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Sustainable water management under future uncertainty with eco-engineering decision scaling

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Managing freshwater resources sustainably under future climatic and hydrological uncertainty poses novel challenges. Rehabilitation of ageing infrastructure and construction of new dams are widely viewed as solutions to diminish climate risk, but attaining the broad goal of freshwater sustainability will require expansion of the prevailing water resources management paradigm beyond narrow economic criteria to include socially valued ecosystem functions and services. We introduce a new decision framework, eco-engineering decision scaling (EEDS), that explicitly and quantitatively explores trade-offs in stakeholder-defined engineering and ecological performance metrics across a range of possible management actions under unknown future hydrological and climate states. We illustrate its potential application through a hypothetical case study of the Iowa River, USA. EEDS holds promise as a powerful framework for operationalizing freshwater sustainability under future hydrological uncertainty by fostering collaboration across historically conflicting perspectives of water resource engineering and river conservation ecology to design and operate water infrastructure for social and environmental benefits.

Securing the supply and equitable allocation of fresh water to support human well-being while sustaining healthy, functioning ecosystems is one of the grand environmental challenges of the twenty-first century, particularly in light of accelerating stressors from climate change, population growth and economic development. Rehabilitation of ageing infrastructure and construction of new infrastructure are now widely viewed as engineering solutions to mitigate future climatic uncertainty in the hydrologic cycle[1]. Indeed, the construction of tens of thousands of dams in the twentieth century helped secure water supplies and fuel economic development in industrialized countries, and developing economies are now pursuing massive new infrastructure projects with thousands of new dams proposed for hydropower production and water supply security[2].

Despite the economic stimulus provided by many dams historically, the global experience with dam building warns that traditional approaches to water infrastructure development in a rapidly changing world carry severe risks of economic and environmental failure. First, large water projects are very capital-intensive and long-lived, costing billions of dollars to plan, build and maintain. Yet, they are vulnerable to biased economic analyses[3], cost overruns and construction delays, and changing environmental, economic and social conditions that can diminish projected benefits[4,5]. Under a variable and changing climate, large water infrastructure may even risk becoming stranded assets[6]. Second, the principles of economic efficiency inherent in cost-benefit analysis dominate project design and performance assessment, making integration of social and environmental benefits and costs into a comprehensive economic evaluation a significant challenge[7,8]. These costs can be substantial, as evidenced by human displacement[5,9], local species extinctions[10] and the loss of ecosystem services such as floodplain fisheries and other amenities[11,12].

As unanticipated economic, social and environmental costs accumulate with ageing water infrastructure, society is investing in restoration projects to partially undo longstanding environmental degradation, including modifying flow releases from dams[13,14] and, in some cases, dam removal[15]. As global-scale impairment of aquatic ecosystem function becomes increasingly documented and articulated[16,17], there is urgent need for a broader conception of sustainable water resource management that formulates environmental health as a necessary ingredient for water security and the social well-being it supports[18–20]. Notably, new national directives are emerging to develop and manage river ecosystems in more environmentally sustainable ways that retain social benefits, including in the USA[21], Europe[22,23] and Australia[24].

Towards a sustainable water management paradigm

Here, we ask if a more sustainable water management philosophy can be forged to guide investment in, and design of, water infrastructure while avoiding adverse (and sometimes irreversible) social and environmental consequences. We consider 'sustainable water management systems' to be those that meet the needs of society over the lifetime of the infrastructure while also maintaining key ecological functions that support the long-term provision of ecosystem goods, services and values, including biodiversity maintenance. These systems would embrace the principle of resilience, that

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is, the capacity to persist with functional integrity under changing social and environmental conditions[25]. Indications of this emerging perspective are reflected in calls for greater focus on demand-side management, rather than supply-side solutions[26], as well as 'green' infrastructure approaches, such as 'soft-path' solutions[27] and managed natural systems[28]. Deep uncertainty about future climate raises significant concerns about how to achieve long-term economic benefits and performance reliability of major water projects[29,30]. This unprecedented uncertainty renders traditional approaches to the design of long-lived infrastructure inadequate, requiring new decision-making approaches[31]. In the context of a changing (non-stationary) hydrologic cycle, incorporation of alternative design and management principles can be viewed as reducing risk in infrastructure investment by enhancing 'robustness' (satisfactory performance under a wide range of uncertain futures) and 'adaptive capacity' (the ability to be modified rapidly and economically in response to changing, unforeseen conditions)[32,33].

Planning for resilient, robust and adaptive water infrastructure to achieve social, economic and environmental objectives under a highly uncertain future presents novel challenges. First, contrasting paradigms in water resource engineering and in conservation ecology have dominated the broader societal debate about infrastructure design and operation over the past several decades[34,35], and these perspectives have typically been antagonistic. However, the fields of water resource engineering and conservation ecology are now independently re-examining long-held, foundational assumptions, in no small part because of concerns about climate change and other forms of non-stationarity (Box 1). These philosophical shifts are subsequently creating the possibility of revisiting ingrained presumptions about barriers to collaboratively attaining more sustainable water resource management. Second, methods for integrating ecological principles into water infrastructure design and operation to satisfy multiple objectives have been proposed[8] but are not well established in practice[36,37]. The key question emerges of how to operationalize sustainable water management to couple engineering design principles with ecosystem requirements in the context of non-stationary stressors (for example, changes in climate, water use, population growth and land-use change).

A new analytical framework to climate adaptation planning has emerged that aims to facilitate the sustainability dialogue between water resource engineers and conservation ecologists. This approach, called decision scaling[38,39], was developed as an alternative to prevailing top-down climate risk assessment methods in the water resources community that rely on projecting climate conditions several decades into the future to assess risk, primarily through the use of global circulation models (GCMs). GCM projections, however, have large, irreducible uncertainties[40] and poor capability of representing climatic variability (for example, storm intensity-duration-frequencies) that water resource engineers require to design water infrastructure[41,42]. Thus, GCMs are often of limited use to water resource planners and decision makers attempting to understand and mitigate climate risks in the immediate to mid-term management future[43,44].

Decision scaling, by contrast, is a bottom-up risk assessment approach that engages decision makers by starting with stakeholder-determined metrics that define acceptable system performance. System vulnerability is then assessed by evaluating the sensitivity of metrics (for example, ability to meet a water delivery target) to a variety of non-stationary threats, such as climate change, demographic change and economic trends that occur over management-relevant timescales. The decision scaling approach has been applied to evaluate climate risks to water management systems focused on engineering performance indicators, such as water supply reliability[38], flood risk estimation[45] and cost-benefit analysis[46], as well as climate-sensitive hydrologic indicators[47].

As in the water resources arena, ecosystem management is increasingly focused on reducing the vulnerability of sensitive species, ecological processes and natural resource production to a variety of non-stationary stressors through risk analysis[48] and stakeholder-driven processes[49]. For example, in regulated rivers, environmental flows to sustain desired ecological processes or conditions downstream of dams are often defined through vulnerability assessments involving scientists, government agencies and water users[50]. Similarly, 'smart licenses' are being devised to protect the stakeholder-defined needs of both the environment and water users under anticipated climate variability and change[51]. More broadly, formal decision frameworks, such as structured decision making[52], are being adopted by natural resource agencies to identify critical ecological thresholds and guide adaptive management to achieve sustainable outcomes. Thus, decision scaling is consistent, in terms of process and scope, with bottom-up approaches that ecosystem managers are familiar with and often rely on for decision making.

Eco-engineering decision scaling

Expansion of the existing decision scaling framework to consider both engineering and ecological performance affords a powerful

Box 1 | Shifting paradigms in water resource engineering and conservation ecology.

Rapid climate change, population growth and economic trends are generating unprecedented uncertainty about how to achieve sustainability targets for water management and ecosystem conservation, as well as simultaneous opportunities to find common ground. First, traditional water resource engineering is struggling with climate non-stationarity (unknowable uncertainty about future hydrologic conditions) and seeking new approaches to guide infrastructure planning and avenues for secure economic investment under a wide range of climate scenarios[77]. Second, climate variability and change plus the pervasive effects of human activities on ecosystems are broadly challenging conservation and restoration ecology, which have traditionally defined ecosystem management targets by reference to historical ('natural') conditions and focused on habitat reserve strategies[78]. Emerging perspectives in aquatic ecology now place biological conservation in the context of highly altered and non-stationary hydrosystems that require active management within human-dominated landscapes to sustain critical ecosystem functions[79–81]. These perspectives align with a broader conservation approach of "managing for resilience"[82], which focuses on maintaining key processes and relationships in social-ecological systems so that they are robust against a wide range and variety of perturbation from climate or other stressors. This paradigm represents a departure from traditional conservation biology in that it emphasizes the endurance of system-wide properties (rather than a sole focus on individual species) and promotes reconciliation of conservation objectives with the alteration of natural systems by human influences[81,83]. Together, emerging paradigms in ecology and engineering are giving rise to potential new levels of cooperation and communication across these (traditionally conflicting) disciplines. For example, ecologists are now developing socially contextualized conservation tools to inform water infrastructure management ('environmental flows'[50,84,85]) and water resource engineers are actively exploring how to incorporate these into infrastructure operations[86,87] with implications for multiple objective evaluation approaches[8,88].

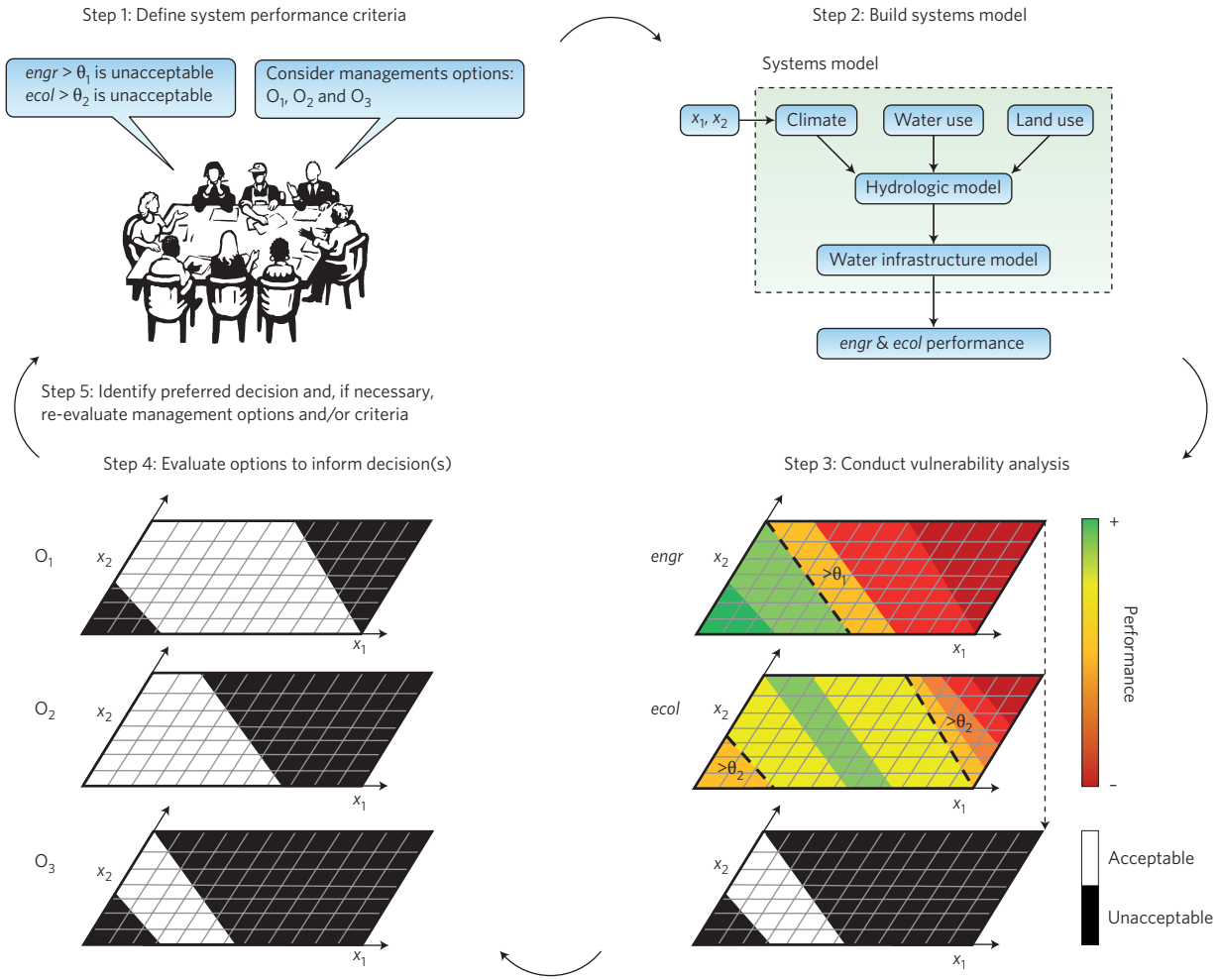

Figure 1 | The five steps of eco-engineering decision scaling (EEDS). See main text and Box 2 for a detailed description of each step.

new analytical approach to operationalize sustainable water resource management in the face of future hydrologic uncertainty. We refer to the integrated analysis of these complementary domains as eco-engineering decision scaling (EEDS), and it builds from the multiple-objective decision scaling approach used for policy evaluation in the International Upper Great Lakes Study[53,54]. The conceptual significance of EEDS is that it allows explicit evaluation of trade-offs between engineering design features and socially valued ecological performance associated with water resource development. More specifically, this trade-off analysis occurs in the initial stages of project development, so that economic, engineering and ecological vulnerabilities can be simultaneously compared. Such early evaluation of ecosystem vulnerability is necessary to reveal a range of potential design and management options in complex social-ecological systems[55]. This new approach is closely aligned with planning principles that engineers often follow, such as the Principles and Guidelines used by the US Army Corps of Engineers (USACE)[56], and similar guidance documents in Europe[57].

The EEDS framework significantly contrasts with approaches typically used to assess the environmental impacts of water infrastructure projects, and it can be summarized as a five-step process shown visually in Fig. 1 and described in detail in Box 2. Traditionally, initial project conception and design are driven by economic assessment of expected direct costs (for example, financing, construction and maintenance) and benefits (for example, revenue from hydropower production and water supply or avoided damages). Typically, several competing economically viable alternatives are developed in engineering designs before environmental impacts are considered. In the EEDS approach, however, both engineering and environmental performances are quantified and simultaneously compared across management alternatives under the range of future uncertainty. Ecological performance indicators must be clearly defined and quantitative, but significantly, they need not be monetized (which is often challenging or infeasible[58]) to allow comparison with traditional economic indicators. Furthermore, the EEDS approach can accommodate multiple performance metrics representing a diverse suite of economic, social and ecological objectives (for example, ref. 8). For the sake of simplicity, we present only two metrics in our conceptual framework (Fig. 1) and three metrics in our case study below. Ultimately, stakeholders assess viable decision pathways based on the aggregate performance of all metrics and implement management options according to values and preferences.

Iowa River case study

We illustrate the EEDS framework through a hypothetical example of a water resource decision problem for an existing flood management project. Coralville Dam was constructed in 1958 by the USACE on the Iowa River to protect Iowa City and downstream farmlands from flooding (Fig. 2). Iowa City also has a series of floodplain levees in place to reduce flood risk. Since 1990, several severe runoff events have resulted in unscheduled water releases from the dam spillway, raising concerns that extreme floods are becoming more frequent and that current management operations are inadequate for controlling flood risk. We apply EEDS to evaluate the potential economic costs associated with altered climate regimes

Box 2 | The eco-engineering decision scaling framework: an iterative five-step process.

The EEDS framework comprises five distinct and iterative steps (Fig. 1). Step 1 is a stakeholder-driven process to identify a set of possible management decision options (for example, O_1, O_2 and O_3 in Fig. 1), performance indicators (for engineering, *engr*, and ecology, *ecol*) and user-specified thresholds (θ_1 and θ_2) that define conditions under which the system no longer performs at an 'acceptable' level. Performance indicators represent key system values or services important to stakeholders. In the engineering domain, performance criteria could include, for example, reliability of water supply, reduction in expected flood damage, or the internal rate of return for a proposed project. Ecological performance metrics are also identified to represent desirable environmental conditions or ecosystem services. Such performance criteria could include maintaining a minimum population size for target species, or sustaining a specified areal coverage of riparian forests via overbank flows. Other metrics representing important ecosystem processes, such as flood regimes or sediment transport dynamics, could also be selected, depending on the nature of the study system, stakeholder preferences and data availability. Similarly, more spatially extensive metrics, such as connectivity among river segments, could be developed for multiple infrastructure components, such as siting of dams throughout a river network.

Step 2 in EEDS requires development of a systems decision model that relates changes in climate and other stressors (for example, population growth, shifts in water demand and land-use change) to engineering and ecological performance outcomes. This would typically be implemented through any of several integrated water management models, such as the Water Evaluation and Planning (WEAP) system[89], or by linking basin hydrologic models (for example, the Variable Infiltration Capacity (VIC) model[90] and the Distributed Hydrology-Soil-Vegetation Model (DHSVM)[91]) with water management operating rules to calculate resultant performance indicators. A systems decision model provides the basis for evaluating the consequences of management options across a wide range of plausible values in key climate variables and other system stressors (x_1 and x_2 in Fig. 1).

In Step 3, a vulnerability analysis (stress test[45]) is performed to exhaustively evaluate how the engineering and ecological performance indicators of the system respond to changes in climate or other input parameters (that is, the x_1 and x_2 variables). Performance indicators can be mapped visually in a plausible climate space (see Supplementary Information for details) to identify the conditions under which the system fails to satisfy both engineering and ecological indicators. The sensitivity of the system to input and model parameters can also be explored to identify variables and sources of uncertainty that have the greatest influence on performance outcomes[35]. For example, an assessment of system vulnerability to a wide range of plausible states may reveal that non-climate factors (such as population growth and shifts in water demand) are of greater concern than potential changes in climate variability.

The approach can also highlight combinations of specific changes that lead to failure, such as a given magnitude of warming and drying. Then, the acceptability of a particular decision can be assessed according to the degree to which the engineering and ecological performance indicators are mutually satisfied over a spectrum of plausible future conditions.

In Step 4, alternative management options can be specified in the systems model to evaluate how the multiple domains of acceptable performance and their mutual overlap vary among the available management options. The option with the greatest overlap in the domains of acceptable performance among chosen indicators would be considered as the most robust and sustainable in the face of future uncertainty. In this way, decisions are assessed according to their ability to provide mutually robust performance, that is, satisfy both the engineering system and ecosystem performance indicators over the widest range of future uncertain conditions.

Finally, in Step 5, decision makers (stakeholders and policy makers) assess the feasibility of either moving forward with the most promising option or developing new options that may better satisfy objectives, thus reiterating the process. Decision makers may also decide to consider alternative performance metrics or preference thresholds for re-evaluation. Considerations that affect the political or institutional feasibility of some options may be difficult to incorporate into computational models, necessitating the engagement of policy makers throughout the decision process to ensure credible and relevant options. In this way, EEDS is an iterative decision-making process that is consistent with emerging adaptive and ecosystem-based water management frameworks[52,92].

that increase flood risk and explore how alternative flood-control management strategies could affect both engineering and ecological performance indicators. Extensive data on dam operations, system hydrology and flood inundation risk (Supplementary Information) make the system amenable to a hypothetical exploration of EEDS in a plausible management scenario.

Identification of performance indicators, acceptability thresholds and decision options (step 1, Fig. 1). We begin by defining stakeholder interests as chiefly concerned with minimizing economic damages from flooding and with maintaining key ecological functions of the downstream aquatic and riparian ecosystems. Coralville Dam is primarily a flood-control project, and stakeholders receive economic benefits from flood protection in the form of avoided flood damages. We use estimated annual costs (EAC) from flood damage as our engineering performance metric to evaluate costs of alternative decision options (Supplementary Table 1). We assume stakeholders are willing to pay up to 1.5-times the long-term average costs (1959–2010) for the benefit of avoiding flood damages. This threshold is a 50% increase in historical average EAC to allow for reasonable future management costs (for example, building levees and reimbursing crop loss) that were not used when calculating the current EAC.

The assessment of ecological performance is focused on key facets of the flow regime of known ecological importance[59,60]. First, we consider high flows that inundate floodplains thereby providing shallow, low-velocity and highly productive habitat for freshwater organisms[12]. Many fish species time their spawning with floodplain inundation, and their young take advantage of nutrient-rich floodplain habitats before entering the river channel[61]. The periodic inundation of floodplains is also essential to the health of riparian plant communities[62]. These ecological functions can be provided when floodplains are inundated for an extended period of time, generally up to several weeks per year. Second, we consider the rate of flow fluctuations caused by water releases from the dam, which affects the availability and variation of in-channel habitat downstream. When artificially increased by reservoir release operations, fluctuating flows can adversely affect fish and other aquatic organisms[63].

We defined two ecological performance metrics for our case study. A floodplain performance threshold was set as the historical annual average of floodplain area that is inundated for at least seven consecutive days, derived from estimated relationships

between discharge and floodplain area from Coralville Dam to river mile 46 of the Iowa River (Supplementary Fig. 2). This threshold is an intentionally simplified measure of floodplain function (that is, timing of floods is not considered), and it is based on an assumed stakeholder preference for avoiding the loss of future floodplain functions relative to historical conditions. A second metric was defined by the magnitude of daily changes in outflows from the reservoir during periods when flows are being released rapidly in response to upstream inflows. We calculated a flow recession rate (difference between consecutive daily flow magnitudes) and set a threshold of +30% of the natural daily recession rate, that is, relative to the recession rates of unregulated inflows into the reservoir (see Supplementary Information for details). For both metrics, we make the simplifying assumption that biological communities and ecosystem functions will persist under future climate conditions if flood inundation patterns are maintained and excessive flow recession rates are avoided.

Our hypothesis is that re-engineering of the current flood risk management system could provide the opportunity both to reduce the system's vulnerability to flood risk associated with rapid climate change and to satisfy ecological objectives for sustaining more resilient downstream aquatic and riparian ecosystems. By quantifying the trade-off space between the economic costs of engineering design and maintenance and the environmental benefits under alternative flood-risk management strategies, we aim to identify a robust option that meets both objectives under a wide range of hydrological conditions in an uncertain future. To examine these trade-offs, we modelled engineering and ecological performance metrics over a range of future climates, subject to four hypothetical management options: (1) maintain status quo (SQ), that is, current levee height and reservoir operating rules; (2) re-operate the reservoir (RR) by modifying existing reservoir operation rules to allow for increased emergency flow releases during the growing season, which would increase reservoir capacity for capturing storm runoff; (3) raise existing levees (RL) to increase flood protection around Iowa City; and (4) jointly re-operate the reservoir and raise levees (RR+RL).

Developing the decision systems model (step 2, Fig. 1). We used publicly available hydro-climatic data along with reservoir operations and hydraulic mapping data from the USACE (Supplementary Information) to develop a water management systems model of the Iowa River basin. We used this model to evaluate how the engineering performance indicator (EAC) and the ecological indicators (floodplain inundation area and flow recession rate) independently respond to climate variability (Supplementary Fig. 1). A rainfall-runoff model of the basin was calibrated with historical climate and discharge data to predict daily inflows to Coralville Reservoir. Inflows were then fed into a reservoir operations model to estimate outflows to the Iowa River below the dam. Next, a river hydraulics model was used to estimate the daily downstream inundation area as a function of river discharge to allow estimation of annual costs (US$), floodplain inundation and flow recession rates. The systems model was modified for each of the four management strategies by specifying higher levees and/or alternative reservoir operation rules.

Vulnerability analysis (steps 3 and 4, Fig. 1). We generated a large stochastic input series of climate data[64] with altered mean temperature, mean precipitation and daily precipitation coefficient of variation (Supplementary Information). Simulated data were then fed into the decision systems model (Supplementary Fig. 1) to evaluate performance outcomes under specified management options and climate futures. Results of the vulnerability analysis were plotted across the range of climate variables relevant to flood risk management. As our primary demonstration of the EEDS framework, we evaluated how thresholds in performance indicators responded

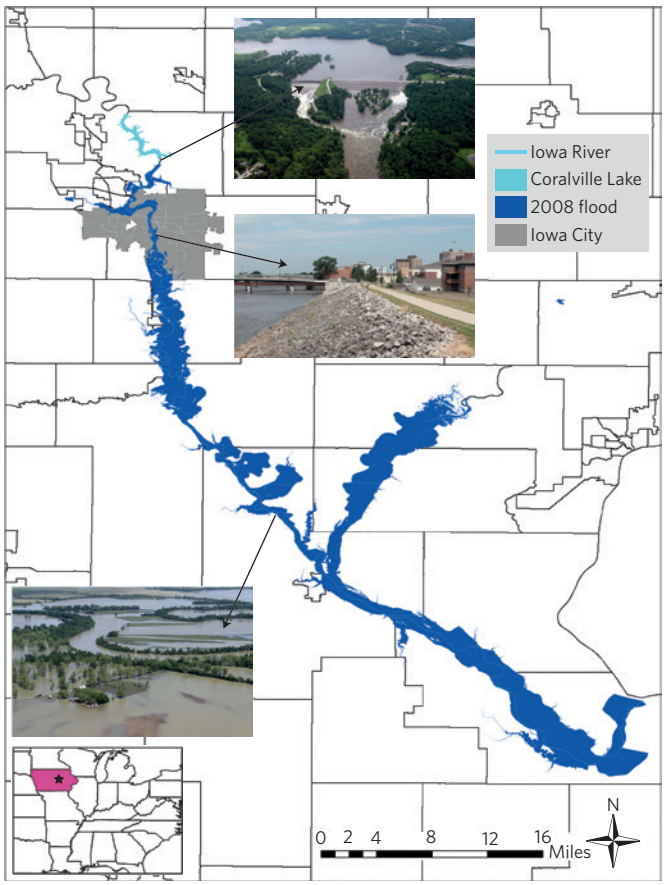

Figure 2 | Iowa River study area near Iowa City, Iowa, USA. This map shows Coralville Dam with flooding spillways and the extent of the 2008 flood that breached some levees in Iowa City (urban footprint shown in grey) and extensively inundated downstream floodplain farmland and riparian habitats (dark blue).

to deviation in predicted mean annual discharge and daily precipitation coefficient of variation (CV), two hydro-climatic variables of relevance in flood forecasting. As an alternative analysis, we explored vulnerability in a future climate space directly comparable to GCM climate projections, in which system performance was evaluated over a range of predicted mean annual temperature and mean annual precipitation values (Supplementary Information).

Our results (Fig. 3) show how changes to the two hydro-climatic variables (displayed as orthogonal axes) affect system performance and potentially cross stakeholder-defined vulnerability thresholds. Each pixel represents a climate state simulated through the systems model. The engineering indicator (EAC, first column of Fig. 3) and the ecological indicator (floodplain inundation, second column) are plotted in a future climate state space defined by change in average annual daily flow and the variability of the daily precipitation series for each of the four management options. The indicators are expressed as the magnitude of change relative to mean historical conditions. The third column in Fig. 3 displays the domain of 'mutually acceptable performance', delineated by the white area that satisfies both the acceptable EAC and floodplain inundation performance criteria. In Fig. 4, the flow recession metric (third column) is included with the EAC and floodplain metrics to evaluate multiple-metric responses to the four management options. The shaded plots in the fourth column of Fig. 4 show the mutually acceptable performance for all three indicators. The mutually acceptable space can be quantified and, if desired, probabilities assigned[65]. Here, visual inspection is sufficient.

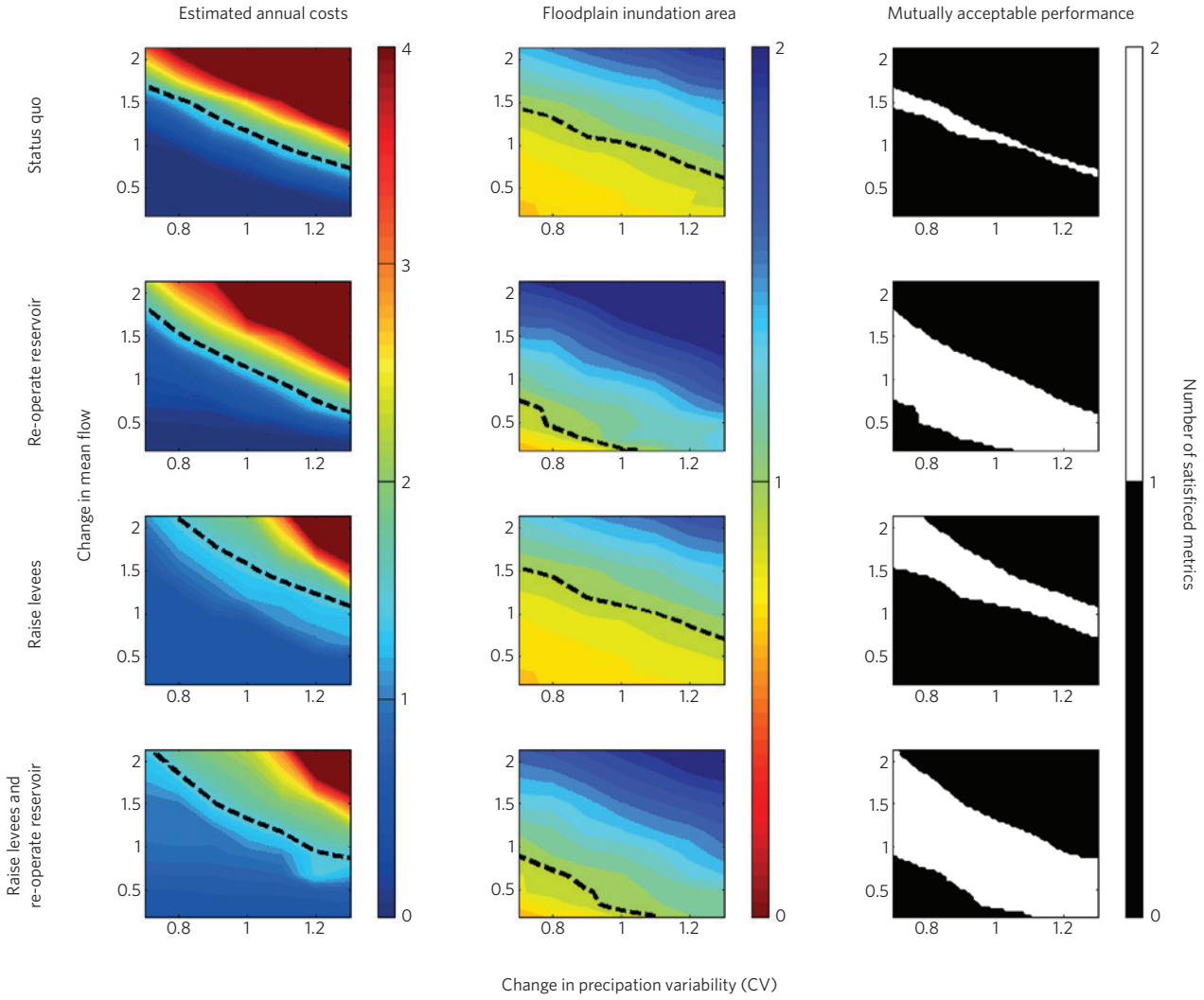

Figure 3 | Two Iowa River system performance indicators mapped in a variable future climate space defined by change in annual precipitation variability and mean annual flow for each of 4 management actions (rows). The first column shows estimated annual costs (engineering performance indicator), expressed as values relative to the historical long-term (1959–2010) mean, with values exceeding the threshold (dashed line) of 1.5-times the historical level (shown by colour scale) being unacceptable. The second column indicates the floodplain inundation area (ecological performance indicator), with values falling below the threshold (dashed line) value of the historical mean (shown on colur scale at 1.0) deemed unacceptable for floodplain inundation. The overlapping domain of mutually acceptable performance for the two indicators is shown as white space in column 3.

Evaluation of trade-off space with alternative decision options (steps 4 and 5, Fig. 1). We evaluate the premise that the system can be managed to meet both engineering and ecological objectives by examining the independent and joint responses of performance metrics to the different management options in Figs 3 and 4.

Figure 3 shows that for all four management options, the EAC metric is more likely to exceed the acceptable threshold level (dashed line) as precipitation CV increases (more frequent, large floods) and as average annual flow increases (wetter conditions). The floodplain performance indicator shows the reverse pattern, with wetter, more variable precipitation leading to greater floodplain inundation. Superimposing the EAC and floodplain inundation response surfaces reveals a domain of mutually acceptable performance (white space in the third column of Fig. 3). The SQ management strategy affords little overlap in mutually acceptable climate space. Similarly, the RR strategy has virtually no effect on the system's engineering performance relative to SQ. There is, however, a slight contraction in the climate space associated with catastrophic flood damages, that is, those that are most expensive (for example, ≥4 times the historical EAC).

In contrast, the ecological floodplain performance indicator is significantly enhanced under the RR strategy, with floodplain inundation areas greater than mean historical conditions for all but the driest and least variable of simulated climate futures. The RL management action greatly reduces the vulnerability to unacceptable flood damage relative to SQ, yet it has no detectable effect on floodplain inundation. Only under wetter, more variable climates would floodplain inundation exceed the performance threshold under the RL action. When levees are raised in combination with reservoir re-operation (RR+RL), slightly higher costs are projected for EAC compared to the RL option (due to crop-damage costs incurred by controlled flood releases); however, floodplain inundation is achieved fully as in the RR option, so that the overall domain of mutually acceptable performance is larger than all other options (white space in Fig. 3). Thus, the RR+RL action would provide the most robust management strategy for an uncertain future, that is, it would satisfy economic (EAC) and ecological (floodplain inundation) goals over the broadest range of hydro-climate states.

Inclusion of the flow recession rate metric allows evaluation of prospects for achieving sustainable management for more than two

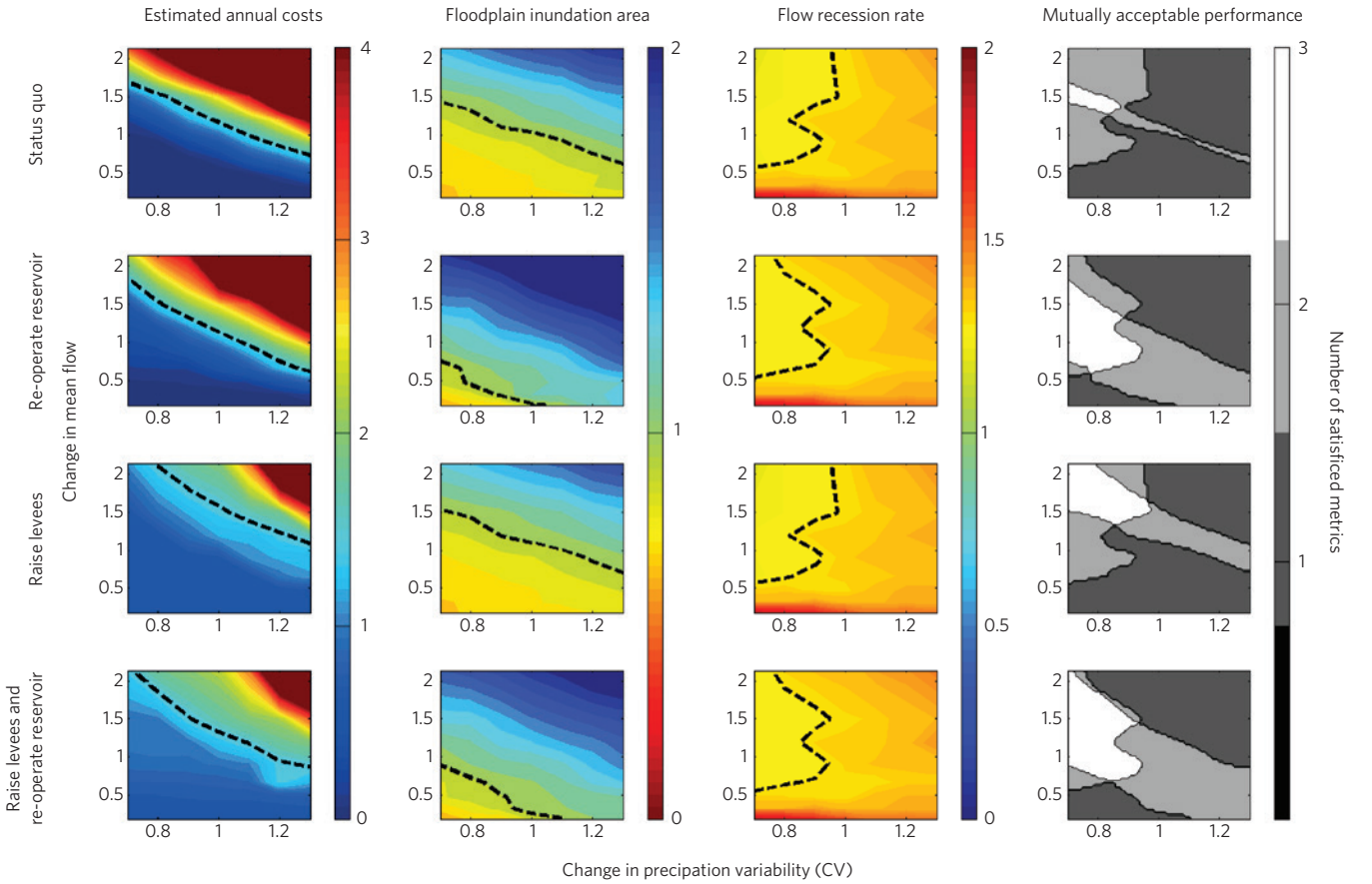

Figure 4 | Three Iowa River system performance indicators mapped in a variable future climate space defined by change in annual precipitation variability and mean annual flow for each of 4 management actions (rows). The estimated annual costs and the floodplain inundation area are as in Fig. 3. The third column is the flow recession rate indicator, with values exceeding the threshold of +30% of historical, unregulated inflow recession rates (shown on colour scale at 1.3) being unacceptable (to the left of the dashed line). Mutually overlapping performance for all combinations of the three indicators (one engineering and two ecological) is shown in the fourth column for each of four management actions.

metrics simultaneously (Fig. 4). In general, this ecological metric is sensitive to precipitation variability but remains below the target threshold (+30% of historical 'natural' average recession rate) only when change in precipitation variability is low and mean daily flow is at or above 50% of the historical mean. None of the three active management options (RR, RL or RR+RL) modify the performance of this metric relative to the SQ option, which is perhaps not surprising given Coralville's primary design function of flood control. Other options would need to be explored to modify flow recession rates and enhance performance of this indicator.

By combining the flow recession rate metric with the EAC and floodplain inundation metrics, we can project a space for all three (Fig. 4, fourth column) that shows a more constrained domain of mutually acceptable performance compared with the previous two-metric example (Fig. 3). However, the comparison of all management options again shows that the RR+RL option provides the largest opportunity to achieve performance objectives in an uncertain future. To potentially expand the climate domain under which the flow recession rate criterion is satisfied, future iterations of the EEDS process could consider additional changes in reservoir reoperations (that is, restriction of flow release rates from the reservoir), a choice that stakeholders may or may not be willing to pursue.

Overall, these findings suggest that raising levees could provide substantial benefits in reducing flood damage under a wetter and more variable climate future. However, in drier and less variable future climate states, relatively low flood risks would make levees an unwise economic investment. Similarly, the results indicate that ecological benefits of floodplain inundation from re-operation would be realized under current and moderately wetter climate conditions. If the climate were to shift to extreme wet or dry states, the ecological benefits of re-operation are less clear for floodplains because in very dry years there would be insufficient water available to activate floodplains and the abundance of water in very wet years would make the effects of dam re-operation negligible.

We recognize that all simulated climate states evaluated in the system model are not equally plausible; however, the purpose of the vulnerability analysis is to determine how much the climate must change before the system is at risk of crossing key performance thresholds in the hypothetical example presented here. Once system failures are identified, judgments must be made regarding the plausibility of the conditions causing such failure using available climate information (such as downscaled GCMs, historical and palaeoclimate records, and so on) and expert opinions about other sources of future hydrologic change (such as changes in runoff from land use change, growing human water demand, and so on). Confronting the performance under changing temperature and precipitation with climate change scenarios can help to identify if projected climate change is a threat and when a tipping point[57] might be reached and require active management actions.

To place our results in the more conventional context of climate vulnerability analysis, we used downscaled, bias-corrected climate model ensembles (from the Coupled Model Intercomparison Projects 3 and 5; CMIP3 and CMIP5[66]) and plotted these projections over the system response surfaces to indicate the potential

range of plausible future climate changes experienced in the Iowa River system by 2050 (Supplementary Fig. 3). These GCM projections suggest that the system is vulnerable to climate change and that the RR+RL action is favoured for reducing economic and ecological risks to projected climate changes over the next several decades.

Ultimately, decision makers in this system would have to assess the costs, benefits and political will to implement new flood control alternatives. In our example, it seems that raising the levees and changing operations confers the greatest robustness to climate change uncertainty. Timing of decisions and rates of change of climate are issues of detail that must be addressed by policy makers and stakeholders as they implement EEDS (or any form of adaptive management) in real-world applications, similar to the climate-risk planning effort undertaken in the Great Lakes[32]. For example, the resources required to implement reservoir reoperations are likely to be less than constructing new levees, as well as being reversible, suggesting that a staged implementation approach may be appropriate. This could be potentially triggered by evidence of worsening climate conditions, as has been described by the 'adaptation pathways' approach, an emerging policy-analysis tool[67,68].

EEDS as a foundation for sustainable management

Deep uncertainty about future hydrology undermines traditional approaches for the design and operation of water infrastructure to achieve 'reliable' performance[29,30] and poses an unprecedented challenge for sustaining healthy, resilient freshwater ecosystems. On a global scale, current infrastructure (dams and irrigation works) is extensive and a significant driver of freshwater ecosystem degradation[16,60,69–71]. Historical evidence clearly indicates that human decisions on the design, location and operation (or reoperation) of water infrastructure such as dams will have both immediate and long-term effects on the health and resilience of freshwater ecosystem function and biodiversity[72,73]. Given the inevitability of much new and redesigned water infrastructure, a new spirit of cooperation and collaboration among water resource engineers and conservation ecologists is needed to improve design and operate water infrastructure efficiently to meet both human and ecosystem needs in a socially acceptable and sustainable way.

EEDS is a framework that can provide a transparent process for operationalizing sustainable water management through integration of socio-environmental objectives in a decision-oriented vulnerability assessment framework. This approach has several strengths. First, it is designed to manage risk of uncertainty and provide guidance to managers and decision makers by focusing on the vulnerability of engineering and ecological indicators to a range of hydrologic futures. It does not rely solely on downscaled GCM projections to assess climate risks but can include a wide range of sources of hydrologic non-stationarity, including historical and palaeoclimate records and modelled land-use change information and changing water allocations.

Second, EEDS represents only a relatively small adjustment to the existing water management decision-making processes. The key change is in assessing ecosystem vulnerabilities equally and early in the design process, so that trade-offs can be identified and addressed accurately in the beginning of the planning process and thus help inform social choices[55]. While engineering objectives of a project may sometimes be perceived as irreconcilable with ecological performance targets, it is possible that strategies for satisfying even modest ecological objectives may improve economic performance of water infrastructure systems, as has been shown with the restoration of coastal wetlands for wave-surge protection[74] and the incorporation of floodplains and wetlands in flood design[61]. Other non-hydrological applications of EEDS are possible, such as designing and operating dams to minimize harmful distortions in water temperature and sediment regimes that have quantifiable downstream ecological impacts. EEDS might also be used to identify when proposed water management designs are not compatible with socially valued ecological features. Similarly, EEDS could conceivably be applied to a range of non-aquatic engineering design questions where engineering and ecological trade-offs are significant. Regardless of the specific project context, a full exploration of decision consequences on multiple performance indicators in a formal analytical framework can promote informed and transparent decision-making by enabling discussion about mutually satisfying solutions in water management planning and infrastructure design.

Third, the EEDS framework can help inform a wide variety of management decisions that need to balance ecosystem sustainability with desired economic objectives. Ecological performance objectives can be construed broadly; for example, from economically valuable fisheries to a highly desirable environmental amenity that has significant non-market value for stakeholders. As such, the decision framework is structured in a way that is relevant to those who are affected by planning and decisions. The EEDS framework is also well suited to 'scale up' to whole-basin planning to evaluate how planned infrastructure projects could meet both economic performance and ecosystem services under changing climate and water development in large rivers in the developing world[72].

Finally, the EEDS framework can inform decisions regarding existing water infrastructure systems, such as reoperation of downstream discharge releases from dams (as illustrated in our Iowa River case study), or decommissioning of projects. In developed countries such as the United States, thousands of dams built in the early to mid twentieth century no longer provide their intended benefits due to infrastructure decay, the loss of storage capacity from sediment accumulation and increased hazard risk owing to downstream development[63]. The convergence of ageing infrastructure with growing concern over trends of environmental degradation is providing unprecedented opportunities for ecosystem restoration[64]. However, climate change and uncertainty about ecosystem responses to infrastructure modification or removal make it difficult to identify economically and environmentally acceptable strategies. Similarly, there is growing interest in the re-operation of functioning water infrastructure as a mechanism to buffer aquatic and riparian ecosystems against climate change in regulated rivers[14]. EEDS analysis can provide an operational framework for evaluating the consequences of different management options by explicitly quantifying trade-offs among engineering design options and environmental objectives under plausible ranges of hydrologic non-stationarity.

Conclusion

Integrated water resources management for both human economic needs and ecosystem health is increasingly recognized as essential to societal well-being[20,75]. However, progress towards more sustainable forms of water management is hampered by conflicting interests, existing economic policies, inflexible infrastructure design and a lack of quantitative, transparent tools to facilitate critical decision-making. Debates around the construction of water infrastructure are long-standing[4,35] and will no doubt continue in the face of extensive proposed dam building globally[2]. Our aim here is not to advocate for or against the necessity of water infrastructure, but rather to argue that, in those situations where water infrastructure will be constructed or re-operated, a new paradigm of sustainable water management is needed, one that can be more effectively achieved when conservation ecologists collaboratively engage with water resources engineers to incorporate ecosystem performance goals in the decision-making process.

A key continuing challenge for rational water resource management is to provide a practical approach to assist planners and decision makers in navigating complex problems and diverse interest groups who are confronted by uncertain and changing conditions. As effective adaptive decision-making is most likely to succeed where stakeholders are fully engaged, we believe the EEDS offers the

potential to serve as the foundation of a new management platform that advances freshwater sustainability while meeting human needs for water. Further refinement could include how to accommodate future changes in societal cost functions (for example, due to population growth) and shifts in ecological requirements under transient climate and socio-economic conditions, as well as how to sequence management actions in a fashion that promotes long-term success. One promising future possibility is to link EEDS with emerging techniques that help to identify when adaptation actions should be taken, such as the adaptation tipping point approach[57], as well as with techniques that help to identify alternative adaptation routes, such as dynamic adaptation pathways approaches[68,76]. Managing the future will necessarily occur in an adaptive context; therefore, equally robust monitoring and evaluation plans will be needed to ensure that decisions are drawing upon the best available information when evaluating the consequences of alternative decision options and management strategies.

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Author contributions

N.L.P. and J.H.M. conceived the original project. N.L.P., T.E.G. and C.M.B. led the drafting of the text. C.M.S., C.M.B., T.E.G. and N.L.P. led the case study analysis. N.L.P, C.M.B., T.E.G., J.H.M, M.A.P., C.M.S., R.L.W., M.H., G.F.M., K.C.D. and A.B. contributed to the intellectual content through workshop participation and writing.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence should be addressed to N.L.P.

Competing financial interests

The authors declare no competing financial interests.