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A complex systems approach for multiobjective water quality regulation on managed wetland landscapes

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Abstract. Management of wetland ecosystems that are tightly coupled with human systems typically requires balancing multiple objectives to ensure that a range of ecosystem services are provided for the benefit of society. We describe how adopting a complex systems approach may provide managers with the appropriate conceptual tools to achieve social and ecological objectives in a multifunctional wetland landscape. We illustrate the applicability of the approach using the Grasslands Ecological Area (GEA) in California as a case study. Human intervention has shaped and reshaped the GEA over the past century, affecting the ability of the landscape to provide ecosystem services. Ecological disaster in the 1980s precipitated transformative change in the management system toward an approach that adopts many of the recommended actions for complexity. Present-day management, which balances multiple social and ecological objectives, has led to improved water quality, restoration of wetland habitats, and a general increase in system complexity at the landscape scale. New research and real-time monitoring systems facilitate adaptive management and heterogeneous responses of wetland management entities. We argue that taking a complex systems approach to management in the GEA provides a common, and inclusive, conceptual model for all stakeholders and may lead to a more sustainable and ecologically resilient landscape over the long term.

Key words: complex systems; coupled human–environment systems; ecosystem management; ecosystem services; sustainability; water quality; wetlands.

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INTRODUCTION

Landscapes can be viewed as complex human–environment systems composed of tightly coupled social, technological, and ecological components that collectively contribute to system resilience and capacity to cope with change (Liu et al. 2007, Parrott and Meyer 2012). Over the past century, landscapes in many regions of the world have been intensively managed, typically to produce a single resource or service demanded by humans. Such single resource-based management regimes have often simplified landscapes and contributed to degradation of ecological resilience. Loss of ecological resilience makes human communities highly vulnerable to changes in the ecosystem's capacity to function according to historical baselines (Berkes et al. 2003,
Messier et al. 2015). For this reason, the importance of maintaining multifunctional landscapes that provide a diversity of resources or ecosystem services is becoming increasingly recognized (Foley et al. 2005, Nelson et al. 2009, O’Farrell and Anderson 2010). New management approaches that adopt a view of the landscape as a dynamic mosaic of interacting human and biophysical components are required to achieve this objective; however, few successful examples exist. Recently, the approach of complex systems science and associated paradigms such as “resilience thinking” (Folke et al. 2010) have been proposed as frameworks for developing more sustainable resource management (Parrott and Meyer 2012, Filotas et al. 2014, Messier et al. 2015). Such frameworks provide methods for characterizing and analyzing landscapes as dynamic, nonlinear systems of social and ecological components and processes in interaction across multiple spatial, temporal, and hierarchical scales. Here, we describe how a taking a complex systems approach may be appropriate for achieving multiple objective management goals, using the Grasslands Ecological Area (GEA) of managed wetlands in California as a case study. While this landscape is a highly managed, complex ecological system, we argue that the current management regime contributes to maintaining the adaptive capacity of this coupled human–environment system by juggling the requirements of multiple stakeholders and working to erase historical legacies that have compromised ecological function.

Complex systems science provides a framework for viewing regional landscapes as complex social-ecological systems (Parrott and Meyer 2012). Landscapes exhibit many properties of complex systems such as: cross-scale linkages, emergence (local events that can have system-wide impacts), heterogeneity, nonlinear dynamics, system memory, and prediction uncertainty (Levin 1999, Anand et al. 2010, Parrott and Lange 2013). Complex systems science defines concepts such as landscape “resilience” and “sustainability” in the context of combined human processes and natural processes. Landscape resilience emphasizes the functioning of the whole social-ecological system, and refers to the capacity of the system to adapt and respond to change while still retaining the same function, structure, identity, and feedbacks (Holling 1996, Adger 2000, 2006, Folke 2006). “Sustainability” of a landscape can be described in terms of the ability of the human and natural subsystems to persist and support one another over time (Bender et al. 2012). Both sustainability and resilience of regional landscapes is highly dependent upon the capacity of human and institutional stakeholders in the governance system to learn, adapt, and innovate in response to changing conditions (Berkes and Ross 2013, Bristow and Healy 2013, 2014).

Recognizing that a landscape is a complex system changes the way landscape-scale resource management should be carried out (Harris 2007, Parrott and Meyer 2012, Messier et al. 2015). Adopting a complex systems management approach involves working with a conceptual model of the landscape as a dynamic, interconnected system, and applying management interventions that embrace and nurture heterogeneity at multiple scales so as to support system resilience and adaptive capacity. The approach also requires increased understanding of system variability through enhanced observation and monitoring, and the use of predictive decision support tools that can accommodate future uncertainty (Baker et al. 2004, Bolte et al. 2006, Parrott 2011).

In this paper, we study a multifunctional wetland landscape in California, United States undergoing change as a result of regulatory pressures to control salt export to a water quality impaired river. We document how decades of human interventions in this system led to an erosion of ecological resilience and eventual crisis, leading to a transformative change in the governance system and management regime. While a complex systems approach was not explicitly applied during this transformation, many of the recommendations for management of complex systems were carried out and may have contributed to increasing system resilience at the landscape scale. We explore how applying a complex systems management approach might yield insights into multiobjective management of the wetland resources and offer new opportunities for decision support.

**Case Study:** The Grasslands Ecological Area, California

The Grasslands Ecological Area (GEA) in California, United States is a diverse landscape
complex comprised of annual and permanent wetlands and vernal pools, riparian habitat, native rangeland, and farmland incorporating an area of nearly 80,000 ha (Fig. 1). The wetlands and riparian habitat of the GEA encompass the largest contiguous wetland complex west of the Rocky Mountains and are a significant stop over for millions of local and migratory waterfowl of the Pacific Flyway. The regional wetlands are home to millions of waterfowl and shorebirds, a diverse community of moist-soil vegetation, and other common and endangered wildlife (Mason 1969, Small 1974, Cogswell 1977, Grassland Water District 1986, Shuford et al. 1998, Sibley 2000).

Historically, the wetlands of California were a vital ecosystem component, necessary for the health of waterfowl populations and waterways of the Central Valley. Although the remaining wetlands have lost most of their natural functions, they still provide habitat for a broad range of species and those species rely on the health of the wetlands for sustainability of their populations. Prior to 1850, there were an estimated 5 million acres of wetlands in California. Today, less than 6% remain (Hartmann and Goldstein 1994). Despite their limited extent, the remaining wetland complexes provide habitat for 19% and 60% of the wintering waterfowl in the continental United States and on the Pacific Flyway, respectively (Gilmer et al. 1982).

These wetland landscapes serve not only migratory waterfowl but also various cultural and economic human activities within the GEA associated with hunting activities. Hunting is practiced by 160 duck clubs within the Grassland Water District (GWD)—this provides recreational opportunities to the thousands of hunters who are members and guests of these clubs as well as commercial benefits to the restaurants, supermarkets, and other service industries that support these private clubs. The refuges and Grassland Water District also provide direct and indirect employment to a large number within the GEA. The state and federal wildlife refuges provide educational and other recreational benefits to the public and draw from neighboring counties as well as the Bay Area given that the GEA provides the largest contiguous wetland area in the western United States. These wetlands also contain rare and endangered plant species as well as unique ecological assemblages that only occur within this complex managed ecosystem. These activities provide further economic and cultural benefit to the region.

**Management history**

The wetland landscape is thus a complex system that has been extensively shaped and reshaped by human activities over the past century, significantly affecting ecosystem service provisioning by the landscape (Fig. 2). Prior to extensive agricultural development, the landscape was composed of the San Joaquin River in its natural floodplain and a large area of natural grasslands regularly inundated by spring floods. Agricultural development beginning in the 1850s led to drainage and conversion of wetlands in all but the lowland areas as well as channelization of the landscape for irrigation and drainage purposes. This period saw an increase in heterogeneity of land cover and a diversification of users of the resource with recreational use expanding. Water quality, however, generally decreased during this time as a result of agricultural sources re-routing drainage water into holding ponds in the wetlands. In the early 1980s, selenium toxicosis in waterfowl due to evapoconcentration in open drainage ponds was first recognized in Kesterson Reservoir, a 1200-acre system of ponds originally designed to act as a holding reservoir for subsurface agriculture drainage en-route to a discharge point in the Sacramento-San Joaquin Delta. The pitiful images of waterfowl embryo and chick deformities brought about by high selenium levels in resident waterfowl brought about a nation-wide outcry from the environmental community if, for no other reason, because this wetland complex is protected under international treaty under the Migratory Bird Treaty Act of 1918. This ecological disaster also brought to light the complex inter-relationships between management of the wetlands for waterfowl-based recreation and protection, wetland diversity and the degradation of water quality, and loss of ecological resilience that follows the need for an imported water supply. A scarce water supply encourages a management regime that often needs to use agricultural return flows to fully meet wetland water supply requirements. The aftermath of the Kesterson
disaster was a catalyst in the subsequent transformation in the water governance system and in particular a recognition that agriculture and agricultural return flows could be detrimental to the environment.

Today, water levels in the wetlands are carefully managed primarily to meet waterfowl food resource requirements and wetland diversity goals. The fall flood-up occurs between the months of August and October, and the spring drawdown occurs during the months of February, March, and April (Fig. 3). Wetland drawdowns are timed to make invertebrate resources available during peak waterfowl and shorebird migrations and to correspond with optimal germination conditions (primarily soil moisture and temperature) for naturally occurring moist-soil plants (Smith et al. 1995). This seasonal cycle aids ecological processes and can be adapted to promote desired species (Fredrickson and Laubhan 1995). The most abundant moist-soil plant managed and selected for in the wetlands of the GEA is swamp timothy (Crypsis schoenoides) because of its value and productivity as a protein source for migrating waterfowl and its adaption to the hydro-period of the region. Management for swamp timothy requires flooding in the fall, typically in August, and retaining the ponded water throughout the winter to provide foraging and loafing habitat for waterfowl, shorebirds, and other waterbirds. These wetlands are drained in spring, usually around mid-March when soil and air temperatures coincide with swamp timothy phenologic preferences. The timing of swamp timothy managed wetland’s drawdown occurs at a time when the San Joaquin River into which the water is released typically does not have the assimilative capacity to adequately dilute brackish drain water from these wetlands. In an effort to reduce the impact of wetland drainage to the San Joaquin River, it was proposed that the wetland drawdown schedule be modified, when feasible, to coincide with increased assimilative capacity in the San Joaquin River. In practice, managed wetland return flow scheduling is one of a number of options that could be employed in concert with options in agricultural areas to prevent violation of river salinity objectives such as drainage reuse and recycling, temporary storage in drainage holding ponds, and drainage treatment.

Stakeholders have yet to agree on a formula for allocating salt load and prioritizing drainage management actions among those with direct discharge to the San Joaquin River.

Altering wetland drainage schedules affects the timing and rate of drawdown of wetland ponds and hence the forage value of the wetlands for migrating and wintering shorebirds and waterfowl. However, wetland spring drainage, timed for optimal habitat conditions, occurs when San Joaquin River and tributary spring flow are minimal and downstream agriculturalists in the South Delta begin to irrigate their crops. The water quality of the San Joaquin River downstream of the wetland complex may adversely affect germination and crop yields of the South Delta farmers’ salt-sensitive crops. Studies have suggested that approximately 10% of the San Joaquin River’s annual flow, and 30% of its annual salt load, passes through wetlands within the Grasslands Basin, which includes the Grassland Water District (GWD) (Grober et al. 1995, Karkoski et al. 1995, Quinn and Karkoski 1998). Wetland salinity management measures also affect the productivity and diversity of vegetation that can be grown in the watershed (Rosenberg and Sillett 1991).

Delayed wetland drawdown, which, as previously described, is one of a number of options for changing salt load export to the river was originally chosen to coincide with the Vernalis Adaptive Management Plan fishery releases which previously occurred between mid-April and mid-May each year. Scheduled fish flows for both attraction and migration still occur but are now more closely tied to agency optimal timing forecasts. Although the delayed drawdown could help to improve water quality conditions in the San Joaquin River, wetland managers and landowners in the GEA remain concerned that a prolonged hydro-period could reduce swamp timothy germination rates and productivity due to environmental conditions more aligned to watergrass production. In addition, the delayed drawdown may increase salt concentrations of the waters in the ponds, which may increase soil salinity and ultimately reduce the inherent ability of the wetlands to continue to produce the standing biomass that is crucial to sustaining the populations and health of the waterfowl and shorebirds of the Pacific Flyway.
Fig. 1. Location of the Grassland Ecological Area (GEA), California, USA. Study sites described in this paper are shown as black patches (Source: Quinn et al. 2011).
Research to support present-day management

In 2005, a 4-yr study was undertaken to investigate the various water quality and biological impacts of a modified hydrology to swamp timothy-managed wetlands of the GEA (Quinn et al. 2010). The study measured responses of swamp timothy seed and biomass production and distribution, avian usage, soil salinity, and water quality at six-paired wetland sites to the prolonged wetland hydro-period produced by a delayed drawdown—these responses were compared using the same metrics to wetlands subject to a traditional (normal) wetland drawdown schedule. The six-paired wetland sites were carefully chosen to be representative of the range of landscape conditions within the 80,000 ha GEA. The paired wetlands were adjacent to each other in all cases but one and were of roughly equal size although they ranged in area from 20 ha to 80 ha across the six-paired sites. The project sought to investigate the feasibility of developing multiobjective wetland operation protocols to optimize wildlife habitat subject to water quality constraints in the Grassland Basin and San Joaquin River.

A major outcome of the study based on soil salinity mapping of the wetland soils and swamp timothy productivity assessment was that wetland impoundments showed little significant
change in either metric after a single year of a delayed pond drawdown until after April 15 (approximately 1-month delay). However, statistically significant impacts were recoded after a second year of delayed drawdown in the same treatment impoundments (Rahilly et al. 2010). This suggests that wetland delayed drawdown can be used as a means of controlling salt export, but the designated wetland impoundments need to be rotated after a single year. These project findings and others have been used to refine best salinity management practices for those wetlands that receive the most saline supply water and that are more susceptible to salt-related impacts to wetland habitat quality. These findings are also useful in helping to determine those areas within the GEA that are both resilient to salinity impacts and situated upon the landscape to allow a measure of salinity export control. These factors will ultimately inform a decision support system (DSS) to assist wetland, urban, and agricultural water managers tasked with managing the timing of salt loads delivered to the San Joaquin River to maintain compliance with State salinity objectives.

**Regulatory issues**

Increased surface water supply allocations under the Central Valley Project Improvement Act have created a greater need than existed previously to coordinate the release of seasonal wetland drainage with the assimilative capacity of the San Joaquin River, because of the additional salt load diverted to Joaquin Basin wetlands. Coordinated releases will help achieve salt and boron water quality objectives and potentially improve the quality of downstream agricultural diversions and lead to more optimal

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**Fig. 3.** Timing of the GEA wetland drawdown period is carefully managed to meet ecological objectives, by ensuring the salt load does not exceed the San Joaquin River (SJR) assimilative capacity while maintaining sufficient water levels in the wetlands for waterfowl habitat and to promote growth of desired species of wetland vegetation. Salt load contribution measured from monitoring stations in the Northern Division of the Grassland Water District (NGWD) (Source: Quinn et al. 2004).
fish habitat in the main stem of the San Joaquin River and Sacramento-San Joaquin Delta. Improved scheduling of west-side discharges can assist in avoiding conflict with critical time periods for early season irrigation as well as fish rearing and remove an important stressor leading to improvements in the San Joaquin River salmon fishery.

The California Regional Water Quality Control Board (CRWQCB) announced its salt and boron total maximum daily load (TMDL) in April of 2002, for the San Joaquin river basin. For the first time, the wetland discharges are to be regulated as part of this TMDL. The CRWQCB has adopted a conditional waiver implementing a DSS (Quinn and Karkoski 1998, Quinn and Hann 2003) which utilizes real-time management to determine the ability of the San Joaquin River to assimilate discharges from irrigated lands, including wetlands, while maintaining salinity levels below the TMDL. Through advances in data acquisition technology, this DSS is now permitting real-time water quality management in the GEA.

**Real-time water quality management**

To achieve real-time water quality management, system status information must stream on a continual basis to allow timely actions to meet the desired water quality goals. Placement of sensors within water structures, telemetered via cell phone networks to an Internet-based server where information can be stored, enables pertinent water management decision support. For example, information on river stage and water quality over time can aid wetland managers in the evaluation of the assimilative capacity of the river in the context of potential alternative drawdown scenarios. The TMDL adopted by the CRWQCB requires use of real-time river flow and stage data from the Vernalis compliance monitoring station to assess the river’s 30-day running average assimilative capacity (Quinn and Karkoski 1998). These data are available on-line from the California Digital Exchange Center but need to be combined to estimate daily salt assimilative capacity. A web portal has been developed to calculate the assimilative capacity of the river automatically as well as to provide the information needed from all available real-time flow and salinity monitoring stations for short-term forecasting of river salinity (see http://sjrrtm.opennrm.org/).

With the local installation of flow and salinity sensors in the wetland complexes, a DSS is under continued development to allow wetland managers both to share information among the collaborating state, federal, and private entities, and to coordinate their actions to ensure sustained compliance with water quality objectives during the spring drawdown period. The implementation of this technology will permit coordinated and collaborative real-time management by the various stakeholder groups in a way that was not previously possible.

**MANAGEMENT OF THE WETLAND LANDSCAPE AS A COMPLEX SYSTEM**

While present-day management of the GEA has not been developed explicitly using a complex systems approach, many of the characteristics of the way the wetlands are managed contribute to system complexity and possibly to increased resilience of the whole socio-ecological system. Parrott and Meyer (2012) identified five key characteristics of complex systems that should be incorporated in a complex systems management approach and linked these to specific management actions that can be carried out at the landscape scale. Translating each of these specific characteristics into activities can lead to a more profound understanding of the dynamic nature of the landscape and potentially new insights for future management. In the following sections, we identify how each of these actions is currently carried out in the GEA, and discuss how management could be changed to further support complexity in the system.

**Action 1: Develop a conceptual model of the landscape as a complex system**

As described above, the wetland landscape of the GEA is the product of almost a century of intense human management. Today, it can be viewed as a tightly coupled social-ecological system, with many ecological patterns and processes (e.g., dominant vegetation types, hydrological flows) that exist as a result of human intervention. The system is managed by a multiplicity of stakeholders, each operating to meet
the demands of different end-users (water purveyors, agriculturalists, hunters, birders, and other recreational users) accessing different resource units (water, waterfowl, fish, recreational space). The governance system involves small private landholders, stakeholder interest groups, state and federal governments, each of which is operated within different constraints to meet different objectives. The complexity of the governance system gives rise to heterogeneity in management actions and outcomes, which has the potential to contribute to emergent and heterogeneous ecological responses at the scale of the whole wetland complex, ultimately increasing ecological resilience. The system is dynamic, and driven by unpredictable inputs. Many local-scale processes and actions related to water management may have emergent landscape-scale outcomes related to the ability of the wetland complex to absorb additional drainage water, to withstand drought, or to support wildlife.

While none of the groups or individuals involved in management of the GEA has explicitly applied a complex systems lens to interpreting the landscape, such a viewpoint, which would acknowledge feedbacks and interconnections between different system components, may arise through increased monitoring efforts (Action 2, below). We argue that adopting a conceptual model of the GEA as a complex system may provide a useful framework for interpreting system dynamics, and particularly for understanding how individual-scale decisions related to water management can sometimes have cumulative and compounded effects on the system as a whole.

This conceptual model could begin as a simple schematic or network representation of the three wetland entities within the GEA and help define relationships between water supply and quality, schedules, water use, and land management practices within each wetland management area. By embracing a conceptual modeling approach, new or altered management actions can be framed in terms of which entities or processes will be affected, either directly or indirectly. Our experience has been that the development of a simple, diagrammatic representation of the system function and feedbacks under consideration is both vital and empowering. Furthermore, the development of such a systems diagram will facilitate the process of making explicit the critical assumptions and values of wetland managers in the three entities. As this process will be internal to the wetland entities, it should elicit more candor and factual accounting than might be possible in a more public forum involving a wider array of stakeholders. Simple examples of such diagrams can be found in Parrott et al. 2012 and literature on stakeholder network analysis (Bodin and Crona 2009, Mills et al. 2014). We recommend the creation of such a diagram for the GEA, illustrating the interaction network of public and private stakeholders involved in management of the wetland complex, to facilitate further dialog and understanding about system complexity and the governance structure.

Action 2: Identify emergent patterns and processes by monitoring the landscape at multiple spatial and temporal scales

Until the imposition of salt load limits for both agricultural and seasonal wetland drainage exports to the San Joaquin River, most monitoring conducted on these landscapes was directed at water conservation in the case of agriculture, waterfowl use and diversity in the case of the refuges, and hunting success in the case of the private duck clubs. The refuges have enjoyed a relatively stable, high-quality source of water supply since the mid-1980s, largely from water pumped from the Sacramento—San Joaquin Delta. Routine water quality monitoring of either imported water or exported water has not been a consideration for wetland resource management until relatively recently. The design and installation of a new network of flow and salinity monitoring stations will be necessary to better characterize landscape water quality and identify potential salt-induced impacts when restrictions to salt export occur in those years when San Joaquin River assimilative capacity is limited. The GWD has a longer history of dealing with salinity issues and for the past decade has had in place a state-of-the-art, web-accessible monitoring system that provides real-time data for continuous characterization of the 20,000 ha of seasonal wetland as well as data specifically to support operations. The District also maintains a number of the paired individual wetland impoundments.
carried over from the research project previously described. This allows landscape wetland habitat monitoring at an appropriate landscape scale for observing incremental impacts that may not be readily observable at a more regional scale and, more critically, provides a mechanism to build stakeholder confidence by creating an opportunity for local involvement. Even though an individual stakeholder duck club or cattle operation may not be monitored, the fact that resources are being dedicated to land areas of this scale provides a level of stakeholder assurance difficult to achieve by other means.

This combination of multiple monitoring efforts carried out by different levels of governance and at different spatial and temporal scales greatly increases the potential for detecting cross-scale interactions and emergent patterns in the system, as well as contributing to better understanding of the system. Over time, such understanding may contribute to increased local knowledge about the usual range of variability within the system, allowing for rapid responses when the system shows signs of shifting states. In addition, advanced, real-time monitoring will also facilitate dynamic re-allocation of water release schedules in response to water quality, allowing for adaptive management interventions that better reflect the actual state of the wetlands and assimilative capacity of the river.

**Action 3: Develop and maintain adaptive management capacity as a buffer against undesirable change**

Fostering adaptive capacity in the ecological and social subsystems of the GEA is important for maintaining landscape-scale resilience and the continued provisioning of multiple ecosystem services by the wetlands in the face of uncertain future climate, economic, and environmental conditions. Leading up to the Kesterson crisis, ecological resilience of wetlands in the Southern Division of GWD was greatly compromised as a result of overloading from agricultural drainage. Today, ecological resilience is likely increasing due to restoration efforts that have improved habitat quality. Social resilience may also be increased as a result of new regulatory measures and the multiple scales of governance and heterogeneity of stakeholders involved in management of the wetlands.

The combination of public and private ownership may increase adaptive capacity at the landscape scale by providing for a multiplicity of responses to potential disturbances or future stress on the wetlands. The state and federal refuges not only receive a better quality and more reliable water supply but also are managed in a top-down manner typical of government agencies where resources are often available for intensive monitoring and habitat resource optimization. In GWD, by way of contrast, 160 duck clubs and cattle operations, each with its own Board of Directors, are served by a smaller permanent staff with fewer in-house resources. This can have impact on the capability of the GWD to respond to critical events and the level of expertise that can be mobilized when opportunities arise, such as an increase in San Joaquin River assimilative capacity that could accommodate more salt load from GEA wetlands for a limited period. The institutional structure of the government-run wetland resource agencies allows them to be less risk averse with the ability to optimize the functionality of the wetland resource.

Measurement of water use efficiency in managed seasonal wetlands uses different metrics than the more traditional efficiency measures used in agricultural irrigation. These are focused on maximizing the diversity of plant and animal species supported by wetland habitat and include aesthetic considerations that limit the appropriateness of certain types of water conveyance and distribution technology in natural riparian waterways and wetland settings. The focus on diversity vs. habitat for certain species of waterfowl favored by hunters is what distinguishes the wetland landscape of the federal wildlife refuge from the private duck clubs with the State-run refuges.

Providing private entities with the ability to monitor flow and water quality also allows for adaptive management interventions that better reflect the actual state of the wetlands and assimilative capacity of the river.
GWD that serves multiple stakeholder decision makers—having one or more clubs subjected to delayed wetland drawdown on a regular ongoing basis to meet River salinity objectives would likely invite litigation. This potential equity issue is not manifested within the state and federal refuges where the natural hierarchy of a government agency provides cover for making tradeoffs between subareas within each wetland management complex. In the case of GWD, this dilemma is partly assuaged by hiring wetland management consultants, many of whom were former employees of GWD or the state or federal wildlife management refuges. Their gravitas within the culture of the wetland management community allows them certain discretion at making wetland drawdown decisions and would likely circumvent perceived equity concerns by landowners suffering potential habitat damage due to a delayed drawdown to meet GEA obligations for salt management.

**Action 4: Mimic natural processes to the extent possible to take advantage of system internal memory**

The seasonally managed wetlands that make up the GEA share the common goal of mimicking, to the extent possible, the hydrology, and wetland function of the historic floodplain prior to the construction of the levees and channelization of the San Joaquin River. The functional differences between the management practiced by the federal and state refuges and the private duck clubs and cattle operations are more related to economic realities in the case of the GWD and the individual agency vision and actionable goals in the case of the wildlife management agencies. For GWD, hunting success is closely related to the economic worth of the particular duck club, the join fee it can charge, and the annual dues it can extract from its members. The value of a membership if sold or traded, for those clubs with a restricted membership is strongly correlated with the bird harvest at each Club. In general duck clubs in the southern division of GWD whose soils retain a salinization memory from past irrigation with saline agricultural drainage water are less desirable than those in the northern division where the water supply is mostly from fresher sources.

The residual salts retained in wetland soils, even after almost 30 yr of effective reclamation with better quality water, produce a wetland habitat that is adapted to the soils and salinity in the current water supply. Wetland managers likewise have adapted their functional habitat designs and forage quality goals to the moist-soil plants favored by this slightly brackish wetland environment.

**Action 5: Embrace consideration and analysis of ensembles of alternative futures and future system states**

Managing from a complex systems approach requires an acknowledgment of future uncertainty and the development of decision tools that do not rely on single forecasts. Management needs to consider the range of possible and probable future states for a system and seek to maintain the system within an envelope of desirable future states. For the GEA, there are insufficient long-term monitoring data to document the historical (preagriculture) state of the wetland, and given the changing human demands on the system, it is unlikely that a return to the historical state would be desirable.

Due to the lack of data, and the multiplicity of stakeholder objectives, there is therefore no common conceptual model or decision framework that has been adopted to guide management and there is not necessarily a common vision of the alternate futures possible for the wetland complex. There is a common recognition, however, that these wetlands were brackish wetlands historically and the vegetation community should not be that of a freshwater wetland. An envisioning project, bringing stakeholders together to establish a shared vision of the wetland as a complex system and to discuss alternate future scenarios, would be a logical next step in the process of ensuring a sustainable resource and performing restoration where and when necessary. Such a project would help to increase stakeholder communication, trust and information sharing, and contribute to a collective understanding of the wetland complex as a larger system to which each stakeholder contributes. It would also facilitate coordination of salinity and drainage management.

Salinity and drainage management practices such as reuse and groundwater conjunctive
use, more typically associated with irrigated agriculture, are being considered in future alternative planning of these seasonally managed wetlands under active salinity management. Wetland managers will need to first reconcile their habitat management objectives and develop mechanisms to share and collectively manage annual wetland drawdown schedules. This level of coordination has not hitherto taken place between the three wetland governance entities but will be necessary if real-time salinity management is to be successfully implemented. Coordination of salt load export to the San Joaquin River will also be necessary with agricultural water districts outside of the GEA. The equivalent of a spokesperson will be needed to represent the wetland entities to participate in real-time forecasting of San Joaquin River assimilative capacity and in salt loading scheduling activities to prevent exceeding river salinity objectives. Some wetland managers have been reluctant to join agricultural stakeholder coalitions because of a fear that wetland return flow water quality will become associated and linked to some of the chemical and pesticide effluents more germane to agricultural return flows. Wetland managers fear that this could lead to unreasonable monitoring requirements and increased costs of compliance.

Drought in California and 2 yr of federal water supply contract reductions to 75% of normal scheduled deliveries to wetland entities has added an additional stressor to seasonal wetland management because of these water shortages. Water reuse, development of groundwater resources, and curtailment of wetland impoundment flow-through (small volume of wetland drainage that is used to maintain pond water circulation) are being used for the first time to maintain essential wetland function. However, there is uncertainty as to how changes to current practices in response to both water supply and salinity constraints will affect long-term wetland health and function. No mutually acceptable conceptual model or decision framework exists partly because of a lack of long-term monitoring data, inadequate analytical resources to process, and disseminate data to inform decisions and, most significantly, because these issues are relatively recent and wetland managers are working within existing knowledge paradigms. An adaptive approach embracing some of the core principals of complex system science is needed but this needs to become a shared approach across existing wetland entities.

**Discussion**

How has system complexity of the GEA evolved over time? Figure 4 provides a qualitative assessment of the complexity of the GEA. The variables chosen are those properties of complex systems which are most relevant to management of the GEA and to the ability of the system to sustain its ecological functions, specifically ecosystem services provisioning (Fig. 2). The properties assessed for the ecological subsystem include: (1) resilience, referring to the ability of the system to maintain or recover its essential functions after disturbance; (2) heterogeneity, a property common to all complex systems relating to the diversity of components as well as their nonuniform arrangement in space and time; (3) emergence, the spontaneous arrangement of system components to form patterns and structures evident only at a higher scale or level of organization; typically the presence of these emergent structures feeds back upon the lower level components and reinforces the process leading to emergence. An example would be the formation of patchy clumps of vegetation in arid systems, the presence of which influences available water and reinforces the formation of patches; (4) self-organization, which refers to the formation of persistent structures and dynamics in an open system, resulting from the response of system components to a flow of energy, material, or information across the system boundary. An example is the formation of whorls and vortexes in a turbulent fluid. As for emergence, self-organization is not directed or controlled by any single component in the system. The last ecological system property studied is (5) uncertainty, which, in a complex system, results from a combination of stochastic (random) events occurring within and externally to the system, as well as nonlinear deterministic dynamics, including chaos, all of which reduce the ability to predict system-level dynamics. Human interventions typically seek to reduce uncertainty in managed natural resource systems. Robustness, or the ability of the system
to persist and maintain its functions despite the loss of components, is assessed for both the ecological and social subsystems. For the social system, *hierarchy* refers to the degree of structural organization, particularly the number of scales of governance (e.g., federal, state, local) within the management system. *Adaptive capacity* refers to the ability of the social system to learn and innovate, and possibly transform management practices, in response to change. Adaptive capacity is enhanced through access to information about the state of system and the degree to which this information is shared between stakeholders.

By viewing the GEA as a coupled social-ecological system, we can assess overall system
complexity as the combined properties of the social and ecological parts of the system. In this way, we see that the system has evolved from a state of high ecological complexity but low social complexity (assessed based on apparently minimal use of the region by aboriginal peoples), to a present state of lower ecological complexity which is arguably compensated for at the system level by increased social complexity. If the overall complexity of the system can be measured as the total area of the petals on the “flowers” in Fig. 4, the present-day GEA has a level of complexity that would be close to that of the predevelopment period. System complexity was greatly reduced in the intervening years, however, by a management regime that sought to decrease uncertainty in hydrological flows, leading to greatly compromised ecological heterogeneity and resilience, and stifling of the processes leading to emergence and ecological self-organization. We argue that the Kesterson crisis, in which toxic selenium levels in drainage ponds caused large-scale deaths and deformities of waterfowl protected by international treaties, had a transformatory effect on the system. This period of transformation led to a new management regime that, through ecological restoration and increased social capacity, has recovered system complexity in the GEA.

Increased social capacity in the system is the result of improvements in communication and coordination that have taken place in a variety of forms following the Kesterson crisis—the most profound, in the case of the US Bureau of Reclamation, was the decision to recast the agency’s mission from one of design and construction of infrastructure to facilitate irrigation development to a greater focus on environmental stewardship and efficient use of existing water resources. For other agencies, it has meant the more formal establishment of standing committees to oversee issues such as future wetland water supply and compliance monitoring within a coalition of wetland and agricultural water districts to meet the requirements of the salinity TMDL. The Regional Water Quality Control Board, which has the responsibility of salinity TMDL enforcement, has, in the past decade become more open to working closely with stakeholders to collectively explore salinity management options. The Central Valley Salinity Coalition initiative is an outgrowth of this new collaborative contract between regulators and stakeholders—with the mission of developing an updated coordinated Water Quality Basin Plan for the San Joaquin and Sacramento Basins. This forum allows these entities to develop an improved universe of discourse and develop common conceptual models of system function. The GEA will benefit from continued collaborative efforts by the current stakeholders that seek to maintain ecological complexity and nurture the adaptive capacity of the management system.

Conclusion

The Grasslands Ecological Area is a complex social-ecological system—management of this system requires an understanding of the interacting human and natural processes operating on the landscape within a continuum space and time. Traditional management practices are ill equipped to provide informed guidance to address the resource management challenges brought about by salinity regulation and water shortages. A new paradigm is needed that brings people together to (1) help develop a shared conceptual model and understanding of the system as a complex system, (2) establish shared goals regarding salt load targets and future state of the wetlands, based on future water use scenarios, and (3) anticipate potential changed priorities into the future. This complex systems perspective addresses the issue of scale through which the existing system is “observed” allowing for new explanations for a variety of phenomena that are not readily explained by current system conceptual models operating at a single hierarchical level. In the case of the GEA, current conceptual models may not be coherent given the different resource management objectives of the state, federal, and private wetland entities. Hence, a new framework built upon a complex systems perspective might accommodate these objectives within a multihierarchical continuum that recognizes the multiple-scale structural and dynamical patterns of the larger system. Such a perspective also helps to view the wetland ecosystem as a dynamic system constantly in flux. The role of the wetland biologist can thus expand to include a role of ecological engineer—striving to understand the underlying workings of the system and to allow the system to manage itself within
certain constraints. This notion of self-design, a fundamental construct of complexity theory, suggests that a system will self-select and optimize to perpetuate those processes best adapted to prevalent environmental conditions (Parrott 2002, Odum and Odum 2003). Ecological managers should strive to maintain the capacity of the ecological system to self-organize and pay attention to the roles of diversity and heterogeneity at all system scales to ensure ecosystem long-term function.

Taking a complex systems approach to management of a multifunctional landscape can facilitate development of a shared conceptual and analytical framework upon which a common vision and mutually beneficial goals can be developed. The complex systems paradigm is useful in that it supplies new vocabulary and concepts, inviting each governance entity to rethink and translate its resource management goals and strategies into a new common framework. This sort of activity can lead to reexamination of cultural and legacy management norms that would otherwise remain off-limits, and ultimately lead to better multiobjective management of landscapes as complex social-ecological systems.

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