A coupled human–natural system analysis of freshwater security under climate and population change

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Limited water availability, population growth, and climate change have resulted in freshwater crises in many countries. Jordan's situation is emblematic, compounded by conflict-induced population shocks. Integrating knowledge across hydrology, climatology, agriculture, political science, geography, and economics, we present the Jordan Water Model, a nationwide coupled human–natural-engineered systems model that is used to evaluate Jordan's freshwater security under climate and socioeconomic changes. The complex systems model simulates the trajectory of Jordan's water system, representing dynamic interactions between a hierarchy of actors and the natural and engineered water environment. A multiagent modeling approach enables the quantification of impacts at the level of thousands of representative agents across sectors, allowing for the evaluation of both systemwide and distributional outcomes translated into a suite of water-security metrics (vulnerability, equity, shortage duration, and economic well-being). Model results indicate severe, potentially destabilizing, declines in freshwater security. Per capita water availability decreases by approximately 50% by the end of the century. Without intervening measures, >90% of the low-income household population experiences critical insecurity by the end of the century, receiving <40 L per capita per day. Widening disparity in freshwater use, lengthening shortage durations, and declining economic welfare are prevalent across narratives. To gain a foothold on its freshwater future, Jordan must enact a sweeping portfolio of ambitious interventions that include large-scale desalinization and comprehensive water sector reform, with model results revealing exponential improvements in water security through the coordination of supply- and demand-side measures.

water security | multiagent model | Jordan | multisector dynamics | hydroeconomic modeling

Jordan, a nearly land-locked nation, has a tenuous freshwater future. The country's water challenges stem from having extremely limited natural water availability with few alternatives for generating new supply and dependence on transboundary rivers and groundwater (Fig. 1*A*). Flows in the lower Jordan River, which marks Jordan's western border with Israel and the West Bank, are estimated to have declined by nearly 90% since predevelopment conditions (1), mostly due to the diversion of the upper Jordan River into the National Water Carrier by Israel (2). The Yarmouk River tributary, currently Jordan's primary surface-water source, is also largely captured by upstream Syria (3–6). Throughout the country, groundwater is being rapidly depleted, with observed groundwater-level declines of 0.9 to 3.5 m/y since 1995 in the country's most highly productive aquifer (7, 8). To the south, Jordan competes with Saudi Arabia for shared groundwater from the fossil Disi regional aquifer (9). Jordan has long sought construction of the Red Sea–Dead Sea conveyance project, which would desalinate Red Sea water, transport the freshwater north to Amman, and dispose of the saline brine to the Dead Sea. Although first conceived of in the 1960s, project costs and fragile international cooperation have stood in the way.

Climate change and population growth further threaten Jordan's tenuous situation (10). Rainfall decline in Jordan is already evident over the past century (11, 12), while climate models predict further increased temperatures with doubling in the frequency, duration, and intensity of droughts by 2100 (13). Jordan's growing population has been punctuated by sudden, large refugee influxes (10, 14). In 2010, Jordan's population was 7.2 million, growing to over 10.8 million by 2020, a period when at

Significance

Jordan is facing an unfolding water crisis, exacerbated by climate change and conflict-induced refugee influxes. We present a freshwater security analysis for the country, enabled by an integrated systems model that combines simulation of Jordan's natural and built water environment with thousands of representative human agents determining water allocation and use decisions. Our analysis points to severe, potentially destabilizing, declines in Jordan's freshwater security. Without intervening measures, over 90% of Jordan's low-income population will be experiencing critical water insecurity by the end of the century. To gain a foothold on its water future, Jordan must enact an ambitious portfolio of interventions that span supply- and demand-side measures, including large-scale desalinization and comprehensive water-sector reform.

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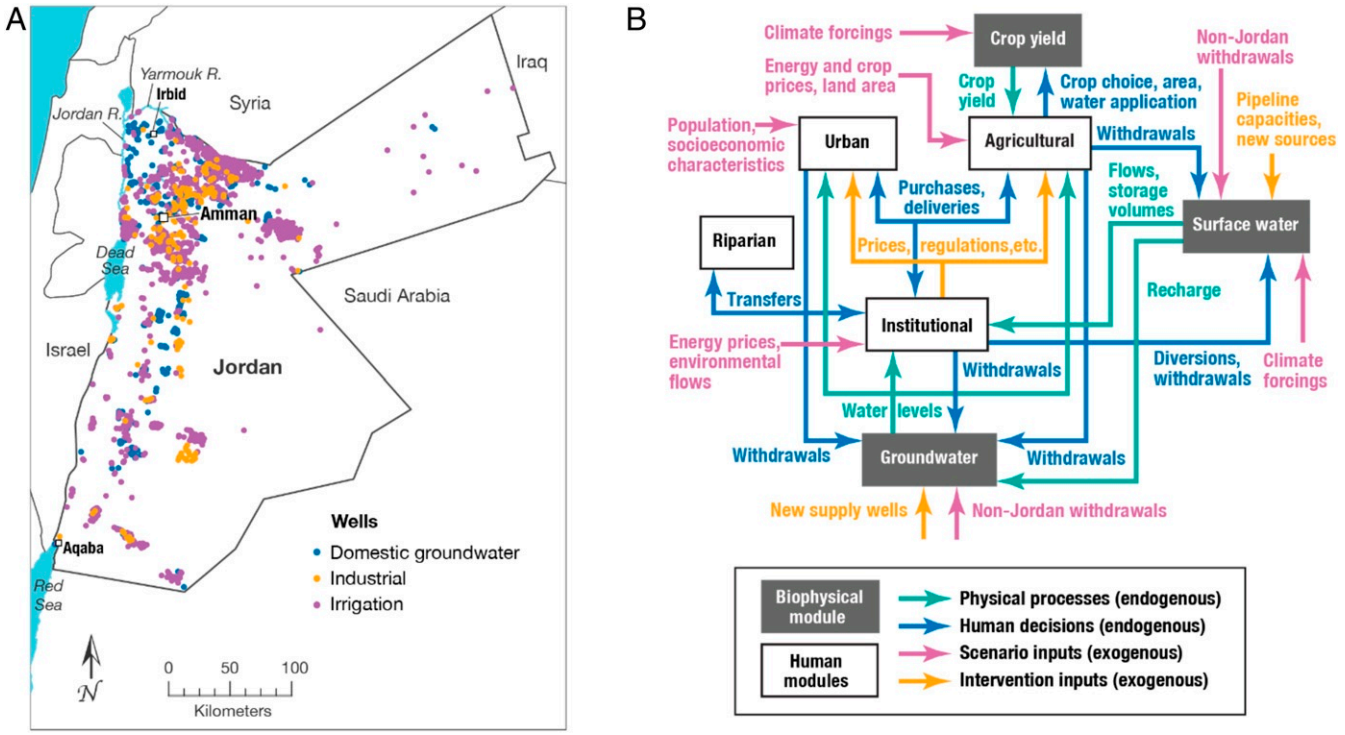


Fig. 1. Map of Jordan and conceptual model. (*A*) Jordan relies on surface-water sources (primarily the Yarmouk River) and groundwater wells for water supply. The most recent record of total freshwater use from Jordan's MWI is 1,054 MCM for 2017, with groundwater contributing 59% of the total supply, surface water 27%, and treated wastewater 14%. The domestic sector uses 45% of all water, agriculture 52%, and industry 3%. Groundwater is the primary source for the domestic sector, constituting over 70% of its supply. For the agricultural sector, groundwater constitutes 46% of the supply for irrigation, surface water 28%, and treated wastewater 26%. (*B*) The JWM consists of two types of modules: human modules (white rectangles) and biophysical modules (gray rectangles) of natural and engineered physical phenomena. The systems model includes interactions between modules, distinguished by endogenous human decisions (blue lines), endogenous physical flows and production (green lines), and exogenous scenarios (pink lines) and human interventions (yellow lines).

least 1.1 million Syrian refugees fled Syria's 2011 war to Jordan (2, 15). In response to water shortage, Jordan has implemented significant water-supply efficiencies. In Amman, the largest city and capital, over 95% of wastewater is treated and recycled. However, Jordan's water-distribution system is inefficient and intermittent. Approximately 50% of Jordan's piped supply is lost as "nonrevenue water" (NRW), due to either physical factors (e.g., pipeline leaks) or administrative issues (e.g., water theft, incorrect meter readings, or underbilling). On average, households in the capital of Amman receive piped water for only 36 h per week (16), with lower-income neighborhoods receiving as low as 24 h of municipal supply, while higher-income households receive up to 5 d of uninterrupted supply per week (17). As a result, urban users purchase expensive water delivered by tanker trucks that obtain water from private agricultural wells through both formal and informal tanker-water markets (17, 18). Ecological impacts related to both groundwater and surface-water withdrawals by Jordan and upstream riparian nations in the Jordan River Basin have been severe, with notable examples including the drying of the Azraq Oasis, a Ramsar wetland (19, 20), and the shrinking of the Dead Sea, whose shoreline is receding by ∼1 m/y (21).

The situation in Jordan is emblematic of water crises around the world, in which rapid population growth, intensifying water use, sudden demographic shocks, climate change, transboundary water competition, and institutional challenges pose serious threats to freshwater security (22–28). In the face of such global changes, an overarching sustainability goal is the long-term provision of freshwater as formalized in the 2015 Sustainable Development Goals (29). Given the complex and interacting physical and socioeconomic facets of such a challenge, there has been a growing call for analytic frameworks to evaluate freshwater systems that account for both the physical processes that govern freshwater supply and the human institutions and behaviors that influence the management, allocation, and consumption of water (30–36). Here, we present such a coupled human–natural-engineered system framework to explore the long-term impacts of a suite of policy interventions aimed at achieving freshwater security in Jordan in the face of anticipated changes in climate, population, and the economy.

Coupled Human–Natural Systems Modeling Approach

We introduce the Jordan Water Model (JWM), a nationwide, modular, multiagent water policy-evaluation model (Fig. 1*B*). This tool integrates biophysical modules that simulate natural and engineered phenomena with human modules that represent behavior at multiple levels of decision-making. The hydrologic and agricultural modules are developed by using spatially distributed, process-based, groundwater, surface-water, piped-network conveyance, and crop water-use models, capturing water-resource depletion and impacts of climate change. The human modules comprise agents, here defined as autonomous entities that make decisions in relation to one another and in response to hydrologic and socioeconomic conditions in the system. The model has 1,923 agents representing water managers, suppliers, and water-user groups across sectors. A simplified conceptual diagram of the JWM is shown in Fig. 1*B*.

The biophysical and human modules coevolve in dynamic fashion, with endogenized human decisions impacting the state of

the natural system, and the altered state of the natural system subsequently influencing human decisions as the model proceeds in time. Such dynamic interactions are further resolved across multiple spatial scales and hierarchical decision-making levels. Exogenous driving factors (e.g., precipitation or commodity prices) are used to represent changing future conditions, acting as external perturbations that are modulated through the complex system, with impacts rippling from environment to agents and from agents back to the environment across space and over time. In an illustrative subprocess for a given model time period, an institutional agent coordinates groundwater pumping for large municipal wellfields, while individual farmer agents determine pumping at local wells, each basing their pumping decisions on changing surface-water availability, local groundwater levels, cost of extraction, socioeconomic conditions, and human objectives. These pumping decisions feed into a unified physics-based groundwater module, which simulates spatially explicit hydraulic head responses in the groundwater system and establishes the updated hydrologic state for subsequent agent decisions. These multiscale, spatially distributed, coupled interactions are prevalent throughout the integrated model, including a multitude of agent–agent and agent–environment interactions.

The JWM combines these components into an integrated multiagent model for evaluation of nationwide freshwater security, rigorously attempting to capture all significant physical and human features and their interactions across an entire country's water sector. The integrated model adopts a modular structure and is implemented in an object-oriented software architecture (37), in which each module represents a specific component of Jordan's water system (*Materials and Methods* and *SI Appendix, Methods*). The model is run from 2006 to 2014 to represent historical conditions (validation results are included in *SI Appendix, Model Validation*) and from 2016 to 2100 to simulate future conditions, proceeding on monthly time increments.

Future Narratives

The JWM is used to simulate future narratives of system change through the end of the century. The narratives represent plausible future conditions and are quantitatively represented via exogenous model inputs that fall into two categories: scenarios and interventions. "Scenarios" are defined as those physical and socioeconomic conditions considered outside the scope of influence of a water policy maker or manager (e.g., climate change, commodity prices, population change, refugee influxes, etc.). "Interventions" are implementations of government policies and development of infrastructure that are within the purview of Jordanian water policy makers or managers, now or in the future. We compare model results based on "narratives," with a narrative defined as a unique combination of scenario and intervention assumptions.

The *scenario component* of the narratives is distinguished by four assumption sets, representing optimistic, drier climate, population growth, and crisis conditions. These sets are adapted from the Intergovernmental Panel on Climate Change's representative concentration pathways (RCPs) for climate projections (38, 39) and shared socioeconomic pathways (SSPs) for population and socioeconomic projections (40). For socioeconomic conditions, the growth of household incomes and commercial establishments is related to the SSP gross domestic product (GDP) projections. Two crop-price scenarios are also defined independently of the RCPs and SSPs, one in which crop prices remain steady relative to historical conditions, and a second in which crop prices increase relative to historical conditions. All monetary values in the scenario projections and future model results are adjusted for inflation and presented in year 2010 US dollar (USD) values. Socioeconomic growth assumptions are described further in *Materials and Methods* and *SI Appendix, Methods*. The scenarios also distinguish whether agricultural production in the Syrian portion of the Yarmouk River basin recovers or remains low, as has been the case in recent years, which significantly impacts transboundary river water flows into Jordan (4).

The intervention component of the narratives is distinguished by four portfolios characterizing a range of strategies that include supply enhancement, demand management, and sectoral water reallocation. Interventions represent levers that have the potential to improve Jordan's freshwater security. They include major new or modified infrastructure, such as major desalination projects (e.g., Red Sea desalination), adjustments to water prices, equalization of piped supply distribution, reduction in pipe leaks, sectoral water reallocation, and enforcement aimed at eliminating water theft. Potential interventions were identified based upon a variety of reports on Jordan's water resource and supply plans and discussions with stakeholders in Jordan's water sector, including a timeline for implementation of the various interventions. The four intervention portfolios are compared against a baseline portfolio in which the system remains at status quo (current infrastructure conditions as of the year 2019).

Combining four scenario sets and five intervention portfolios (Table 1), we generate 20 narratives that represent plausible storylines of Jordan's freshwater system trajectory. Narratives cover a broad range of future conditions involving both controllable and uncontrollable factors from the perspective of a Jordanian water policy maker.

Freshwater Security Metrics. To characterize future freshwater security in Jordan, we consider natural and human system impacts of policy interventions and scenarios represented in the 20 future narratives. *Natural system impacts* focus on temporal changes in the country's available surface-water and groundwater resources, as well as water available to different categories of consumers (e.g., farmers, urban dwellers, or industry). For *human system impacts*, we estimate per capita water-resources availability across sectors and, focusing on the domestic sector, a set of four water-security metrics quantifying vulnerability, equity, shortage duration, and economic well-being attributable to the changing water use of Jordan's household population. The freshwater security metrics are described further in Table 2.

Stress, Sensitivity, Intervention, and Counterfactual Tests. In addition to the modeled narratives, a set of stress, sensitivity, scenario/intervention, and counterfactual model tests is conducted to identify structural features, inputs, and parameters that significantly impact water-security outcomes. This suite of test runs further provides a means of evaluating the reasonability and stability of model behavior and insight into complex system interactions and interdependencies. The definition and method of implementation for each category of test run is described below.

- Stress test – Applying a percentage change to an exogenous model input (e.g., population).
- Sensitivity test – Adjusting model parameters or endogenous module inputs/outputs by a percentage (e.g., groundwater drawdown).
- Scenario/intervention test – Implementing an individual scenario assumption (e.g., RCP 8.5) or intervention (e.g., inclusion of the Red Sea–Dead Sea desalinization project) that is unpackaged from other scenario or intervention assumptions.
- Counterfactual test – Implementing a structural model modification to represent a hypothetical situation (e.g., removing the refugee agent population from the model).

To compare impacts across the tests, a set of indicators is identified that include water delivery and transfer amounts, the state

Table 1. Twenty future model narratives consisting of four scenario sets and five intervention portfolios

	Description
Scenario sets	
1) Optimistic	Moderate climate change (RCP 4.5), higher transboundary flows (agriculture in the Syrian Yarmouk remains low), moderate socioeconomic growth (SSP 2), crop prices steady
2) Drier climate	Adverse climate change (RCP 8.5), lower transboundary flows (agriculture in the Syrian Yarmouk recovers), SSP 2, crop prices steady
3) Population growth	RCP 4.5, higher transboundary flows, aggressive population growth (SSP 3)
4) Crisis	RCP 8.5, lower transboundary flows, SSP 3, crop prices increase, refugee wave in 2030
Intervention portfolios	
a) Baseline	No additional interventions
b) Supply enhancement	Red Sea–Dead Sea desalinization phase 1 (80 MCM/year), Red Sea–Dead Sea desalinization phase 2 (150 MCM/year), all other planned water supply projects (132 MCM/year), physical NRW reduction (50% of current losses)
c) Demand management	Doubling of piped water tariffs for higher tiers, equalization of piped supply availability for all household users on a per capita basis, administrative NRW reduction (50% of current losses)
d) Agriculture to urban transfer	25% transfer of groundwater production capacity from agricultural to municipal sector
e) Aggressive action	Supply enhancement plus demand management plus agricultural to urban water transfer

of the hydrologic system, agricultural sector performance, and urban water-security metrics. Changes across this set of metrics are determined for each model test, recorded as a percentage difference relative to a baseline model run. A complete list of conducted test runs is included in *SI Appendix*, *Sensitivity Analysis* and Fig. S5.

Results: Jordan's Evolving Water-Security Problem

Growing Population, Dwindling Water Resources. Across all scenario conditions, Jordan experiences significant growth in population and decrease in freshwater resources availability, resulting in marked declines in water use on a per capita basis (Fig. 2). Under moderate population growth assumed in SSP 2, the total population grows from 9.7 million to 21.4 million people by the end of the century, a 121% increase and 1.4% average annual growth rate. Under more intensive population-growth assumptions in SSP 3, the total population grows to 28.8 million, a 197% increase and 2.3% average annual growth rate. With another refugee wave of similar magnitude to the recent influx due to the Syrian war and underlying SSP 3 conditions, the total population grows to 32 million by the end of the century.

As population trends upward, available water resources shrink. Even under optimistic scenario conditions, groundwater levels decline by approximately 60% in Jordan's highly populated northern governorates, containing the largest cities of Amman, Zarqa, and Irbid, as well as some regions in the south. In over 20% of the region where groundwater is exploited, there is groundwater decline of more than 50% of saturated aquifer thickness by end of the century relative to year 2016. Declining levels result in reduced groundwater-production capacity, with a loss in production capacity of 78 million cubic meters (MCM)/year by the end of the century compared to conditions in 2016 (a 12% reduction in groundwater production capacity over this time period).

For transboundary surface water flows into Jordan from Syria, the country's most significant source of surface water in recent history, the scenarios cover two trajectories of climate change and two trajectories of Syria's utilization of the Yarmouk River (13). Surface-water availability decreases across all four combinations of these scenario conditions, with the most substantial flow decrease due to adverse climate-change impacts (RCP 8.5) and intensive irrigated agriculture upstream of Jordan in the Syrian Yarmouk basin. Under the most optimistic conditions (RCP 4.5 with low water use in Syria), average total surface-water inflow during the last two decades of the century decreases by 25% compared to the 2016–2020 period (from 232 MCM to 173 MCM).

The combined effects of growing population and declining water availability result in marked declines in per capita water use on a sectoral basis. In the optimistic-baseline narrative, annual per capita water use across all sectors decreases by over 50% from nearly 100 m^3 per person in 2020 to 43 m^3 per person by the end of the century. In the household sector, annual per capita water use decreases from 31 to 14 m^3. Agricultural water use on a per capita basis decreases from 59 to 24 m^3 annually. By the end of the century, the combined effects of population growth and shrinking water availability cut per capita water use roughly in half across all sectors. The sectoral water availability estimates are further extended across all future narratives (Fig. 3). Under worst-case conditions (baseline-crisis), annual per capita water use across all sectors drops to nearly 30 m^3 per person by the end of the century.

Widescale Decline of Household Water Security. We further evaluate water-security impacts on end consumers, translating results at the agent level to a set of metrics quantifying water availability, vulnerability, equity, economic well-being, and shortage duration that can be attributed to the changing water use of Jordan's population. For the current study, we focus our water-security analysis on the household population, though we note that commercial and agricultural end users are also represented in the model.

Results from the optimistic-baseline narrative reveal widescale decline in water security across all four metrics for Jordan's household sector, even under relatively favorable future conditions. The percentage of water-vulnerable population increases from 16 to 58% for normal-income households, while the lower-income households experience a drastic increase from 52 to 91% (Fig. 4). The Gini coefficient of water use, which provides a measure of water-use equity across the population, reveals widening disparity in water use, with the Gini coefficient increasing by 31% by the end of the century compared to conditions at the start of the model run (Gini coefficient value of 0.23 at baseline starting conditions) (Fig. 5). Shortage durations indicate that by the end of the century, higher-income households fall below the critical water-use threshold (40 L per capita per day [LPCD]) for 7 consecutive months per year on average, while lower-income households fall below this threshold for 11 consecutive months on average (Fig. 6). Economic well-being attributable to changing water use declines significantly, with higher-income households experiencing an annual consumer surplus loss

Table 2. Freshwater security metrics used to evaluate future impacts

Metric	Calculation	Description of indicator
Natural system impacts		
Groundwater depletion	Unconfined aquifer saturated thickness relative to 2016 levels at groundwater wells	Groundwater availability for water supply. Also an indicator of ecological health, as streams and wetlands are primarily baseflow-dependent ecosystems.
Surface-water availability	Total reservoir inflows relative to average historical flows	Surface-water availability for water supply. Also an indicator of aquatic ecosystem health.
Human system impacts		
Sectoral water availability	Total water available for each sector on a per capita basis	Total water availability on a per capita basis for each sector, providing an aggregate assessment of water availability for human needs.
Household water security: Vulnerability	Percentage of households receiving less than 40 LPCD on an average annual basis	Number of higher-income and lower-income households falling below a critical water-use threshold of 40 LPCD, averaged on an annual basis. Higher-income households are defined as the top 90% of household income earners, and lower-income the bottom 10%.
Household water security: Equity	Gini coefficient of per capita water use measured across the household agent population	Economic disparity in per capita water use across the household population, measured as a percentage change in the Gini coefficient relative to 2016 conditions for the optimistic-baseline narrative.
Household water security: Economic well-being	Consumer surplus changes associated with water use	Change in household economic well-being associated with changes in water use, measured as a difference in consumer surplus loss relative to 2016 conditions for the optimistic-baseline narrative.
Household water security: Shortage duration	Maximum number of consecutive months a household receives less than 40 LPCD (capped at 12)	Duration over which a household experiences water use below the critical water-use threshold of 40 LPCD.

equivalent to $340 USD relative to starting conditions, and lowest-income households experiencing a $245 USD loss (Fig. 7). This equates to a consumer surplus loss equivalent to 11% of income for the lowest-income households solely attributable to reduced water use.

Aggressive Action Needed to Bolster Jordan's Water Sector. Results from the optimistic-baseline narrative, in which widespread declines in water security are observed despite optimistic scenario assumptions, point to the critical need for identifying interventions that can bolster Jordanian water security under a precarious future. Extending our analysis, the model is run across 20 narratives combining various scenario and intervention assumptions (as detailed in Table 1). Utilizing results from the 20 model narratives, we evaluate the efficacy of various intervention portfolios toward enhancing Jordan's water security across a range of scenario conditions.

For all narratives except those in which the aggressive-action portfolio is instituted, household water vulnerability trends steeply upward, increasing up to 98% depending on the narrative and household-income category. For the lower-income population, household water vulnerability reaches over 80% for all narratives that exclude the supply-enhancement interventions. In the worst-case-scenario conditions (crisis) with no interventions, water vulnerability reaches 80% for the higher-income population and 96% for the lower-income population.

The supply-enhancement, demand-management, and agricultural-to-urban intervention portfolios result in modest improvements in water security compared to the baseline, though the percentage of water-vulnerable population still reaches at least 50% or higher for the lower-income household population by the end of the century. During the earlier portion of the time horizon (pre-2040), demand-management and supply-enhancement portfolios are comparable at curbing an increase in water vulnerability, particularly for the lower-income household population.

The demand-management portfolio contains policies aimed at distributing the existing water more efficiently and equally. Under the severe conditions approaching 2100 in the population-growth and crisis scenarios, the urban water-supply systems receive too little water to give everyone at least 40 LPCD. In this situation, providing more equal access to water actually entails reducing some households' consumption below the 40 LPCD threshold, so that other households' consumption can be lifted out of even more dire conditions (e.g., below 30 LPCD). Consequently, shortage durations measured by the 40 LPCD criterion increase under the demand-management portfolio, even though its policies still have a beneficial effect in mitigating dire conditions for a large share of the population and raising the average daily water consumption. As scenario conditions worsen and the total water supply available reaches levels of absolute scarcity, the efficacy of the demand-management interventions quickly tapers off and exacerbates water-vulnerability increases and shortage durations by the end of the century relative to the baseline (no-intervention) portfolio.

Out of the individual intervention portfolios (i.e., excluding aggressive action), the supply-enhancement portfolio is the most effective at mitigating rising water vulnerability. The aggressive-action portfolio, which combines all ameliorative interventions, results in significant mitigative effects across all scenarios. With the aggressive-action portfolio, improvements to household water security are compounded by the combined impacts of increased total supply and the redistributive effects of the demand-management interventions. Under these combined interventions, household water vulnerability remains below 20% through the end of the century under nearly all conditions (with the exception of the low-income population under crisis conditions).

The calculated Gini coefficients of water use across the modeled household agent population for all narratives are shown in Fig. 5, presented as a percentage difference in the Gini coefficient compared to starting conditions in the optimistic-baseline narrative. Besides narratives that include demand-management measures, all narratives see an increase in the Gini coefficient, indicating widening disparity in water use compared to current conditions. The demand-management portfolio results in

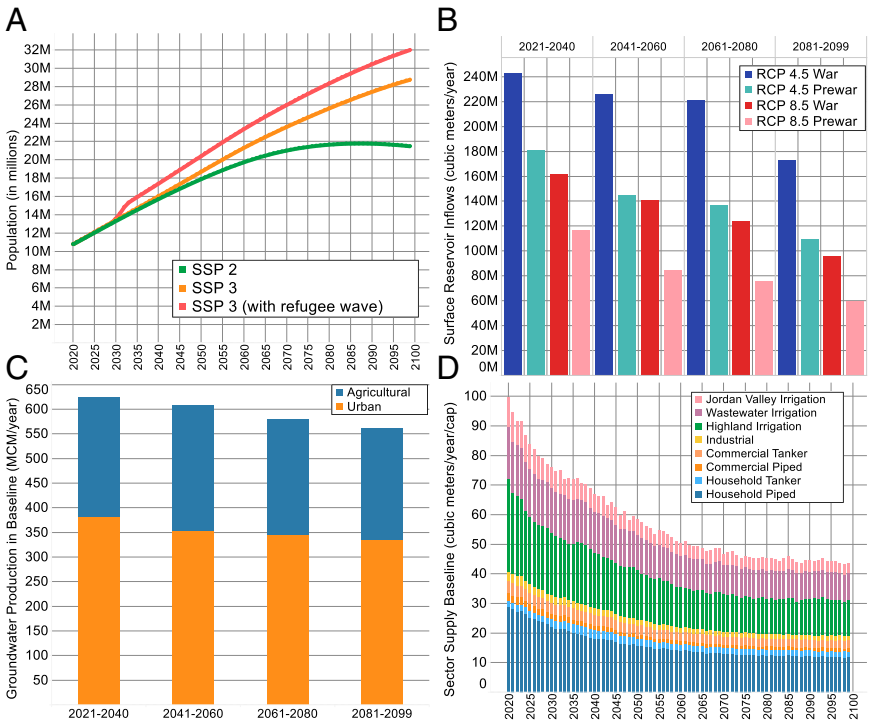


Fig. 2. Population growth and water availability in Jordan. Increasing population and decreasing water resources availability will place increasing strain on Jordan's water system. (*A*) Jordan's population increases from 9.7 million to 21.4 million people by the end of the century under moderate growth assumptions, while under crisis conditions, the total population reaches 32 million by the end of the century. (*B*) Surface-water availability decreases across all four combinations of scenario conditions, with the most substantial flow decrease due to adverse climate-change impacts (RCP 8.5) and intensive irrigated agriculture upstream of Jordan in the Syrian Yarmouk basin ("prewar" conditions). Under the most optimistic conditions, average total surface-water inflow during the last two decades of the century decreases by 25% compared to current conditions. (*C*) Even under optimistic scenario conditions, declining groundwater levels result in reduced groundwater production capacity, with a loss in production capacity of 78 MCM/year by the end of the century compared to current conditions. (*D*) In the optimistic-baseline narrative, annual per capita water use across all sectors decreases in half from nearly 100 m^3 per person in 2020 to 43 m^3 per person by the end of the century.

an improvement in equity over the entire modeled time horizon, though equity gains gradually decline as scenario conditions worsen. By the end of the century, the Gini coefficient for the demand-management narratives ranges from 29 to 34% lower (higher equity) compared to starting conditions in the baseline. The aggressive-action portfolio sees improvements in water-use equity that are largely sustained across the entire time horizon, with a 42 to 45% decrease in the Gini coefficient value (depending on scenario conditions) compared to current conditions.

The shortage-duration metric indicates the number of consecutive months that households fall below a critical water-use threshold of 40 LPCD in any given year. Prior to midcentury, baseline scenarios show similar shortage-duration values, because climate and socioeconomic impacts have yet to diverge across scenarios. By 2100, the baseline-policy scenarios exhibit a marked difference in shortage durations for 90% of the population, ranging from 6 to 10 mo between optimistic and crisis scenarios. For lower-income households, the average shortage durations asymptotically approach 12 of 12 mo per year in the latter part of the century, so differences between scenarios are muted. Most lower-income agents persistently experience a critical water shortage, while some agents remain shielded from this situation by better local supply conditions. The supply-enhancement portfolio results in significant reductions in shortage duration, though low-income households still experience up to 9 mo of consecutive shortage by the end of the century under crisis-scenario conditions. In the aggressive-action portfolio, shortage durations are curbed to between 0 and 4 mo, with the longest experienced by low-income households under crisis-scenario conditions. The aggressive-action portfolio also largely closes the disparity gap in shortage durations experienced between higher- and lower-income households.

Household water users experience significant economic losses across all narratives, measured in terms of the change in consumer surplus (the difference between the price consumers pay and what they would be willing to pay) attributable to changes in water use relative to starting conditions for the optimistic-baseline narrative. Apart from the aggressive-action portfolio, the most substantial mitigation of consumer surplus loss is observed for the supply-enhancement portfolio for lower-income households. For the early part of the century, lower-income users experience an increase in consumer surplus relative to starting baseline conditions, though these gains dissipate post-2040. The aggressive-action portfolio significantly curbs household economic loss, though higher-income households still experience an annual loss ranging from $109 to $131 USD, and lower-income households experience a loss of $34 to $56 USD, depending on the scenario conditions. In the most pessimistic narrative (baseline-crisis), population-corrected total consumer surplus loss across the entire population reaches an annual value of $691 million USD by the end of the century.

Socioeconomic versus Climate-Induced Impacts. Supplementing the narrative runs, scenario and stress tests indicate the relative importance of socioeconomic versus climate-change drivers on Jordan's future water security. In scenario tests, the implementation of SSP 3 population, GDP, and income assumptions (relative to SSP 2) result in a 10% increase in household water vulnerability, whereas implementation of RCP 8.5 (relative to RCP 4.5) increases household water vulnerability by 5%. In related stress-test runs, a 10% increase in the household population leads to an 11% increase in household water vulnerability. In contrast, a climate-related stress test imposing a 50% decrease in surface-water inflows to reservoirs only leads to a 2% increase in household water vulnerability compared to baseline conditions.

Complex System Interactions and Intersectoral Dynamics. Sensitivity tests and counterfactual simulations further highlight system interactions and reveal complex interdependencies between sectors and system components. Notable results (the full set of test run results is in *SI Appendix*, *Sensitivity Analysis* and Fig. S5) related to the household sector include:

1. A 24% increase in household water vulnerability and 18% decrease in farmer profits, if water supply via tanker markets is eliminated.

2. A no-refugee counterfactual test reduces household water vulnerability by 14%.
3. Doubling of groundwater drawdown rates results in a 10% increase in household water vulnerability.
4. A doubling of crop prices results in a 376% increase in total farmer profits and a 13% increase in household water vulnerability.
5. A 50% increase in household income results in a 24% increase in the volume of water transferred through the tanker market.
6. Implementation of the Red Sea–Dead Sea project (or a desalination project of equivalent capacity) reduces household water vulnerability by 60% and water-use disparity by 8%, while equalizing household supply durations reduces vulnerability by 6% and water-use disparity by 35%.

Discussion and Conclusion

The integrated model of Jordan's human–natural-engineered water system described here, the JWM, is an example of a comprehensive multiagent model with coupled biophysical and human modules deployed to inform water management and policy decision-making at the country scale. We demonstrate the ability to simulate thousands of consumer agents, including farms and urban users, alongside formal and informal institutions, such as government water suppliers and informal tanker water markets, that are spatially and temporally interconnected through a network of decision-making and a shared natural and built water environment. Modeled water-allocation and water-use decisions are performed by a diverse cast of modeled agents that map onto real-world water-sector actors, dynamically interacting with process-based biophysical modules that simulate the changing state of the natural and built hydrologic system.

Using the multiscale integrated model, we evaluate systemwide, sectoral, and distributional water-security impacts for a wide range of supply- and demand-side interventions under future scenarios of climate, population, and socioeconomic change to the end of the century. The multiagent approach enables the diagnosis of impacts at the level of individual agents, allowing for the evaluation of both systemwide and distributional water-security outcomes.

Our model narratives paint a sobering outlook for Jordan's future water security. Considering a range of climate and socioeconomic scenarios and a broad suite of potential interventions, results suggest severe impacts on environmental and human well-being measured in terms of water-resource depletion, per capita water supply availability, and consumer water-security impacts, the latter quantified via metrics of vulnerability, equity, shortage duration, and economic loss.

While water-security declines touch upon every segment of the population, these impacts are particularly severe for the lowest-income households. Across all narratives, households experience drastic increases in water vulnerability, as measured by the percentage of households that drop below a critical water-use threshold of 40 LPCD, reaching up to 91% of the population for the most-vulnerable, low-income segment of Jordan's population under crisis-scenario conditions without intervening measures. Widening disparity in water use across the household population is formally quantified through calculation of changes in a Gini coefficient of water use, which reveals significant declines in water-use equity, particularly in the absence of demand-management interventions. Lower-income households suffer economic losses equivalent to 12% of household income relative to current conditions and fall under the critical water-use threshold nearly 12 consecutive months on average by the closing year of the century, indicating that nearly all lower-income households cross the critical water-use threshold and never recover.

To gain a foothold on its water future, our analysis suggests that Jordan and its international partners must take aggressive action. This would entail implementing all currently planned water projects, including the full-scale Red Sea desalination project, reducing water theft and physical losses, raising piped-water tariffs on higher-water-use tiers, reallocating water from the agricultural to urban sector, and equalizing the distribution of piped water supply for urban users. With implementation of this sweeping set of infrastructure enhancements and policy measures, marked improvements are observed across all evaluated metrics. Household water vulnerability remains below 33% through the end of the century for both higher- and lower-income households across all scenarios, a dramatic

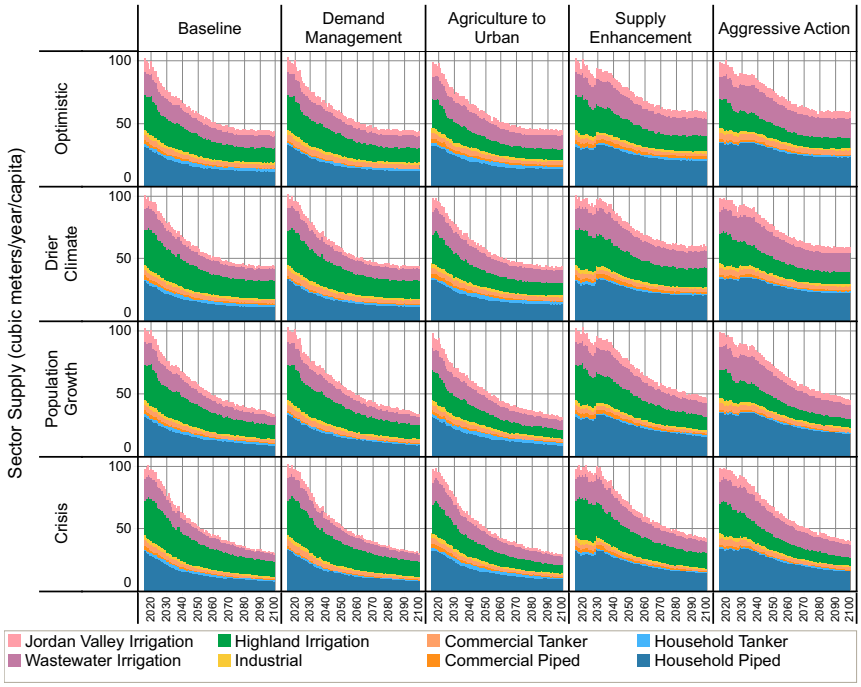


Fig. 3. Sectoral per capita water supply across future narratives. Due to a combination of increasing population and shrinking water resources availability, annual per capita water supply drops significantly across all narratives. In the baseline-optimistic narrative, annual per capita water supply totaled across sectors decreases by over 50% from nearly 100 m^3 per person in 2020 to 43 m^3 per person by the end of the century. Even under optimistic scenario conditions, with the implementation of the full suite of interventions considered in the analysis, total water supply still declines to 58 m^3 per person by the end of the century.

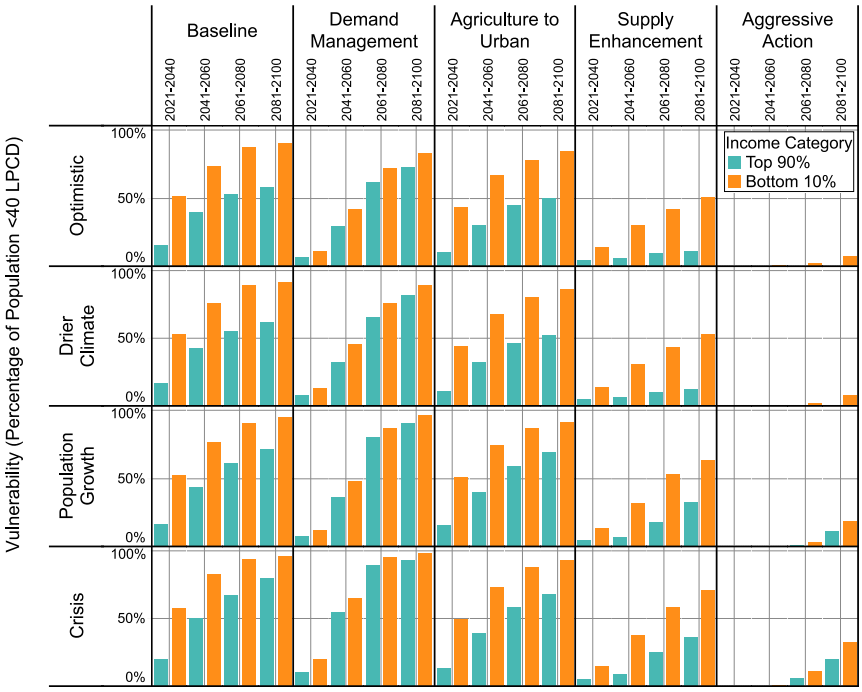


Fig. 4. Household water vulnerability across future narratives. Results for household water vulnerability across the 20 model narratives, measured as the percentage of the population that uses less than 40 LPCD averaged over a given year, are shown. Household water vulnerability is further distinguished between a low-income household category (bottom 10% of households by household income) and the rest of the population. Under optimistic conditions and no new interventions, the percentage of water-vulnerable population increases from 16 to 58% for normal-income households, while low-income households experience an increase from 52 to 91%. For all narratives except those in which the aggressive-action portfolio is instituted, household water vulnerability trends steeply upward. In the worst-case narrative (crisis scenario conditions with no interventions), water vulnerability reaches 80% for the high-income population and 96% for the low-income population. With the aggressive-action portfolio, improvements to household water security are compounded by the combined impacts of increased total supply and the redistributive effects of the demand-management interventions. With these combined interventions, household water vulnerability remains below 20% under all narratives besides for lower-income households in crisis conditions.

improvement over the baseline no-intervention portfolio. The aggressive-action portfolio further results in a substantial narrowing of the water-use disparity gap, with an improvement in water-use equity compared to current conditions that is sustained through the end of the century (as measured through the Gini coefficient of water use). In the earlier portions of the model horizon, the aggressive-action portfolio in fact results in water-security improvements compared to current conditions. As scenario conditions worsen, water security across all metrics degrades, though this decline pales in comparison to intervention portfolios that focus singularly on supply enhancement or demand management.

The multiagent approach adopted in the JWM further enables the evaluation of aggregate and distributional measures of water security and the comparative evaluation of both supply- and demand-side interventions. Results from the aggressive-action portfolio reveal the compounding benefits of packaging demand and supply measures alongside one another. Across all water-security metrics, the improvements observed in the aggressive-action portfolio cannot merely be ascribed to additive benefits from the individual interventions. Rather, the interventions work in synergistic fashion, with beneficial impacts increasing nonlinearly as interventions are combined.

A notable example of this can be observed in the crisis narratives, in which the demand-management portfolio results in a worsening of water vulnerability by the end of the century when implemented independent of supply-enhancement measures. However, when packaged with the supply-enhancement and sectoral-reallocation interventions, we see a dramatic decrease in the percentage of lower-income population that is water-vulnerable at the end of the century from 97 to 33%. With the supply-enhancement intervention alone, the percentage is only reduced to 71%, while the agriculture-to-urban intervention only sees a reduction to 93%. Similar, nonlinear effects are observed with the equity, shortage-duration, and economic-loss metrics. Although supply- and demand-management interventions are often presented as opposing alternatives in water-policy debates in Jordan and beyond, our analysis suggests that the two modes of system interventions have a mutually enhancing effect and are critically needed in tandem to bolster water security for Jordan's population.

Scenario tests further distinguish the individual contributions of climate and socioeconomic changes on water-security outcomes, indicating that socioeconomic drivers outweigh climate drivers in exacerbating water-security declines. While many studies evaluating future water security focus exclusively on climate-change impacts, our results indicate that socioeconomic changes will likely outweigh climate change in terms of detrimental impact on Jordan's water security. More rapid population growth (as represented in the SSP 3 socioeconomic scenario) results in a 10% increase in household water vulnerability relative to the baseline (RCP 4.5 and SSP 2), whereas more adverse climate conditions (as represented in the RCP 8.5 climate scenario) only result in a 5% increase. An additional refugee wave in 2030 of equal magnitude to the recent Syrian refugee wave likewise results in a 10% increase in water-insecure households relative to the baseline.

Similar outcomes are observed in the stress-test runs comparing socioeconomic versus climate drivers. When population is increased by 10%, the percentage of vulnerable households increases by 11%. In contrast, a climate-focused stress test involving a 50% decrease in surface-water inflows to reservoirs results in a mere 2% increase in water-vulnerable households. These results point to the need to carefully consider future socioeconomic changes in future assessments of water security, as these may overshadow water-supply impacts from climate change, especially for regions undergoing substantial demographic shifts such as Jordan.

Structural-model tests further reveal unexpected interactions and interdependencies across sectors and stakeholders, illustrating the importance of adequately representing dynamic agent interactions, including noncentralized supply features, such as informal water-transfer mechanisms. In Jordan, one such interconnection is notably observed between the agricultural and urban sectors, in which governmental and private agricultural actors access a shared common-pool groundwater resource. Due to municipal water-supply shortages, urban consumers supplement piped water with groundwater purchased from farmers via informal tanker markets. In counterfactual simulations, the

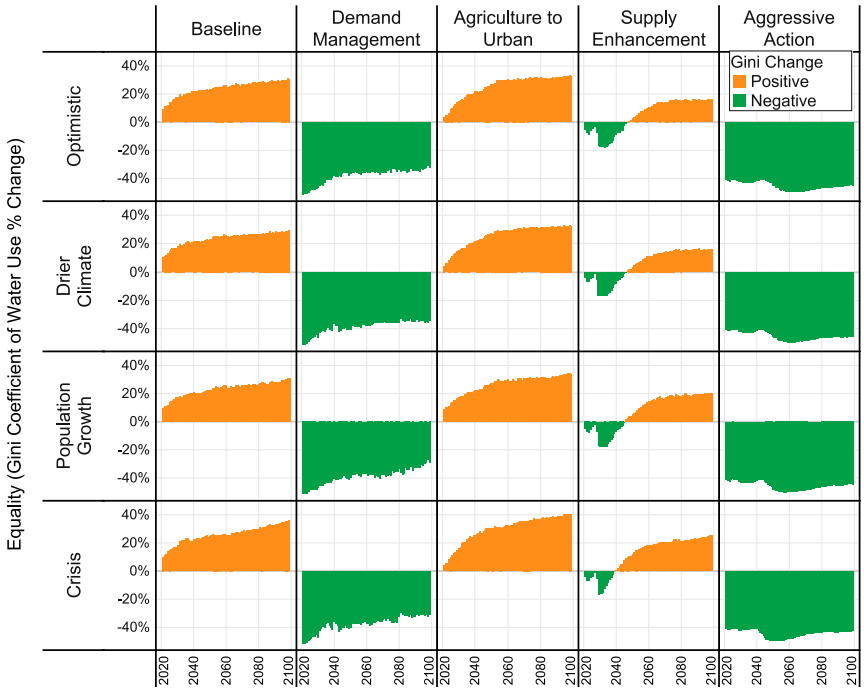


Fig. 5. Household water equity across future narratives. Household water equity is measured by calculating a Gini coefficient of water use. A maximum Gini coefficient value of 1.0 indicates the greatest disparity in per capita water use between all household agents, while a coefficient of 0 indicates complete equity in water use (i.e., per capita water use is the same across all household agents). The results are presented as a percentage difference in the Gini coefficient compared to starting conditions in the optimistic-baseline narrative. In the optimistic-baseline narrative, the Gini coefficient reveals widening disparity in water use, increasing by 31% by the end of the century compared to conditions at the start of the model run (Gini coefficient value of 0.23 at baseline starting conditions). Besides narratives that include demand-management measures, all narratives see an increase in the Gini coefficient, indicating widening disparity in water use compared to current conditions. The demand-management portfolio results in an improvement in equity over the entire modeled time horizon, though equity gains gradually decline as scenario conditions worsen. By the end of the century, the Gini coefficients for the demand-management narratives are about 30% lower (higher equity) compared to starting conditions in the baseline.

percentage of water-vulnerable households increases by 24% when tanker markets are restricted and by 13% when crop prices are doubled, illustrating the critical role tanker markets and the agricultural sector play for household water security in Jordan. Traditional modeling approaches commonly ignore such dynamics, potentially resulting in severe misdiagnosis of water security.

In the century ahead, Jordan faces the grand challenge to secure its water future. Jordan's population, already reeling from the impacts of refugee influxes, is yet expected to grow twofold to threefold by the end of the century. Meanwhile, the country's water resources will dwindle further under the impacts of climate change and groundwater mining. If Jordan carries forward passively, our integrated multiagent model results point to severe, potentially destabilizing water-security impacts on Jordan's population. To gain a foothold on its water future, Jordan needs to implement an ambitious, politically challenging portfolio of coordinated supply- and demand-side measures to mitigate water-security declines driven by socioeconomic growth and climate change. Such an undertaking presents a monumental, yet imperative, effort for Jordan and its international partners in the decades ahead.

Materials and Methods

The JWM adopts a systems-based, multiagent, modular approach, in which each module represents a specific component of Jordan's water system. The model is implemented in an object-oriented software architecture (37). The individual modules are developed and calibrated independently, and subsequently integrated by identifying significant interactions and feedbacks between system components. The integrated model consists of two generally distinguishable types of modules: 1) biophysical modules encompassing quantitative simulators of natural phenomena and built physical systems; and 2) human modules, which represent human agency at multiple levels of decision-making.

The biophysical modules include rigorous simulation of pumping impacts on groundwater depletion, watershed rainfall–runoff under historical and future climate conditions, reservoir storage changes, water-supply network routing, tracking of raw and treated wastewater, and crop water use and yields. The human modules adopt a multiagent simulation approach, capturing human decisions through autonomous model entities called agents. These agents simulate national, subnational, and consumer decision-making in response to changes in the hydrologic and socioeconomic environment and interact with each other. A total of 1,923 agents are mapped onto real-world organizations and consumer groups across the country, consisting of 804 household agents, 1,005 commercial-establishment agents, 84 farmer agents, 14 large industrial plants, and 16 institutional agents. Each individual module adopts a specific spatial resolution, with output translated to Jordan's subdistrict administrative unit (89 in total) for communication across modules.

The individual biophysical and human modules are described further in the following sections. Further implementation details for the integrated modeling framework and each of the individual modules are presented in *SI Appendix, Methods*.

Biophysical Modules. The biophysical modules consist of interacting groundwater, watershed, routing, reservoir, wastewater, and crop water-use modules that are used to simulate the major natural and engineered physical features comprising Jordan's water system.

Groundwater module. The groundwater module simulates groundwater levels in all aquifers across the country, utilizing an existing spatially distributed numerical groundwater model of the region developed by the French Geological Survey for the Jordanian Ministry of Water and Irrigation (MWI) (41). The original MODFLOW model consists of 12 layers and approximately 350,000 model cells, accounting for all major aquifers that are accessed within the country for groundwater supply. To reduce computational intensity and complexity, the three-dimensional MODFLOW model is translated into a response matrix using a linearization approach well established in the groundwater-modeling literature (42).

Watershed module. The watershed module captures surface flows for each of the main watersheds throughout the country utilizing the rainfall-runoff model, the Soil and Water Assessment Tool (SWAT) (43). SWAT models were developed for the main watersheds throughout the country, including the Yarmouk, Zarqa, Side Valleys, and Mujib/Walah surface-water basins, described in further detail in ref. 13. The SWAT models are calibrated based upon monthly streamflow data provided by the MWI.

Reservoir module. The reservoir module determines the storage volumes of the main surface-water reservoirs in the country (including Al-Wehdah, Wadi Arab, Ziglab, King Talal, Karameh, Shueib, Kafrein, Wala, Mujib, and Tannour) by accounting for reservoir inflows (from the watershed module), releases (determined by various human modules), evaporation, and other losses in a mass balance equation.

Routing module. The routing module handles routing through the main water-transmission system, ensuring that the mass balance is maintained throughout the water network. Though presented here as an independent module for descriptive purposes, the routing module is handled internally

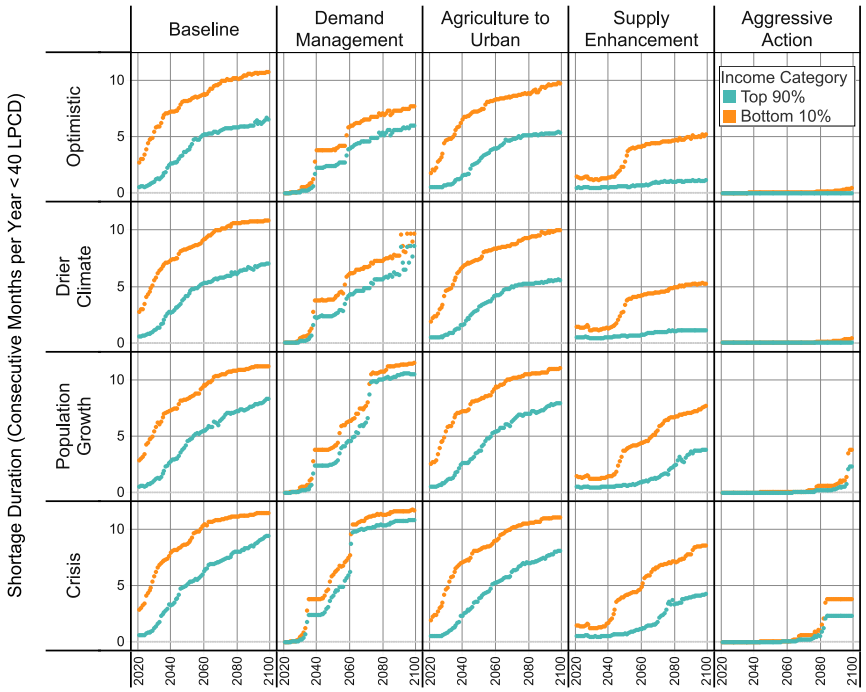


Fig. 6. Household water-shortage durations across future narratives. Household water-shortage duration is measured by the average number of consecutive months that households fall below a critical water-use threshold of 40 LPCD in any given year. For the baseline, demand-management, and agriculture-to-urban intervention portfolios, the average number of consecutive months ranges from 8 to 12 mo by the end of the century for the lower-income-household agent population and 5 to 11 mo for the rest of the population. The highest shortage durations are observed in the demand-management portfolio, with lower-income-household users reaching 12 consecutive months of water use below 40 LPCD on average by the end of the century (indicating that households persistently experience critical water shortage). The supply-enhancement portfolio results in significant reductions in shortage duration, though low-income households still experience up to 9 mo of consecutive shortage by the end of the century under crisis-scenario conditions. Shortage durations are strongly reduced in the aggressive-action portfolio to between 0 and 4 mo, with the longest shortage durations experienced by lower-income households under crisis-scenario conditions. The aggressive-action portfolio also largely closes the shortage duration gap between higher- and lower-income households.

within the Jordan Valley Authority (JVA) and Water Authority of Jordan (WAJ) modules via mass balance constraints defined in the JVA and WAJ optimization procedures. The routing module also accounts for physical NRW losses in the water-distribution network.

Wastewater module. The wastewater module is used to simulate wastewater flows from urban users (connected to the sewer system) to wastewater treatment plants and the treated effluent flows from the wastewater treatment plants to various reservoirs and irrigation water users throughout the country. For urban users connected to the sewer system, the module assumes that a fixed percentage of total water use is nonconsumptive and enters the wastewater system. Information on Jordan's wastewater system, including treatment plants, treatment-plant capacities, and treated wastewater destinations, is based on information from Jordan's National Strategic Wastewater Master Plan (44).

Crop water-use module. The crop water-use module determines the net irrigation requirements necessary to sustain historical crop yields under increasing climate-change impacts. The relationship between crop yields and irrigation requirements is captured by the relationship defined in the Food and Agricultural Organization of the United Nations 33 equation (45), which has been widely used in integrated water-resources studies (46).

Human Modules. The human modules simulate the allocation and consumption of water from the piped network, tanker-water markets, groundwater wells, and surface-water abstractions in response to changing biophysical, socioeconomic, and policy conditions. The modules allow for economic assessments of the value of water to the water users. They consist of submodules of urban and agricultural water-user agents and allocation institutions for piped and tanker water.

Urban water-user agents. A total of 1,823 representative urban water-user agents capture various types of households, refugee households, and commercial establishments across all 89 subdistricts of Jordan. These water-user agents determine their demand for piped and tanker water and their utility derived from water consumption by applying a tiered supply-curve approach (18, 47), based on econometric demand-function estimates (48) parameterized with census and survey data for households and establishments (n = 16,153). Piped-water demands account for local supply intermittency and storage constraints. Tanker-water demand is the residual demand remaining after the consumption of piped water. Projections of future agent parameters are based on the SSPs (38, 39) and regressions of income and establishment numbers onto the GDP.

Agricultural water users. The agricultural water-user module simulates farmers' crop choices in 84 subdistricts that, together with the crop water-use module, determine the groundwater abstractions for irrigation and minor uses of supplementary surface water. The module covers all agricultural areas in Jordan that are mainly irrigated with groundwater or rainfed, while the rest is covered by the JVA Module. Farmers' crop choices are determined by applying a Positive Mathematical Programing approach (49) of profit maximization. They respond to simulated temperature and precipitation developments via the crop water-use module, as well as scenario inputs capturing changes in prices, costs, or regulatory constraints on land and water use. Farmers can sell unused well-water quantities to the tanker-water market module.

Central Water Authority. The Central Water Authority (CWA) is an institutional agent that is used to represent decision-making at the national level (e.g., management of transboundary water transfers, allocations between the JVA and WAJ). The primary role of the CWA module is to determine water releases from the Al-Wehdah Dam (Jordan's largest surface-water reservoir along the Yarmouk River on the border with Syria), water transfers with Israel via Lake Tiberias, diversions from the Yarmouk River and Lake Tiberias into the King Abdullah Canal (KAC), and transfers from the KAC to Amman at Deir-Allah. The CWA adopts a hybrid optimization and rule-based approach to determine the set of decisions described above.

JVA. The JVA is the institutional authority that supplies surface water to farms in the Jordan Valley via the KAC system. The primary role of the JVA module is to minimize Jordan Valley farmers' supply–demand deficit, while also maintaining target water levels in its reservoirs, accounting for projected inflows into the KAC.

WAJ. The WAJ is a government body responsible for water allocation in the country, excluding the Jordan Valley. The module determines cost-minimizing groundwater abstractions and transfers between governorates to pursue per-capita supply targets for each of Jordan's 12 governorates. The WAJ module uses inputs on population from the urban water-user module, on network topology and capacity from the water-conveyance network module, on well-field yields and costs from the groundwater module, and on surface-water availability from transboundary sources from the CWA module.

Local piped-water-allocation institutions. Local piped-water-allocation institutions in each of Jordan's 12 governorates receive bulk water quantities allocated to their governorate by the WAJ water-conveyance network. They then distribute this bulk water quantity across all subdistrict-level urban water-user agents of the various sectors and supply duration classes within their governorate. We use an algorithm employing observed subdistrict-level piped supply durations, reflecting access to the public water network, as distribution weights in an iterative allocation of piped water to users.

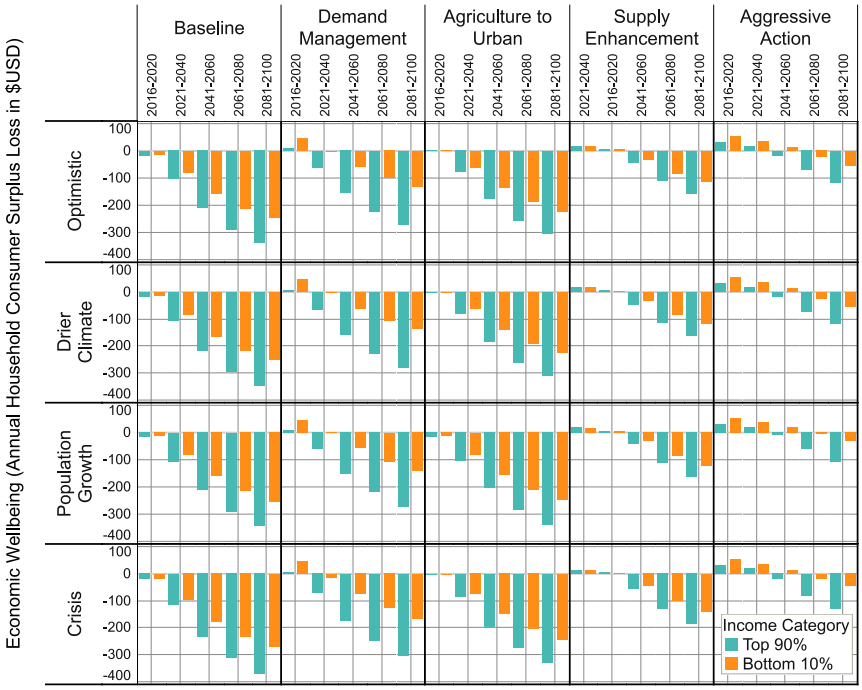


Fig. 7. Household economic well-being across future narratives. Household economic well-being is measured in terms of consumer surplus changes (attributable to changing water use) compared to starting conditions in the baseline-optimistic narrative. Consumer surplus is calculated from model results by integrating between household agents' demand curves and the costs they face. Household users experience significant economic losses across all narratives, measured in terms of the change in consumer surplus relative to starting conditions for the optimistic-baseline narrative. Consumer-surplus differences between narratives are muted, particularly comparing the optimistic scenario, which adopts SSP 2, to the population growth and crisis scenarios, which adopt SSP 3. The latter scenarios lead to lower per capita water availability, exacerbating potential consumer-surplus losses. However, lower incomes associated with SSP 3 result in reduced willingness to pay for water, offsetting those consumer-surplus losses. Apart from the aggressive-action portfolio, the most substantial mitigation of consumer-surplus loss is observed with the supply-enhancement portfolio for lower-income households. The aggressive-action portfolio significantly curbs household economic loss, though higher-income households still experience an annual loss ranging from $109 to $131 USD and lower-income households experience $34 to $56 USD loss, depending on the scenario conditions.

Tanker-water market institution. The tanker-water market institution represents all water transfers via tanker trucks on private markets across Jordan via a spatial price-equilibrium approach (50). This approach determines the welfare-maximizing set of tanker-water transfers based on the agricultural opportunity cost of water at its rural source, water-user agents' demand for tanker water, and the transportation costs required to get the water from one to the other.

Validation and Sensitivity Analyses. The integrated model is validated against observed system-level data, which are defined as observations that are dependent upon the dynamic interactions of multiple modules rather than the behavior of a single module (e.g., deliveries to consumers, water-market prices, groundwater levels, etc.) to evaluate whether the model captures historical system dynamics and patterns effectively. Validation tests, comparing model outputs to observed urban and agricultural water consumption, are presented in *SI Appendix, Model Validation* and Figs. S3 and S4. Sensitivity analyses, showing responses of various model metrics to a broad set of stress, sensitivity, intervention, and counterfactual tests, are described in *SI Appendix, Sensitivity Analyses* and Fig. S5.

Data Availability. The JWM code, including all data required to run the model, is archived at the Stanford Digital Repository and available for download (https://purl.stanford.edu/zw908ds8394).

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