Microeconomic Ensemble Modeling to Inform Robust Adaptation to Water Scarcity in Irrigated Agriculture

C. Dionisio Pérez-Blanco, Ph.D.[1]; Carlos Gutiérrez-Martín, Ph.D.[2];
Laura Gil-García[3]; and Nazaret M. Montilla-López, Ph.D.[4]

Abstract: This paper compares the economic performance of a dam construction strategy versus a no dam construction (i.e., the statu quo) strategy under multiple scenarios and using a multimodel ensemble of three microeconomic mathematical programming models. The result is a database of simulations representing multiple plausible futures which offers information on uncertainty regarding scenario assumptions and model structure (through the ensemble spread). Using an iterative robust decision-making framework, simulation results are coupled with experts' knowledge and opinion to detect vulnerabilities in the proposed strategies, quantify potential trade-offs between responses, and identify a robust adaptation strategy. Methods are illustrated as applied to the Órbigo Catchment in Northwestern Spain, where the Douro River Basin Authority (DRBA) will decide in the coming months whether to build two dams to enhance irrigation water supply and reliability. Simulation results show that, for most scenarios and models considered, dam construction costs lead to water prices beyond the willingness of local cereal-growing irrigators to pay. Following a robust decision-making process, parties to the decision unanimously declared the status quo (i.e., no dam construction) strategy to be preferred to the dam construction strategy. This outcome substantiates the need for economic assessments of dam construction projects that account for nonlinear responses by agents to complement technical assessments in decision making. **DOI: 10.1061/(ASCE)WR.1943-5452.0001385.**

Introduction

Water resources management has traditionally involved large amounts of concrete: dams, canals, reservoirs, and other water works feature prominently in expansionary water economies, where the costs of increased water use are relatively low (UN 2018). Growing population and GDP projections toward higher water demand, combined with decreasing water supply projections due to climate change, signal that this expansionary water economy is coming to an end along with "cheap" water (OECD 2015; World Bank 2016). In many arid and semiarid regions worldwide, water economies have already transitioned from an expansionary to a mature phase where high, growing, and elastic (at low prices) demands meet inelastic supplies with "sharply rising incremental costs . . . , more direct and intense competition . . . and greatly increased interdependencies among water uses" (Randall 1981, p. 196). Deploying water works in mature water economies inevitably entails a reallocation of benefits among users that needs to be properly assessed and balanced. Positive returns from new water works cannot be taken for granted anymore; instead, relevant trade-offs will emerge (WDC 2000). Critically, the intrinsic complexity of managing trade-offs is further compounded by the nonmechanistic dynamics and multiple potential equilibria of complex socioecological systems, resulting in the emergence of deep uncertainty.

Deep uncertainty is a step on the scale of uncertainty between probabilistic uncertainty and total ignorance (Kwakkel et al. 2010). Under deep uncertainty, "experts do not know or the parties to a decision cannot agree upon (i) the external context of the system [i.e. scenario uncertainty], (ii) how the system works and its boundaries [i.e. parameter and structural uncertainties within models], and/or (iii) the outcomes of interest from the system and/or their relative importance [i.e. weighting]" (Lempert et al. 2003, p. 11). While adequate under conditions of probabilistic uncertainty, conventional consolidative modeling that uses a complete probabilistic description of plausible scenarios and a single system model to generate point predictions is no longer appropriate under deep uncertainty, since it artificially reduces uncertainty and risks, providing more information than is warranted by available evidence. Use of consolidative modeling and point predictions to inform dam construction projects in the past frequently led to contingencies or "surprises" arising from "the non-mechanistic dynamics of complex adaptive socio-ecological systems" and resultant scenario and modeling uncertainties (Anderies et al. 2006, p. 867). For example, dam construction throughout northwestern United States has provided significant supplies of low-priced electricity and stimulated economic activity, while contributing to declines of anadromous fish by interfering with upstream/downstream migration, eventually leading to cases of dam removal (Loomis 2002, 1996). In Spain, the national dam inventory reveals that 15 dams recently built for irrigation purposes are redundant (i.e., in most years, any water stored in these dams could be stored elsewhere in other dams) due to decreasing water inputs caused precisely by upstream irrigation expansion (MITECO 2019). A report recommended the

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[1] Research Associate, Dept. of Economics and Economic History, Universidad de Salamanca, Francisco Tomás y Valiente s/n, Salamanca 37007, Spain (corresponding author). ORCID: https://orcid.org/0000-0002-7777-4317. Email: dionisio.perez@usal.es

[2] Associate Professor, Dept. of Agricultural Economics, Universidad de Córdoba, Campus Rabanales, Ctra N-IV km 396, Edificio Gregor Mendel, Córdoba 14071, Spain.

[3] Ph.D. Researcher, Dept. of Economics and Economic History, Universidad de Salamanca, Francisco Tomás y Valiente s/n, Salamanca 37007, Spain.

[4] Postdoctoral Researcher, Dept. of Agricultural Economics, Universidad de Córdoba, Campus Rabanales, Ctra N-IV km 396, Edificio Gregor Mendel, Córdoba 14071, Spain.

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decommissioning of the dams, albeit acknowledging that some previous ecological functions may have been irreversibly lost (Ecologistas en Acción 2018). The causes for these "surprises"—not anticipated by point predictions—include (1) nonlinear responses by economic agents, which may lead to additional water demand that exceeds the additional supply made available in the reservoir (Di Baldassarre et al. 2018; Srinivasan et al. 2017); (2) skewed projections of costs and benefits (Ansar et al. 2014; Flyvbjerg et al. 2005); and (3) the straightaway neglect of relevant costs and benefits (e.g., impact on fish populations) (Ziv et al. 2012).

In conditions of deep uncertainty, using point predictions to inform dam construction can be "counter-productive and sometimes dangerous" (Lempert 2019, p. 24). This calls for alternative decision-making frameworks that shift the focus away from point predictions and optimality and toward identification of no-regret/low-regret solutions, where priority is given to the avoidance of unfavorable contingencies (i.e., robustness) (Groves et al. 2015). Robustness-based decision-making frameworks to inform dam construction include information-gap decision theory (Korteling et al. 2013), decision scaling (Taner et al. 2017), the scenario-neutral approach (Prudhomme et al. 2010), robust optimization (Gorissen et al. 2015), real options analysis (Steinschneider and Brown 2012), and robust decision-making (Lempert et al. 2003). Unlike a single system model and set of parameters and a complete probabilistic description of possible scenarios to generate a point prediction, robustness-based frameworks can be used to run multiple simulations to assess the performance of proposed strategies against a variety of (1) possible scenarios (scenario uncertainty) (Lempert et al. 2003); and (2) system models through alternative parameters and model structures (parameter and structural uncertainties within models) (Yao et al. 2018). This information can be used by analysts to identify futures where "proposed strategies meet or miss their objectives," and "identify, frame, evaluate, modify, and choose robust strategies" (Lempert 2019, p. 25).

Conventional robustness-based frameworks force system models considering alternative climate, weather, and/or socioeconomic scenarios to build a simulation database that samples scenario uncertainty to inform robust decisions. Bertoni (2020), Bertoni et al. (2019), Block and Strzepek (2010), Borgomeo et al. (2018), Jeuland and Whittington (2014), Nassopoulos et al. (2012), Ray et al. (2018), and Ziv et al. (2012), among others, applied this approach to dam construction. Such exploratory analysis often uses multimodel climate ensemble experiments to generate scenario inputs that force system models (see, for example, Borgomeo et al. 2016; Steinschneider and Brown 2012; Taner et al. 2019, 2017 for applications to dam construction/operation). However, the uncertainty involved in system models themselves is typically unaccounted for, and where included it focuses on parameter uncertainties. In other words, while robustness-based frameworks explore system responses to multiple scenarios, the relevant system is typically represented using a single model (e.g., hydrologic model) and often considering a single set of parameters.

Use of a single system model and/or a set of parameters may well lead to surprises. Perhaps counterintuitively, a deeper understanding of complex socioecological systems typically comes with increased uncertainty as the system grows in the number of models, processes, and scenarios, and as cascading uncertainties amplify the range of forecasts (Saltelli et al. 2013). This is consistent with the widening model uncertainty ranges observed in ensemble experiments in systems of relevance for water resources planning and management, notably climate (IPCC 2014) but also hydrologic (Cloke et al. 2013), macroeconomic [e.g., through computable general equilibrium ensemble experiments (Elliott et al. 2012)] and microeconomic systems [e.g., through microeconomic model ensemble experiments (Sapino et al. 2020)]. Accordingly, numerical forecasts obtained through a single system model and set of parameters should be expected to reveal "huge uncertainty bounds" when complemented with a thorough or "even a standard" sensitivity analysis (Saltelli and Funtowicz 2014, p. 1).

Echoing the research just mentioned, Herman et al. (2015, p. 04015012-5), called for "sensitivity analysis to become a required tool to improve the transparency of model assumptions in water systems planning." To this end, robustness-based frameworks can extract lessons of value from methods for "uncertainty and global sensitivity analysis of model parameters, data and observations" (Baroni and Tarantola 2014, p. 26). Efforts in this direction include (1) robust optimization frameworks that stress-test the risk-aversion coefficients of the decision maker's objective function to assess their impact on modeling results (Ray et al. 2012); and (2) multicriteria decision analysis frameworks that stress-test decision makers' weights and key system model parameters (e.g., discount rate) (Manikkuwahandi et al. 2019). More limited progress has been made toward the integration of model structure uncertainty in robustness-based frameworks for water systems planning. A rare example is available in Mustafa et al. (2020), who used Bayesian model averaging to sample model structure uncertainty considering four conceptual versions of MODFLOW. A literature review of past studies that assessed dam construction under deep uncertainty conditions, and the sources of uncertainty sampled (scenario, parameter and structural uncertainties), is available in Appendix I (Appendices I–VI can be found in Supplemental Materials).

The contribution of this paper is the integration of an *ensemble of multiple human system (microeconomic) models* that sample model structure uncertainty (through the ensemble spread) into robustness-based frameworks to inform dam construction decisions. This is done through the development of an ensemble experiment of three mathematical programming microeconomic models that reproduce the behavior of water users (irrigators in our application). Mathematical programming models use the relationships observed in historical data to reveal utility functions that explain behavioral responses through deep parameters (preferences, resources constraints) that are insensitive to policy change and therefore adequate to model agents' responses and provide policy advice (Lucas 1976). The microeconomic ensemble is subsequently used to simulate the economic performance of dam construction versus no dam construction (i.e., the status quo) under multiple climatological, hydrologic, and socioeconomic scenarios (scenario uncertainty). Using a robust decision-making framework (Lempert et al. 2003), the multimodel and scenario ensembles are coupled with experts' knowledge and opinion to iteratively (1) create multiple plausible futures through scenario exploration using three alternative models, (2) identify key vulnerabilities of proposed strategies (i.e., combinations of scenarios, models. and strategies that miss objectives), and (3) subjectively propose new scenarios or choose the preferred strategy.

The proposed framework is applied to the Órbigo Catchment in the Douro River Basin, Spain, where the Douro River Basin Authority (DRBA) will decide in the coming months whether to build two additional dams to enhance reliability of the irrigation supply: La Rial (23 million m^3) and Los Morales (11 million m^3). After receiving a positive environmental assessment from the Spanish Ministry for the Ecological Transition (BOE 2018), the DRBA commissioned us to undertake a study of the economic repercussions and feasibility of dam construction (involving a pricing instrument for cost recovery) as compared to the status quo where no dam is built. Should the economic assessment of the project be positive, the reservoirs of La Rial and Los Morales will be built.

Case Study Area: The Órbigo Catchment

The Órbigo Catchment is an otherwise water abundant area exposed to drought events whose frequency and intensity "are projected to increase due to climate change" (DRBA 2017, p. 151). Total withdrawals amount to 484.9 million m^3 per year, with agriculture at 95.9% being the most relevant user. On the other hand, water supply during an average year totaled 1,436.5 million m^3 for the period 1980–2016–(nearly three times as much as the average withdrawals of 484.9 million), with a minimum historical supply of 740.3 million m^3 and a maximum historical supply of 3,242.7 million m^3 over the same period (DRBA 2016).

Despite its relative water abundance, the current regulation system in the Órbigo Catchment is insufficient to fill supply-demand gaps during drought years. The Barrios de Luna Reservoir, with a capacity of 308 million m^3, regulates supply in the entire Órbigo Catchment and provides water to the 150,000 inhabitants and industries of León and La Bañeza (a high-priority use demanding 20 million m^3/year) and to 55,000 ha of irrigated land in the Páramo Leonés (a low-priority use demanding 272 million m^3/year), while ensuring minimum environmental flows in the Luna and Órbigo rivers (high priority: 60 million m^3/year) (DRBA 2017). Imbalances between storage capacity (308 million m^3) and dependent water demand (352 million m^3) become apparent during droughts, when water shortages constrain water availability in the irrigated areas of the Páramo Leonés (DRBA 2016). To avert economic losses, during droughts the irrigated areas of the Páramo Leonés are supplied external water resources formally committed to the irrigated area of Payuelos in the nearby Esla-Valderaduey Catchment, which is not yet fully developed. As the latter irrigation system develops, transferred resources will decrease and effectively constrain water supply in the Páramo Leonés irrigated area.

The recurrent and relevant water surpluses observed in the Órbigo Catchment, which cannot be stored with available infrastructure, have led the DRBA to attribute supply-demand imbalances in the Órbigo Catchment to insufficient storage capacity and to look for options to accumulate excess water during average and wet years (DRBA 2016). However, building additional storage infrastructures in the Órbigo Catchment has proved challenging. The most promising location for a new reservoir, the Omaña River, with the capacity to store up to 200 million m^3 in a tributary of the Órbigo River, was rejected in 1993 due to a negative environmental assessment by the relevant Spanish ministry (BOE 1993). After decades of analysis and debate, the DRBA is now assessing the feasibility of an alternative infrastructure project that involves the construction of two smaller reservoirs for irrigation water supply in the Órbigo Catchment: La Rial (23 million m^3) and Los Morales (11 million m^3). In line with the EU cost recovery principle (OJ 2000), the financial and environmental costs of the project will be charged to agricultural water users benefiting from the reservoirs—namely, the irrigators within the agricultural water demand units (AWDUs) of the Páramo Leonés (water users and direct beneficiaries) and other AWDUs within the Órbigo Catchment (indirect beneficiaries through enhanced water security) (Fig. 1). AWDUs, the basic irrigation unit in agricultural water planning in Spain, comprise local irrigation communities with common hydrological (e.g., water source), spatial (i.e., territory), and administrative characteristics (DRBA 2016); they make up the relevant agent in the microeconomic models in the ensemble used in this paper. Irrigated crops in the case study area are sugar beet (6% of irrigated surface), corn (74%), irrigated cereals (notably wheat and barley, 13%), irrigated sunflower (1%), potatoes (2%), alfalfa (2%), and others (2%).

Amid significant opposition from environmental groups and municipalities in the area surrounding the reservoirs (Carrizo de la Ribera, Cimanes del Tejar, Llamas de la Ribera, and Las Omañas), the project received a positive environmental assessment in May 2018 (BOE 2018). The second and last step in the decision of whether to build the two reservoirs involves an economic feasibility and impact assessment. Should the project be found economically

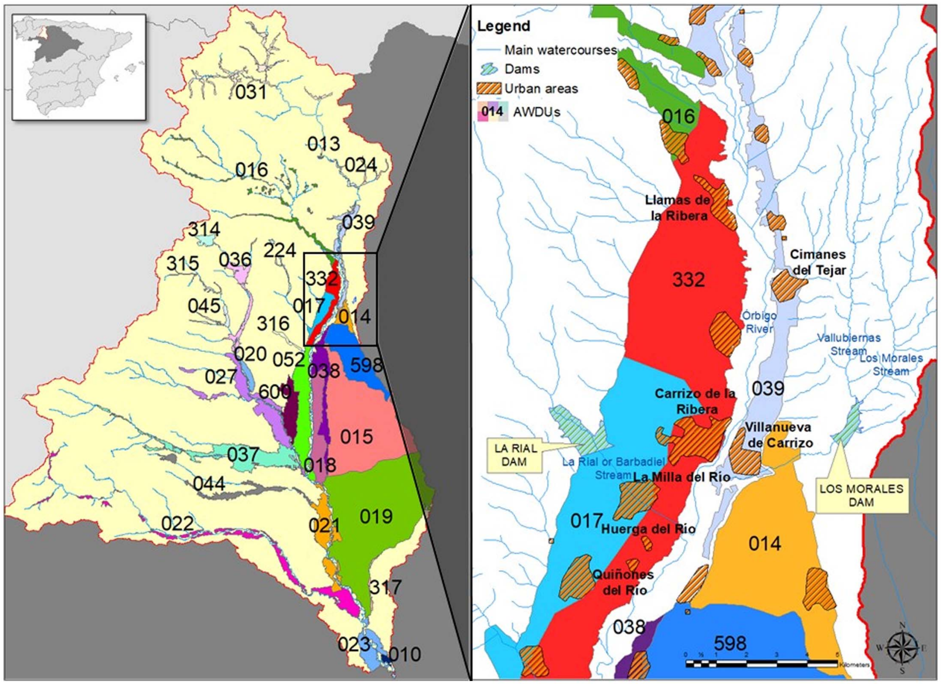

Fig. 1. Órbigo Catchment and detail of area surrounding La Rial and Los Morales dams. AWDUs 015, 018, 019, 021, 038, 317, and 598 are direct beneficiaries of dam construction in the Páramo Leonés; AWDUs 010, 014, 016, 017, 020, 022, 023, 027, 036, 037, 039, 044, 045, 052, 224, 314, 315, 316, 332, and 600 are indirect beneficiaries in the remaining Órbigo Catchment.

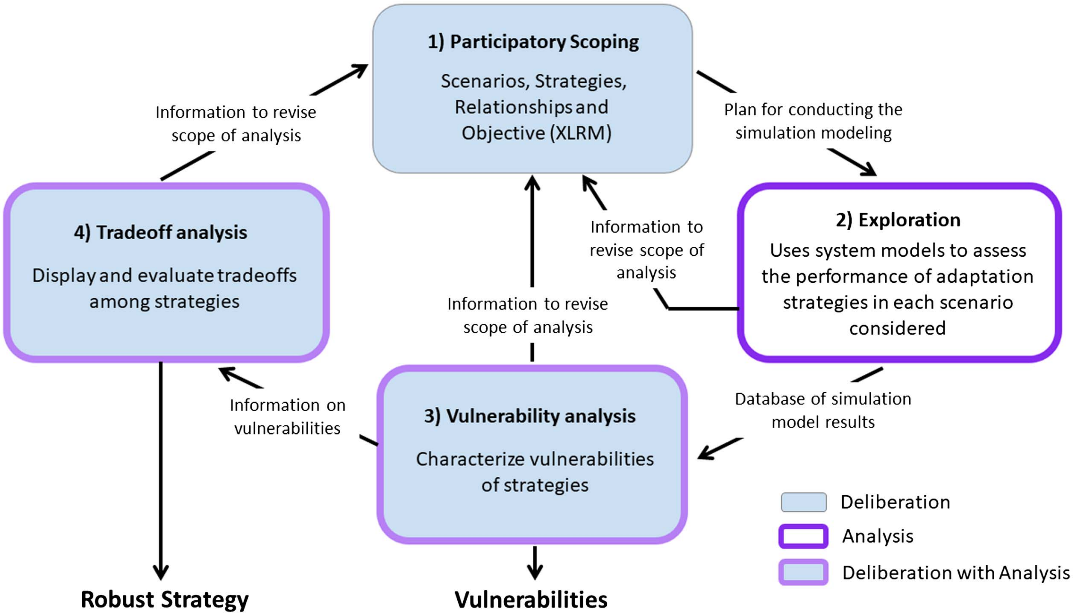

Fig. 2. Schematic of the iterative robust decision-making process. (Adapted from Lempert et al. 2013.)

feasible, the reservoirs of La Rial and Los Morales will be built.

Methods

This paper adopts an extended robust decision-making framework that accounts for both model structure and scenario uncertainty. Robust decision making was originally developed by the RAND Corporation and is nowadays a widely used policy assessment tool (Lempert 2019). It is based on an iterative process known as "deliberation with analysis," in which "parties to a decision deliberate on their objectives and options; analysts generate decision-relevant information using system models; and the parties to the decision revisit their objectives, options, and problem framing influenced by this quantitative information" (National Research Council 2009, p. 73). Robust decision making means that both analysts and the parties to the decision are integral parts of research, contributing to the analysis along four iterative stages (Lempert et al. 2013): (1) participatory scoping, (2) exploration, (3) vulnerability analysis, and (4) trade-off analysis (Fig. 2). The main contribution of this paper resides in the first stage, where system models are defined and an ensemble experiment is proposed.

Participatory scoping (the first stage) is typically articulated within a framework called XLRM (Table 1), where analysts and parties to the decision define scenarios (X), strategies (L), relationships/system models (R), and performance metrics (M) (Lempert et al. 2003). Each of the elements in the XLRM framework is discussed further in the following subsections. The main contribution of this paper involves R (system models), where we use a multimodel ensemble instead of following the conventional approach relying on a single system model. This contribution is presented in detail in the subsection "Relationships/System Models (R): Microeconomic Ensemble Modeling." In exploration (the second stage), analysts run system models to assess the performance of adaptation strategies in each scenario. The result is a large database of simulations representing the set of plausible futures under alternative strategies and scenarios and (in our case) model settings. In vulnerability analysis (the third stage), analysts and parties to the decision scrutinize simulation results and related performance indicators to identify vulnerabilities in selected strategies: simulation outputs where the proposed adaptation strategy does not meet a predefined performance criterion or set of criteria and is not considered robust. In trade-off analysis (the fourth stage), analysts and parties to the decision build on the vulnerability analysis to identify the robust, better-performing strategy building on the detailed performance indicators produced in the second stage. The indicators are aggregated through automated constrained-optimization, including minimization of maximum regret and identification of the best worst-case output value (*Maximin*), which are two notoriously conservative procedures (McPhail et al. 2018). This information is used to inform expert judgment, which uses heuristic methods to decide on the strategy to adopt (Lempert and Groves 2010).

Table 1. XLRM framework for Órbigo Catchment dam construction

Element	Component
Scenarios (X)	Dam construction costs Environmental costs Pumping costs Drought return period (water supply scenarios) Reliability (water supply and dam operation scenarios)
Strategies (L)	Dam construction Status quo
Relationships/system models (R)	Projection model (Gutiérrez-Martín and Gómez 2011) Weighted-goals model (Montilla-López et al. 2018) Iteration model (Gómez-Limón et al. 2016)
Performance metrics (M)	Relative performance based on regret indicator: foregone income in status quo minus foregone income in dam construction

Parties to the decision and analysts may decide to reset the analysis and conduct a new iteration, starting from another scoping exercise (first stage) in which they revisit scenarios (e.g., to include new ones previously unaccounted for or to modify the range of previously considered scenarios) and strategies (e.g., to propose modifications to adaptation strategies that ameliorate vulnerabilities). In our application to the Órbigo Catchment, the strategies available were set following an intricate and rigid administrative and legal procedure that formally reduced the decision-making process to a choice between two strategies: dam construction versus the status quo (BOE 2018). As a result, parties to the decision did not revise the strategies initially considered (although it could not be precluded that more robust alternatives exist, such as economic instruments such as water markets). Analysts and parties to the decision did revise the scenarios.

Three complete iterations of Stages 1–4 were run until a set of scenarios was agreed upon and a strategy was chosen. Iterations were articulated around three in-person meetings (held on April 16, 2019, May 27, 2019, and July 30, 2019, involving 7/2/3, 6/2/3, and 8/3/4 participants from the DRBA/Spanish Ministry for Ecological Transition/Academia), where analysts and parties to the decision exchanged information and engaged in discussions via multiplayer role-play interaction (Appendix II). In-person meetings were complemented with virtual bilateral meetings between analysts and parties to the decision. The iterative robust decision-making process used a "scenario simulator" tool that linked scenarios with their implied consequences. The tool was progressively updated as new scenarios/scenario ranges were identified. This resulted in a set that combined prespecified scenarios suggested by analysts building on available data (traditional scenario analysis) and scenarios based on subjective judgments generated during the iterative robust decision-making process.

To inform the multiplayer role-play interaction, analysts generated a database of simulations ahead of each of the three in-person meetings using the ensemble of system models. This database evolved between meetings as the set of scenarios considered was adjusted following the iterative scenario design process discussed previously. Importantly, as an outcome to deliberation, new scenarios could also be suggested *during* the role-play interaction. In order to provide the necessary inputs to inform the multiplayer role-play discussion, analysts used the scenarios considered before the in-person meeting as a reference to define thresholds as discussed in the next section and then ran multiple simulations at even intervals as discussed in the section "Simulation Results." These simulations could be subsequently used to approximate the outputs of new scenarios suggested during the in-person meetings.

The process just described helped analysts and parties to the decision revise their objectives, options, and problem framing based on quantitative information from the models, agree on a final set of scenarios, and *identify a robust strategy.*

Scenarios (X)

The following scenario sets were considered: (1) construction, (2) environmental, (3) pumping cost (uncertainty surrounding the environmental and socioeconomic costs of dams), (4) water supply (uncertainty surrounding future climate and its impacts on water availability), and (5) dam operation (uncertainty surrounding the management of water stocks).

Dam Construction Costs Scenarios

Dam construction costs are detailed in the inception report of the La Rial and Los Morales construction project. The total of EUR 63 million (INCISA 2018), applying the standard amortization period (50 years) and interest rate (2%) (Agencia Tributaria 2019), yields an annuity of EUR 2,004,862. Since cost overruns are common in infrastructure projects in Spain, several cost overrun scenarios were initially designed. However, this was a sensitive issue during deliberations with the parties to the decision and was eventually removed in subsequent iterations of the robust decision-making process. Consideration of cost overruns would have increased the cost of the dam construction strategy across all scenarios and models while having no impact on the status quo strategy, thus making the regret performance indicator consistently more favorable toward the status quo for all scenarios and models. Since the final decision was the status quo, introducing cost overruns would not have had an impact on the decision.

Dam construction costs as they appear in the project inception report include the cost of building the dams plus a series of flanking measures "to avert environmental costs" through afforestation and other interventions to reproduce flooded ecosystems in the vicinity of the reservoir (BOE 2018); however, they leave out the foregone economic benefits from the loss of free-flowing water courses, which should be recovered as environmental costs (OJ 2000) and include watershed ecology, fish-spawning habitat, fishing, recreational services, and safety (Foley et al. 2017; Loomis 2002).

Environmental Costs Scenarios

Environmental costs are obtained using environmental valuation techniques. With "unlimited time and resources," economists would prefer to conduct original environmental valuation studies (Arrow et al. 1993). However, such original ad hoc studies are expensive and laborious. Conducting one would have consumed most (if not all) of the resources available for this study, only to obtain one of the many inputs needed. Thus, we relied on a benefit transfer method, which approximates environmental costs through estimates obtained from original studies elsewhere. A straightforward benefit transfer approach, as adopted in our research, consists in "transferring a mean estimate from another study/studies to a different context" (i.e., a mean value benefit transfer) (Rosenberger and Loomis 2003, p. 472). For example, an original study that reports the mean economic value per person of a set of ecosystem services, x, in Location A can be multiplied by the population of Location B to approximate the economic value of x in Location B. Government agencies, such as the US Army Corps of Engineers, often approve mean estimate values to avoid conducting ad hoc environmental valuation studies for every project (Honey-Rosés 2008).

Obviously, reliance on a single estimate for the benefit transfer can lead to potentially large errors. This is addressed using multiple mean value estimates, instead of just one (Honey-Rosés 2008), which in our research are used to create multiple environmental costs scenarios that more comprehensively sample scenario uncertainty. Appendix III is a literature survey from the Environmental Values Reference Inventory (EVRI 2021) on the environmental costs/benefits of dam construction/removal. Because environmental costs/benefits are typically reported as current year lump-sum (i.e., single payment) values in foreign currency per person, they need to be converted to 2019 values [using the exchange rate and GDP deflator series from the World Bank (2020)] and transformed into annuity values to be comparable with construction and pumping costs. Considering a standard amortization period (25 years/one generation) and discount rates (2%–6%) (Loomis 2002, 1996; Zhao et al. 2013), the annuity payment for the environmental costs of the dams ranges between EUR 238,269 (2% discount rate) and EUR 1,076,977 (6%) using the population in the Órbigo Catchment as a reference (156,603 inhabitants), and between EUR 3,869,929 (2%) and EUR 17,492,129 (6%) using the population in the entire Douro River Basin as a reference (2,543,527 inhabitants). A third scenario, considering the population of the whole of Spain as a reference was initially designed, but was discarded in subsequent iterations of the scenario design process.

Pumping Costs Scenarios

La Rial and Los Morales present the handicap of having to pump most of the inflows to the reservoirs (77%, or 26.1 million m^3) from the Velilla and Carrizo canals, leading to additional energy and other related costs. The design of the pumping infrastructures of La Rial and Los Morales mimics an existing infrastructure in the Payuelos Canal, which has been operating since 1993. Using yearly primary data supplied by the DRBA for the period 1999–2014 for the pumping infrastructure in the Payuelos Canal, the average pumping cost for La Rial and Los Morales is estimated at EUR $0.02/\mathrm{m}^3$. Based on consultations with the directors of the Órbigo and Esla-Valderaduey Exploitation Systems, a pumping cost interval between EUR 0.01 and EUR $0.04/\mathrm{m}^3$ was used in the simulations (Directors, Órbigo and Esla-Valderaduey Exploitation Systems, personal communication, 2019; INCISA 2018).

Full cost recovery of construction, environmental, and pumping costs is prescribed in European and Spanish legislation (OJ 2000). However, implicit subsidies to agriculture through lower cost recovery is common practice in Spain and elsewhere in Europe (Rey et al. 2019). During the first iteration of the robust decision-making process, cost recovery other than 100% was explored through partial or total (i.e., 0% cost recovery) subsidization of the dams. However, following deliberations during the robust decision-making process, cost recovery levels were eventually set at 100% in all cost scenarios in the last iteration.

Water Supply Scenarios

Analysts initially designed four water supply scenarios based on alternative future streamflow estimates. The first and second scenarios are based on historical hydrologic data for the periods 1941–2015 (long series) and 1980–2015 (short series) (CEDEX 2016), following common practice in hydrologic planning in Spain (stationary climate). The third and fourth scenarios are based on hydrologic projections from MAGRAMA's (2017) latest assessment on the impact of climate change on water resources (nonstationary climate). Streamflow estimates were used to simulate future water availability for the AWDUs of the Páramo Leonés using the DRBA's watershed planning and management software AQUATOOL (Andreu et al. 1991). The water availability estimates thus obtained can be used to determine the return period of droughts, or the frequency with which hydrologic conditions would strengthen the water allocation constraint of irrigators in the Páramo Leonés in the absence of La Rial and Los Morales dams. In conditions of stationarity, the drought return period ranges between approximately five (long series) and four (short series) years (i.e., water resources from La Rial and Los Morales are used every four to five years). Under climate change, the drought return period is estimated to range between approximately three and two years. Following the feedback from DRBA hydrologists during the iterative scenario design process, these return period estimates (two to five years) were complemented with a more extreme discretionary return period of one year (i.e., droughts develop into structural scarcity). The reason to consider this return period is that MAGRAMA's 2011 report on the impact of climate change on water resources significantly overestimated streamflow, which was adjusted downward in the 2017 report (MAGRAMA 2017, 2011); hydrologists from the DRBA voiced their concerns that this could happen again and suggested the inclusion of this discretionary scenario.

Dam Operation Scenarios

Two dam operation scenarios were developed based on the La Rial and Los Morales Project inception report (INCISA 2018). In the first one, La Rial and Los Morales are used exclusively to supply water for irrigation purposes; in the second one, they are used to supply water for irrigation purposes and to regulate minimum environmental flows in the Órbigo River in concert with the upstream Barrios de Luna Dam, which results in higher periodic water releases from La Rial and Los Morales and reduces their ability to accumulate water stock.

Water supply scenarios and dam operation scenarios were combined into a modified version of AQUATOOL 6.7.8, where La Rial and Los Morales dams are included, to simulate future water stock and the reliability of the two dams. During drought years, the expected water stock at the beginning of the irrigation campaign signals the dams' reliability. In conditions of stationarity, Los Morales is expected to be at a 100% of its capacity during drought years La Rial between 48.6% and 77.1% depending on the dam operation scenario; under climate change, Los Morales is expected to again be at 100% of its capacity during drought years and La Rial, between 42.9% and 68.6% depending on the dam operation scenario. Combined with dam capacity, reliability can be used to determine the water supply made available by La Rial and Los Morales during droughts or, alternatively, the water restriction that irrigators would experience during a drought in the absence of the dams. For example, in conditions of stationarity La Rial and Los Morales could supply up to 22.2 million m^3, or 8.2% of the 272 million m^3 of irrigation water allotment to the AWDUs of the Páramo Leonés if we consider the lower threshold of 48.6%; and up to 28.7 million m^3, or 10.6% of the water allotment to the AWDUs of the Páramo Leonés if we consider the upper threshold of 77.1%. Following the feedback from DRBA hydrologists during the iterative scenario design process, these reliability values were complemented with discretionary reliability values set between 30% and 100% in La Rial; and between 70% and 100% in Los Morales.

Strategies (L)

Our study considered two strategies: dam construction and the status quo.

Under the status quo strategy, no reservoir is built and the Payuelo irrigation system is fully developed. In the absence of dams and complementary resources from the Payuelo system, droughts would strengthen the water allocation constraint in the AWDUs of the Páramo Leonés (Fig. 1) by up to 34 million m^3 as compared with the alternative dam construction scenario (i.e., the combined capacity of the two reservoirs). This represents 12.5% of the water allocation to the AWDUs of the Páramo Leonés (272 million m^3) and would likely cause significant impacts on agricultural income.

Under the dam construction strategy, the reduction in water allocation to the AWDUs of the Páramo Leonés under the status quo is averted, although this comes at the expense of increasing water prices to recover the construction, environmental, and pumping costs of the two dams, which would also cause impacts on agricultural income (DRBA 2019). Water prices are charged to all AWDUs in the Órbigo Catchment, including the those of the Páramo Leonés and elsewhere in the Órbigo Catchment (Fig. 1), through a volumetric price.

Relationships/System Models (R): Microeconomic Ensemble Modeling

This paper uses a multimodel ensemble to sample model structural uncertainty through the ensemble spread, which complements the scenario uncertainty typically accounted for in conventional robust decision-making applications. Adding structural uncertainty to conventional scenario uncertainty sampling offers a deeper understanding of complex socioecological systems, as new sources of uncertainty not previously considered help parties to the decision to identify and address ex-ante undesirable surprises. Three standard nonlinear microeconomic positive multiattribute utility programming (PMAUP) models that rely on three calibration methods are used in the ensemble: projection (Gutiérrez-Martín and Gómez 2011), weighted goals (Montilla-López et al. 2018), and iteration (Gómez-Limón et al. 2016), which together represent the ensemble components used to sample model structure uncertainty. PMAUPs are mathematical programming models that use historical data to establish the microfoundations (i.e., preferences) explaining agents' responses through a policy-invariant utility function. PMAUP models adopt a multiagent approach to elicit the behavior of rational agents according to the theory of planned behavior (TPB). A defining characteristic of multiagent approaches is their capacity to solve autonomous constrained optimization/programming problems that account for the heterogeneity of agents (i.e., AWDUs) (Schreinemachers and Berger 2011). The assumption of rationality in an agent's observed choices means PMAUP adopts a positive approach that calibrates the parameters of an objective function that accurately reproduces observed behavior considering existing constraints: the closer the simulated decision to the observed decision, the more accurate the model. Finally, the multiattribute utility function builds on the TPB, which states that "agent's behavior is driven by the multiple attributes of objects (including but not limited to profit) and farmers' beliefs regarding these attributes" (Gómez-Limón et al. 2016, p. 21).

PMAUP models have been used in Spanish water institutions such as the DRBA to inform agricultural and water policy, notably in the context of the adaptation of river basin plans to the EU Water Framework Directive (OJ 2000). This was instrumental in ensuring understanding of the simulation outputs and informed feedback from parties to the decision. In participatory scoping during the first iteration, analysts proposed the inclusion of additional mathematical programming models to more comprehensively sample model structure uncertainty (e.g., Sapino et al. 2020); however, following deliberations with the parties to the decision, this proposal was discarded due to the inability to offer training toward an adequate understanding of the new models with the available resources.

The utility maximization problem that PMAUP models aim to solve can be mathematically stated as follows:

$$\underset{x}{Max}\, U(\mathbf{x}) = U(z_1(\mathbf{x}); z_2(\mathbf{x}); z_3(\mathbf{x}) \ldots z_m(\mathbf{x})) \tag{1}$$

$$\text{s.t.:}\, 0 \leq x_i \leq 1 \tag{2}$$

$$\sum_{i=1}^{n} x_i = 1 \tag{3}$$

$$\mathbf{x} \in F(\mathbf{x}) \tag{4}$$

$$\mathbf{z}(\mathbf{x}) \in R^m \tag{5}$$

The objective function agents aim to maximize, $U(\boldsymbol{x})$, adopts a Cobb-Douglas specification ($U(\mathbf{x}) = \prod_{p=1}^{m}(\mathbf{z}_p(\mathbf{x})^{\alpha_p})$), which yields an "accurate" representation of agent's behavior and has the advantage of having a single global optimum (Gómez-Limón et al. 2016; Sampson 1999). The objective function [i.e., $U(\mathbf{x})$] features multiple attributes, $\mathbf{z}(\mathbf{x})$, (in our case profit, risk avoidance, and management complexity avoidance through total labor avoidance) that are conflicting (e.g., profit versus risk avoidance), which ensures convexity. This means that increasing one utility-relevant attribute, say profit, will reduce another utility-relevant attribute, say risk avoidance. Attributes are measured so that "more-is-better," meaning that, all else being equal, increasing the value of an attribute increases utility. Attributes are also dimensionless and are normalized by dividing each one by its maximum feasible value. The decision variable is a vector, $\mathbf{x}$, denoting the fraction of available land allotted to each crop, x_i. The economic agent will select the vector $\mathbf{x}$ or crop portfolio that delivers the combination of attributes that maximizes its utility within a domain $F(\mathbf{x})$, which includes a number of land, water, policy, and agronomic constraints. Among these, the water constraint is of particular relevance for our simulations and can be represented as

$$\sum_{i=1}^{n} w_i x_i \leq W \tag{6}$$

The water constraint states that the summation of crop water requirements, w_i, times the share of land allotted to each crop, x_i, cannot exceed water availability per hectare, W.

Although all three PMAUP models share the same constraints and form of the objective function (Cobb-Douglas), there are significant differences in the methodology they use to determine the objective function parameters. Both the projection and the iteration method equalize the marginal rate of transformation of the efficient frontier to the marginal rate of substitution of the objective function to generate a system of equations which, after being solved, reveals the objective function parameters. The difference between the projection and iteration methods is the technique used to determine the tangency point along the efficient frontier that allows calculation of the marginal rate of transformation. The projection method establishes multiple tangency points (implying multiple solutions) by orthogonally projecting the attributes to the efficient frontier. Among all possible solutions, the one with the lowest error is chosen (the one that minimizes the distance between the simulated and observed crop portfolio and attributes). On the other hand, the iteration method projects the observed attributes through the efficiency frontier and onto an "ideal" point where the value of each utility-relevant attribute is set to its maximum (this "ideal" point is unfeasible due to convexity and trade-offs between attributes). At the intersection point with the frontier, the weights of each attribute are calculated and projected iteratively until they do not vary from one iteration to another, at which point parameters are elicited. Finally, the weighted-goals programming method does not rely on basic economic equality between the marginal rate of transformation and the marginal rate of substitution; instead, it reproduces the observed attribute values through a combination of the attribute vectors resulting from each attribute's optimization. Like the iterative method, the weighted-goals programming method provides a single solution for the parameters. The method that more closely follows standard microeconomic theory is the iteration method; however, literature suggests that it does not necessarily correlate with a more accurate representation of realized behavior (Sapino et al. 2020), which warrants the use of multiple PMAUP models to sample model structure uncertainty.

Appendix IV describes in detail the calibration procedures for the three PMAUP methods considered, including the calibration residuals used to assess goodness of fit. The attributes and data inputs used for model calibrations and simulations are described in Appendix V, and calibration results and calibration errors are presented in Appendix VI; they include a sensitivity analysis of crop portfolios and attributes of the scenarios and models considered.

Performance Metrics (M)

Performance can be assessed through relative criteria (comparison among strategies) or absolute criteria [comparison against some predetermined indicator(s)]. Relative performance criteria are usually preferred when uncertainties and simulation outcomes are manifold, and parties to the decision aim to identify strategies that perform relatively better than alternatives over a large number of scenarios—the case of dam construction versus the status quo.

As stipulated in the La Rial and Los Morales Project inception report (INCISA 2018), this paper uses a relative performance criterion based on a "regret" performance indicator that measures the difference between the (annual equivalent) foregone income (measured through "changes in Gross Value Added") in the status quo strategy and the foregone income in the dam construction strategy, where a positive (negative) value indicates a superior economic performance of the dam construction (no construction/status quo) strategy. Gross value added (GVA) is a function of returns to labor (salaries) and capital (profit), and is the indicator typically prescribed by Spanish institutions to measure economic performance of water works/policies, as in our study. Note that GVA is an imperfect indicator of welfare that excludes nonmarket value and externalities and does not capture income equality, among other factors.

The foregone income in the status quo strategy is obtained by simulating the response of each microeconomic agent in the Páramo Leonés to the irrigation restrictions (Eq. 6) that would be experienced during a drought in the absence of La Rial and Los Morales dams. These simulations are based on the reliability scenarios (i.e., combinations of water supply and dam operation scenarios) discussed in the subsection "Scenarios." Note that the relevant range of the irrigation restriction simulations that emerged from the set of scenarios agreed in the last iteration of the robust decision-making process is 5.4%–12.5%. The corresponding foregone income for each agent is obtained and aggregated for the entire Páramo Leónes area to obtain the overall economic losses. On the other hand, the foregone income in the dam construction strategy is obtained by simulating the response of each microeconomic agent in the Órbigo Catchment to the increase in water prices that results from alternative combinations of construction, environmental, and pumping costs (based on the scenarios described in the subsection "Scenarios"). Note that the relevant range for the pricing simulations that emerged from the set of scenarios agreed in the last iteration of the robust decision-making process is EUR 0.005–$0.048/\mathrm{m}^3$. The corresponding foregone income for each agent is obtained, and aggregated for the entire Órbigo Catchment area to obtain the overall economic losses. The regret indicator is calculated for every possible combination of scenarios and models. Note that income losses due to irrigation restrictions (status quo strategy) occur only during drought years whereas those in the water-pricing simulations (dam construction strategy) apply to all years (both dry and wet). In order to transform income losses in the status quo strategy into their annual equivalents, they must be divided by the return period considered (from the return period scenarios in the subsection "Scenarios").

Simulation Results

Status Quo (Irrigation Restriction Simulations)

A series of simulations were run where the water allocation constraint in the AWDUs of the Páramo Leonés is progressively strengthened at even intervals of 0.05% to sample scenario uncertainty. Fig. 3 shows the impact of reduced water availability on returns to capital/profit (measured through gross margin), labor (through hours of work), and total agricultural income (through GVA) using the three models considered (model structure uncertainty). The unlined area represents the relevant range of the irrigation restriction simulations that emerged from the set of scenarios agreed in the last iteration of the robust decision-making process, namely 5%–12.5%. The lined area shows the range of irrigation restriction simulations considered in the first and/or second iterations but excluded in the last iteration.

Irrigation restrictions trigger adaptive responses by irrigators through crop portfolio decisions, which are conditional on the choice of model. Consistent with the literature on mathematical programming models, crop portfolio decisions in the three models considered are largely driven by crop profitability (z_1), the most relevant attribute in explaining agents' behavior (see Appendix VI for calibration

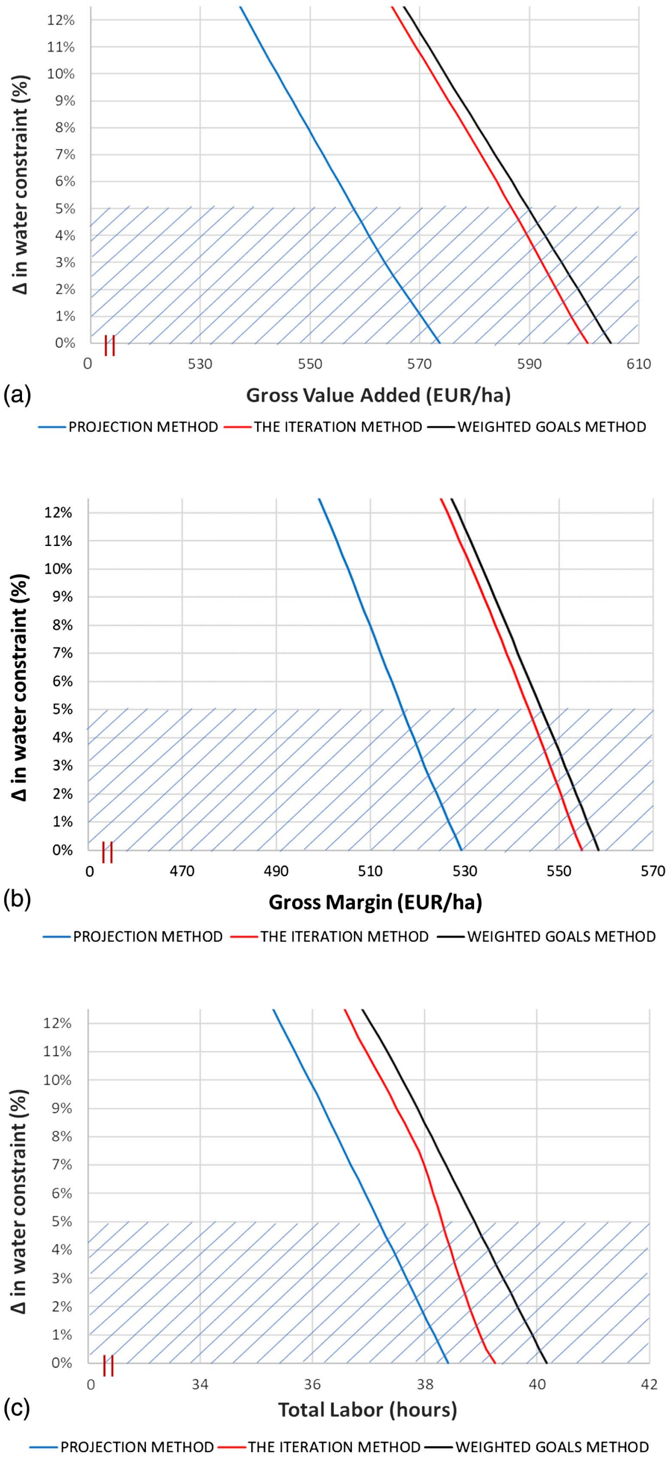

Fig. 3. Impacts of irrigation restrictions on (a) GVA; (b) profit (measured through gross margin); and (c) labor.

results). Irrigators in the Páramo Leonés respond to reductions in water allotments through land reallocations toward less water-intensive crops (extensive margin), mostly from corn to irrigated wheat; and through land reallocations from irrigated to rainfed agriculture (superextensive margin), mostly from corn to rainfed cereals while keeping constant the surface of those crops returning relatively higher profit and utility levels such as sugar beet, potato, and alfalfa. Since irrigated crops at the margin also happen to be extensive crops (wheat and corn represent 74% of the agricultural land in the Páramo Leonés), water restrictions in the interval 5%–12.5% do not affect most valuable crops and have a limited impact on profit, labor, and GVA. Although the overall trends for crop responses, profit, labor, and GVA are similar for all three models, however, there are nontrivial dissimilarities among them. For example, the estimated surface of irrigated wheat, one of the major crops in the case study area, can range between 3,400 and 5,800 ha (+70.6% difference) depending on the model considered. The surface of sunflower is also highly volatile among models and can range between 0 and 1,087 ha in the baseline without any irrigation restriction, which shows that nontrivial differences between model outputs can occur in the calibration stage (see Appendix VI for a comprehensive sensitivity analysis of attributes and crop portfolio responses to scenarios and models considered). These differences between crop portfolios have significant impacts on the GVA. Depending on the irrigation restriction simulation considered, profit can be between 4.3% and 5.8% higher for the model defining the upper threshold of the ensemble compared with the model in the lower threshold, and can be between 4.5% and 4.9% higher for labor. Accordingly, we can expect disagreements between models in terms of the preferred strategy, particularly in those scenarios where the estimated foregone income for both strategies is close.

Dam Construction (Water-Pricing Simulations)

A series of simulations were run where the water prices charged to the AWDUs of the Órbigo Catchment are progressively increased at even intervals of EUR $0.001/\mathrm{m}^3$ (scenario uncertainty). Fig. 4 shows the impact of increased water prices on profit, labor, and total agricultural income/GVA with the three models considered (model structure uncertainty). Again, the unlined area represents the relevant range for the pricing simulations that emerged from the set of scenarios agreed in the last iteration of the robust decision-making process, namely from EUR 0.005 to $0.048/\mathrm{m}^3$. The lined area reports the range of irrigation restriction simulations considered in the first and/or second iterations but excluded in the last iteration.

Unlike water restrictions, which are felt by irrigators of the Páramo Leonés only, incremental water prices apply to all irrigators within the wider Órbigo Catchment. Irrigators in the Órbigo Catchment respond to higher prices by shifting toward less water-intensive (extensive margin) and/or rainfed crops (superextensive margin) depending on the model. In the price range between EUR 0.00 and EUR $0.023–0.029/\mathrm{m}^3$ (depending on the model), irrigators respond by either progressively replacing corn with less water-intensive irrigated wheat (extensive margin adjustment—projection method); reducing the surface of wheat, other irrigated cereals, and sunflower and increasing that of rainfed crops (superextensive margin adjustment—iteration method); or keeping the irrigated surface at similar levels (weighted-goals method). This leads to nontrivial differences in the surface of crops predicted by the different models. For example, the estimated surface of irrigated wheat, one of the major crops in the case study area, can range between 2,247 ha (iteration method) and 4,170 ha (projection method) (+86%) depending on the model considered for a price increase of EUR $0.026/\mathrm{m}^3$ (see Appendix VI for details on crop portfolio responses to water prices). After a price increase of EUR $0.023–0.029/\mathrm{m}^3$ (depending on the model), the surface of corn is abruptly reduced in all three models and replaced with rainfed crops (superextensive margin adjustment—projection and iteration methods) or with a combination of irrigated and rainfed wheat (extensive and superextensive margin adjustment—weighted-goals method). The surface of corn continues decreasing in the interval EUR $0.29–0.048/\mathrm{m}^3$, where it is substituted by irrigated and rainfed wheat, rainfed

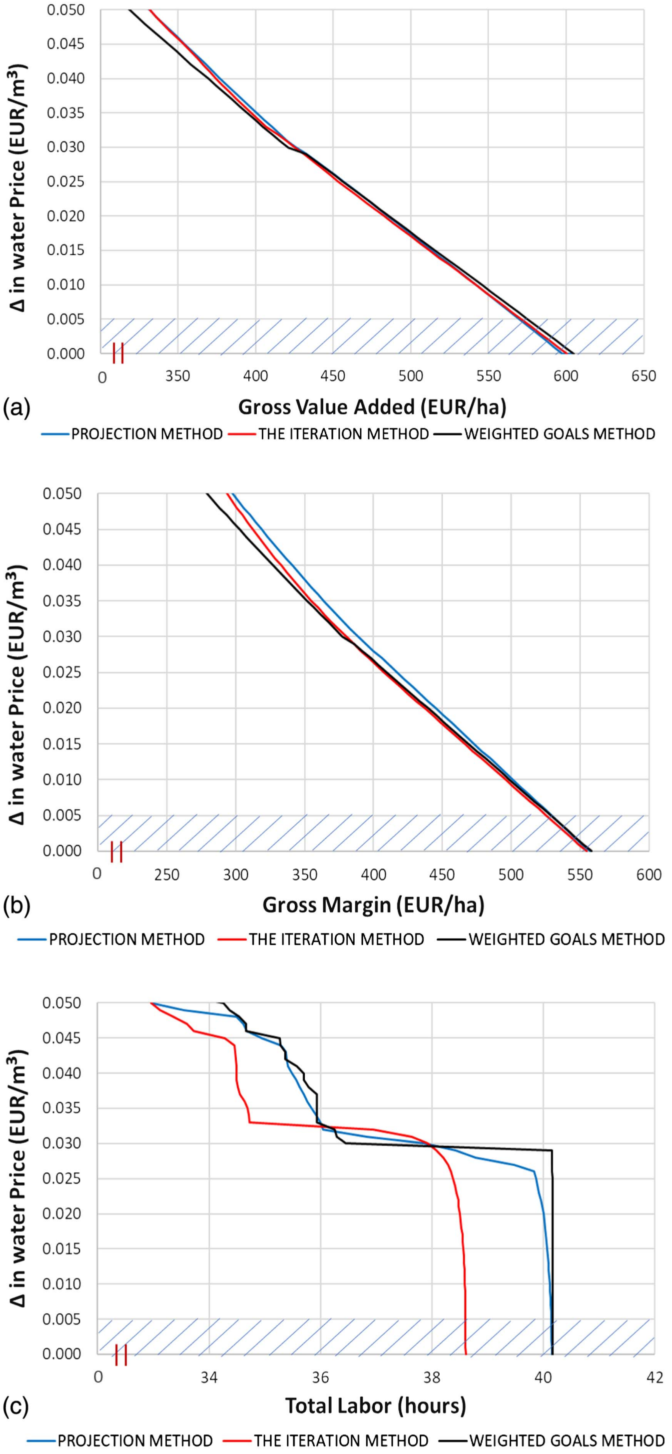

Fig. 4. Impacts of water pricing on (a) GVA; (b) profit (measured through gross margin); and (c) labor.

cereals, and rainfed sunflower (extensive and superextensive margin adjustment). Again, nontrivial differences are observed between models regarding the timing and intensity of the extensive and superextensive margin adjustment. For example, the surface of rainfed cereals can range between 497 ha (iteration method) and 3,612 ha (weighted-goals method) (+627%) for a price increase of EUR $0.030/\mathrm{m}^3$. At a EUR $0.048/\mathrm{m}^3$ price increase, the surface of corn has been reduced 25.1%–27.4% (depending on the model) with respect to the situation without water prices. The surface of cultivars returning relatively higher profit and utility levels, such as sugar beet, potato, and alfalfa, remains stable in most models and pricing simulations, with the exception of the iteration method, which predicts a reduction in the surface of sugar beet and alfalfa after a price increase of EUR $0.025/\mathrm{m}^3$, Note that even where profitable crop surfaces remain constant, the per-hectare returns from these crops is reduced due to higher water prices. Accordingly, profit and total income/GVA experience a continued and significant decrease along with higher water prices. Labor is kept constant until corn is rapidly replaced with less labor-intensive crops in the price increase interval between EUR 0.023–0.029 and EUR $0.03–0.033/\mathrm{m}^3$, which leads to a significant reduction of 10%–11% in working hours (depending on the model). Beyond the EUR $0.03–0.033/\mathrm{m}^3$ price increase interval, labor experiences a progressive reduction along incremental prices as corn is replaced by less water-intensive and rainfed crops.

Comparison of Strategies

The simulation results reported in Figs. 3 and 4 were used to compare the foregone agricultural income under the status quo and dam construction strategies for every model and combination of scenarios, and to obtain the related regret/performance indicator. Fig. 5 is an example of the tables used to convey performance indicators to the parties to the decision during the iterative robust decision-making process. In each table, the horizontal axis represents the irrigation restriction (in decreasing order from the origin, at 0.05% intervals); the vertical axis, the increase in water prices (in increasing order from the origin, at EUR $0.001/\mathrm{m}^3$ intervals). Each table cell represents a unique combination of models and scenarios (irrigation restrictions, water prices, and return period) and reports the related performance indicator. Positive (negative) values, which indicate superior economic performance the dam construction (no construction/status quo) strategy, are shown in light green (dark red). Using the scenario simulator tool, parties to the decision can navigate alternative scenario combinations in the tables and examine the associated performance of every model considered. Results for the three models were presented simultaneously in three tables, which the user could zoom in on to examine the details. Note that for some of the scenarios considered, different models offer different results in terms of the strategy preferred. The identification of this disagreement is a major contribution of our research and highlights the need for parties to the decision to consider ensembles of models when assessing the expected performance of alternative strategies under uncertainty.

Analogously to Figs. 3 and 4, the unlined area in Fig. 5 reports the range of simulations and related performance indicators that emerged from the set of scenarios agreed in the last iteration of the robust decision-making process (irrigation restrictions: 5.4%–12.5%; price increase: EUR $0.005–0.048/\mathrm{m}^3$; return period: 1–5 years—leading to 16 irrigation restrictions × 44 prices × 5 return periods × 3 models = 10,560 performance indicators). The lined area refers to the range of simulations and related performance indicators from the sets of scenarios considered in the first and/or second iterations but excluded in the last iteration. Note that the lined area is shown here for informative purposes and was not displayed during the last

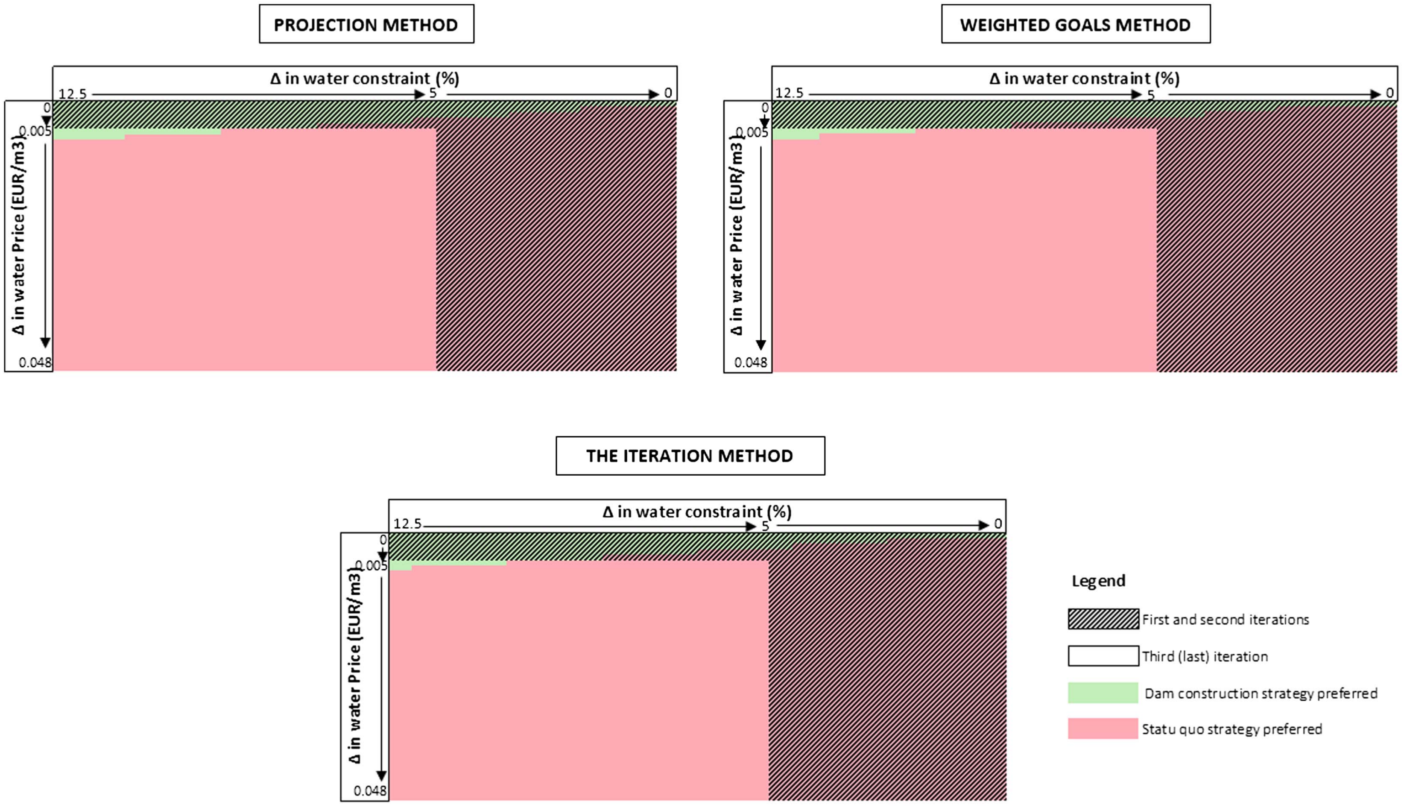

Fig. 5. Relative performance (difference in GVA) of status quo versus dam construction strategy (one-year return period).

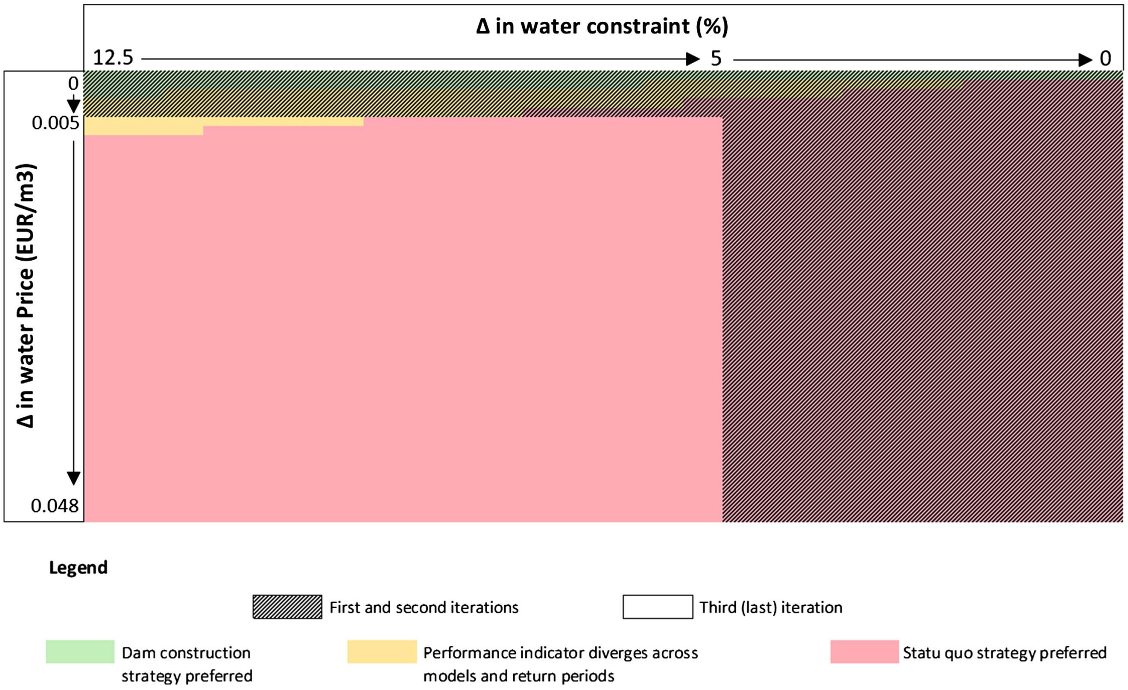

Fig. 6. Performance indicators for which dam construction strategy is preferred minus performance indicators for which the status quo strategy is preferred, for each combination of water prices and irrigation restrictions.

iteration of the robust decision-making process. Fig. 5 reports results for an illustrative 1-year return period.

Fig. 6 summarizes the relative performance of the status quo strategy versus the dam construction strategy considering all models and combinations of scenarios across two variables: water prices and irrigation restrictions. Fig. 6 assigns a value of 1 to the green cells in Fig. 5 and a value of −1 to the red cells, repeating the process for all the possible combinations of return periods and models and aggregating the results. This synthesizes the 10,560 performance indicators in the last iteration into 704 indicators that can each be shown in the cell of a single table (16 irrigation restrictions × 44 prices). Where the aggregated results favor the dam construction (no construction/status quo) strategy for all models and return periods, the cell is shown in green (red); the cells in yellow show those cases where the performance indicator diverges across models and return periods. As we add ensemble experiments to scenario uncertainties, cascading uncertainties amplify the range of forecasts and expand the area in yellow in Fig. 6. This adds new layers to decision making but also warns parties to the decision about sources of uncertainty previously not considered, which may lead to undesirable surprises.

Aggregation of the performance results in Fig. 6 shows that, for most combinations of scenarios and models considered, dam construction costs lead to water prices beyond the willingness of local cereal-growing irrigators to pay and the status quo strategy is revealed as preferred. This is particularly true for the last iteration of the robust decision-making process (unlined area), where cost recovery levels are set at 100% and water prices have a lower threshold of EUR $0.005/\mathrm{m}^3$. In fact, in the last iteration and for return periods higher than 1 year, the status quo strategy is preferred for *all* combinations of scenarios and models considered. For a return period of one year, the status quo strategy is strictly preferred to the dam construction strategy in all but 10 of the 704 scenario combinations. Of the 10 cases, the sign of the performance indicator diverges across at least two models in 4 of them. This means that the dam construction strategy is strictly preferred to the status quo strategy only in 6 of the 10,560 combinations of scenarios and models considered in the last iteration while the opposite happens in 10,550 combinations.

Importantly, it is not possible to establish with certainty which one among the 10,560 combinations of scenarios and models and related performance indicators explored in the last iteration will be realized. Different stakeholders may have different visions of the future, and perspective determines expectations on performance. In a context of deep uncertainty, determining the preferred strategy requires a robust decision-making process.

Robust Decision-Making Results

Initially, minimization of maximum regret (*MiniMax regret*) and identification of the best worst-case output value (*Maximin*) automated constrained-optimization procedures were obtained to inform deliberations. Where applied to the relevant range of simulations that emerged from the last iteration of the scenario design process (irrigation restrictions: 5.4%–12.5%; price increases: EUR $0.005–0.048/\mathrm{m}^3$; return period 1–5 years), automated constrained optimization methods showed a preference for the status quo scenario. The *Maximin* criterion—identifying for each available strategy the worst possible outcome to subsequently select the strategy that optimizes the worst possible economic result (i.e., maximization among the minimums)—revealed a strict preference for the status quo strategy for all models and scenarios considered. Application of the *MiniMax regret* criterion, which aims to minimize the risk of adopting strategies with significant regret, showed a similar outcome, with the status quo strategy being preferred in 99.8% of the combinations of scenarios and models.

Outcomes of automated constrained-optimization methods, along with the performance indicators in Fig. 5, were used as inputs to inform expert judgments based on heuristic methods through the iterative robust decision-making process described in the "Methods" section. In most iterations and for most participants, the preferred strategy matched that obtained using automated constrained-optimization methods (i.e., status quo strategy). As noted previously, some participants voiced concerns regarding future climate and hydrology, and whether this could significantly increase the return period of droughts in the area and make the two dams a prerequisite to meet yearly allotments on a regular basis. However, the high costs of dam construction resulted in water prices whose impact on agricultural income was beyond that of irrigation restrictions, including scenarios where droughts developed into structural scarcity (i.e., one-year drought return period), reliability was 100%, and resources from the projected dams were used every year. Critically, during the final meeting on July 30, 2019, *all* participants agreed that scenarios where the water price increase was below EUR $0.007/\mathrm{m}^3$ were "improbable." Note that for scenarios where the water price increase was EUR $0.007/\mathrm{m}^3$ or higher, simulation results showed the status quo strategy to be strictly preferred over the dam construction strategy (Fig. 5). Accordingly, following the three in-person meetings, the status quo strategy (i.e., no dam construction) was unanimously declared preferred to the dam construction strategy. This outcome substantiates the need for economic assessments of dam construction projects that account for nonlinear responses by agents (e.g., irrigators) to complement technical assessments in decision making: even when technically sound from an engineering perspective, dam construction projects can have poor economic performance and questionable economic rationale. This was the case for La Rial and Los Morales. It is preferable that economic analyses be based on deep/structural parameters (e.g., utility functions, preferences, resource constraints) rather than nonstructural parameters (e.g., statistical relationships based on historical data), since the latter are susceptible to change when the rules of the game are changed (e.g., a new reservoir that increases supply) and can provide misleading policy recommendations (Lucas 1976). It is also advisable to account for modeling uncertainty: as shown in this paper, nontrivial differences between the outcomes predicted in different models may emerge, potentially influencing the decision on preferred strategy.

The research outcomes discussed here led the DRBA to provisionally reject the construction of La Rial and Los Morales dams, although this decision has yet to be ratified by the Spanish Ministry for the Ecological Transition. The interim government Spain had from June 2018 decided to postpone ratification until a more stable government was constituted. Following the installation of a coalition government in January 2020, the final decision on the construction of La Rial and Los Morales dams was expected during the first half of 2020 but was delayed again because of the COVID-19 outbreak.

Conclusions

This paper assesses the economic impacts of dam construction versus no dam construction (i.e., the status quo) in the Órbigo Catchment (Spain) through computational simulations that reveal the outcomes of both strategies considering multiple models (model structure uncertainty) and scenarios (scenario uncertainty). Using an iterative robust decision-making framework, the database of simulations is coupled with experts' knowledge and opinion to identify robust adaptation strategies. Following deliberations in three in-person meetings and a series of bilateral virtual meetings, parties to the decision determined that water prices for dam construction cost recovery below EUR $0.007/\mathrm{m}^3$ were "improbable." Since the status quo was revealed to be preferred to the dam construction strategy in all simulations where the water price increase was EUR $0.007/\mathrm{m}^3$ or higher, the DRBA decided to provisionally reject the construction of La Rial and Los Morales dams.

Some key features of the study can be revisited and improved, in future research. First there is the issue of weighting among scenarios and models, which is the subject of a long-standing debate. We avoided the use of weighting; instead, simulation results were presented to the parties to the decision as shown in Fig. 5, without any weight attached to scenarios or models. It has been argued that when "probabilistic information is not considered, each potential vulnerability is equally important on the overall robustness, which can also be interpreted as an implicitly equal weighting" (Taner et al. 2019, p. 3660). On the other hand, we did not know the precise heuristic reasoning used by the parties to the decision during the iterative robust decision-making process. It may be that these parties implicitly allotted weights to some scenarios and/or models based on their experience. Therefore, we cannot state that each model/scenario was equally weighted only because we did not explicitly assign weights. The issue of weighting simulation outcomes, particularly those obtained with different models, or leaving that open to interpretation by decision makers, remains debatable.

Another aspect of our study to be revisited is the number of elements considered in the multimodel ensemble. During the first participatory scoping stage in our study, analysts proposed the inclusion of additional mathematical programming models (such as positive mathematical programming or linear programming models) in the ensemble so to more comprehensively sample model structure uncertainty; however, following deliberations with the parties to the decision, this proposal was finally discarded. The parties had noneconomist backgrounds with limited knowledge of microeconomic mathematical programming models, and they argued that understanding the functioning of additional models with a different structure, to be capable of interpreting simulation results, would demand a learning process that was not warranted given the resource constraints of the project. These deliberations drew attention to the concept of bounded rationality—how knowledge limitations, time constraints, and the tractability of the problem limit the capacity of decision makers to process relevant information. In the case of robustness-based frameworks, bounded rationality reveals a trade-off between the analyst's objective of thoroughly sampling (model, scenario) uncertainty and the limited capacity of nonexpert modelers to correctly interpret all this information (Grant and Quiggin 2013). With sufficient resources, learning can play a role in mitigating this limitation, for example through the design of successive decision-making processes of increasing complexity that "train" analysts and parties to the decision and make possible the inclusion of new and potentially relevant uncertainty layers to the problem. In our application to the Órbigo Catchment, the scenarios where the performance predicted in the three models diverged were mostly discarded by decision makers during the last iteration of the robust decision-making process (lined area in Figs. 5 and 6). This means that adding new models, in this particular case, would have no impact on the final decision. However, if scenarios where models diverged had been considered by decision makers, the use of an expanded multimodel ensemble would have been advisable to more thoroughly identify disagreements between models and identify strategies that should be avoided (and may otherwise be deemed robust where using a single model).

The models included in the ensemble can also be improved. Alternative attributes could be explored in the PMAUP models, which at present explore only profit, risk aversion, and management complexity aversion through total labor avoidance. For example, direct cost avoidance could be used as a proxy for management complexity aversion, or alternative attributes such as weather forecasts could be included; however, the introduction of additional attributes is ultimately constrained by data availability and their relevance in explaining observed agent behavior. Moreover, the current approach to the agronomic production function, which is based on the conventional mean variance method where each crop has one expected yield and one expected water withdrawal value attached, could be replaced/complemented with production functions that more accurately represent real-life crop management practices such as deficit or supplementary irrigation. This would change the structure of the models and lead to new elements in the ensemble.

Beyond specific improvements to the microeconomic ensemble, the representation of the microeconomic system could be complemented with ensembles of models representing the hydrologic and/or macroeconomic systems (e.g., Cloke et al. 2013) to assess interaction and feedback in complex human-water and human-human systems. Importantly, these improvements may conflict with the bounded rationality issue noted previously.

Additional sets of scenarios potentially relevant to dam construction elsewhere will have to be considered in future applications. For example, cost overrun was deemed a sensitive issue during our deliberations and excluded from the list of scenarios. This did not have an impact on our assessment, which selected the status quo over dam construction regardless; however, future assessments must be aware of, and incorporate this scenario since cost overruns, common in Spain and elsewhere, undermine the dam construction scenario. Regarding the iterative robust decision-making process, alternative automated constrained-optimization methods for robust decision making could be incorporated in future applications, such as the bounded rationality framework (Marshall 2013).

Finally, a comprehensive analysis of adaptation policies and adaptive behavior needs to go beyond engineering-based strategies and include soft adaptation strategies (e.g., regulations, economic instruments). In our study in the Órbigo Catchment, the omission of alternative soft adaptation strategies was warranted since the project inception report was concerned only with the economic viability of dam construction versus the status quo. Importantly, considering our study finds that dam construction strategy is not a robust option, future responses to water scarcity in the Órbigo Catchment will likely come from soft adaptation strategies, most notably economic and regulatory instruments. A similar situation will be realized in other mature water economies (Rey et al. 2019). The literature on quotas and pricing highlights the effectiveness of both strategies in addressing supply-demand imbalances, albeit at potentially large operation and design costs. Beyond the significant abatement costs that are widely reported, quotas and prices "involve a wealth transfer from agricultural water users to society and are typically met with resistance," thus increasing "institutional transaction costs (the costs of the reform) that may delay or block progress" toward their adoption (Pérez-Blanco and Gutiérrez-Martín 2017). Markets and Payment for ecosystem services, on the other hand, can generate Pareto-efficiency improvements and thus overcome these barriers, albeit they conflict with the EU's polluter-pays principle and are limited to a few pilot projects. Decision making under such uncertainties will demand the application of robustness frameworks to inform the performance of both hard and soft adaptation strategies.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

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Supplemental Materials

Additional data is available online in the ASCE Library (www.ascelibrary.org).

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