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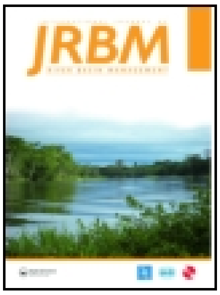

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Assessment of flood management systems' flexibility with application to the Sacramento River basin, California, USA

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Research paper

Assessment of flood management systems' flexibility with application to the Sacramento River basin, California, USA

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ABSTRACT

Water resources managers and researchers have concluded that increasing system flexibility will provide flood management systems advantages in meeting objectives under uncertain future hydrologic conditions. However, despite the frequent use of the term flexibility, demonstration of the concept to analysis and design of flood management systems has yet to be conducted. Building upon previous studies of flexibility in the fields of information technology and social-ecological systems, among others, we outline an approach to investigate how structural and non-structural flood management actions relate to system flexibility. We assess flexibility using metrics that describe flexibility by five characteristics: slack, redundancy, connectivity, adjustability, and compatibility/cooperation. We apply this flexibility assessment to four proposed flood management strategies, each with a unique suite of management actions, for the Sacramento River basin in California, USA. The foci of benefits differ between the four different flood management strategies, with varying emphasis on protecting urban communities, rural and agricultural improvements, and ecosystem restoration. The suite of proposed structural and non-structural actions has the potential to increase all five flexibility characteristics, though only a selection of actions are included in each of the four management strategies. The flexibility assessment reveals a disproportionate emphasis in all strategies on increasing slack in the current system as well as a concentration of expenditures towards structural versus non-structural components. Only two of the assessed strategies improve all five flexibility characteristics, and these two strategies also include the greatest number of actions that provide flexibility benefits. We do not find a clear link between these more flexible strategies and their time and cost-effectiveness in terms of reduction in damages. The outlined method provides a useful tool for comparing the flexibility of potential management strategies, and further application can provide more insight into broader thinking on flood management under uncertainty.

Keywords: Flexibility; flood risk management; adaptive capacity; climate change; robustness; uncertainty

1 Introduction

With water resources under increasing pressure from population growth and climate change, scientists and managers frequently assert the need for additional flexibility in the systems and infrastructure that retain, divert, and deliver water. The need for flexibility is fundamentally driven by uncertainty and changing conditions (Zhao and Tseng 2003). For water resources systems, including the human and physical components that contribute to managing water within a river basin, the recent rise in flexibility recommendations relates to substantial changes in hydrologic and socio-economic conditions. Although uncertainty has plagued managers for as long as water resources have been developed, the deep uncertainty (Lempert et al. 2003) in hydrology under climate change far exceeds any uncertainty flood managers confronted in the past (Hall and Solomatine 2008). Faced with a wide range of uncertain and changing future hydrologic conditions, flexible systems that can adapt to change quickly and effectively are thought to provide advantages over inflexible systems (Pahl-Wostl *et al.* 2007, Wilby and Dessai 2010).

Furthermore, changes in attitudes towards risk and uncertainty coincide with the call for more flexibility in water resources management. For example, through the present day, flood managers primarily utilize risk analysis in planning and evaluating water resources systems and projects. Risk is most commonly analysed in relation to the ability of the system or components to withstand a probabilistic flood size (NRC 2000). However, increased uncertainty due to climate change and other future changes calls into question our ability to describe performance outcomes of future

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flood management strategies with probability distributions, a requisite for risk-based analysis (Frederick *et al.* 1997, Milly *et al.* 2008). As such, addressing climate change in water resources planning has led to an increased emphasis on uncertainty analysis, utilization of large ensembles of future scenarios, and a rise in recommendations for flexibility, resilience, adaptive capacity, and robustness (Lempert *et al.* 2003). In line with this shift in the framing of future conditions and uncertainty, the overarching goals of the water resources management analyses shift from seeking an optimal strategy for a limited set of future expectations, to seeking flexible, robust, and adaptive strategies that perform reasonably well over a wide range of uncertain, but plausible future scenarios (Frederick *et al.* 1997, Lempert *et al.* 2003).

The contribution of flexibility to the performance of water resources systems in an uncertain future is embedded in its relation to concepts of resiliency and adaptive capacity from the study of social-ecological systems. For example, resilience in human systems has been defined (Walker *et al.* 2004) as 'the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks.' We (DiFrancesco and Tullos in press) define flexibility of water resources systems 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.' A key distinction in these concepts is the reference to an external disturbance. Both resilience and adaptive capacity are defined in terms of a stress or disturbance and an answer to the question: Adaptation or resilience of what to what? (Carpenter *et al.* 2001, Gallopín 2006). In contrast, a system's flexibility can be assessed without classification of an external disturbance, as we do in this manuscript. Yet, flexibility nonetheless provides a means for the system to respond to the changes generated by a disturbance. Flexibility is thus thought to contribute to a system's resiliency and capacity to adapt as well as to the system's robustness, which describes the capacity to perform over a large range of uncertain, but plausible future scenarios (Lempert *et al.* 2006).

However, while it is generally agreed that flexibility contributes to long-term resiliency and robustness, it is less clear how the broad collection of management actions and infrastructure available to water resources managers contributes to a system's flexibility. In particular, it is unclear how best to prioritize maintenance of, and improvements to, flood risk management systems, which can be achieved through actions aimed towards both structural, physical components (S) of the system as well as the non-structural, operations, and management components (NS) (Pyoun and Choi 1994, Byrd and Turner 2000, Wang and De Neufville 2004). Structural flood management components include dams, levees, diversions, etc., whereas non-structural components refer to laws and regulations, zoning, flood forecast-warning systems, and awareness raising. For a variety of reasons, recent discussions of flood risk management have shifted away from a reliance on a few large structures to consideration of the complete spectrum of both structural and non-structural solutions (Galloway 1997, Werritty 2006). One predominant reason for this shift is that non-structural actions generally provide more reversible and less expensive mechanisms to reduce flood risk than structural actions. This reversibility represents higher flexibility in the system, ensuring that future options remain open and thus supports adaptive management strategies (Kundzewicz 2002). Along similar lines, Sayers *et al.* (2012) recommend increasing flexibility, used interchangeably with adaptability, by implementing solutions that can be modified if the future should turn out to be different from expectations. Often non-structural solutions provide more adaptability and real options than non-structural actions (Sayers *et al.* 2012). However, characteristics of flexible systems go well beyond reversibility and adaptability (DiFrancesco and Tullos in press), and it is currently unclear how structural and non-structural management actions contribute to the broad range of characteristics that comprise a flexible flood management system.

The goal of this study is thus to investigate how structural and non-structural flood management actions relate to system flexibility in the Sacramento River basin, California. More specifically, we ask these key questions:

(1) How do individual management actions contribute to the different flexibility components?
(2) How are structural and non-structural actions different in their impacts on flexibility?
(3) How do different management objectives, represented in the four Central Valley Flood Protection Plan (CVFPP) management strategies, lead to different outcomes for flexibility characteristics?
(4) Is there a relationship between flexibility and cost-/time-effectiveness of management strategies?

Following DiFrancesco and Tullos (in press), we examine five characteristics of flexibility – slack, redundancy, connectivity, adjustability, and compatibility/cooperation – to identify areas in which flood management systems exhibit inflexibilities or can achieve increased flexibility. Using the Sacramento River basin, California, USA, as a case study, we apply an approach to assess the impact of proposed management actions on system flexibility. For this analysis we utilize information provided in the 2012 CVFPP regarding the current Sacramento flood management system. This plan includes four proposed flood management strategies, each comprising more specific flood management actions (CA-DWR 2012). The following analysis examines the number, type, and cost of proposed actions that would affect each of the five flexibility characteristics.

2 Operationalization of the term flexibility

The few in-depth examinations of flexibility and attempts to measure flexibility primarily come from the fields of: Information Technology (IT) (Duncan 1995, Byrd and Turner 2000, Golden and Powell 2000, Turner and Lankford 2005); adaptive capacity of social-ecological systems (SESs) (Adger *et al.* 2005, Smit and Wandel 2006); management (Fayol 1916); manufacturing (Pyoun and Choi 1994); planning (Pye 1978); and water resources (Sayers *et al.* 2012, Gersonius *et al.* 2013). Studies from IT fields represent the first and most thorough attempts to assess the flexibility of a system (Duncan 1995, Byrd and Turner 2000, Golden and Powell 2000, Turner and Lankford 2005). Each of these studies in the IT field delineates between different characteristics of flexible systems that represent areas in which flexibility can be gained or lost. DiFrancesco and Tullos (in press) adapt these delineations, identifying five characteristics of flexible water management systems:

- Slack: degree of excess capacity or underutilization;
  - Example: reservoir flood storage capacity in excess of design flood volume;
- Redundancy: degree of repetitiveness and diversity of options available to meet objectives;
  - Example: number of flood storage facilities within the system;
- Connectivity: ability of any component to attach to any of the other components inside and outside the system;
  - Example: number of conjunctive use operations in place;
- Adjustability: ability to add, modify, and remove any component of the system and/or its operations;
  - Example: level of governmental approval needed to adjust reservoir operations plans (rule curves) or storage allocation;
- Cooperation: ability to utilize and share available information across components;
  - Example: use of decision support systems (DSS) in planning and operations.

These flexibility characteristics can be mapped to structural and non-structural components within a flood management system or actions that enhance or degrade flexibility. We summarize the relationships between flexibility characteristics and flood risk management actions using a set of metrics (Table 1, adapted from DiFrancesco and Tullos in press). Examining these relationships highlights a few key points related to assessing flexibility. First, while the assessment of system flexibility can occur in isolation, in general, more meaning can be gained if flexibility is used as a relative assessment, such as comparison between different systems or management actions. Second, similar to adaptive capacity (O'Brien and Leichenko 2000, Turner *et al.* 2003, Luers 2005), flexibility is not a steady feature of a system as it can change over time in response to changes in human and physical system components. For example, one metrics to assess system slack examines reservoir capacity in excess of a probabilistic flood (Table 1, S1). Larger floods, a common climate projection in many regions (Cameron *et al.* 2000, Milly *et al.* 2002, IPCC 2007, Das *et al.* 2011), would consume slack in the system, decreasing flexibility in this regard. As such, the assessment of flexibility at any given time is a snapshot of the system and must be reassessed when internal or external physical or human components change. Third, some actions contribute to multiple flexibility characteristics and may impact flexibility characteristics differently. For example, new levees can increase conveyance capacity and thus slack (Table 1, S3), while also decreasing connectivity (Table 1, C2) and potentially adjustability (Table 1, A3). Finally, all of the flexibility metrics can be assessed for individual management actions, with the exception of the redundancy metric R2a and R2b (Table 1). When evaluating redundancy in terms of the diversity of the suite of structural versus non-structural options or management actions (Table 1, R2a and R2b), we assess the combination of system components or management actions. Additional discussion on the derivation of the flexibility characteristics and metrics, as well as the features of flexible water resources systems, is presented by DiFrancesco and Tullos (in press).

3 Data and methods

3.1 *Study area*

The Central Valley of California, USA, contains areas with some of the highest flood risk in the country (USACE 2002). The 70,500 km^2 Sacramento River system, the focus of this study, drains the northern portion of the Central Valley, while the San Joaquin River system drains the 39,000 km^2 southern portion (Figure 1). These two river systems meet in the Sacramento–San Joaquin Delta (Delta), the largest estuary on the west coast of the USA. Prior to land reclamation and the construction of upstream dams, the low-lying valley floor flooded regularly during large, seasonal storms. The first European explorers to reach the valley in the early nineteenth century estimated that high flows north of the Delta covered distances greater than 8 km on the eastern side of the river and 5 km on the western side (Kelley 1989). Researchers believe that these events are related to the influence of atmospheric rivers across the Sacramento basin, narrow corridors of concentrated moisture travelling over the Pacific Ocean from near Hawaii (Dettinger *et al.* 2011). These atmospheric river storms can drop most of the region's annual precipitation totals over the course of a few days.

In the Sacramento and San Joaquin basins, efforts to regulate floods began simultaneously with settlement and continue to this day. Currently, the State Plan of Flood Control (SPFC), administered by the California Department of Water Resources (CA-DWR), guides flood management planning in the basin, in coordination with many other state, federal, and local entities. The SPFC includes facilities (levees, weirs, dams, pumping plants, bypass basins, etc.); lands (fee title, easements, and land-use agreements); operations and maintenance requirements of SPFC facilities, conditions (terms, memorandums of understanding, regulations, etc.); and programmes and plans. Although the

Table 1 Example metrics to assess flexibility in flood management systems. Unless noted, larger metric values indicate greater flexibility (DiFrancesco and Tullos in press)

	ID	Metric description	Metric evaluation	Units
Slack	S1	Excess reservoir capacity in a 100-year flood	$\frac{\text{maximum reservoir flood storage capacity}}{(\text{3 day 100 year flood inflow volume} - \text{3 day objective release outflow volume})}$	m^3/m^3
	S2	Excess stream capacity in a 100-year flood	$\frac{\text{stream conveyance capacity}}{\text{100 year flood discharge}}$	cms/cms
	S3a	Dam capacity to release and convey flood waters	$\frac{\text{stream conveyance capacity downstream of dam}}{\text{outlet} + \text{spillway capacity}}$	cms/cms
	S3b	Weir capacity to intake flood waters into bypass	$\frac{\text{weir intake capacity}}{\text{100 year flooddischarge}}$	cms/cms
	S4	Bypass capacity to store discharge in excess of stream capacity	$\frac{\text{flood bypass storage capacity}}{\text{3 day 100 year flood volume} - \text{3 day stream conveyance capacityvolume}}$	m^3/m^3
	S5	Excess funding in relation to expected damages	$\frac{\text{annual flood funding}}{\text{Expected Annual Damages (EAD)}}$	\$/\$
Redundancy	R1	Surface storage options (reservoirs and bypasses)	$\frac{\text{number of surface storage facilities (reservoirs and bypasses)}}{\text{number of major tributaries}}$	#/#
	R2a R2b	Structural vs. non-structural diversity (by number, R2a, and by cost R2b)[a]	$\left(\frac{s}{N}\right)^2 + \left(\frac{\text{ns}}{N}\right)^2$, where s is number/cost of structural components; ns is number/cost of non-structural elements; and N is total number/cost of components (*lower value is more flexible*)	#/# \$/\$
	R3	Delegation of management responsibility	Number of agencies committed to flood management	#
Connectivity	C1	Ground- and surface water connections	$\frac{\text{number of conjunctive use operations}}{\text{number of reservoirs}}$	#/#
	C2	Potential for floodplain connection	$\frac{\text{total river length}}{\text{leveed river length with } \geq \text{ 100 year protection}}$	km/km
	C3	Longitudinal connectivity	$\frac{\text{number of dams/weirs with safe fish passage}}{\text{number of dams/weirs}}$	#/#
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*)	Federal/ state/local
	A2	Opportunities to annually vary flood storage space	$\frac{(\text{maximum flood storage space} - \text{minimum flood storage space})}{\text{maximum flood storage space}}$	m^3/m^3
	A3	Ability to expand storage and conveyance capacity by levee set backs	$\frac{\text{length of levees with } > x \text{ m. buffer to infrastructure}}{\text{total levee length}}$	km/km
Compatibility/ coordination	CC1	Access to data	Water managers have access to future hydrologic projections at relevant temporal and spatial scales	Binary
	CC2	Access to data analysis tools	Water managers have tools and ability to analyse and utilize essential data for reservoir planning and operations	Binary
	CC3	Intra-basin coordination of operations	$\frac{\text{number of reservoirs with coordinated operating agreements}}{\text{number of reservoirs}}$	#/#

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

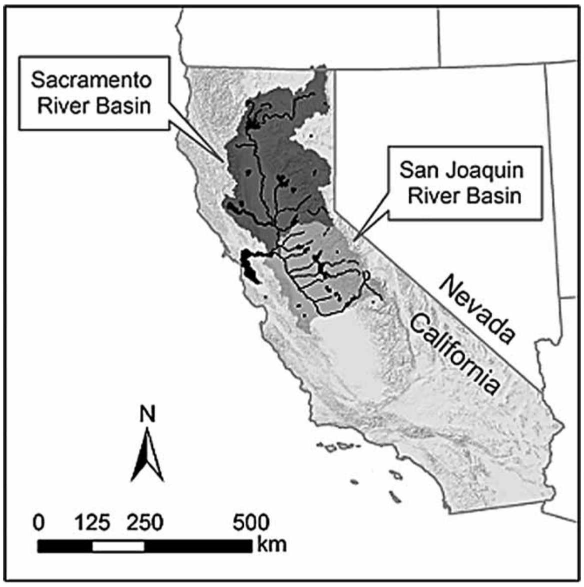

Figure 1 Location map of the Central Valley, CA.

SPFC has prevented billions of dollars in flood damages since its inception, some SPFC facilities currently face an unacceptably high chance of failure (CA-DWR 2010a). In addition, an unintended consequence of the long-term effort to reduce flooding is that development and population growth behind levee-protected areas have increased flood damages over time (CA-DWR 2012). Thus, although the probability of flooding has decreased, the damages generated when floods do occur are much greater, resulting in a net long-term increase in flood risk (CA-DWR 2012).

3.2 *Methods to analyse flexibility in the CVFPP*

In response to increasing flood damages, highlighted during flooding in the 1990s, the California State Legislature directed CA-DWR to prepare the CVFPP along with other supporting documentation (CA-DWR 2012). The primary goal of the CVFPP is to improve flood risk management, but the plan also includes supplemental goals to improve operations and maintenance; promote ecosystem functions; improve institutional support; and promote multi-benefit projects. The CVFPP and associated documents contain information regarding the current state of the SPFC as well as proposed actions for addressing the primary and supplemental goals now and into the future. Several factors contribute to managers' concerns about the SPFC, including some factors that refer to specific inflexibilities in system components (CA-DWR 2010b). We compile and categorize the deficiencies in system flexibility noted in the CVFPP (Table 2) based on their relationship to the flexibility characteristics and metrics in Table 1. For example, managers' noted insufficient storage capacity indicates that the current system lacks sufficient slack in terms of metric S1 (reservoir capacity) and/or S4 (bypass capacity).

In total, the CVFPP analysed four strategies, which we also use in this study, to address the identified inflexibilities (Table 2) and other deficiencies in the SPFC. The CVFPP began its initial analysis by outlining three preliminary strategies. Each of the three strategies emphasizes different overarching goals. The first strategy, henceforth referred to as 'Design Conveyance', aims to re-establish the original Design Conveyance capacity of the SPFC facilities, primarily through levee improvements throughout the system. The second strategy, henceforth referred to as 'Population Centres', focuses on protecting high-risk Population Centres through physical improvements to levees around urban areas and small communities. The third strategy, henceforth referred to as the 'Enhance System' strategy, aims to enhance the flood management system storage and conveyance capacity through widening floodways, reconnecting floodplains, and increasing floodwater storage. The Enhance System strategy incorporates all of the management actions of the first two strategies, along with other multi-benefit actions. After assessing the costs and benefits of these three strategies, the CA-DWR developed a fourth strategy to pursue, which combines the strengths of each preliminary strategy, termed the 'Combined' strategy. It includes both regional actions to improve levees and reduce flood risk in urban areas, small community and rural-agricultural areas, as well as large system improvements, such as bypass expansion.

Each of the strategies developed for the CVFPP contains a suite of management actions aimed at addressing the overarching goals of the strategy. The CVFPP identified eight broad classes of flood management system elements that address the key types of improvements needed to meet the 2012 CVFPP plan's goals, including (1) bypasses, (2) ecosystem restoration, (3) flood structure improvements, (4) residual risk, (5) rural-agriculture improvements, (6) small community improvements, (7) storage and operations, and (8) urban improvements. The CVFPP further divided each element into more specific flood management actions. To maintain consistency with the CVFPP, in this manuscript we retain the same categorization of management actions under the eight classes of system elements.

We assess our first study question regarding the contribution of each proposed management action towards system flexibility by determining the impact of each of the 29 proposed actions listed in the CVFPP (CA-DWR 2012) on the flexibility metrics in Table 1. Due to the lack of specificity regarding the outlined actions, we could not calculate the absolute system flexibility under each management strategy. Rather, for each management action we determine whether it would increase (1), have no effect (0), or decrease (-1) each flexibility metric. Actions can impact more than one metric and characteristic. For example, a new flood bypass would increase storage capacity, a component of the slack measurement (Table 1, S4), as well as the number of storage facilities, a measure of redundancy (Table 1, R1). Under each of the eight major elements, we summed the number of actions that would enhance flexibility characteristics, as well as the number of actions that may reduce flexibility. Some of the included actions seem to have little relevance for flood management (e.g. improved fish passage), but they still address at least

Table 2 Inflexibilities in the SPFC identified in the CVFPP and categorized based on whether the inflexibility relates to structural (S) or non-structural (NS) components of the flood system

Characteristic	Example inflexibilities	Metrics (Table 1)
Slack	• Insufficient flood storage capacity to regulate flood flows (S)	S1, S4
	• Inadequate capacity to convey design flows in approximately half of the channels evaluated (S)	S2
	• Accumulation of sediment in bypasses (NS)	S4
	• Current federal, State, and local funding mechanisms are not adequate to sustain effective flood management (NS)	S5
	• Insufficient funding for:	S5
	– Maintenance and improvements (NS)	
	– Flood fight (NS)	
Redundancy	• Flood management is often made difficult by the large number of agencies and entities involved (NS) (note: too much flexibility)	R3
Connectivity	• Loss and fragmentation of habitat and lack of connectivity between floodplains and river systems (S)	C2, C3
Adjustability	• Water control manuals based on a limited period of record (NS)	A1
	• Existing flood management system does not provide the level of protection desired and/or required because of the following:	A1
	– System designed for different uses and levels of protection and (S)	
	– New legislation increased protection req. for urban and urbanizing areas (NS)	
Compatibility/ cooperation	• Water control manuals not designed to accomplish system-wide coordinated operations (NS)	CC3 (and A1)
	• Lack of coordination (planning and implementation) (NS)	CC3
	• Lack of comprehensive mutual aid agreements covering flood response (NS)	CC[a]
	• Inconsistent and/or conflicting federal, State, and local maintenance standards, practices, and implementation (NS)	CC[a]
	• Limitations of emergency response capabilities to flood threats include the following:	CC1, CC2, CC3
	– Institutional capacity, resources, and coordination (NS)	
	– Not using available forecasting technology in operations decisions (NS)	
	– Inadequate snow and flow sensor data (NS)	
	– Poor or outdated flood risk information and maps (NS)	
	– Conflicts between maintenance practices and ecological processes (NS)	

[a] There is currently not a metric specifically dedicated to measuring this inflexibility, but it fits within the flexibility characteristic's definition.

one of the supplemental goals in the CVFPP. In addition, actions that integrate ecosystem improvements early in the planning stage may allow for a more holistic approach to restoration, rather than traditional project-by-project compensatory mitigation (CA-DWR 2012).

Second, we assess the structural and non-structural diversity of the suite of proposed actions and the impact of structural and non-structural management actions on flexibility. We first categorize the suite of proposed actions based on whether they apply to structural or non-structural elements in the flood management system. We then assess structural diversity (Table 1, R2a and R2b), based on number of projects and expenditures, and the extent to which structural and non-structural actions impact each of the five flexibility characteristics.

Third, we assess how different management goals, represented in the four CVFPP management strategies, lead to different outcomes for flexibility characteristics. We summarize the expenditures for each management strategy to illustrate the relationship between management goals and actions. We also compare the four management strategies based on the number of included actions that increase each of the flexibility characteristics as well as the expenditures dedicated towards increasing each of those characteristics.

Finally, we conduct a cursory analysis of the relationship between flexibility and cost- and time- effectiveness of each management strategy. We assess cost-effectiveness using the mid-range expected cost of each strategy in comparison to the strategy's ability to improve flood risk management, the primary goal of the CVFPP. We use the CVFPP's estimate of each strategy's potential to reduce expected annual damages (EAD) as a measure of its ability to meet the primary flood risk reduction goal (CA-DWR 2012). Similarly we assess time-effectiveness as the reduction in EAD per year of strategy implementation. We compare these simple efficiency measures to the flexibility of each strategy.

4 Results

4.1 *Management action contribution to flexibility characteristics*

The management actions proposed in the CVFPP have significant potential to address the identified inflexibilities in the system. All but 2 of the 29 proposed actions have the potential to increase one or more of the flexibility characteristics (Table 3). Four of the actions increase more than one flexibility characteristic. The actions disproportionately address slack in the system, with 55% of the actions contributing to increased slack and only 21%, 21%, and 17% of the actions contributing to adjustability, compatibility/ cooperation, and redundancy, respectively (Table 3). Only one action increases connectivity, via improvements to fish passage structures that increase the movement of floodwaters and aquatic species into and out of the bypass system, i.e. longitudinal connectivity (Table 1, C3). Furthermore, another 24% of the actions reduce connectivity, through levee improvements that further limit lateral river–floodplain connections (Table 1, C2). Notably, the proposed management actions also focus more frequently on modifying the existing components rather than introducing new components, as evident by the relatively few individual actions that increase the redundancy, or number of options in the system. Of the 18 actions that increase slack in the system, only three also increase system redundancy through introducing new components to the system. The remaining 15 actions increase slack by enlarging the capacity of components in the existing system.

4.2 *Flexibility of structural and non-structural management actions*

Assessment of the redundancy of the suite of management actions in terms of the diversity of the number of structural versus non-structural actions (Table 1, R2a) and redundancy in terms of expenditure (Table 1, R2b) yields different results. The CVFPP contains almost an even split in the number of proposed structural versus non-structural actions (Table 4). As such, calculating diversity in the number of proposed actions (Table 1, R2a) yields a value extremely close to the optimum 0.5, with 1 indicating no diversity. Despite the relatively balanced number of structural and non-structural actions, structural actions require significantly greater investment. Implementing the structural actions would cost seven times more than the cost of the non-structural actions yielding an R2b value of 0.78 (Table 4). Structural rural-agricultural levee improvements require the greatest expenditure of all elements. This action includes repairs and improvements to 21 km of levees in order to provide rural communities protection from a 100-year flood.

The structural versus non-structural elements also impact the flexibility characteristics differently (Table 5). The structural actions overwhelmingly increase slack in the system, with 12 of the 15 actions contributing to flexibility attributed to slack. In contrast, only one structural action increases connectivity and only two increase adjustability. None of the structural actions increase redundancy or compatibility/cooperation. Alternately, the contributions of non-structural actions to flexibility are spread across the range of characteristics, with four or more non-structural actions increasing slack, redundancy, adjustability, and compatibility/coordination. Furthermore, although the suite of actions contains less non-structural than structural actions, the number of non-structural actions that provide positive impacts on the flexibility characteristics is greater (Table 5, row totals).

4.3 *Flexibility of management strategies proposed in the CVFPP*

The different objectives of the four CVFPP management strategies, represented through the suite of management actions and elements in each strategy, leads to different outcomes for flexibility characteristics. In all strategies, the greatest portion of expenditures is allocated to either rural-agricultural improvements or urban improvements, depending on the strategy objective (Table 6). The strategies that focus on Population Centres and Design Conveyance only contain management actions in three or four of the eight flood management elements, respectively. Alternatively, the Enhance System and Combined strategy include a more diverse array of management actions that address all eight of the broad elements. While none of the metrics in Table 1 explicitly consider the diversity of elements, this diversity is consistent with increased flexibility in terms of the redundancy characteristic.

To further compare the impact of the different strategies on flexibility, we assess the number of actions in each strategy that impact each flexibility characteristic (Table 7 and Figure 2(a)) as well as the expenditure on strategy actions that increase each of the flexibility characteristics (Figure 2(b)). In every strategy, slack represents the flexibility characteristics impacted by the largest number of actions. In addition, the majority of costs for each strategy address slack in the system, ranging from 82% of project costs in the Combined strategy to 94% for the costs for the Design Conveyance strategy (Figure 2(b)). While the Enhance System and Combined strategies include actions that address every flexibility characteristic to some extent, the Design Conveyance and Population Centres strategies do not include any investments towards improving the connectivity or adjustability of the system. Further, the Enhance System and Combined strategies include management actions that increase the greatest number of flexibility metrics (Table 7).

4.4 *Relationship between flexibility and cost- and time-effectiveness*

We also compare each strategy in terms of absolute and relative costs and benefits, based on financial cost, implementation time, and reduction in EAD. In absolute terms, the Enhance System strategy has the highest reduction in EAD at $246,500,000, but also costs the most and takes the longest time to implement (Table 8). In contrast, the Population Centres strategy provides a comparable reduction in EAD by $202,504,000, but costs considerably less and takes the least amount of time to implement (Table 8). The Population Centres strategy also reduces EAD

Table 3 Impact of management actions on flexibility characteristics, organized by broad flood management elements

Major elements and management actions	Structural (S)/non-structural (NS)	Slack	Redundancy	Connectivity	Adjustability	Compatibility/cooperation
Bypasses		**3**	**1**	**-2**	**2**	**0**
Agricultural conservation easements	NS	0	0	0	1	0
Land acquisition for bypass expansion	NS	1	1	0	1	0
Levee improvements for new and expanded bypasses	S	1	0	-1	0	0
New levee construction	S	1	0	-1	0	0
Ecosystem restoration		**0**	**0**	**1**	**0**	**1**
Ecosystem restoration and enhancement (habitat development)	NS	0	0	0	0	0
Fish passage collaboration	NS	0	0	0	0	1
Fish passage structures	S	0	0	1	0	0
Flood system structures		**2**	**0**	**0**	**0**	**0**
Improvements to weir, bypass, and dam outlet structures	S	1	0	0	0	0
System erosion and bypass sediment removal projects	NS	1	0	0	0	0
Residual risk		**1**	**2**	**0**	**2**	**4**
Additional flood information collection and sharing	NS	0	0	0	0	1
Additional forecasting and notification	NS	0	0	0	0	1
Develop enhanced O&M programs and regional maintenance	NS	0	1	0	0	1
Identification and repair of after event erosion	S	0	0	0	0	0
Land use and floodplain management integration	NS	0	0	0	0	1
Local flood emergency response planning	NS	0	1	0	0	0
Purchasing and relocating homes in the floodplain	S	0	0	0	1	0
Raising and waterproofing structures and building berms	S	0	0	0	1	0
Sacramento channel/levee management and bank protection	S	1	0	0	0	0
Rural-agricultural improvements		**4**	**0**	**0**	**0**	**0**
Achieve SPFC levee design capacity in non-urban areas	S	1	0	0	0	0
Non-urban levee erosion repair	S	1	0	0	0	0
Setback levees	S	1	0	0	0	0
Site-specific rural/agricultural levee improvements	S	1	0	0	0	0
Small community improvements		**1**	**0**	**-1**	**0**	**0**
100-year protection levee improvements	S	1	0	-1	0	0
Storage and operations		**2**	**2**	**-1**	**2**	**1**
Easements for flood water storage	NS	1	1	0	1	0
Forecast-Coordinated Operations/Forecast-Based Operations	NS	0	0	0	0	1
Allocate new reservoir flood storage/enlarge flood pool	NS	1	1	-1	1	0
Urban improvement		**3**	**0**	**-3**	**0**	**0**
200-year protection levee improvement	S	1	0	-1	0	0
Achieve SPFC levee design capacity in urban areas	S	1	0	-1	0	0
Non-SPFC urban levee improvements	S	1	0	-1	0	0
GRAND TOTAL		**16**	**5**	**2 (-7)**	**6**	**6**

Note: Negative numbers indicate actions that reduce system flexibility.

most efficiently in terms of reduction in EAD per dollar spent and reduction in EAD per implementation time (Table 8). The Combined approach ranks second to Population Centres in terms of implementation time, EAD reduction/cost, and EAD reduction/time, while providing a greater absolute reduction in EAD (Table 8).

The flood management strategies can be compared based on the cost-effectiveness, time-effectiveness, and contribution to flexibility (Table 8). The relationship between these three factors that may contribute to selection of a flood management strategy is not clear and it is not immediately evident that strategies emphasizing flexibility lead to more time- and cost-effective solutions over the short term. Flexibility and implementation time appear to be inversely related, primarily because the more flexible approaches take more time to enact. There also appears to be a contrary relationship between flexibility and cost-effectiveness. This is due to the high cost of implementing flexible solutions. Finally, while establishing the Population Centres is the most effective strategy from the time and cost perspective, it is not effective from the perspective of increasing flexibility.

Table 4 Structural versus non-structural diversity in terms of number of projects and expenditure

	Number of actions	Expenditure for actions ($M)
Structural	16	18,892
Non-structural	13	2678
Total	29	21,571
Metric R2	0.51	0.78

5 Discussion

The 2012 CVFPP and associated documents identify critical inflexibilities and deficiencies in the current Sacramento Valley flood management system (Table 2). The CVFPP outlines four overarching strategies, each containing a suite of structural and non-structural management actions to address the identified deficiencies. Each strategy emphasizes different objectives and approaches to achieving those objectives, yielding different impacts on system flexibility.

Overwhelmingly, the actions proposed in the CVFPP address slack in the system over other flexibility characteristics. This emphasis on increasing slack may be of concern, since other characteristics can be important. For example, while slack ensures that sufficient excess capacity exists in the system, redundancy ensures that the capacity of the system is spread among a variety of options, similar to the resilience that diversity offers in ecosystems subject to disturbance (Elmqvist *et al.* 2003, Folke *et al.* 2004). The CVFPP management actions emphasize modifying existing infrastructure over introducing new components to the flood management system that would increase redundancy. To some extent this may reflect the notion that all of the best storage sites are already taken (Minton 2001). However, it also reflects a lack of openness to implement actions that may deviate from how floods have been managed in the past. Furthermore, public comments at the Central Valley Flood Protection Board meeting (24 February 2012, Sacramento, CA) on the draft 2012 CVFPP revealed opposition by the agricultural community to any actions that increase slack and redundancy of flood storage capacity at the perceived expense of agricultural lands. Opposition was particularly

Table 5 Number of structural versus non-structural components that impact each flexibility characteristic

	Slack	Redundancy	Connectivity	Adjustability	Compatibility/cooperation	Total
Structural	12	0	1 (−6)	2	0	15 (−6)
Non-structural	4	5	0	4	6	19
Total	16	5	1 (−6)	6	6	

Table 6 Comparison of flood management strategies in the CVFPP based on estimated cost expenditures ($M) for each major flood management element

Flood management element	Design conveyance	Population centres	Enhance system	Combined
Bypasses	0	0	3132	3132
Ecosystem restoration	0	0	335	801
Flood storage and operations	80	0	2820	80
Flood system structures	0	0	605	605
Residual risk	812	1494	724	1695
Rural-agricultural improvements	11,073	0	14,731	896
Small community improvements	0	1003	345	555
Urban improvements	6093	5527	5527	5527
Grand total	18,058	8024	28,218	13,290

Table 7 Number of actions in each CVFPP strategy, which increase or decrease the flexibility metrics

# increase	# increase (# decrease)	# decrease

	ID	Metric description	Design Capacity	Population Centers	Enhance System	Combined
Slack	S1	Excess reservoir capacity in a 100 year flood		1	3	1
	S2	Excess stream capacity in a 100 year flood	4	4	9	9
	S3a	Dam capacity to release and convey flood waters		1	2	2
	S3b	Weir capacity to intake flood waters into bypass			1	1
	S4	Bypass capacity to store discharge in excess of stream capacity			1	1
	S5	Excess funding in relation to expected damages				
	Slack Total		**4**	**6**	**16**	**14**
Redundancy	R1	Surface storage options (reservoirs and bypasses)			3	1
	R2a	Structural vs. non-structural diversity (# of actions)				
	R2b	Structural vs. non-structural diversity (cost, $, of actions)				
	R3	Delegation of management responsibility	2	2	2	2
	Redundancy Total		**6**	**2**	**2**	**5**
Connectivity	C1	Ground- and surface water connections	0	0	-1	0
	C2	Potential for floodplain connection	-2	-3	-5	-5
	C3	Longitudinal connectivity	0	0	1	1
	Connectivity Total		**-2**	**-2**	**-3**	**1 (-6)**
Adjustability	A1	Ability to revise operations plans	0	0	0	0
	A2	Opportunities to annually vary flood storage space	0	0	3	1
	A3	Ability to expand capacity by levee set backs	0	0	2	3
	Adjustability Total				**0**	**5**
Compatibility/ Coordination	CC1	Access to data	2	3	3	4
	CC2	Access to technology and data analysis tools	1	1	2	2
	CC3	Intra basin coordination of operations		4	5	5
	Compatibility/ Coordination Total		**3**	**7**	**8**	**10**
GRAND TOTAL			**18 (-2)**	**22 (-3)**	**13 (-2)**	**16 (-3)**

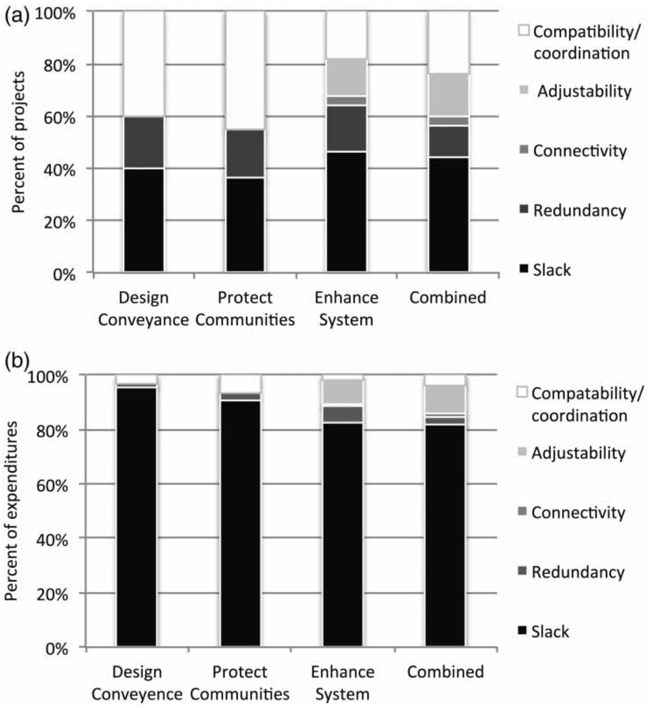

Figure 2 Percentage of flexibility characteristics enhanced by each management strategy by (a) number of actions and (b) total mid-range cost.

focused on the proposed new bypass on the Feather River and new Sacramento River easements.

Examination of the ratio of structural to non-structural actions, a measure of the system-wide redundancy, leads to different conclusions depending on whether we examine the relative number or relative cost of structural and non-structural actions. The legislation guiding the 2012 CVFPP requires CA-DWR to consider both structural and non-structural methods for improving flood management (CA-DWR 2012). This mandate is in line with the shift away from a reliance on large flood structures to more of an integrated flood management strategy (Galloway 1997, Werritty 2006). While the plan meets this criterion with a balanced number of structural and non-structural actions under consideration, the proposed structural actions would cost nearly seven times more than the non-structural actions. It may be the case that non-structural actions cost less than structural actions to achieve the same level of flood risk reduction. Alternately, the higher cost of structural actions may indicate that the plan still relies more heavily on the structural system over non-structural actions. Because the CVFPP only provides EAD estimates for each flood management strategy, and not individual actions, we are not able to eliminate either of the explanations as possible reasons why structural actions have such higher emphasis from the investment perspective.

The contribution to flexibility varies across the CVFPP strategies. Strategies that emphasize Population Centres and restoring the Design Conveyance of the system utilize fewer elements and contribute to fewer flexibility characteristics than strategies (e.g. Enhance System and Combined) that have broader management goals. Based on our analysis, the Enhance System and Combined strategies contribute to larger increases in flexibility in the Sacramento flood management system than do the Design Conveyance or Population Centres strategies. The former two strategies include a more diverse portfolio of flood management actions (Table 6), which in turn leads to improvements in a wider range of flexibility characteristics (Table 7 and Figure 2). Alternately, by focusing almost entirely on physical levee improvements and residual risk, the Design Conveyance and Population Centre strategies omit actions that could increase connectivity and adjustability in the system (Table 7).

As noted by researchers outside of the water resources field (Nemetz and Fry 1988, Duimering *et al.* 1993, Byrd and Turner 2000), flexibility comes at a price. Flexible technologies tend to cost more than traditional, less flexible equipment and products. The Enhance System strategy is the most expensive but also generates the greatest reduction in EAD. Furthermore, the Enhance System strategy represents the greatest number of opportunities to increase system flexibility (Table 7) as well as a more diverse number of actions (Figure 2(a)) and expenditures (Figure 2(b)) dedicated to increasing the five flexibility characteristics. Alternately, the Population Centres strategy is the least expensive and most cost efficient in terms of EAD reduction (Table 8), yet also one of the least flexible strategies (Table 7). The Combined strategy, as CA-DWR intended, represents a middle ground in terms of cost, increased flexibility, reduction in EAD, and time to implement (Table 8).

Importantly, this simple economic analysis neglects to consider the benefits each strategy provides in terms of the supplemental goals, namely to improve operations and maintenance; promote ecosystem functions; improve institutional support; and promote multi-benefit projects. These omissions may represent significant factors that influence decision-making. For example,

Table 8 Comparison of strategies by costs, benefits, and implementation time

	Units	Design capacity	Population centres	Enhance system	Combined
Cost	$	$9,114,450,000	$6,727,850,000	$17,312,800,000	$10,037,600,000
EAD reduction	$	$128,404,000	$202,504,000	$246,565,000	$213,144,000
Implementation time	yrs.	33	18	38	23
EAD reduction/cost	$/$M	$14,000	$30,000	$14,000	$21,000
EAD reduction/implementation time	$/yr	$3,951,000	$11,572,000	$6,575,000	$9,473,000

the explicit inclusion of promoting ecosystem functions as a goal of the CVFPP represents a unique and controversial element of the plan. The legislation guiding the CVFPP requires that ecosystem restoration be included as a goal of the plan in response to the degradation of riverine habitats and ecosystem functions through changes in land use, construction of dams and levees, water pollution, and other causes (CA-DWR 2012). However, ecosystem enhancement features were only included in the Enhance System and Combined strategies and not the Design Capacity or Population Centres strategies. The actions listed under the ecosystem restoration element as well as ecosystem enhancements integrated into other flood management elements would increase lateral and longitudinal connectivity in the system. Interestingly, connectivity is also the only flexibility characteristic according to which the management actions have the potential to decrease by improving levees and thus further limiting floodplain–river connectivity. By omitting ecosystem enhancement actions, the Design Capacity and Population Centres strategies only include actions that would decrease connectivity. Broadly speaking, it appears as though the ecosystem restoration projects included in the Enhance System and Combined strategies have the potential to provide connectivity benefits that counteract the negative impact on connectivity resulting from other management actions.

6 Conclusions

Flexibility is often given as a critical component to reliably managing water resources in an uncertain hydrologic future. Particularly with respect to flood management, when a wide range of future conditions is anticipated, flexible water resources systems are expected to outperform fixed, optimized solutions, based on stationary conditions. However, limited examples exist for how to assess and measure the flexibility of water management systems and proposed management actions. In this study we develop and apply an approach to assess the inflexibilities in an existing flood management system as well as the flexibility of proposed management actions in the Sacramento River basin, CA. We investigate a set of characteristics within which flood management systems can increase flexibility and categorize management actions based on their contribution to system flexibility.

Key findings of this analysis include those related to the CVFPP specifically and more broadly to the management of floods and floodplains. Regarding the CVFPP, we find a disproportionate emphasis on increasing system slack over other characteristics of flexibility. Slack in the system provides surplus capacity to cope with uncertain and changing conditions. The need for these improvements at the present time indicates that the original SPFC did not include enough slack to keep up with changing hydrological and socio-economic conditions in the region.

We find that very few individual management actions increase the redundancy of the system by increasing the number of tools available to managers. This indicates that managers are choosing to emphasize improvements in the current system, particularly related to increasing capacity, over introduction of new system actions. In terms of system-wide redundancy, we find evidence of a general relationship between the diversity of major elements represented in management actions and the number of flexibility characteristics enhanced. The Enhance System and Combined strategies include a diverse array of actions representing all eight of the broad flood management system elements and also contribute to increasing flexibility under all five characteristics. On the contrary, the strategies that include fewer broad elements address, at most, three of the five flexibility characteristics.

The CVFPP strategies appear to equally emphasize structural and non-structural management options when the number of actions is considered. However, when costs of the management actions are considered, the emphasis on structural options is far greater than non-structural options. It is not clear whether this discrepancy between number of actions and the cost of actions is due to higher costs associated with structural options for flood management or to a disproportionate prominence of structural options in the CVFPP portfolio based on projected expenditures.

Finally, it appears that tradeoffs exist between cost-effectiveness, time-effectiveness, and contribution to flexibility. Focusing on population centres results in the cheapest and quickest solution to reducing flood damages, but contributes little to the flexibility of the system and excludes benefits to some areas of the basin. Strategies that increase flexibility appear to cost more and take longer to implement, but also provide the greatest overall reduction in flood damages and benefits to the range of basin residents and ecosystems. Thus, management strategies that balance cost-effectiveness, time-effectiveness, and contribution to flexibility are likely to have the greatest benefits over the long term.

Future work should investigate several systems to see if the trends found in our assessment of the CVFPP are consistent across systems, and thus representative of broader thinking on flood management. Additional work is also needed to (a) assess the magnitude of management actions impact on flexibility; (b) examine the relative contributions of the flexibility characteristics to adaptive capacity; and (c) develop flexibility metrics for other operating objectives (e.g. hydropower generation, water supply, environmental benefits, recreation, etc.). Furthermore, we note that the benefits of flexibility may not be fully realized under present conditions, as it is primarily advocated as a tool to improve system performance under uncertain, changing future conditions. Additional economic analysis to evaluate the long-term economic benefits of increased flexibility should be evaluated.

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