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Ecohydrological and socioeconomic integration for the operational management of environmental flows

B. A. Bryan,[1,7] A. Higgins,[2] I. C. Overton,[3] K. Holland,[3] R. E. Lester,[4] D. King,[1] M. Nolan,[1] D. Hatton MacDonald,[1] J. D. Connor,[1] T. Bjornsson,[5] and M. Kirby[6]

[1]*CSIRO Ecosystem Sciences, Waite Campus, Urrbrae, South Australia 5064 Australia*
[2]*CSIRO Ecosystem Sciences, Dutton Park, Queensland 4102 Australia*
[3]*CSIRO Land and Water, Waite Campus, Urrbrae, South Australia 5064 Australia*
[4]*School of Life and Environmental Sciences, Deakin University, Warrnambool, Victoria 3280 Australia*
[5]*SA Department for Water, Adelaide, South Australia 5000 Australia*
[6]*CSIRO Land and Water, Black Mountain, Canberra, ACT 2601 Australia*

Abstract. Investment in and operation of flow control infrastructure such as dams, weirs, and regulators can help increase both the health of regulated river ecosystems and the social values derived from them. This requires high-quality and high-resolution spatiotemporal ecohydrological and socioeconomic information. We developed such an information base for integrated environmental flow management in the River Murray in South Australia (SA). A hydrological model was used to identify spatiotemporal inundation dynamics. River ecosystems were classified and mapped as ecohydrological units. Ecological response models were developed to link three aspects of environmental flows (flood duration, timing, and inter-flood period) to the health responses of 16 ecological components at various life stages. Potential infrastructure investments (flow control regulators and irrigation pump relocation) were located by interpreting LiDAR elevation data, digital orthophotography, and wetland mapping information; and infrastructure costs were quantified using engineering cost models. Social values were quantified at a coarse scale as total economic value based on a national survey of willingness-to-pay for four key ecological assets; and at a local scale using mapped ecosystem service values. This information was integrated using a constrained, nonlinear, mixed-integer, compromise programming optimization model and solved using a stochastic Tabu search algorithm. We tested the model uncertainty and sensitivity using 390 Monte Carlo model runs at varying weights of ecological health vs. social values. Integrating ecohydrological and socioeconomic information identified environmental flow management regimes that efficiently achieved both ecological and social objectives. Using an ecologically weighted efficient and socially weighted efficient scenario, we illustrated model outputs including a suite of cost-effective infrastructure investments and an operational plan for new and existing flow control structures including dam releases, weir height manipulation, and regulator operation on a monthly time step. Both the investments and management regimes differed substantially between the two scenarios, suggesting that the choice of weightings on ecological and social objectives is important. This demonstrates the benefit of integrating high-quality and high-resolution spatiotemporal ecohydrological and socioeconomic information for guiding the investment in and operational management of environmental flows.

Key words: decision analysis; ecosystem services; environmental flows; integrated modeling; operations research; optimization; trade-offs; water resources; wetland.

Introduction

Water extraction and regulation of natural flow regimes has increased the production of socioeconomic values flowing from rivers through activities such as agriculture, hydropower, navigation, recreation, and urban water supply (Poff et al. 2007). This has come at the expense of river ecosystems (Gordon et al. 2010). Alteration of the quantity, timing, duration, frequency, rate of change, and quality of environmental flows now threatens the *ecological health* (the vigor, organization, and resilience; Rapport et al. 1998) of river ecosystems globally (Kingsford 2000, Poff et al. 2007, Doll et al. 2009, Poff and Zimmerman 2010). The restoration of more natural environmental flows is required to correct the imbalance between the decline in ecological health and the production of socioeconomic values from river ecosystems to ensure their sustainability (Baron et al. 2002, Arthington and Pusey 2003, Arthington et al. 2010, CSIRO 2012). In highly regulated rivers, more natural flow regimes can be returned through the strategic operation of flow control infrastructure such as dams, regulators, and weirs (Galat and Lipkin 2000,

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[7] E-mail: brett.bryan@csiro.au

Bednarek and Hart 2005, Rood et al. 2005, Richter and Thomas 2007, Higgins et al. 2011, Watts et al. 2011). Compatible, high-quality (i.e., accurate, precise), and high-resolution (i.e., landscape spatial scale and daily/monthly temporal scales) ecohydrological and socioeconomic information is required to support operational environmental flow management decisions that efficiently achieve both ecological and socioeconomic objectives (Hillman and Brierley 2002, Cai 2008, de Lange et al. 2010).

Increasingly, researchers are integrating ecohydrological and socioeconomic information in environmental flow management models (King et al. 2003, Prato 2003, Brouwer and van Ek 2004, Golet et al. 2006, Loucks 2006, Suen and Eheart 2006, Davis 2007, Brouwer and Hofkes 2008, de Lange et al. 2010, King and Brown 2010, Holzkamper et al. 2012). However, few studies have integrated high-quality and high-resolution hydrological, ecological, economic, and social data to support the operational management of environmental flows. In many cases, part or all of the underpinning data used in such studies is either conceptual, abstract, hypothetical, stylized, or simplified representations of complex realities (e.g., Letcher et al. 2007, Coram and Noakes 2009, Hughes and Mallory 2009, de Lange et al. 2010, Stewart-Koster et al. 2010, Grafton et al. 2011). Undoubtedly, these studies have provided valuable methodological advances, and have supported decision-making, stakeholder engagement, and policy design. However, a range of factors (e.g., incompatible or inappropriate temporal and spatial scales, low precision and accuracy, uncertainty, and model bias) resulting from the use of simplified input data limit the practical utility of the results for operational environmental flow allocation and investment decisions (Cai 2008, de Kok et al. 2009, de Lange et al. 2010).

While a full review of the data sophistication of integrated environmental flow models is beyond the scope of this paper, we will describe some common limitations. To capture hydrological dynamics, many integrated models of environmental flows have used single-dimensional linear network models with environmental flows occurring between interconnected nodes (e.g., Letcher et al. 2007, George et al. 2011*a*, *b*, Yin and Yang 2011). Without a spatial approach, linking hydrological flow rates with environmental flow metrics for specific areas of river ecosystem types is not possible and the ability of the model to capture key ecohydrological processes is limited. Some recent studies have incorporated high-resolution spatial hydrological data in integrated models (e.g., Schluter et al. 2006, Higgins et al. 2011). Ecological responses to natural flow regimes have often been specified based on single species/ecosystems (e.g., Overton et al. 2006, Schluter et al. 2006) or ecosystem-wide generalizations (Yin and Yang 2011). Recent studies have begun to include a broader diversity of ecological responses to natural flow regimes (e.g., Yang et al. 2011).

Some economic values have been well specified in integrated models, with the most common being the profitability for agriculture and other consumptive uses of water (Brouwer and Hofkes 2008, Cai 2008). Conversely, broader social values have often been absent, qualitative, or quantitative but oversimplified. For example, multi-criteria analyses have sought to score the social value of flow management options against a range of criteria (e.g., Prato 2003, Brouwer and van Ek 2004, Bryan 2010). Often social values have been reduced to considerations of equity, water security for consumptive uses, or power generation (e.g., Suen and Eheart 2006). However, a few examples of detailed social data used in integrated environmental flow assessments are emerging. These include the comprehensive assessment of nonconsumptive recreational values and cultural resource assessments (Golet et al. 2006), and willingness-to-pay studies (Kragt et al. 2011). The DRIFT model (King et al. 2003, King and Brown 2010) is one of very few environmental flow allocation models that has integrated detailed and high-quality ecohydrological and socioeconomic information at spatial and temporal resolutions capable of informing operational environmental flow management decisions.

Hillman and Brierley (2002) summarized four information needs to support integrated assessments of environmental flows, which we used as a foundation for this paper. These include: (1) current and natural flows; (2) links between hydrological and ecological processes; (3) the economic, social, policy, and cultural context; and (4) operational flow management. Information on river hydrology is required in the form of hydrographic time series data characterizing current and natural flow regimes at various points along the river (Galat and Lipkin 2000), including ecologically important low and peak flows. As many river ecosystems are characterized by low-gradient, spatially heterogeneous floodplain habitats, hydrographic flow regimes need to be translated into a spatial extent of inundation (Shaikh et al. 2001, Overton 2005, Powell et al. 2008). River ecosystems need to be classified and mapped based on their species composition and structure (Cunningham et al. 2009), and their natural flow regime needs to be quantified (Verhoeven et al. 2008, Merritt et al. 2010). This linking can enable the identification of areas and ecosystems inundated at any given flow rate. Subsequently, metrics of ecological health can be quantified based on the comparison of altered and natural flow regimes (Poff et al. 2010, Saintilan and Overton 2010, Lester et al. 2011). Economic information may include a variety of values such as the costs of management actions, damage costs of changed flow regimes, or the opportunity costs of foregone consumption of water used for the environment. Social values may be diverse, they may include a range of use and nonuse values (King et al. 2003), and they may vary between people (Hatton MacDonald et al. 2011) and across landscapes (Raymond et al. 2009). Decision models can integrate this information to support cost-effective investment decision-making and operational management regimes that improve the ecological health of river ecosystems and reduce the trade-offs for social values (Golet et al. 2006, Watts et al. 2011).

We used a transdisciplinary approach combining mixed methods to develop, apply, and integrate high-quality and high-resolution ecohydrological and socioeconomic information to support cost-effective investment in operational-level environmental flow management along the highly regulated 600-km South Australian (SA) River Murray. While many environmental flow applications are focused on instream flows (and associated minimum flows), it is the lateral floodplain-inundating high flows that are the important driver of ecological health in this system. We used daily hydrographs to calculate monthly mean and peak flow rates at the SA border under natural conditions and under current development and extractions. We combined this with a 30-m spatial resolution inundation model (the River Murray Floodplain Inundation Model [RiM-FIM]) to define specific areas of inundation given flow rates and weir heights (Overton 2005). We used 1:20 000-scale floodplain vegetation and wetland mapping to classify the distribution of 18 *ecohydrological units*. Response functions were derived for 16 ecological components including eight vegetation types, and two bird and six fish functional types characterizing the impact of environmental flows (i.e., flood duration, timing, and inter-flood period) on the ecological health of each component at various life stages (Young et al. 2003). Flow management infrastructure (e.g., flow regulators, moving off-take pipes and pumps) were sited and the dimensions estimated using LiDAR and orthorectified aerial photography. Infrastructure costs were quantified using engineering cost models. We also quantified social values at two complementary scales: the total economic value of three key environmental assets (i.e., floodplain vegetation, waterbirds, and native fish) from a national survey (Hatton MacDonald et al. 2011), and local, spatially explicit ecosystem service values (Raymond et al. 2009). We then combined these ecohydrological and socioeconomic information layers in an integrated model to support cost-effective investment in, and operational management of, environmental flows. Here, we performed Monte Carlo runs of the model to evaluate the sensitivity of weighting ecological vs. social objectives and to illustrate model uncertainty. Comparing an efficient ecologically weighted scenario with an efficient socially weighted scenario, we assessed the benefits of integrating both ecohydrological and socioeconomic information in environmental flows management. We compared the optimal investments and the operational environmental flow management regimes of these two scenarios, including weir manipulation, regulation operation, and dam releases. Finally, we discuss how the model has been used to support the development of a business case for national and state government investment of $60 million (all $ values in Australian dollars) in environmental flow management.

Methods

Study area

The 97 424-ha study area encompasses the lower River Murray floodplain (Fig. 1), which passes through an agricultural mosaic of semiarid to Mediterranean climate. River flows are regulated by six weirs (named Lock 1 through Lock 6), and several wetlands have existing flow control structures. The valley section of the River Murray from the SA border to Overland Corner is characterized by wide (5–10 km) shedding floodplains with diverse wetlands including anabranches, billabongs (oxbows), and deflation basins. The gorge section from Overland Corner to Mannum is characterized by a narrower and less diverse floodplain (2–3 km wide) constrained by 30 m high limestone cliffs within which the river meanders. The floodplain below Mannum is highly regulated and modified for agricultural production (Walker and Thoms 1993).

Major floodplain vegetation types include *Eucalyptus camaldulensis* (river red gum) and *E. largiflorens* (black box) communities. The study area provides important habitat for native waterbirds and fish species. Riparian ecosystems (e.g., watercourses, wetlands, floodplains) have been subject to several threats, including: flow regulation and the over-allocation of water resources for consumptive uses; increased salinity, turbidity, and nutrient levels; invasive species; drought; and climate change (Leblanc et al. 2012).

The River Murray supplies water to high-value irrigated agriculture and is one of the main sources of fresh water for the city of Adelaide and much of rural South Australia. The river also holds significant social values, particularly cultural and recreation values (Raymond et al. 2009, Bryan et al. 2010, Hatton MacDonald et al. 2011).

Together, the Australian and South Australian (SA) governments plan to invest around $60 million in environmental flow management in the study area over the next few years. The model presented in this paper was developed with the SA government to support environmental flow investment and management decisions. The objectives of the investment are to: enhance the ecological and social values of river ecosystems; conserve water; and improve water security for irrigators. Investment options for achieving these objectives include: better management of existing flow control structures (weirs, regulators); building and managing new flow control structures (regulators); and moving irrigation off-takes from backwaters and wetlands to the main river channel. In this paper, we extended this scope in considering an additional, complementary flow management option: the strategic upstream releases of environmental flows.

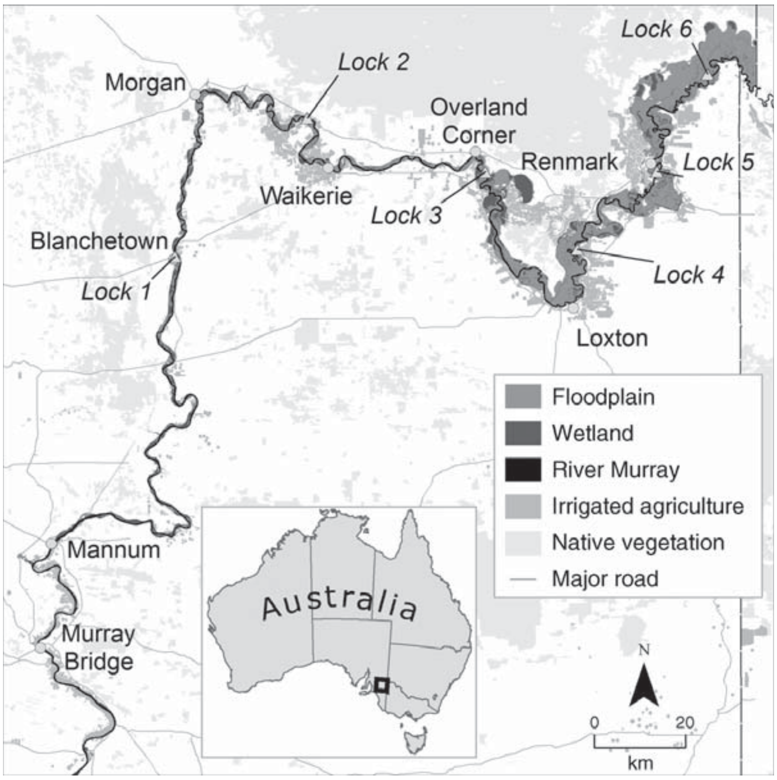

FIG. 1. Location of the South Australian River Murray study area.

Hydrology

River flow rates.—Hydrographs detailing mean daily flow rates over the SA border, modeled under natural and current conditions based on historical climate for the period 1895–2006, were acquired from the Commonwealth Scientific and Industrial Research Organisation (CSIRO)'s Murray-Darling Basin Sustainable Yields project (MDBSY; CSIRO 2008). MDBSY developed and integrated models of daily rainfall–runoff, groundwater recharge, river systems, and surface–groundwater exchanges in a consistent way across the Murray-Darling Basin to assess the impacts of climate and development on flows. Central to the modeling are 5-km spatial resolution interpolated daily historical climate data layers. River model performance overall has been rated as very good to excellent in reproducing most flow characteristics except low flows (Van Dijk et al. 2008). Natural flows were modeled for daily historic climate data and assume no flow regulation or extractions. Current flows were modeled for the same period, but include existing flow regulation and extractions. We summarized the monthly mean and peak flows for inclusion in the integrated model.

Inundation.—The spatial extent of inundation was modeled using RiM-FIM (Overton 2005), a Geographic Information System (GIS)-based decision support tool that we rewrote for use in our integrated model. RiM-FIM relates historic inundation extents captured using 30-m spatial resolution Landsat imagery to river flow rates at the SA border. For a given flow rate at the SA border, RiM-FIM can calculate river heights at 627 trigger points located at 1-km intervals along the river. Raising and lowering weirs also alters river heights achieved under a given flow rate, and RiM-FIM includes a hydraulic model of backwater curves to capture this (Overton 2005). Trigger points are hydrologically connected to a specific geographic area called a flood inundation response unit (FIRU). Thereby, RiM-FIM is able to predict the spatial extent of inundation and wetland connectivity across the floodplain for any combination of weir configuration and river flow rate at the border. RiM-FIM has been found to underestimate flood extents by $\sim$15% compared to aerial photography (Overton 2005). For input into the integrated model, we calculated the *commence-to-fill* flow rate for all parts of the study area (i.e., the flow rate at the SA border at which they become inundated) under all weir configurations.

Ecology

Ecosystem mapping.—Building on the operational landscape unit (Verhoeven et al. 2008) and vegetation flow response guild approaches (Merritt et al. 2010), we used a classification process to define and map river ecosystems into 18 *ecohydrological units*. First, we intersected 1:20 000-scale watercourse and wetland mapping with 1:20 000-scale floodplain vegetation mapping that covered all non-wetland and watercourse areas. The distinction between watercourses/wetlands

TABLE 1. Classification of floodplain ecohydrological types.

Floodplain ecohydrological type	Characteristics	Flooding frequency (yr)	Typical species
Riparian	fluctuation tolerators, woody	1–5	*Eucalyptus camaldulensis*, *Eucalyptus largiflorens*, *Acacia stenophylla*
High floodplain	fluctuation tolerators, woody	>5	*Eucalyptus largiflorens*, *Acacia stenophylla*
Emergent	amphibious fluctuation tolerators, static shallow water <1 m deep or permanently saturated soil	<1	*Typha* spp., *Phragmites australis*, *Cyperus gymnocaulos*, *Juncus usitatus*
Terrestrial dry	will not tolerate inundation, and tolerates low soil moisture for extended periods	>5	*Atriplex vesicaria*, *Rhagodia spinescens*, *Enchylaena tomentosa*
Salt tolerant	tolerant of high soil or water salinity	>1	*Halosarcia pergranulata*, *Pachycornia triandra*
Lignum	fluctuation tolerator, woody	1–5	*Muehlenbeckia florulenta*

and floodplain areas is that the former are predominantly influenced by hydrological processes, whereas ecological processes more strongly influence the latter.

We then delineated functionally different areas of wetlands, watercourses, and floodplain using the South Australian Aquatic Ecosystems database (Jones and Miles 2009). Three watercourse ecohydrological units were classified based on permanence (permanent, seasonal, ephemeral). Eight wetland ecohydrological units were classified based on permanence (permanent or temporary), vegetation presence (wetland, swamp, or lake), wetland surface water hydrology (overbank flow, throughflow, terminal branch), and the presence of salt-tolerant vegetation (saline swamp).

Floodplain areas were subsequently classified into six ecohydrological types (riparian, high floodplain, emergent, terrestrial dry, salt tolerant, and lignum) by aggregating the 72 vegetation communities occurring on the floodplain and their natural flow regime (Table 1). The rationale for using vegetation types as the basis for ecohydrological classification is that they are an integrated and emergent property of the biophysical environment of an area including the flow regime, soil properties, groundwater depth, and groundwater salinity. As floodplain vegetation is long lived, with some individuals dated to over 500 years old, its distribution provides an indicator of the natural flow regime rather than the current altered flow regime.

TABLE 2. List of the 16 ecological components assessed in this study.

Ecological component	Life stages
Floodplain vegetation	
Black box (*Eucalyptus largiflorens*)	A, S
Floodplain red gum (*Eucalyptus camaldulensis*)	A, S
Riparian red gum (*Eucalyptus camaldulensis*)	A
Lignum (*Muehlenbeckia florulenta*)	A, S
Salt-tolerant vegetation	A
Chenopods	A
Wetland vegetation	
Phragmites australis	A, S
Ribbonweed herbland (*Vallisneria americana*)	A, S
Waterbirds	
Colonial nesting waterbirds	B
Waterfowl and grebes	A
Fish	
Main channel specialists	A, Sp
Flood spawners	A, Sp
Wetland specialists	A, Sp
Freshwater catfish	A, Sp
Main channel generalists	A, Sp
Low flow specialists	A, Sp

Notes: Key to life stages: A, adult; S, seedling; B, breeding; and Sp, spawning. See Appendix A for a full list of life stages and data sources, and Appendix C for ecological health functions describing environmental flow requirements.

Ecological responses to environmental flows.—To quantify the effect of flows on ecological health, we adapted response functions for 16 ecological components including vegetation assemblages (floodplain and wetland) and faunal guilds (waterbirds and fish; Table 2). The health of each ecological component depends on specific environmental flow requirements. Ecological response functions estimate the health of each ecological component as a function of environmental flow represented by three key flow indicators: flood timing, flood duration, and inter-flood period. Ecological responses vary from 0 to 1, where 0 indicates intolerable habitat conditions and 1 indicates ideal conditions. Where relevant, separate response curves were specified for ecological components at different life stages (e.g., seedling and adult life stages for vegetation; spawning and adult life stages for fish; Table 2). Originally elicited through a combination of expert knowledge and literature review, ecological response functions were primarily sourced from the Murray Flow Assessment Tool (MFAT; Young et al. 2003). The response functions have been reviewed and endorsed by the Scientific Review Panel of the Murray-Darling Basin Commission's Living Murray Initiative (Murray Flow Assessment Tool [MFAT]; *available online*).[8]

We validated and updated MFAT ecological response functions for floodplain vegetation (Young et al. 2003) using an analysis of natural flow regimes combining the natural hydrographs and commence-to-fill data. We calculated the mean inundation duration and inter-flood

[8] http://www2.mdbc.gov.au/livingmurray/mfat/

Table 3. Ecological assets and the complete set of alternative states included in choice sets (Hatton MacDonald et al. 2011).

State	Waterbird breeding frequency (yr)	Native fish populations (% of original size)	Healthy vegetation (% of original extent)	Waterbird habitat at Coorong (quality)	Household cost ($/yr for 10 years)†
Current state	10	30	50	poor	0
Alternative states	10, 7, 4, 1	30, 40, 50,60	50, 60, 70, 80	poor, good	20, 50, 75, 100, 125, 150, 200, 250

† Costs shown are in Australian dollars.

period for ecohydrological types under the natural hydrograph on a monthly time scale. Additional information (Overton et al. 2009; Ecological Associates [Malvern, Australia], *unpublished data*) was also used to verify and modify some ecological response functions (Appendix A). Example ecological response functions for adult floodplain river red gum are presented in the *Results*, and all functions are presented in Appendix C.

Ecological components were then spatially allocated by linking to mapped ecohydrological units. Floodplain vegetation communities were readily linked to ecohydrological units based on the dominant vegetation type. Waterbird and fish species were linked to ecohydrological units based on habitat preference information (Young et al. 2003, Overton et al. 2009) and expert opinion. As waterbirds and fish may use several habitats to varying degrees, they were assigned a probability of occurrence in each ecohydrological unit type (Appendix B). Probability scores were used to indicate how often each ecological component is likely to occur within each ecohydrological unit (i.e., never indicated with 0.0; occasionally, 0.25; often, 0.5; and always with 1.0). We used the same likelihood of occurrence scores for all life stages of each ecological component.

Economic costs

We quantified the costs of regulator construction for controlling flows in wetlands and watercourses. Hydrologically connected wetland ecohydrological unit polygons were grouped into 80 complexes that formed investment decision units, and complexes where flow could feasibly be regulated were identified. Each wetland/watercourse polygon was assessed using 2-m spatial resolution LiDAR elevation data, commence-to-fill data from RiM-FIM, and 0.3-m spatial resolution digital orthorectified aerial photography. Regulators (embankments with box culverts and flow control) were individually located and digitized using a Geographic Information System (GIS) in the neck of inlets, and the dimensions (width, depth) calculated to keep wetlands full at rim height. Based on these dimensions, regulator costs were calculated using an engineering cost model (Tonkin Consulting [Kent Town, Australia], *unpublished model*).

We also costed moving irrigation pump off-takes from backwaters to the main river channel to enable manipulation of water levels in backwaters without disrupting extraction for consumptive uses. Using the orthophotography, LiDAR data, and vegetation and wetland mapping, we identified pump locations from pump and meter data and manually digitized pipelines that took the shortest feasible route in connecting all pumps. For each pipeline, we calculated the pipe length, flow rate, and head of pressure required, and length of additional electricity infrastructure required. Based on these parameters, we calculated the costs of moving each off-take using another engineering cost model (Aquaterra [Adelaide, Australia], *unpublished model*). Ongoing operation and maintenance costs were not considered.

Social values

People value the iconic River Murray study area very highly. Social values include direct use (e.g., irrigated agriculture, fresh water, recreation) and indirect use (e.g., education) values, option value (e.g., future use), bequest value (e.g., leave in good condition for future generations), and intrinsic value (e.g., value in and of itself; Bryan et al. 2010). At a broad scale, we quantified the total economic value that people place on three major ecological assets in the River Murray, including waterbird breeding, native fish, and healthy vegetation. Values were derived from a major national survey (3148 survey responses; Hatton MacDonald et al. 2011). The survey also quantified the value of waterbird habitat in the Coorong (a Ramsar-listed estuary to the south of the study area), but these values were not included in this study. The survey asked respondents to consider a set of choices where they were offered the status quo health of the ecological assets, as well as two options which involved different levels of health of particular assets and different household costs (Table 3). The probabilities of different choices and willingness-to-pay for improvements in the condition of the ecological assets were estimated using a multinomial logit model (Hatton MacDonald et al. 2011). Median household willingness-to-pay each year for 10 years for marginal improvement in the three ecological assets were then mapped to ecological components and rescaled to values between 0 and 1 for incorporation into the integrated model.

At a fine scale, we mapped local ecosystem service values as part of larger interview process with 56 community representatives (Raymond et al. 2009, Bryan et al. 2010). The interview began with a guided, open-ended discussion of participant's personally held values for five natural capital assets (water, land, biota, atmosphere, people) and four types of ecosystem

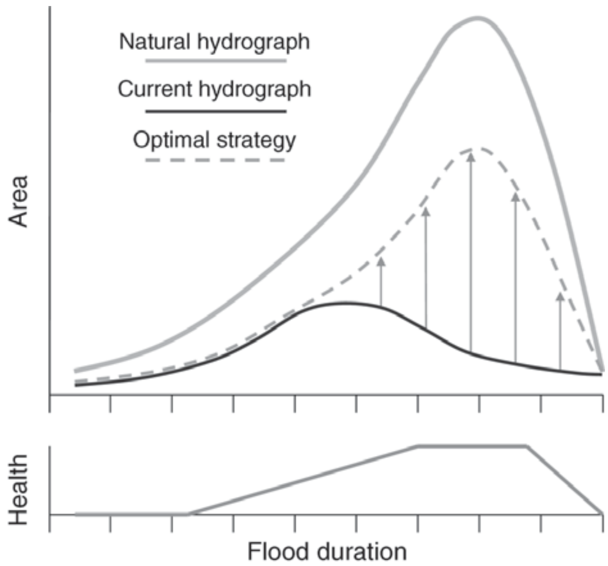

FIG. 2. Illustration of the objective of the model for flood duration for a hypothetical ecological component. The solid black line representing the area under different flood durations under the current hydrograph is moved proportionally (arrows) closer to the solid light-gray line, which is the area under different flood durations under the natural hydrograph. The area under higher flood durations is substantially increased because it is the most underrepresented relative to the natural distribution and because the ecological response function indicates that the health weighting is greatest under these flood durations.

services (provisioning, regulating, cultural, supporting) provided by the broader SA Murray-Darling Basin region. Participants were then asked to locate places to which they ascribed value or threat to natural capital and ecosystem services by arranging small plastic discs on a topographic map (Raymond et al. 2009). To create scarcity and value, participants were given a maximum of 40 green dots to assign positive value and 10 red dots to assign threat (negative value). Place-based values were digitized and overlaid within a GIS to capture spatial ecosystem service value intensities (Bryan et al. 2010). For input into the model, ecosystem service values for each ecohydrological unit polygon were spatially intersected, summed, and rescaled to values between 0 and 1 for comparability with the total economic value scores.

Integration

We built an optimization model to integrate the ecohydrological and socioeconomic information in a detailed spatiotemporal representation of the SA River Murray to identify cost-effective ways of managing environmental flows. The optimization model is a constrained, nonlinear, mixed-integer programming model. While the model operates on a monthly time step for computational tractability, it incorporates within-month flow variability (i.e., mean and peak flows) derived from the daily hydrographs. The model selects wetland complexes for investment (regulator construction and pump relocation) and identifies the optimal management of flow control infrastructure (upstream dam releases, operation of new and existing regulators and weirs) over time to return to more natural flow regimes. The model includes water balance and flow equations, and a key variable in the model is the volume of water in each ecohydrological unit polygon in each month. Inundation depends on the flow at the SA border, weir heights, the commence-to-fill flow rate of ecohydrological units, whether regulators are built and how they are operated, and water losses through evaporation and infiltration (Higgins et al. 2011).

In general terms, the objective of the model was to maximize ecological health, calculated as the areal proportion experiencing more natural flow regimes (flood timing, flood duration, inter-flood period) for ecological components (Fig. 2), especially in areas of higher social value. We used compromise programming to ensure that the representation of ecological components approaches that under the natural hydrograph without undesirable over- or underrepresentation of some components. The major constraints applied in the model ensured that the cost of infrastructure investment was within the total available budget ($60 million), and several specific rules governed weir operation and dam releases.

Mathematically, the objective function (Eq. 1) minimized a weighted sum of ecological health and social values:

$$\mathrm{Min}\, Z = w_{\mathrm{EH}}\mathrm{EH} + w_{\mathrm{SV}}\mathrm{SV} \tag{1}$$

where

$$\mathrm{EH} = \sum_k \left(\frac{H_k}{\mathrm{CH}_k}\right)^c \tag{2}$$

$$\mathrm{SV} = \sum_k \left(\frac{H_k}{\mathrm{CH}_k}\right)^c \times \mathrm{wtp}_k - \delta \times \sum_j S_j \times \mathrm{es}_j \tag{3}$$

and

$$\begin{aligned} H_k = {} & \sum_{\mathrm{mc}} \mathrm{MFT}_k^{\mathrm{mc}} \times \left(\frac{\mathrm{FT}_k^{\mathrm{mc}} - \mathrm{NFT}_k^{\mathrm{mc}}}{\mathrm{CFT}_k^{\mathrm{mc}} - \mathrm{NFT}_k^{\mathrm{mc}}}\right)^c \\ & + \sum_{\mathrm{mi}} \mathrm{MFD}_k^{\mathrm{mi}} \times \left(\frac{\mathrm{FD}_k^{\mathrm{mi}} - \mathrm{NFD}_k^{\mathrm{mi}}}{\mathrm{CFD}_k^{\mathrm{mi}} - \mathrm{NFD}_k^{\mathrm{mi}}}\right)^c \\ & + \sum_{\mathrm{mi}} \mathrm{MIP}_k^{\mathrm{mi}} \times \left(\frac{\mathrm{IP}_k^{\mathrm{mi}} - \mathrm{NIP}_k^{\mathrm{mi}}}{\mathrm{CIP}_k^{\mathrm{mi}} - \mathrm{NIP}_k^{\mathrm{mi}}}\right)^c \end{aligned} \tag{4}$$

where EH and SV represent the total ecological health and social value, respectively, and w_{EH} and w_{SV} are the weights on these values. Ecological health, EH, was calculated as the ratio of the model-calculated ecological health score H_k and current-hydrograph ecological health score, CH_k, for each ecological component k, raised to the power of c, and summed over k (Eq. 2). The

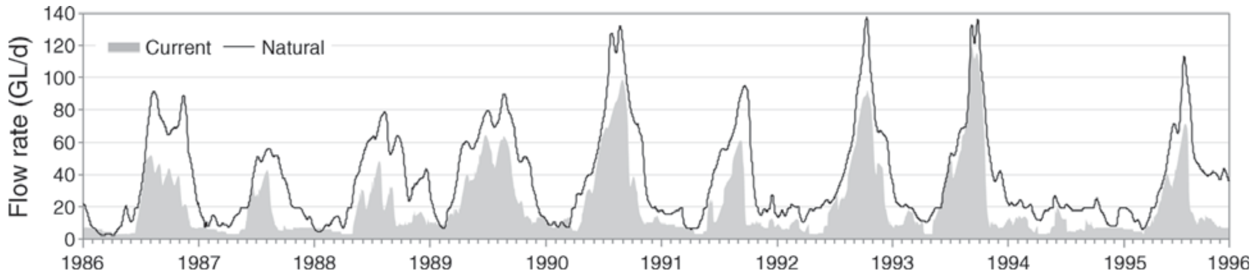

FIG. 3. Daily modeled natural and current daily hydrographs from 1986 to 1996 for the River Murray at the South Australian (SA) border (CSIRO 2008).

weight on the distance to the goal is represented by c (i.e., natural-hydrograph ecological health, NH_k). We used $c = 2$ throughout to create a least squares effect to target larger deviations from the goal over smaller ones. Note that smaller values represent better ecological health as the environmental flows become more natural over greater areas.

Social value (Eq. 3) is calculated as a function of total economic value and ecosystem services value. The total economic value component involves weighting the ecological health for each ecological component k by the willingness to pay score (wtp_k). This emphasizes the return of more natural environmental flows to more highly valued ecological components. The ecosystem services value component is applied for each polygon j (S_j) as a linear function of the number of months that the polygon is inundated, weighted by its ecosystem services value (es_j). This component aims to keep individual highly valued wetlands and floodplain areas inundated as long as possible. The rationale of this implementation aligns with the types of ecosystem services that were most highly valued (e.g., recreation such as water skiing and house boating, food provisioning through irrigation, fresh water supply, and aesthetics) that are dependent upon inundation (Bryan et al. 2010).

In calculating the ecological health score, H_k, of each ecological component k (Eq. 4), MFT_k^{mc} is the flood timing ecological health response ($0 \leq MFT_k^{mc} \leq 1$) when flooding occurs in calendar month (mc). MFD_k^{mi} is the flood duration ecological health response ($0 \leq MFD_k^{mi} \leq 1$) when inundation occurs for mi months. MIP_k^{mi} is the inter-flood period ecological health response ($0 \leq MIP_k^{mi} \leq 1$) when an inter-flood period occurs for mi months for ecological component k. CFT_k^{mc}, NFT_k^{mc} represent the total area becoming inundated in calendar month mc; represent the total area with a flood duration of mi months; and CIP_k^{mc}, NIP_k^{mc} represent the total area with an inter-flood period of mi months for ecological component k under the current and natural hydrographs, respectively. FT_k^{mi}, FD_k^{mi}, IP_k^{mi} are model variables representing the flood timing, flood duration, and inter-flood period. The model then adjusts flows using infrastructure and dam releases such that ecohydrological indicators are as close as possible to what they would be under the natural hydrograph, over greater area, for more ecological components. The current-hydrograph ecological health score, CH_k, is calculated by substituting FT_k^{mi} for CFT_k^{mi}, FD_k^{mi} for CFD_k^{mi}, and IP_k^{mi} for CIP_k^{mi} in Eq. 4.

The nonlinear mixed-integer programming problem contains over 25 000 decision variables, and interdependencies between these variables create extreme combinatorial complexity. For such a large combined investment and operational decision problem, finding a guaranteed optimal solution is currently impossible. We solved the problem using the Tabu search heuristic strategy, which has been found to produce good solutions within a reasonable time (Higgins et al. 2011).

We conducted a series of Monte Carlo simulations to assess the weighting of ecological health vs. social values for the 120-month period from 1986 to 1996. These simulations we also designed to illustrate the uncertainty in model performance. A maximum processing time of 2 h was used for each run to achieve sufficient convergence. In these simulations, we set wtp_k to 0 since the total economic value component of the social value objective (Eq. 3) is strongly correlated with EH. We performed 350 Monte Carlo simulations using random weight combinations for w_{EH} and w_{SV} such that $w_{EH} + w_{SV} = 1$. In addition, to help understand the performance of the model at the extremes, we conducted 20 simulations at the weight combination maximizing ecological health (i.e., $w_{EH} = 1.0$, $w_{SV} = 0.0$) and 20 simulations at the weight combination maximizing social values (i.e., $w_{EH} = 0.0$, $w_{SV} = 1.0$). These 40 Monte Carlo simulations undertaken at extreme weightings were used to identify the maximum possible ecological health and social value scores achievable through environmental flow management.

The ability of the model to identify operational environmental flow management regimes that achieve both ecological health and social value objectives was assessed graphically, creating a Pareto frontier. Weightings from efficient flow scenarios on the Pareto frontier were selected: One prioritizing ecological health (called *ecological efficient*) and one prioritizing social values (called *social efficient*). Operational environmental flow management regimes for these two scenarios were visualized and compared.

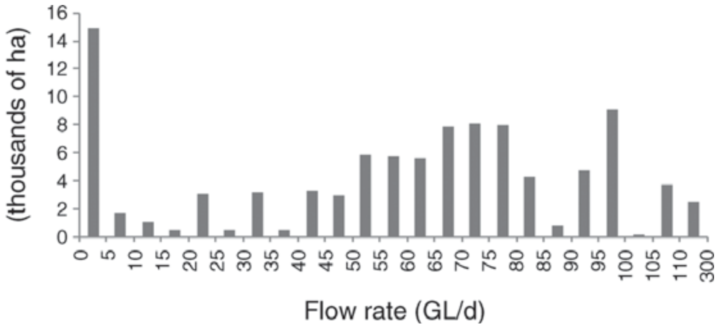

FIG. 4. Area under different commence-to-fill flow rates at the South Australian (SA) border in the study area with weir heights at 0 cm.

RESULTS

We present illustrative results for the ecohydrological and socioeconomic information and its integration. Modeled hydrographs (CSIRO 2008) of daily flows at the SA border show a substantial alteration of natural flows under the current regime (Fig. 3). Based on these hydrographs, median flows at the SA border have been reduced from 11 375 GL/yr (25.7 GL/d) under natural conditions to 5107 GL/yr (9.1 GL/d) under current development. Flood duration of small to medium-sized floods (below 40 GL/d) has been substantially reduced, and the inter-flood period of larger floods (above 70 GL/day) has been greatly extended.

The commence-to-fill flow rates as calculated by the RiM-FIM inundation model ranged from <5 GL/d to 109 GL/d (the upper flow limit of RiM-FIM) with an area-weighted average of 63 GL/d (Fig. 4). Commence-to-fill flow rates displayed a complex spatial distribution across the floodplain (Fig. 5).

A total of 18 ecohydrological units were defined in the study area, and 11 171 individual ecohydrological unit polygons were mapped (Fig. 6). Floodplain units dominated the study area (69 637 ha, 71.5%) with riparian and high-floodplain units covering 18 664 ha and 17 625 ha, respectively. Watercourse units covered 11 117 ha (11.4%) and wetlands 16 675 ha (17.1%). The distribution of ecohydrological units also displayed complex spatial patterns.

Distinct relationships were found between commence-to-fill flow rates and ecohydrological units (Fig. 7). For example, the riparian floodplain unit occurs across the range of flow rates with most area occurring between 60–109 GL/d. Most high floodplain units occur at flow

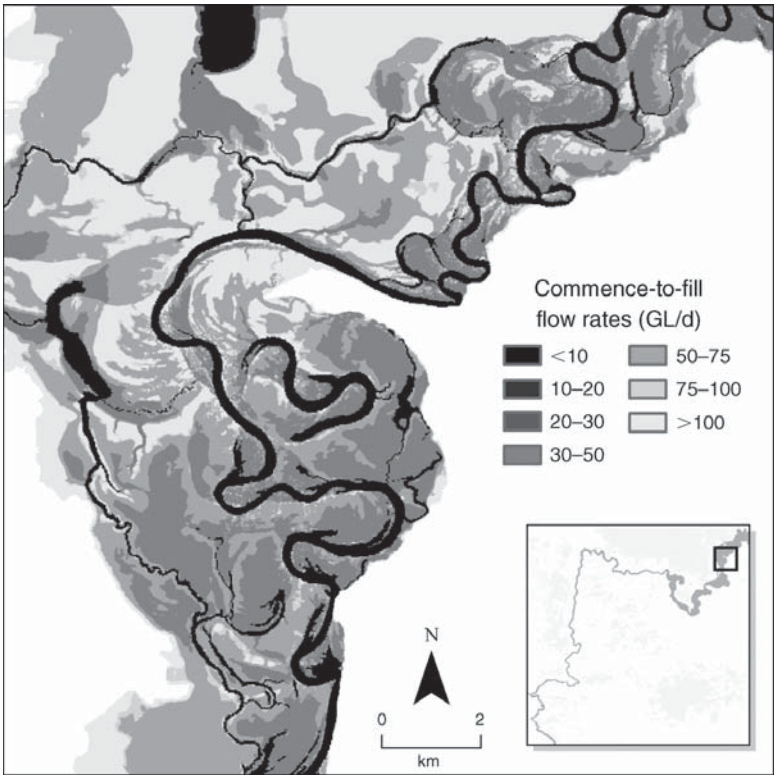

FIG. 5. Spatial distribution of commence-to-fill flow rates for the Ral Ral/Woolenook/Murtho (SA) area with weir heights at 0 cm.

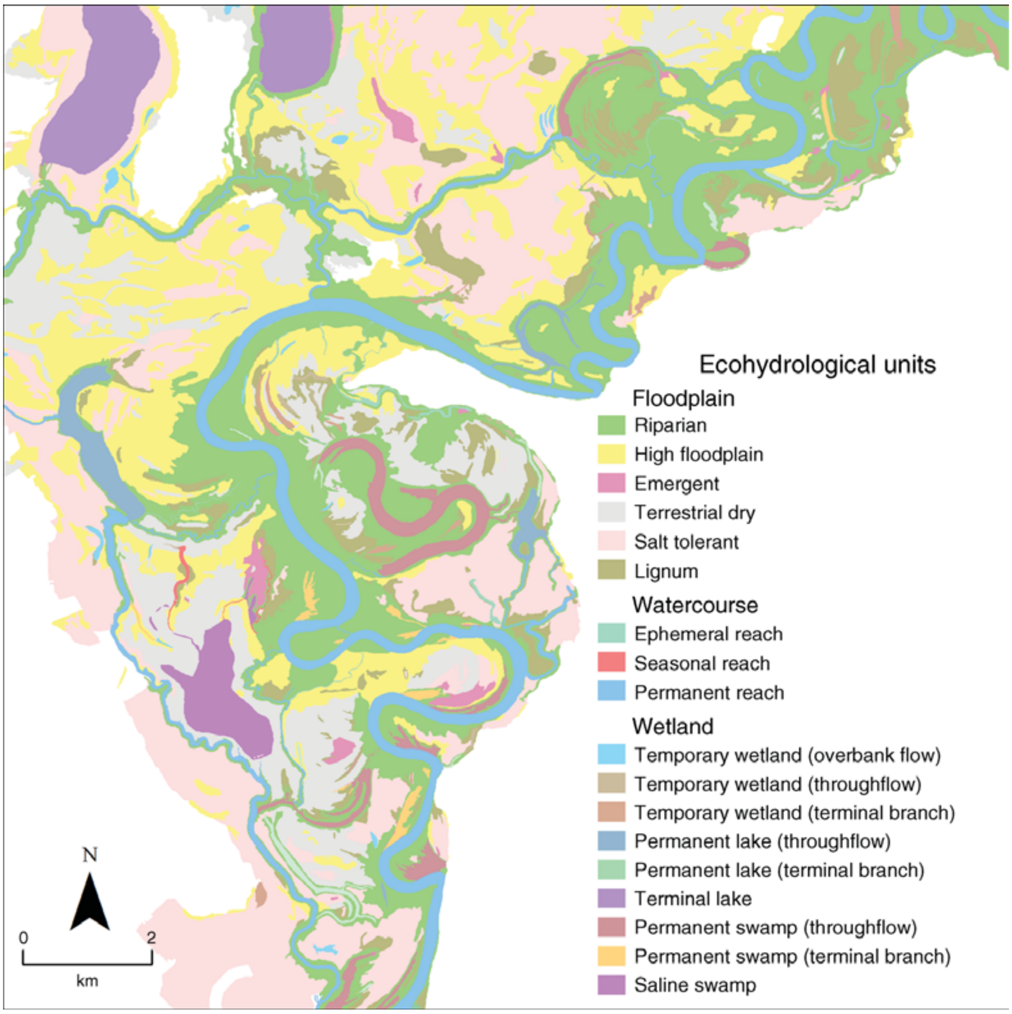

FIG. 6. An example of the spatial complexity of ecohydrological units occurring in the Ral Ral/Woolenook/Murtho area.

rates above 75 GL/d; lignum occurs between 55 and 75 GL/d. Permanent watercourse and wetland units have low commence-to-fill flow rates, whereas temporary watercourse and wetland units occur throughout the range of commence-to-fill flow rates.

A total of 59 ecological response curves were specified for various life stages of the 16 ecological components for relevant aspects of environmental flows (flood duration, flood timing, inter-flood period; Fig. 8; Appendix C).

Eighty wetland complexes were identified as suitable for investment in flow control infrastructure influencing 172 individual wetland/watercourse polygons with a total area of 5536 hectares (Fig. 9). The total cost for all possible infrastructure options was over \$117 million with 153 regulators costing \$52 million and 64 km of new pipe and 36 new pumps costing \$65 million. Infrastructure costs for individual wetland complexes ranged from \$171 600 to \$9 895 696, with a median of \$595 100.

Household willingness-to-pay varied with the marginal improvement in the condition of ecological assets. Aside from waterbird habitat in the Coorong estuary to the south of the study area, waterbird breeding was most highly valued (\$12.00–\$18.64, rescaled score $wtp_k = 1.0$), followed by healthy vegetation (\$2.87–\$4.42, rescaled score $wtp_k = 0.24$) and native fish populations (\$1.71–\$3.58, rescaled score $wtp_k = 0.17$).

Within the study area, people valued water-related ecosystem services most highly, particularly cultural services (e.g., recreation and tourism, bequest and intrinsic), provisioning services (e.g., fresh water, food/fiber), and regulating services (e.g., water quantity and quality). People also valued the built capital (weirs, infrastructure, and so on) and economic and employment opportunities the study area provided. The areas of highest value intensity scores (Fig. 10) were attributed to the River Murray and its wetlands and floodplain areas (especially Chowilla near Lock 6).

The Monte Carlo simulations formed a Pareto frontier representing the efficient trade-offs between ecological health and social value (Fig. 11). With regard to the sensitivity of the integrated model, the narrow band that forms the Pareto frontier illustrates that

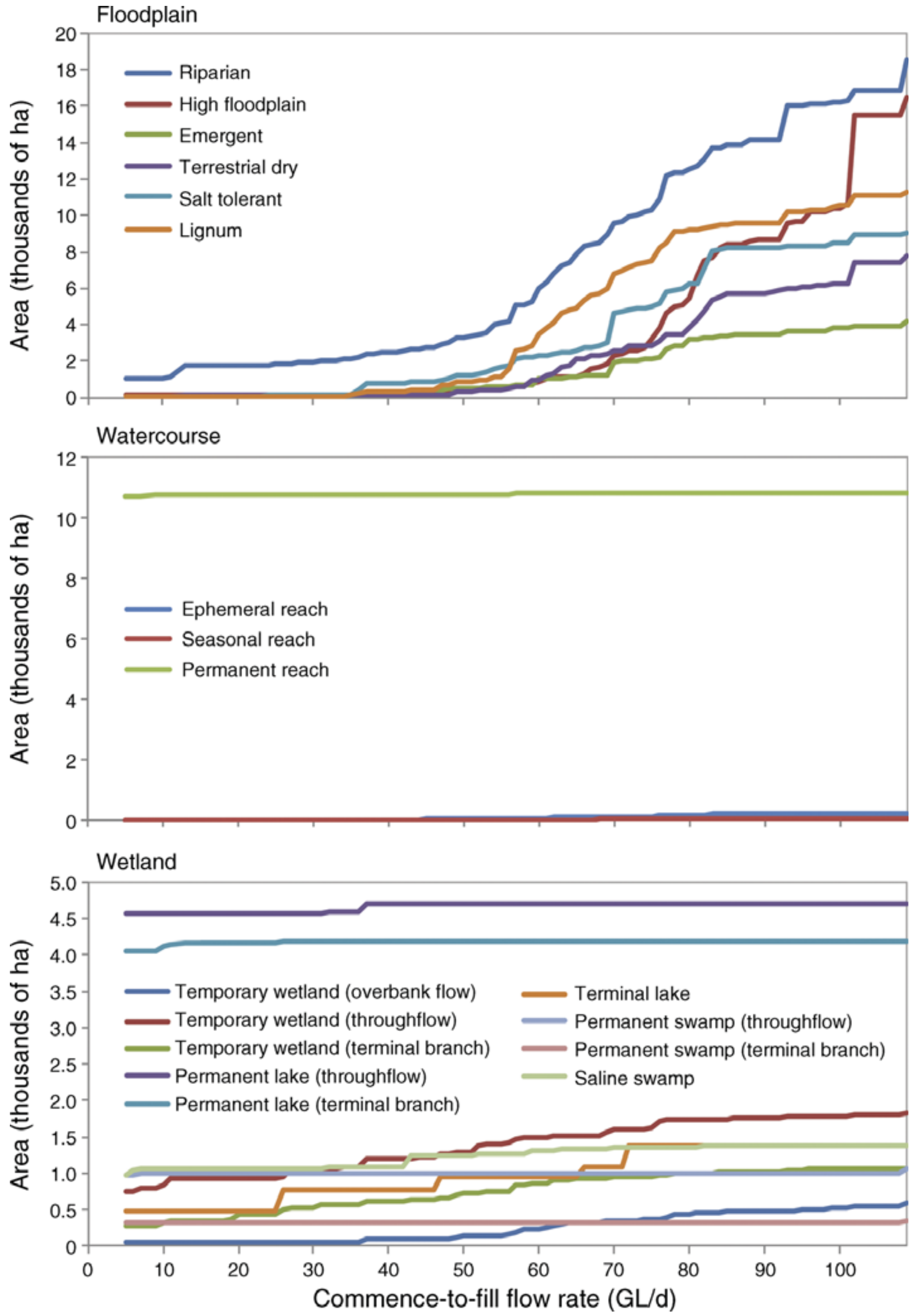

FIG. 7. Commence-to-fill flow rates (up to the 109 GL/d River Murray Floodplain Inundation Model [RiM-FIM] limit) of floodplain, watercourse, and wetland ecohydrological units under the natural flow regime at the SA border.

stochastic variation in the Tabu search strategy results is <10% variation in the model performance. With regard to the performance of the integrated model, substantial efficiencies were demonstrated. Under the *ecological efficient* scenario, the model was able to achieve 60% of the maximum social value for a reduction of only 10% in the maximum ecological value. Under the *social efficient* scenario, the model was able to achieve 70% of the maximum ecological value for a reduction of only 10% in the maximum social value (Fig. 11). Operational flow management regimes required to achieve these two scenarios are presented.

The integrated model of environmental flow management identified the optimal set of wetland complexes for investment in flow control infrastructure under the $60 million budget. A total of 45 wetland complexes were selected for investment in the *ecological efficient* scenario with costs averaging $1.330 million. In the *social efficient* scenario, 48 complexes were selected for investment with costs averaging $1.261 million. A total of 31 wetland

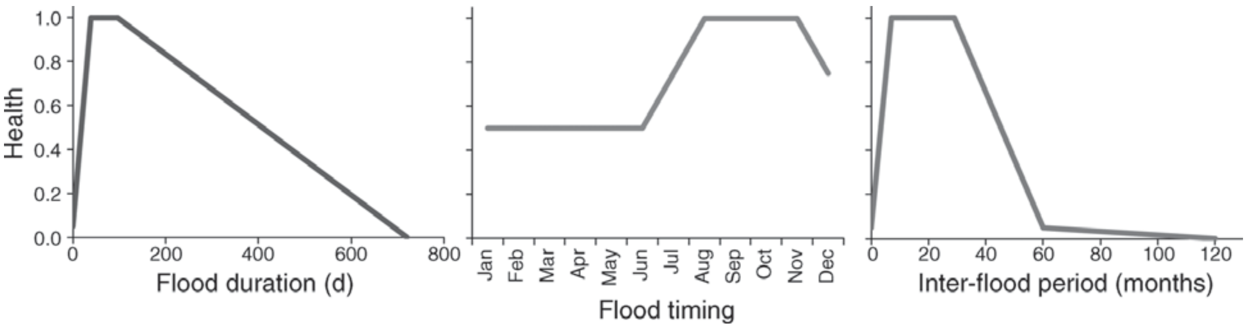

FIG. 8. Example of ecological response functions for the health of adult floodplain river red gums (*Eucalyptus camaldulensis*) to flood duration, flood timing, and inter-flood period.

complexes ($39.089 million) were selected for investment in both scenarios.

Upstream dam releases in the period from 1986 to 1996 were similar for both scenarios. Dam releases both increased the high flow peaks to increase the spatial area of flooding, and increased breadth to prolong flood duration (Fig. 12). The major difference was that, in periods of low flows, flows were held back in the *ecological efficient* scenario to return ecologically important drying cycles, while in the *social efficient* scenario low flows were boosted by dam releases to maintain water in areas of high social value.

Weir operation varied substantially between scenarios (Fig. 13). Most weirs remained at a height of 0 cm most of the time. Heights of the six weirs were changed, on average, 13.17 times (average magnitude 20.25 cm), and 8.50 times (average magnitude 21.86 cm) in the *ecological efficient* and *social efficient* scenarios, respectively.

Regulator operation also varied widely between scenarios. Including the 43 wetland complexes with existing flow control structures, all complexes were open most of the time. The mean number of months closed over the 120-month time series was 41.04 for the *ecological efficient* scenario and 35.30 for the *social efficient* scenario. Some complexes were closed very infrequently with a minimum number of closures in both scenarios of seven months, while others were actively

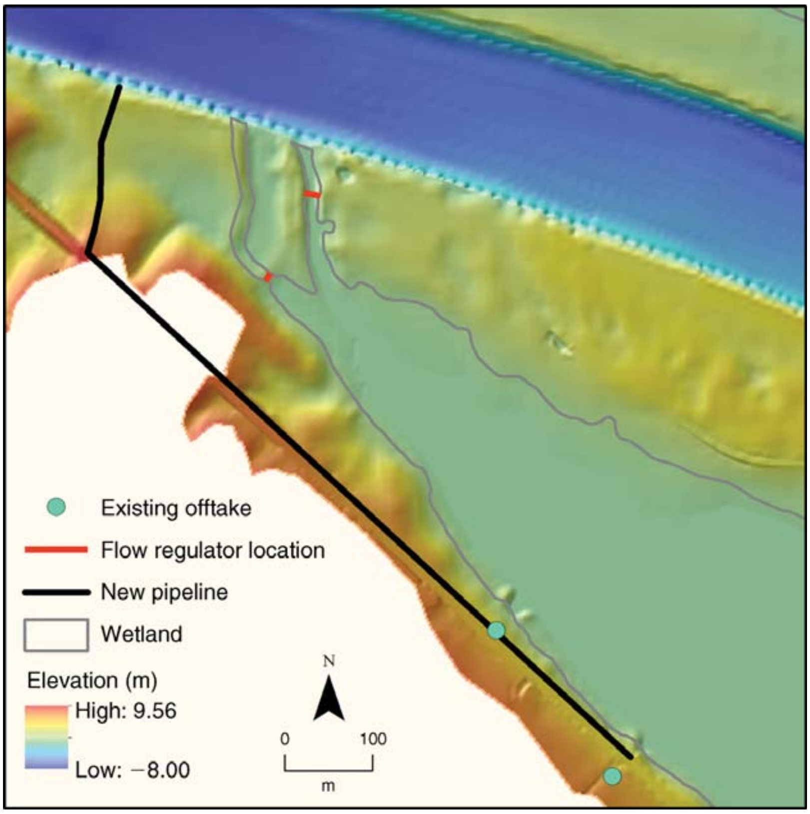

FIG. 9. Example of the siting of regulators for controlling flows and piping for relocating irrigation off-takes in the Lake Bywaters/Walker Flat area. Elevation data is from LiDAR.

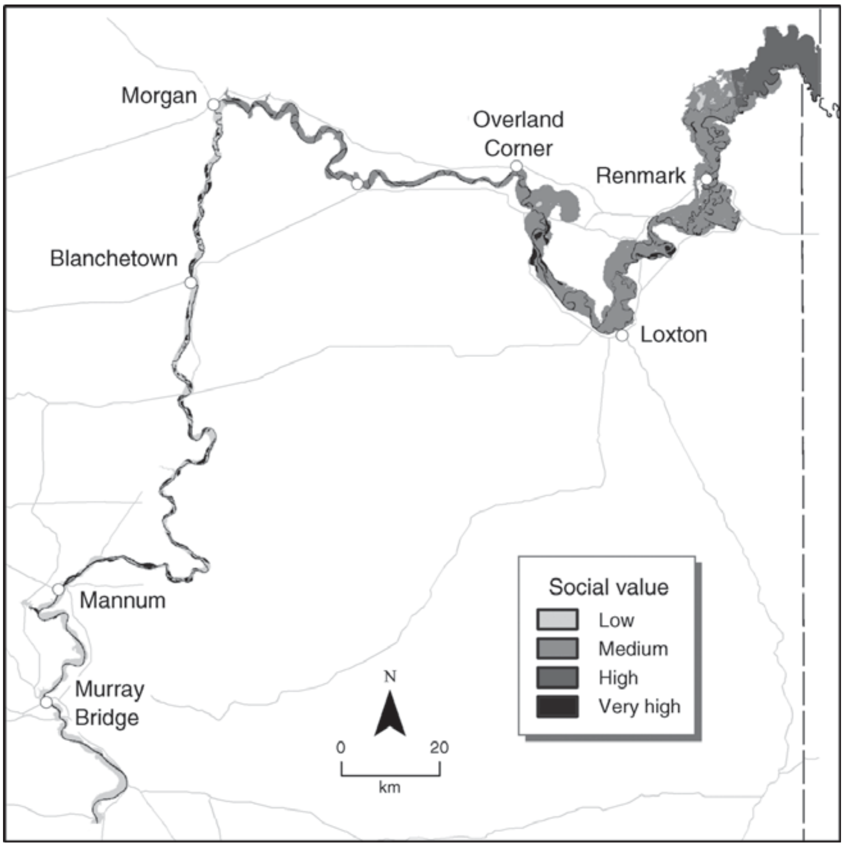

FIG. 10. Spatial distribution of ecosystem service values occurring in the study area (Raymond et al. 2009, Bryan et al. 2010).

managed, being closed for a maximum of 70 months (Fig. 14).

DISCUSSION

This study aimed to help inform decision-makers on the most cost-effective flow control infrastructure investments and to specify the optimal operation of dam releases, weirs, and regulators over time. The goal was to consider both ecological health and socioeconomic values in returning to more natural environmental flows. We have presented a transdisciplinary approach in assembling the high-quality and high-resolution information on ecohydrological processes and socioeconomic values across space and time required to inform cost-effective infrastructure investment and operational environmental flow management decisions. We used mixed methods to develop, apply, and link a variety of models and data to create the suite of information to support integrated modeling for environmental flow management. While we present an illustrative application here, the full optimization model and its innovative solution strategies have been published in detail elsewhere (Higgins et al. 2011).

High spatial and temporal resolution information provided the level of accuracy and precision required for supporting operational environmental flow management in this study. The high spatial resolution of the information assembled in this study enables selection of individual wetland complexes for investment and specifies suitable sites for flow control infrastructure with a level of spatial precision in the order of meters. For a regional analysis, the spatial resolution of underpinning data such as the LiDAR digital elevation model and the orthorectified aerial photography also enabled a high level of precision in economic cost estimation of regulators, pipes, and other pump relocation infrastructure. The high-resolution mapping of river ecosystems as ecohydrological units, commence-to-fill flow rates, and social values enabled a detailed calculation of the ecological health and social values derived from environmental flows. The 59 ecological response functions provided detail and depth in characterizing how the 16 ecological components respond to changes in environmental flows as represented by flood duration, flood timing, and inter-flood period at different life stages. When benefits were combined with costs, the cost effectiveness of investing in and managing individual wetlands, watercourse reaches, and floodplain communities could be evaluated. While the total economic value estimates were specified at a coarse resolution (four major ecological assets), they had a focus on quality and rigor in quantifying willingness to pay based on thousands of respondents. This was complemented by the ecosystem service value mapping, which, although the participants were fewer, the spatial resolution of values mapping was higher.

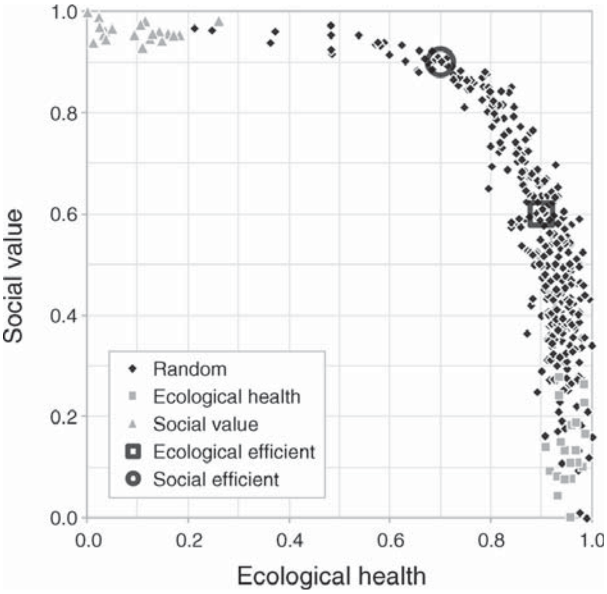

FIG. 11. Performance of the integrated model under Monte Carlo simulation of 350 model runs with random weights for ecological health and social value, plus 20 runs with full weighting on ecological health, and 20 runs with the full weighting on social value. The relative ecological health and socioeconomic value score achieved through optimal operational management of environmental flows is plotted for each model run. The performance of the illustrative *ecological efficient* and *social efficient* scenarios are also plotted.

High spatial and temporal resolution information increases the accuracy and precision of the estimation of economic costs, ecological health, and broader social values.

Compatible and consistent data makes integration and analysis of complex environmental allocation and scheduling problems possible (de Kok et al. 2009). In this study, the modeled natural and current hydrographs provided the information on temporal dynamics of the river system. The commence-to-fill layer enabled the translation of temporal flow rate information into spatiotemporal estimates of inundation. The linking of the ecohydrological unit mapping with ecological response functions enabled the mapping of natural flow regimes in the form of ecological response to environmental flows. The geographic overlay of spatiotemporal estimates of inundation with mapped ecological responses to environmental flows enabled the full integration of hydrological and ecological processes over space and time. Economic costs linked to specific wetlands, and social values linked to specific ecological components and geographic areas, completed the integration of ecohydrological and socioeconomic information at compatible spatial and temporal scales. This fully integrated system representation formed the basis for optimizing environmental flow investment and operational management.

Several previous studies have assembled information on ecohydrological and socioeconomic information for environmental flow management (Hillman and Brierley 2002). However, some aspect of the quality or resolution of the underpinning data has typically been either conceptual, abstract, stylized, or oversimplified, which potentially limits its use for guiding operational environmental flow management. Much of the information assembled herein is of a quality publishable (or already published) as individual studies in their own right. Created and applied in developing countries (Africa and Asia) over the past 15 years, the only other integrated assessment of environmental flows with an information base of comparable quality and resolution is DRIFT (King et al. 2003, King and Brown 2010). While DRIFT takes a different approach to integration (flow scenario assessment rather than optimizing infrastructure investment and flow management), the spatiotemporal information and linkages in DRIFT are similar to this study. Together, the DRIFT approach and our study illustrate the universality of these information needs for integrated environmental flow management (Hillman and Brierley 2002).

While the methods used for developing and integrating information in this study represent a significant advance, several limitations, challenges, and potential enhancements are noteworthy. There are many ways to calculate social values for the environment (Seppelt et al. 2011). Despite the use of innovative methods, there remain weaknesses and significant uncertainties in our estimates (Raymond et al. 2009, Hatton MacDonald et al. 2011). Regarding integration, we illustrated one way of combining a range of ecohydrological and socioeconomic information. Different integration techniques

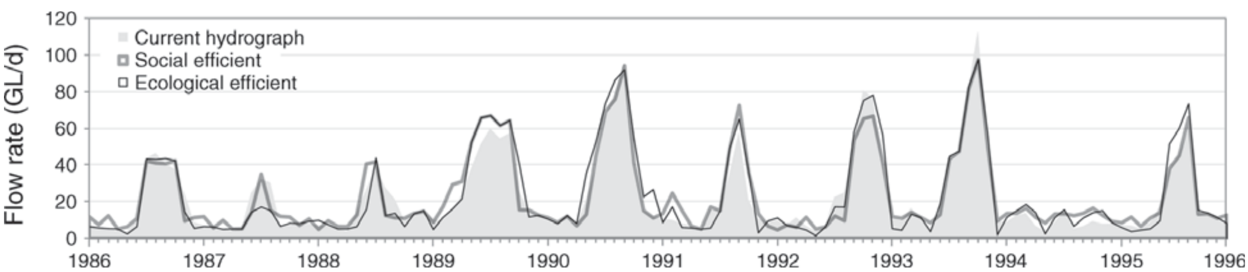

FIG. 12. Optimal monthly dam releases under the *ecological efficient* and *social efficient* scenarios compared to the current hydrograph for the period 1986–1996.

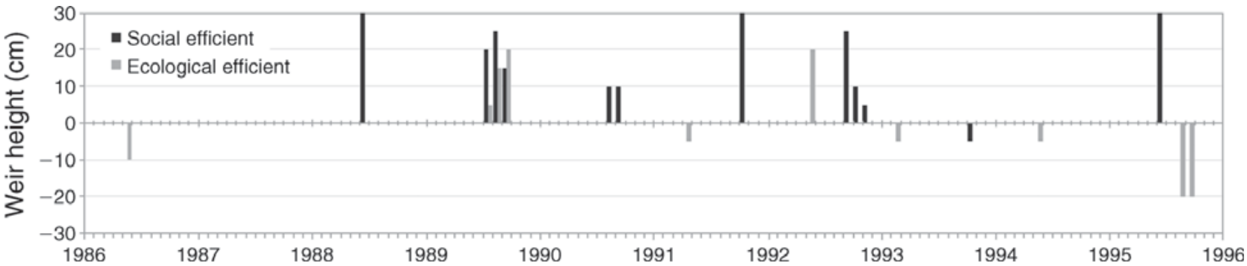

FIG. 13. Optimal monthly weir heights for Lock 6 under the *ecological efficient* and *social efficient* scenarios for the period 1986–1996.

may change the results. A major limitation of our study is the monthly time step used to make the integrated optimization model computationally tractable. Although we incorporated both mean and peak monthly flows derived from a daily hydrograph in the model to capture extrema (see Higgins et al. 2011 for details), important short-timescale hydrographic flow variations can still be generalized. This can have implications such as underestimating the spatial extent of inundation and drying, and failing to capture ecosystem responses related to daily flow dynamics such as rates of change. Management actions such as dam releases would also be better specified on a shorter time step. Potential enhancements to the model include improving the ecological response functions, extending the flow metrics, and considering a broader set of management actions for manipulating environmental flows. A limitation to the generalizability of the techniques used is the availability of key baseline data such as vegetation mapping in developing countries (King and Brown 2006, Hughes and Mallory 2009). One final challenge is the assembly, management, and effective functioning of multidisciplinary teams. Environmental flow management demands that hydrologists, ecologists, social scientists, economists, geographers, mathematicians, and computer modelers communicate complex concepts and information effectively. It also demands a high level of participation of stakeholders and local communities (de Kok et al. 2009).

The outputs of the integrated model are presented here to illustrate the operational-level environmental flow management regimes made possible by the development and application of high-quality and high-resolution ecohydrological and socioeconomic information. While these outputs deserve a much more extensive exploration than can be afforded here, the results demonstrate that by considering both ecological health and social values, substantial enhancements in social value can be achieved with only a minimal trade-off for ecological health, and vice versa. Exploration of this trade-off relationship can enable decision-makers to choose investment and management regimes with known and acceptable social and ecological trade-offs. Both the investments and the operational management specifications were different between the *ecological efficient* and *social efficient* scenarios. For example, more than one-third ($20.911 million) of the budget would be spent on installing regulators in different wetland complexes under the two scenarios. Adjustment of weir heights, regulator operation, and to a lesser extent, dam releases, for managing environmental flows were also very different. This suggests that, while some decisions were more robust (e.g., two-thirds of the investments were common to both scenarios, dam releases were relatively similar), the weighting of ecological health vs. social values significantly affected which investments were made and how flows are managed. The integrated modeling presented here provides a means for making informed choices of weightings on ecological health vs. social values in the management of environmental flows.

Results from our integrated model have been used to support the development of a business case for the investment of around $60 million in environmental flow management prepared by the South Australian government for Commonwealth funding. In informing the business case, model outputs were used to iteratively support dialogue with state government decision-makers around infrastructure investment and flow management decisions. The preferred approach was to weight ecological health more heavily than social value ($w_{EH} = 0.8$, $w_{SV} = 0.2$) based on the rationale of increasing social value, but without compromising ecological health. In an initial screening phase, we presented a list of potential investments, their costs, benefits, and the number of times they were selected in a number of Monte Carlo runs at the selected weight combination. Some wetlands were ruled out due to various sociopolitical (e.g., they were to be funded through another funding scheme) or other unmodeled factors. Subsequently, model results were used as confirmatory where they agreed with expert opinion, and generated discussion and further exploration where they contradicted expert opinion.

CONCLUSION

Increasing the ecological health of, and social values from, highly regulated rivers such as the South Australian River Murray requires the return of more natural flow regimes through investment in and management of flow control infrastructure. Operational decisions such as where to invest in flow control

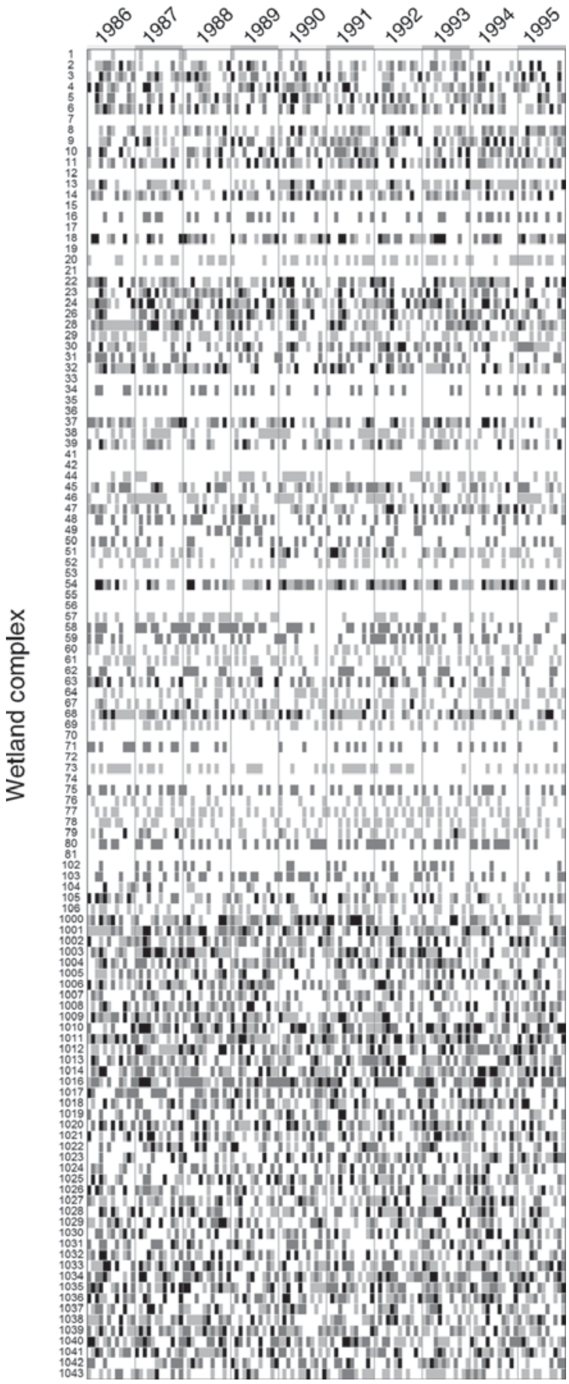

FIG. 14. Optimal monthly regulator operation under the *ecological efficient* and *social efficient* scenarios for the period 1986–1996. White shading indicates that regulators are open in both scenarios, light gray indicates regulators open in the *ecological efficient* scenario and closed in the *social efficient* scenario, dark gray indicates regulators closed in the *ecological efficient* scenario and open in the *social efficient* scenario, and black indicates regulators closed in both scenarios.

infrastructure and how best to operate it over time demands high-quality, high-resolution spatiotemporal information. We took a transdisciplinary approach and used mixed methods in developing and applying this information for supporting integrated environmental flow management. We integrated this information to support the cost-effective investment of $60 million in flow control infrastructure and environmental flow management decisions over the next few years to address the dual goals of ecological health and socioeconomic values. Through combining high-quality and high-resolution ecohydrological and socioeconomic information, cost-effective investments in environmental flow management and operational-level flow management regimes can be identified that efficiently achieve both ecological and social objectives. Both the investments and management regimes differed substantially between the two scenarios. While some decisions were more robust, the weighting of ecological health vs. social values significantly affected which investments were made and how flows were managed. High-quality and high-resolution information can increase the accuracy and precision of investment and management prescriptions. Consistent and compatible information can enable integration and reduce model bias. This leads to better operational environmental flow management and investment decisions. The integration of ecohydrological and socioeconomic information in a decision analysis model is essential for identifying cost-effective solutions for managing river ecosystems so they can continue producing many of the services and functions that society and the environment rely upon.

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Supplemental Material

Appendix A

Source of ecological response curves (*Ecological Archives* A023-052-A1).

Appendix B

Mapping of ecological components to ecohydrological units (*Ecological Archives* A023-052-A2).

Appendix C

Ecological response functions (*Ecological Archives* A023-052-A3).