trinomial lattice model to identify an appropriate foundation size of a parking garage. This analysis balances the upfront costs to incorporate the slack necessary for future expansion with the potential profit provided by the option to expand the garage under uncertain future parking demand.

From a flood risk management perspective, evaluating and appropriately incorporating slack into the design of water resources systems, via dam/bypass sizing, channel/spillway capacity, etc., may help eliminate the need for costly, retrofit constructions.

Flood managers may evaluate the degree of slack based on the normalized excess capacity of reservoirs to store (Table 2, S1) and release (Table 2, S3) flood flows, the downstream channels to convey flood flows (Table 2, S2), and bypasses' ability to store excess channel flows (Table 2, S4). For example, increasing stream conveyance capacity (Table 2, S2) has been identified as a promising option for mitigating climate change impacts of flooding (Brekke *et al.*, 2009). Managers may evaluate the magnitude of a future flood of interest and current stream conveyance capacity (Table 2, S4) to evaluate the excess capacity needed for a flood bypass. Alternately, if flood magnitudes are projected to increase, but the normalized excess reservoir capacity (Table 2, S1) is ≤ 1, then the system could likely benefit from increases in slack related to flood storage.

TABLE 2. Example Metrics to Assess Flexibility in Flood Management Systems. Unless otherwise noted, larger metric values indicate greater flexibility.

	ID	Metric Description
Slack	S1	Excess reservoir capacity: calculated as a dam's flood storage capacity in excess of the amount of water stored in the reservoir to attenuate an *x*-year flood event
	S2	Excess stream capacity: calculated as the stream conveyance capacity in excess of the expected discharge during an *x*-year flood event
	S3	Excess capacity to release and convey floodwaters: calculated as the stream conveyance capacity in excess of an upstream dam's outlet and spillway capacity
	S4	Excess bypass capacity: calculated as the capacity of the bypass to store water that exceeds the stream conveyance capacity in an *x*-year flood event
Redundancy	R1	Surface storage options: number of reservoirs and bypasses per major tributary
	R2	Structural *vs.* nonstructural diversity[1]
	R3	Delegation of management responsibility: number of agencies committed to flood management
Connectivity	C1	Groundwater and surface water connections: percent of reservoirs operated conjunctively with groundwater
	C2	Potential for floodplain connection: percent of river length without levees
Compatibility/ coordination	CC1	Access to data: water managers have access to future hydrologic projections at relevant temporal and spatial scales
	CC2	Access to data analysis tools: water managers have tools and ability to analyze and utilize hydrologic projections for reservoir planning and operations
	CC3	Intrabasin coordination of operations: percent of reservoirs with coordinated operating agreements
Adjustability	A1	Ability to revise operations plans: level of governmental approval needed to adjust reservoir operations plans (rule curves) or storage allocation (*lower level is more flexible*)
	A2	Opportunities to annually vary flood storage space: calculated as the percent of the maximum flood storage space which can be varied
	A3	Ability to expand storage and conveyance capacity with levee setbacks: calculated as the percent of levees with greater than an *x* m buffer to infrastructure

[1]Structural components: dams and reservoirs, levees, walls, diversion channels, bridge modifications, channel alterations, pumping, and land treatment; Nonstructural measures: flood warning and preparedness; temporary or permanent evacuation and relocation; land use regulations including floodway delineation, floodplain zoning, subdivision regulations and building codes; flood proofing; area renewal policies; and conversion to open space (USACE, 1999).

Unfortunately, the need for additional flexibility in water resources is often only realized in hindsight when meeting objectives is made difficult by the inflexibility of the current system, as can be the case when a system lacks slack. For example, a report (CA-DWR, 2010) on the current condition of the California flood management system lists a variety of factors contributing to the inability of the system to meet its designed flood management objectives. These include a lack of slack through insufficient flood storage capacity to regulate flood flows (Table 2, S1 and S4) and inadequate capacity to convey design flows (Table 2, S2 and S3) in approximately half of the channels evaluated (CA-DWR, 2010).

Redundancy

Redundancy generally refers to multiple options performing the same function in a system, such as multiple species performing a same role (e.g., nitrification) in ecosystems (Walker, 1992). Redundancy and the substitution or interchangeability of components are critical to adaptive and robust SESs (Ospina and Heeks, 2010) and ecosystems exposed to disturbances (DeLeo and Levin, 1997; Naeem, 1998). Similarly, robust IT systems are defined by the degree of repetitiveness, labeled in IT analyses as intensity (Turner and Lankford, 2005). In flood management systems, repetitiveness and diversity of options also increase a water resources system's ability to cope or adapt to uncertain, future conditions (Gleick, 2003; IWMI, 2009). Thus, whereas slack ensures the existence of excess capacity in the system to cope with changing conditions and demands, redundancy ensures that this capacity is spread amongst a variety of options. Redundancy then can be measured by the number of storage options available (Table 2, R1), the diversity of those options (Table 2, R2), and the number of groups with vested interests and responsibility for managing the water resources (Table 2, R3).

In addition to a larger number of options (e.g., number of reservoirs and bypasses in each tributary — Table 2, R1), distributing capacity across many different management strategies can also reduce flood risk over the long term. The value of diversity in flood management strategies in meeting capacity requirements has been emphasized by scientists and managers (Gleick, 2003; Pearce, 2004; Rijsberman, 2006; Brooks *et al.*, 2009; Hall and Murphy, 2012) who critique 20th-Century water policies for relying too heavily on "hard path" approaches to meet human demands, including large dams, aqueducts, and levees, as opposed to "soft path" approaches. In contrast to large, centrally managed infrastructure, soft path approaches emphasize lower cost community-scale systems, decentralized and open decision-making, water markets and equitable pricing, application of efficient technology, and environmental protection. Thus, assessing the relative number of structural and nonstructural options for managing floods (Table 2, R2) can identify the balance in a system's portfolio of infrastructure that contributes to reducing exposure to flood risk.

Finally, the number of parties invested in a flood management system (Table 2, R3) can contribute to its flexibility, though generally only up to a point. Many resources, including water, are too complex to be governed effectively by a single agency (Berkes, 2009). Instead, co-management of natural resources, defined as the sharing of power and responsibility between the government and local resource users (Wallace *et al.*, 2003; Adger *et al.*, 2004, 2005b; Armitage *et al.*, 2008; Huitema *et al.*, 2009), can be more effective at achieving management objectives. Different levels of organization, from local to federal, have comparative advantages in the management of resources (Berkes, 2009). In the flood management context, state and federal agencies may provide financial support and expertise not available at the local level, while local institutions have a better understanding of their specific needs and can respond more quickly to flood emergencies. However, the number of parties involved can also decrease the flexibility of a system and the mere existence of multiple agencies does not always lead to effective and adaptive co-management. In some cases (Adger *et al.*, 2005b), individual institutions may simply promote themselves without promoting the flexibility, the overall management structure, or its adaptability.

Connectivity

Connectivity ensures that a system is capable of fully utilizing its redundancy by employing the options available to meet system objectives. Connectivity is generally viewed as a positive attribute of most adaptive systems (but see Fraser *et al.*, 2005, for an alternate perspective). For example, hydrologic connectivity is essential to functioning ecosystems, where hydrologic connectivity refers to the water-mediated movement of materials, energy, and organisms down and across rivers and riparian areas (Kondolf *et al.*, 2006). With respect to water resources management, the term applies to the linkages between infrastructure that promote reliability of moving water across networks (Yang *et al.*, 1996). Increasing connectivity of water supply infrastructure is considered a mechanism to improve the resilience of existing resources as well as to provide security from extreme events in the face of climate change (Wilby and Dessai, 2010).

The need for connectivity in a water resources system includes both natural infrastructure, including rivers, aquifers, and floodplains, and man-made infrastructure, such as reservoirs, constructed bypasses, and irrigation canals. Since a variety of water storage options exist for flood management, each with strengths and weaknesses, connectivity between these structures and flexibility in their use can help hedge against the uncertainty associated with climate change (IWMI, 2009). Connectivity between water system components also allows for shared utilization between flood management and other operating objectives, such as ecosystem restoration or agricultural production, resulting in overall increased system performance.

Connectivity and collective management in the use of surface and groundwater (Table 2, C1), called conjunctive use, can increase storage capacity by utilizing underground aquifers while avoiding the economic, environmental, and social costs of dams. A study (USACE, 2002) conducted in the Central Valley of California found that, via natural replenishment and anthropogenic aquifer storage during times of high flow, conjunctive use operations generated between 92,000 and 322,000 acre-feet (AF) of newly available annual yield per reservoir. Thus, managers may evaluate the balance of conjunctive use options relative to reservoirs to identify whether additional conjunctive use operations can contribute to expanding storage capacity for flood management.

In addition to leading to more efficient utilization of water supplies, increased connectivity, particularly between the main river channel and its floodplains (Table 2, C2), can generate space for storing and attenuating flood events, while also providing increased slack, redundancy, and ecological benefits. Restoring river-floodplain connectivity can increase the ability of the system to cope with the larger and more frequent floods projected under climate change (IPCC, 2007) by utilizing the natural storage capacity of floodplains, subsurface flow, aquifers, in addition to the human-managed storage reservoirs included in the slack characteristic. For example, reconnection of 8,000 ha of floodplain along the Illinois River to allow peak flood waters to inundate strategically designated farmland could halve the probability of flooding 26,000 ha of downstream farmland (Akanbi *et al.*, 1999). This same study found that an alternate management option of raising the levee height (Table 2, S2) could achieve similar risk reduction goals, but at a significantly lower benefit to cost ratio (Akanbi *et al.*, 1999). In heavily leveed rivers (Table 2, C2), such as the Illinois River, it may be more cost effective for managers to reduce flood stage by increasing river-floodplain connections over implementing other management options. Restoring the connectivity of floodplains may also allow upstream reservoirs to remain at a higher elevation during the flood season by increasing downstream flood storage capacity, increasing the available water supply and hedging against scarcity concerns (Opperman *et al.*, 2009).

Compatibility / Coordination

Duncan (1995) emphasizes the ability to share information across any technology component, termed compatibility, as an important determinant of IT flexibility, since information sharing provides easy access to relevant data and lowers the cost of innovation. In order to make informed decisions, water managers need access to hydrologic, operations, and regulatory information (Table 2, CC1). This information includes antecedent, current, and projected future hydrologic and climate data, water demands and usage, reservoir operations, and forthcoming policy and regulatory changes. The information is needed in locations and forms that are accessible and compatible for use by other entities. In addition, compatibility and coordination are needed between policy makers and water resource planners and managers to ensure that policy and regulations, such as the structure or priority of water rights, both inform and are informed by water resources management.

In most cases, a variety of different agencies work within a river basin on different aspects of water management, and each agency is likely to have access to data that may be relevant to others. Furthermore, researchers, water users, and other stakeholders outside of water management agencies also possess data (Table 2, CC1) and analytical tools (Table 2, CC2) relevant to water managers, and vice versa, requiring a multidimensional flow of information. For example, the peer-reviewed literature contains many examples of the potential for ensemble streamflow prediction (ESP) forecasts to improve water system operations (Hamlet and Lettenmaier, 1999; Faber and Stedinger, 2001; Hamlet *et al.*, 2002). However, many water agencies lack access to peer-reviewed literature and to the modeling techniques and decision processes to fully exploit ESP forecasts (Faber and Stedinger, 2001). Assessing the sharing of data and tools in a basin is binary (Table 2, CC1 and CC2), but may vary across user groups.

In addition, within-basin coordination of water resources management and operations (Table 2, CC3) can significantly contribute to system flexibility and robustness. In their recommendations for a sustainable future, the Western Governors' Association (2008) emphasized that ongoing coordination and information sharing between scientists and water managers, along with the various levels of government engaged in planning efforts, is critically needed. Similarly, after the devastating 1997 flood in the Yuba-Feather River system in California, the Yuba County Water Agency (2008) found that sharing weather, water, and management information and the coordination of operational decisions among agencies provided one of the most cost-effective measures for improved flood management (Table 2, CC1 and CC3). The implementation of forecast-coordinated operations in these basins is expected to reduce peak flows of the rivers and the risk of exceeding river channel capacity, as well as improve the notification processes and advance flood warning and preparation times (Yuba County Water Agency, 2008). Similarly, the National Hydrologic Warning Council reported in 2013 that lives were saved during the Colorado floods of 2013 by the coordinated flood warning and management systems that were implemented following flash floods that killed over 140 people in 1976 (Curtis, 2013). Such coordination, both of information and agencies, can be assessed by the number of coordinated agreements in a basin (Table 2, CC3), normalized for example, relative to the number of reservoirs. The normalized metric allows managers to evaluate potential operational gains by determining the relative number of reservoirs operating in isolation.

Adjustability

Khosrowpour (2006) takes a broad interpretation of Duncan's (1995) definition of modularity to include the ability to add, modify, and remove any software, hardware, or data components of the infrastructure with ease and with no major overall effect. Since the use of the term modularity in the IT context usually takes on a specific meaning associated with isolating and standardizing business and system processes (Duncan, 1995), we modify the definition given by Khosrowpour (2006) and rename this flexibility characteristic adjustability, or the ability to add, modify, and remove any component of the system and/or its operations with ease and with no major overall effect. In essence, adjustability describes the ease with which managers can modify the formally described flexibility characteristics — slack, redundancy, connectivity, compatibility/coordination — to adapt to changing conditions.

Relative to adjustability, one of the most widely cited inflexibilities in water management systems refers to the inability to modify system operations in a timely and cost-effective manner due to legal or other regulatory constraints (Hamlet and Lettenmaier, 1999; CA-DWR, 2009; Johnson and Lilly, 2009). At a workshop in 2009, western water managers emphasized the need to "evaluate and revise the legal framework for water management to the extent allowable to ensure sufficient flexibility exists to anticipate and respond to climate change" (Johnson and Lilly, 2009). In particular, these managers stressed the importance of the ability to revise dam operations (Table 2, A1) based on new information without going through costly and time-consuming Congressional re-authorization and/or completing an Environmental Impact Statement every time a change is needed (Johnson and Lilly, 2009).

The ability to modify reservoir operations and storage allocations (Table 2, A1) is one key characteristic of a flexible flood management system. For example, in response to much larger floods in the American River Basin after completion of the Folsom Dam, the initial operations manual and rule curves have been changed three times (Ferreira, 1982; Platt, 1995; NRC, 1999). The current rule curve allows for annually varying flood storage space (Table 2, A2), based on an allowance to utilize upstream reservoir space to store flood waters (Table 2, A1) (Platt, 1995). However, the number and extent of changes to Folsom's operations serves as a unique case. Adjusting the water appropriation policies that evolved over the past 100 years in the western United States and other areas of the western world (CBO, 1997) is often not politically or socially acceptable and presents a prohibitive financial and time expense. Thus, an assessment of the ability to modify reservoir operations (Table 2, A1 and A2) can help identify potential sources of flexibility through areas lacking adjustability.

Alternately, managers can assess the adjustability of the existing levee footprints by calculating the proportion of levees sufficiently distanced from infrastructure (Table 2, A3). High values for metric A3 indicate a greater potential and lower cost to adjust the system and enhance future flexibility characteristics, through efforts to set back levees to increase floodway conveyance capacity (Table 2, S2), reconnect the floodplain (Table 2, C2), and/or construct a bypass to increase slack (Table 2, S1) and possibly redundancy (Table 2, R1).

VALUING THE COSTS AND BENEFITS OF FLEXIBILITY

There may be a point at which more flexibility is no longer desirable and/or the costs outweigh the benefits (Nemetz and Fry, 1988; Duimering *et al.*, 1993; Byrd and Turner, 2000). Too much flexibility can introduce unintended, negative impacts on systems, particularly if individual flexibility characteristics are considered in isolation from others. For example, oversizing reservoir capacity without taking precautions to preserve slack for future times of need may lead to the classic overshoot and collapse problem (Meadows *et al.*, 1972). Alternately, a large number of agencies involved in water resources management and funding, reflective of high intensity and redundancy, can delay and complicate decision making if there is not proper collaboration and communication between the agencies and a formal governance structure in place (National Research Council-Committee on Sustainable Water and Environmental Management in the California Bay-Delta, 2012). Inconsistencies between federal and state flood risk policies are not uncommon (USACE, 2009) and can complicate project permitting. Connectivity can introduce negative human interventions into historically and genetically isolated systems through interbasin transfers or river restoration activities (Fausch *et al.*, 2009). Flexible dam operations and rule curves, reflecting the characteristic of adjustability, provide planners and operators with discretion that could lead to unintended impacts on ecosystems or water supply.

Furthermore, flexibility comes at a price, and flexible technologies tend to cost more than traditional, less flexible equipment and products (Nemetz and Fry, 1988; Duimering *et al.*, 1993; Byrd and Turner, 2000). Retrofitting flood management infrastructure to incorporate more flexibility can require considerable financial investments. For example, increasing the storage capacity, and thus slack, in the American River Basin, California by raising the Folsom Dam will cost an estimated \$314 million (State of California, 2010). It cost \$41-55 million to increase adaptability at Cougar Dam, Oregon by installing a selective withdrawal structure for managing downstream temperatures (Palmer, 2010; Learn, 2011), and \$800 million to modify the Hoover Dam to improve operations under lower flow conditions (Brean, 2012). Increased flexibility may also come with increased technological complexity, which requires advanced management and support staff at additional costs (Byrd and Turner, 2000).

The value of flexibility relates to the uncertainties and changes the system faces (Zhao and Tseng, 2003; Huang *et al.*, 2010). Thus, qualitatively, the value of flexibility is lower in more stable, predictable conditions, whereas the value of flexibility increases with the degree of uncertainty and the projected magnitude of perturbations in future conditions. Furthermore, identifying the appropriate level of flexibility in a system will depend upon the risk tolerance level of decision makers, planners, and other stakeholders, and the extent to which they are willing to accept the inability of the system to fully meet objectives for all plausible conditions (Galloway, 2011). Thus, alternative decision-making models, such as Robust Decision Making (Lempert *et al.* 2003), Real Options theory (Leary, 1999; Heal and Kriström, 2002; Hertzler, 2007), and optimization that maximizes robustness and/or adaptability, may be needed to guide valuation of flexibility in uncertain future conditions. For example, despite the limitations of optimizing to an uncertain future, a manager might implement actions that maximize the range of plausible futures under which the system could meet a performance threshold with secondary objectives or constraints associated with financial costs, creation, or elimination of real options, maintaining a balanced portfolio of flexibility characteristic, etc. Alternately, potential management actions could be evaluated based on the extent to which they increase the range of conditions under which the system could meet a performance target per unit cost for the action. For a flood management scenario, an example action might maintain flood risk below a target expected annual damage for a 10% larger range of plausible futures than the baseline system at a cost of $1 million. This is equivalent to a 1% increase in operational range for every $100,000 invested.

CONCLUSIONS

Given the contribution of flexibility to the adaptive capacity of water resources systems, and the increasing uncertainty in future hydrologic conditions, flexible water resources management systems are likely to perform well over a wide range of conditions. However, flexibility as a concept requires definition and characterization within the context of water resources systems. We define flexibility for the field of water resources management as the inherent ability of the human and physical elements of a system to cope with, adapt to, or alter to better suit uncertain and changing conditions, in a timely and cost-effective manner. Given that, unlike the related characteristic of adaptive capacity, flexibility of a system is determined by its inherent characteristics that are independent of future conditions, we propose metrics that are assessable using system specifications, plans, and management structures, rather than deeply uncertain future projections. Lastly, we identify some potential methods for comparing management strategies for their contribution to flexibility and for making decisions of how to incorporate flexibility into water management systems.

Water resources managers have a wide array of infrastructure, operational, and regulatory options for meeting the objectives of water resources systems. Each option has different performance characteristics, including its contribution to the system's ability to adapt as the severity and uncertainty of climate change materialize. In support of others' recommendations for increased flexibility in water resources systems, as well as the clear benefit of flexibility in other domains, this work contributes to incorporating flexibility in the performance evaluation of the different options available to water resources managers. However, we emphasize that the proposed framework and metrics do not provide direct guidance regarding how much more slack, or other flexibility characteristics, are needed. The manager and public must determine the degree of flexibility in a water resources system based on their acceptable level of risk and the cost of achieving reduced risk. Furthermore, additional investigation of flexibility is warranted to fully understand its role in the planning, design, operations, and management of adaptive water resources systems. In particular, further studies are needed to: (1) apply and evaluate the flexibility metrics in existing water resources management systems (DiFrancesco and Tullos, 2014); (2) conduct case studies to quantify the relationship between system flexibility and adaptive capacity; (3) demonstrate valuation of flexibility; and (4) develop flexibility metrics for other operating objectives (e.g., hydropower generation, water supply, environmental benefits, recreation, etc.).

The conclusions and remaining research gaps reported herein highlight the urgent need for and contribution of synthesis, dialogue, and comparative analysis to the implementation of adaptive, flexible water resources systems. For example, given the important but largely assumed connection between flexibility and adaptive capacity, a critical next step is to assess the value of flexibility in terms of its relationship with climate risk, uncertainty, and adaptive capacity. Comparing the flexibility and adaptive capacity of case study systems would allow for assessment of the extent to which overall system flexibility contributes to adaptive capacity, as well as the relative contributions of each of the flexibility characteristics to adaptive capacity. From such a study, one may synthesize general principles regarding flexibility and adaptive capacity. For example, it may be the case that a subset of the proposed flexibility metrics or characteristics disproportionally relates to a system's adaptive capacity. Alternatively, such study may identify other flexibility metrics not included in this manuscript. Further, the finding of a weak relationship between flexibility and adaptive capacity may indicate that other factors play a larger role in determining a system's ability to adapt and perform under uncertain, changing conditions. It is through these types of multidisciplinary and rigorous analysis that we will understand the best strategies for establishing robust water resources systems in an uncertain future.

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LITERATURE CITED

Adger, W.N., N.W. Arnell, and E.L. Tompkins, 2005a. Successful Adaptation to Climate Change across Scales. Global Environmental Change 15:77-86.

Adger, W.N., N. Brooks, G. Bentham, M. Agnew, and S. Eriksen, 2004. New Indicators of Vulnerability and Adaptive Capacity. Tyndall Centre for Climate Change Research, Norwich. http://www.tyndall.ac.uk/content/new-indicators-vulnerability-and-adaptive-capacity, *accessed* October 2013.

Adger, W.N., K. Brown, and E.L. Tompkins, 2005b. The Political Economy of Cross-Scale Networks in Resource Co-Management. Ecology and Society 10:9.

Akanbi, A.A., Y. Lian, and T.W. Soong, 1999. An Analysis on Managed Flood Storage Options for Selected Levees along the Lower Illinois River for Enhancing Flood Protection. Prepared for the Office of Water Resources Illinois Department of Natural Resources. http://www.isws.uiuc.edu/pubdoc/CR/ISWSCR-645.pdf, *accessed* February 2012.

Armitage, D.R., R. Plummer, F. Berkes, R.I. Arthur, A.T. Charles, I.J. Davidson-Hunt, A.P. Diduck, N.C. Doubleday, D.S. Johnson, and M. Marschke, 2008. Adaptive Co-Management for Social-Ecological Complexity. Frontiers in Ecology and the Environment 7:95-102.

Arthington, A.H., S.E. Bunn, N.L. Poff, and R.J. Naiman, 2006. The Challenge of Providing Environmental Flow Rules to Sustain River Ecosystems. Ecological Applications 16:1311-1318.

Berkes, F., 2009. Evolution of Co-Management: Role of Knowledge Generation, Bridging Organizations and Social Learning. Journal of Environmental Management 90:1692-1702.

Bonder, S., 1979. Changing the Future of Operations Research. Operations Research 27:209-224.

Brean, H., 2012. Third Intake into Lake Mead Hits $5 Million Snag. Las Vegas Review Journal. http://www.reviewjournal.com/news/water-environment/third-intake-lake-mead-hits-5-million-snag, *accessed* October 2013.

Brekke, L.D., E.P. Maurer, J.D. Anderson, M.D. Dettinger, E.S. Townsley, A. Harrison, and T. Pruitt, 2009. Assessing Reservoir Operations Risk under Climate Change. Water Resources Research 45:W04411.

Brooks, D.B., O.M. Brandes, and S. Gurman, 2009. Making the Most of the Water We Have: The Soft Path Approach to Water Management. Earthscan/James & James, Oxford, United Kingdom.

Byrd, T.A. and D.E. Turner, 2000. Measuring the Flexibility of Information Technology Infrastructure: Exploratory Analysis of a Construct. Journal of Management Information Systems 17:167-208.

CA-DWR (California Department of Water Resources), 2009. California Water Plan Update 2009: Integrated Water Management. http://www.waterplan.water.ca.gov/cwpu2009/index.cfm, *accessed* May 2011.

CA-DWR (California Department of Water Resources), 2010. Central Valley Flood Protection Plan Regional Conditions Report. http://www.water.ca.gov/cvfmp/docs/RegionalConditionsReport CVFPP201003.pdf, *accessed* March 2012.

Carpenter, S.R. and W.A. Brock, 2008. Adaptive Capacity and Traps. Ecology and Society 13:40.

Carpenter, S.R., B. Walker, J.M. Anderies, and N. Abel, 2001. From Metaphor to Measurement: Resilience of What to What? Ecosystems 4:765-781.

CBO (Congressional Budget Office), 1997. Water Use Conflicts in the West: Implications of Reforming the Bureau of Reclamations Water Supply Policies. http://www.cbo.gov/ftpdocs/0xx/doc46/wateruse.pdf, *accessed* February 2012.

Chatterjee, S. and B. Wernerfelt, 1991. The Link between Resources and Type of Diversification: Theory and Evidence. Strategic Management Journal 12:33-48.

Curtis, D.C., 2013. Flood Warning Systems Saved Lives During Colorado Flood. National Hydrologic Warning Council Press Release. http://finance.yahoo.com/news/flood-warning-systems-saved-lives-150000047. html, *accessed* October 2013.

DeLeo, G.A. and S. Levin, 1997. The Multifaceted Aspects of Ecosystem Integrity. Conservation Ecology 1:3.

Dietz, T., E. Ostrom, and P.C. Stern, 2003. The Struggle to Govern the Commons. Science 302:1907-1912.

DiFrancesco, K. and D. Tullos, 2014. Assessment of Flood Management Systems' Flexibility with Application to the Sacramento River Basin, California, USA. International Journal of River Basin Management, doi: 10.1080/15715124.2014.917316.

Duimering, P.R., F. Safayeni, and L. Purdy, 1993. Integrated Manufacturing: Redesign the Organization before Implementing Flexible Technology. Sloan Management Review 34:47-56.

Duncan, N.B., 1995. Capturing Flexibility of Information Technology Infrastructure: A Study of Resource Characteristics and Their Measure. Journal of Management Information Systems 12:37-57.

Engle, N.L., 2011. Adaptive Capacity and Its Assessment. Global Environmental Change 21:647-656.

Faber, B.A. and J.R. Stedinger, 2001. Reservoir Optimization Using Sampling SDP with Ensemble Streamflow Prediction (ESP) Forecasts. Journal of Hydrology 249:113-133.

Falkenmark, M. and C. Widstrand, 1992. Population and Water Resources: A Delicate Balance. Population Bulletin 47:1.

FAO (Food and Agriculture Organization), 1993. The State of Food and Agriculture 1993. Rome, Italy. http://www.fao.org/docrep/003/t0800e/t0800e00.htm, *accessed* January 2012.

Fausch, K.D., B.E. Rieman, J.B. Dunham, M.K. Young, and D.P. Peterson, 2009. Invasion Versus Isolation: Trade-Offs in Managing Native Salmonids with Barriers to Upstream Movement. Conservation Biology 23:859-870.

Fayol, H., 1916. Administration Générale et Industrielle. Gauthiers-Villars, Paris, France.

Ferreira, J.; California Department of Water Resources (CA-DWR), 1982. A Preliminary Study of Flood Control Alternatives on the Lower American River. State of California, the Resources Agency, Department of Water Resources, Sacramento, California.

Folke, C., S.R. Carpenter, T. Elmqvist, L. Gunderson, C.S. Holling, and B. Walker, 2002. Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations. AMBIO: A Journal of the Human Environment 31:437-440.

Folke, C., T. Hahn, P. Olsson, and J. Norberg, 2005. Adaptive Governance of Social-Ecological Systems. Annual Review of Environment and Resources 30:441-473.

Fraser, E.D., W. Mabee, and F. Figge, 2005. A Framework for Assessing the Vulnerability of Food Systems to Future Shocks. Futures 37:465-479.

Frederick, K.D., D.C. Major, and E.Z. Stakhiv, 1997. Water Resources Planning Principles and Evaluation Criteria for Climate Change: Summary and Conclusions. Climatic Change 37:291-313.

Gallopín, G.C., 2006. Linkages Between Vulnerability, Resilience, and Adaptive Capacity. Global Environmental Change 16:293-303.

Galloway, G.E., 2011. If Stationarity Is Dead, What Do We Do Now? Journal of the American Water Resources Association 47:563-570.

Gleick, P.H., 2003. Global Freshwater Resources: Soft-Path Solutions for the 21st Century. Science 302:1524-1528.

Golden, W. and P. Powell, 2000. Towards a Definition of Flexibility. In Search of the Holy Grail? Omega 28:373-384.

Gunderson, L.H. and C.S. Holling, 2002. Panarchy: Understanding Transformations in Human and Natural Systems. Island Press, Washington, D.C.

Hall, J. and C. Murphy, 2012. Adapting Water Supply Systems in a Changing Climate. Water Supply Systems, Distribution and Environmental Effects. Nova Science Publishers Inc., Hauppauge, New York.

Hamlet, A.F., D. Huppert, and D.P. Lettenmaier, 2002. Economic Value of Long-Lead Streamflow Forecasts for Columbia River Hydropower. Journal of Water Resources Planning and Management 128:91.

Hamlet, A.F. and D.P. Lettenmaier, 1999. Columbia River Streamflow Forecasting Based on ENSO and PDO Climate Signals. Journal of Water Resources Planning and Management 125:333-341.

Heal, G. and B. Kriström, 2002. Uncertainty and Climate Change. Environmental and Resource Economics 22:3-39.

Hertzler, G., 2007. Adapting to Climate Change and Managing Climate Risks by Using Real Options. Australian Journal of Agricultural Research. Commonwealth Scientific and Industrial Research Organization, 58:985-992.

Holdren, J.P. and P.R. Ehrlich, 1974. Human Population and the Global Environment: Population Growth, Rising Per Capita Material Consumption, and Disruptive Technologies Have Made Civilization a Global Ecological Force. American Scientist 62:282-292.

Huang, D., K. Vairavamoorthy, and S. Tsegaye, 2010. Flexible Design of Urban Water Distribution Networks. World Environmental and Water Resources Congress 2010: Challenges of Change, Providence, Rhode Island, pp. 4225-4236.

Huitema, D., E. Mostert, W. Egas, S. Moellenkamp, C. Pahl-Wostl, and R. Yalcin, 2009. Adaptive Water Governance: Assessing the Institutional Prescriptions of Adaptive (Co-) Management from a Governance Perspective and Defining a Research Agenda. Ecology and Society 14:26.

IPCC (Intergovernmental Panel on Climate Change), 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M. Parry (Editor). Cambridge University Press, Cambridge, United Kingdom; New York City, New York.

IWMI (International Water Management Institute), 2009. Flexible Water Storage Options and Adaptation to Climate Change. Water Policy Brief. http://www.iwmi.cgiar.org/Publications/Water_Policy_Briefs/PDF/WPB31.pdf, *accessed* January 2012.

Johnson, A.M.A. and G. Lilly, 2009. Western States Watershed Study. http://www.westgov.org/wswc/wsws%20main%20report_jan09.pdf, *accessed* February 2012.

Jones, L., E. Ludi, and S. Levine, 2011. Towards a Characterisation of Adaptive Capacity: A Framework for Analysing Adaptive Capacity at the Local Level. Overseas Development Agency, London, United Kingdom.

Khosrowpour, M., 2006. Advanced Topics in Information Resources Management. Idea Group Inc (IGI), Hershey, Pennsylvania.

Kondolf, G.M., A.J. Boulton, S. O'Daniel, G.C. Poole, F.J. Rahel, E.H. Stanley, E. Wohl, A. Baang, J. Carlstrom, and C. Cristoni, 2006. Process-Based Ecological River Restoration: Visualizing Three-Dimensional Connectivity and Dynamic Vectors to Recover Lost Linkages. Ecology and Society 11:5.

Learn, S., 2011. Getting Salmon Past Daunting Willamette Basin Dams Could Have a Big Price Tag — And a Big Payoff. The Oregonian - OregonLive.com. http://www.oregonlive.com/environment/index.ssf/2011/09/detroit_dam_to_restore_wild_ru.html, *accessed* May 2012.

Leary, N.A., 1999. A Framework for Benefit-Cost Analysis of Adaptation to Climate Change and Climate Variability. Mitigation and Adaptation Strategies for Global Change 4:307-318.

Lempert, R.J., S.C. Bankes, and S.W. Popper, 2003. Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis. RAND Corporation, Santa Monica, California. http://www.rand.org/pubs/monograph_reports/MR1626.html, *accessed* January 2011.

Meadows, D.H., D.L. Meadows, J. Randers, and W.W. Behrens, III, 1972. The Limits to Growth: A Report to the Club of Rome (1972). Universe Books, New York City, New York.

Merriam-Webster, Inc., 2003. Merriam-Webster's Collegiate Dictionary. Merriam-Webster, Springfield, Massachusetts.

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer, 2008. Stationarity Is Dead: Whither Water Management? Earth 4:20.

Naeem, S., 1998. Species Redundancy and Ecosystem Reliability. Conservation Biology 12:39-45.

National Research Council-Committee on Sustainable Water and Environmental Management in the California Bay-Delta, 2012. Sustainable Water and Environmental Management in the California Bay-Delta. The National Academies Press, Washington, D.C.

Nemetz, P.L. and L.W. Fry, 1988. Flexible Manufacturing Organizations: Implications for Strategy Formulation and Organization Design. Academy of Management Review 13:627-638.

NRC (National Research Council), 1999. Committee on American River Flood Frequencies. Improving American River Flood Frequency Analysis. The National Academies Press, Washington, D.C.

Opperman, J.J., G.E. Galloway, J. Fargione, J.F. Mount, B.D. Richter, and S. Secchi, 2009. Sustainable Floodplains through Large-Scale Reconnection to Rivers. Science 326:1487-1488.

Ospina, A.V. and R. Heeks, 2010. Linking ICTs and Climate Change Adaptation. University of Manchester, Manchester, United Kingdom. http://africa-adapt.net/media/resources/413/Linking%20ICTs%20and%20Climate%20Change%20Adaptation.pdf, *accessed* October 2013.

Pahl-Wostl, C., 2007. Transitions Towards Adaptive Management of Water Facing Climate and Global Change. Integrated Assessment of Water Resources and Global Change 21:49-62.

Pahl-Wostl, C., 2009. A Conceptual Framework for Analysing Adaptive Capacity and Multi-Level Learning Processes in Resource Governance Regimes. Global Environmental Change 19:354-365.

Pahl-Wostl, C., J. Sendzimir, P. Jeffrey, J. Aerts, G. Berkamp, and K. Cross, 2007. Managing Change toward Adaptive Water Management through Social Learning. Ecology and Society 12:30.

Palmer, S., 2010. Helping Fish Find Their Way. The Register Guard, p. B1.

Patel Center, 2011. Flexible Design of Urban Water Management Systems. Patel School of Global Sustainability, University of South Florida. http://psgs.usf.edu/patel-center/flexible-design/, *accessed* April 2012.

Pearce, F., 2004. Keepers of the Spring: Reclaiming Our Water in An Age of Globalization. Island Press, Washington, D.C.

Pettengell, C., 2010. Climate Change Adaptation: Enabling People Living in Poverty to Adapt. Oxfam Policy and Practice: Climate Change and Resilience 6:1-48.

Platt, R.H., 1995. Flood Risk Management and the American River Basin: An Evaluation. The National Academies Press, Washington, D.C.

Pye, R., 1978. A Formal, Decision-Theoretic Approach to Flexibility and Robustness. The Journal of the Operational Research Society 29:215-227.

Pyoun, Y.S. and B.K. Choi, 1994. Quantifying the Flexibility Value in Automated Manufacturing Systems. Journal of Manufacturing Systems 13:108-118.

Richter, B.D., R. Mathews, D.L. Harrison, and R. Wigington, 2003. Ecologically Sustainable Water Management: Managing River Flows for Ecological Integrity. Ecological Applications 13:206-224.

Richter, B.D. and G.A. Thomas, 2007. Restoring Environmental Flows by Modifying Dam Operations. Ecology and Society 12:12.

Rijsberman, F.R., 2006. Water Scarcity: Fact or Fiction? Agricultural Water Management 80:5-22.

Smit, B. and J. Wandel, 2006. Adaptation, Adaptive Capacity and Vulnerability. Global Environmental Change 16:282-292.

State of California, 2010. California Strategic Growth Plan Bond Accountability, Folsom Dam Raise. http://bondaccountability.resources.ca.gov/Project.aspx?ProjectPK=3860-P1E-041&pid=5, *accessed* May 2012.

Suttinon, P. and S. Nasu, 2010. Real Options for Increasing Value in Industrial Water Infrastructure. Water Resources Management 24:2881-2892.

Turner, D.E. and W.M. Lankford, 2005. Information Technology Infrastructure: A Historical Perspective of Flexibility. Journal of Information Technology. http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.94.6611, *accessed* January 2011.

USACE (United States Army Corps of Engineers), 1999. Flood Damage Reduction. Digest of Water Resources Policies and Authorities. Ch 13. http://140.194.76.129/publications/eng-pamphlets/ep1165-2-1/c-13.pdf, *accessed* February 2011.

USACE (United States Army Corps of Engineers), 2002. Sacramento and San Joaquin River Basins Comprehensive Study. http://www.compstudy.net/reports.html, *accessed* October 2011.

USACE (United States Army Corps of Engineers), 2009. Flood Risk Management-Value to the Nation. http://www.poa.usace.army.mil/Portals/34/docs/engineering/USACEFloodRiskMgmtBrochure.pdf, *accessed* October 2013.

U.S. Water Resources Council, 1983. Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies. Water Resources Council, Washington, D.C.

Vörösmarty, C.J., P. Green, J. Salisbury, and R.B. Lammers, 2000. Global Water Resources: Vulnerability from Climate Change and Population Growth. Science 289:284.

Walker, B.H., 1992. Biodiversity and Ecological Redundancy. Conservation Biology 6:18-23.

Wallace, J.S., M.C. Acreman, and C.A. Sullivan, 2003. The Sharing of Water between Society and Ecosystems: From Conflict to Catchment-Based Co-Management. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences 358:2011-2026.

Western Governors' Association, 2008. Water Needs and Strategies for a Sustainable Future: Next Steps.

Wilby, R.L. and S. Dessai, 2010. Robust Adaptation to Climate Change. Weather 65:180-185.

Wolman, A.; National Research Council (U.S.) Committee on Natural Resources, 1962. Water Resources: A Report to the Committee on Natural Resources of the National Academy of Sciences-National Research Council. National Academies, Washington, D.C.

Wurbs, R.A., 1991. Optimization of Multiple-Purpose Reservoir Systems Operations: A Review of Modeling and Analysis Approaches. DTIC Document.

Yang, S.-L., N.-S. Hsu, P.W. Louie, and W.W. Yeh, 1996. Water Distribution Network Reliability: Connectivity Analysis. Journal of Infrastructure Systems 2:54-64.

Yuba County Water Agency, 2008. Forecast-Coordinated Operations of Lake Oroville and New Bullards Bar Reservoir for Managing Major Flood Events. http://www.water.ca.gov/floodmgmt/docs/fco_brochure_v9_jan2008_update.pdf, *accessed* February 2012.

Zhao, T. and C.-L. Tseng, 2003. Valuing Flexibility in Infrastructure Expansion. Journal of Infrastructure Systems 9:89-97.