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Unexpected growth of an illegal water market

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Supplementary Text 1, Methods 1:

Simulation and validation data

This section outlines the data inputs used by the Jordan Water Model (JWM) and the JWM for Tanker Water Market Analyses (JWM-T) to simulate Jordan's tanker water markets (TWMs). The remainder of the section describes which data the model uses to simulate varying conditions across simulation years (Subsection 1.1) and illustrates this with the example of the validation analyses shown in Fig. 2 of the Article (Subsection 1.2). Additional data used in estimating the demand functions that inform agent behavior in the model and corresponding sensitivity analyses are described in *Supplementary Methods 2, Water demand modeling and sensitivity analyses*.

1.1. Coupled systems simulation inputs

The JWM-T uses a coupled human-natural systems modeling approach to simulate TWMs in Jordan's 89 subdistricts in monthly time steps, accounting for monthly interactions between water users (households, businesses, farms) and institutions (water utilities, water sector authorities, TWMs), as well as between institutions and water resources. The coupled model reflects the varying biophysical and socio-economic conditions in each historical (2006-2015) and future (2016-2050) simulation year and month via (1) updating exogenous model inputs and (2) endogenous interactions between modules. The JWM-T extends the JWM's transport cost simulation, policy interventions and metrics, but uses the same inputs.

Exogenous model inputs: A comprehensive documentation of the exogenous model inputs, their data sources, and the projections used is available in Yoon et al. (2021, *Article and Supplementary Information*). The exogenous model inputs include:

Urban supply and demand modules, main exogenous inputs:

1. **Population** by subdistrict and category (permanent residents, tourists, refugees), updated monthly, future projections by Shared Socio-economic Pathway (SSP) (Riahi et al., 2007, 2017)
2. **Household income** by subdistrict, updated monthly, future projections by SSP
3. **Other household characteristics** by subdistrict (see *Supplementary Table S.1*), updated annually in the historical simulation
4. **Commercial establishment number** by subdistrict and five size categories, updated monthly, future projections by SSP
5. **Public water tariffs by governorate**, updated annually, future projections based on average household income development
6. **Technical and administrative non-revenue water** (leakage and theft) by governorate, updated annually, future projections based on policy targets
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8. **Governorate supply allocation targets** for the bulk water conveyance network, updated monthly, future projections based on governorate population developments

Agricultural and biophysical modules, main exogenous inputs:

1. **Surface water module** climate forcings (precipitation, temperature), other inflows, and agricultural land use in upstream riparians by reservoir, updated monthly, projections based on downscaled inputs for Representative Concentration Pathway (RCP) 4.5 (Yoon et al., 2021; Rajsekhar and Gorelick, 2017)

2. **Groundwater module** assumes monthly recharge values at 1x1km resolution (Yoon, 2017; Yoon et al., 2021)
3. **Yield module** climate forcings (precipitation, temperature) by subdistrict, updated monthly, projections based on RCP 4.5 (Yoon, 2017; Yoon et al., 2021)
4. **Agricultural module** crop prices for the six modeled crop categories, updated annually, projections described in *Supplementary Methods 4, Future Projections*

Endogenous variables: The exogenous inputs listed above drive changes in endogenous variables passed between modules. Interactions between the various modules related to TWMs are illustrated in *Supplementary Figure S.1.* The main endogenous variable changes are:

1. **Groundwater abstraction constraints** by subdistrict, passed monthly from the Groundwater Module to the Bulk Water Conveyance Module and the Farm Agents
2. **Groundwater pumping costs** by subdistrict, passed monthly from the Groundwater Module to the Bulk Water Conveyance Module and the Farm Agents
3. **Public water supply availability** by governorate**,** passed monthly from the Bulk Water Conveyance Module to the Governorate Water Utilities
4. **Tanker water offer quantity and price** by subdistrict, passed monthly from the Farm Agents to the TWM Module
5. **Urban water demands** by agent (see *Supplementary Methods 2.1 and 2.2, Water Demand Modeling*), passed monthly from the Urban Water User Agents to the Governorate Water Utilities and the TWM Module

These variables then shape the water allocations by the Governorate Water Utilities and the TWM Module. A comprehensive documentation of the modules and their interactions is provided in Yoon et al. (2021, *Article and Supplementary Information*).

1.2. Comparison to validation data

The use of annual historical model inputs allows for comparisons of model outputs to independent data from various years. This is demonstrated in the analyses shown in Fig. 2 of the Article. Fig. 2.b compares simulated commercial tanker water prices for 2016 to observed tanker water prices from a commercial establishment survey conducted in that year (n=343; Sigel et al., 2017). This survey used face-to-face interviews supported by business records. The price data obtained were further validated in Sigel et al. (2017) by comparing them to price data from a separate survey of tanker truck drivers (n=300). Fig. 2.c compares a simulation of sales quantities by governorate for 2015 to observed tanker truck registrations by governorate recorded by the Department of Motor Vehicles and Licensing (Sigel et al., 2017). Fig. 2.d compares simulated wastewater influent at Jordan's largest wastewater treatment plant for 2006-2012 to observed influent data[1] for the same years.

[1] Data provided to the authors by the Water Authority of Jordan, displayed in Fig. 2.d.

Supplementary Text 2, Methods 2:

Water demand modeling and sensitivity analyses

This section describes the demand modeling approach used in the Jordan Water Model (JWM) and the JWM for Tanker Water Market Analyses (JWM-T) (Subsection 2.1). Further information on the approach is available in Yoon et al. (2021, *Article and Supplementary Information*). Subsection 2.2 summarizes the econometric demand function estimates based on Klassert et al. (2018) and Sigel et al. (2017) and quantifies their uncertainty. Subsection 2.3 analyzes the sensitivity of model outputs to this uncertainty and uncertainty in tanker offer price parameters, and analyzes its effect on the tanker water market simulation results.

2.1. Water demand modeling approach

The JWM uses a tiered supply curve approach in order to model Urban Water User Agents' water demand. The approach allows for modeling demand for water from multiple sources with a single demand function estimate, by ranking the sources by their cost per m³ (Srinivasan et al., 2009). More expensive water sources are used when more affordable sources are unavailable. This approach is adapted to model tanker water demand in Jordan, when piped water is temporarily unavailable due to supply intermittency or permanently constrained due to limited connection sizes and water pressure (Klassert et al., 2015), see illustration in *Supplementary Figure S.2.* In the JWM, the public water supply constraints experienced by urban water users are determined by a piped water distribution algorithm described in Yoon et al. (2021, *Supplementary Information*, pp. 17-18), using neighborhood-level data on supply durations provided by the Water Authority of Jordan (WAJ) (WAJ, 2015). The piped water consumption outputs from a JWM simulation for 2006-2014 are validated against observed governorate-level data in Yoon et al. (2021, *Supplementary Figure S.3*), with a model fit R^2 of 0.995.

2.2. Econometric demand estimates

Household tanker water demand: Households use tanker water to balance temporary public water supply shortages and local access constraints (Potter and Darmame, 2010; Rosenberg et al., 2008; Sigel et al., 2017). In order to model this, the tiered supply curve approach is applied to an econometric estimate of residential water demand (Klassert et al., 2018), based on household-level water expenditure data from five rounds the Jordanian Department of Statistics' (DOS) country-wide Household Expenditure and Income Survey (HEIS; n=15,811; OAMDI, 2014). The study applies a maximum likelihood estimation (MLE) formulation of a Discrete-Continuous Choice (DCC) model to estimate the following residential water demand function

$$\ln(q) = \beta_0 + \beta_1 p + \beta_2 \ln(y) + Z + \eta + \epsilon \qquad (1)$$

where q is demand quantity, p is water price, y is household income, β_i are demand function coefficients, and Z is the sum-product of additional household characteristics and coefficients (see *Supplementary Table S.1*). The error terms η and ϵ account for household heterogeneity and observation errors, respectively. The DCC formulation compensates for the endogeneity problem resulting from the fact that water tariff rates are a function of the quantity consumed under Jordan's increasing block tariff (Klassert et al., 2018).

Results of the residential demand function estimation are presented in *Supplementary Table S.1.* The log-linear price coefficient yields a price elasticity of -0.24 for the average residential water tariff, which is smaller than the average value of -0.34 reported in Nauges and Whittington's (2009) review of water demand estimates for developing countries, but larger than Salman et al.'s (2008) previous estimate of -0.19 for Jordan. The income elasticity of 0.22 is within the range of 0.2-0.3 reported by Nauges and Whittington (2009). The ratio of unexplained variation in household heterogeneity (σ_η) to unexplained variation by other sources of error (σ_ϵ) is 0.83. This is moderately lower than the ratio of 1.16 found for a comparable log-linear DCC model of water demand in Vásquez Lavín et al. (2017). The two error terms translate to a constant 95% confidence interval (CI) around aggregate demand ranging from -1.1% to +1.1%, narrow due to the large sample size. This 95% CI is used in the sensitivity analysis in Subsection 2.3.

Commercial tanker water demand: Businesses in Jordan purchase a much larger share of their water supply from tanker trucks than households, due to limited piped water connection capacity and high commercial water tariffs (Sigel et al., 2017). Commercial water demand is estimated with a DCC model applied to a representative survey of commercial piped and tanker water use in summer and winter in two Jordanian cities and one rural governorate (n=343; Sigel et al., 2017), building on the modeling approach applied in Zozmann et al. (2019). A Discrete-Continuous Choice (DCC) model with the MLE formulation from Klassert et al. (2018) is used to estimate the following commercial water demand function

$$\ln(q) = \beta_0 + \beta_1 p + \beta_2 pb + \beta_3 \ln(l) + \beta_4 s + Z + \eta + \epsilon \qquad (2)$$

where $q, p, \beta_i, Z, \eta,$ and ϵ remain as defined above, l indicates the number of full-time employees, s is a Boolean variable distinguishing summer and winter observations, and b is a Boolean variable distinguishing small (1-4 employees) establishments from larger ones.

Coefficient estimates for the commercial demand function estimation are summarized in *Supplementary Table S.2.* The log-linear price coefficients translate to elasticities of -0.75 for small and -0.51 for large establishments, both well within the wide ranges of values reported in Worthington (2010) and Renzetti (2015). The two error terms result in a 95% CI of -7.4% to +8.0% used in the following sensitivity analysis in Subsection 2.3.

Agent demand parameterization: In the JWM, each coefficient of the residential demand function is parametrized with individual household characteristics for 804 subdistrict-level household and refugee household agents across Jordan, further distinguished by their average public water supply duration (1-3 categories per subdistrict) and their sewage connection status (connected, unconnected), as described in Yoon et al. (2021, *Article and Supplementary Information*). 1,005 commercial water user agents, distinguished by supply duration and size (five categories) use average country-level demand function parameters, calculated from the survey data for each of size category, and governorate-level establishment numbers by year and size category, further distributed to subdistricts in proportion to population (Yoon et al., 2021; *Article and Supplementary Information*).

2.3. Sensitivity analysis

We conduct eight JWM-T simulations for the year 2015 in order to assess the sensitivity of the tanker water market simulation results to uncertainty in the two demand function estimates and tanker offer prices. A comprehensive quantification of uncertainty in coupled human-natural systems models is challenging, as parametric uncertainty is accompanied by sampling and structural uncertainty (Srikrishnan, et al., 2022). Here, we aim to test the sensitivity of JWM-T results to two key sources of parametric uncertainty affecting our tanker water sales simulations, namely the water demand functions described above and the tanker water offer prices.

Tanker offer price uncertainty: Tanker offer prices are the sum of the opportunity cost of water at its source and the transportation cost to urban users (see *Methods, Spatial Price Equilibrium Optimization*). Transportation cost is determined by the road distance times a coefficient derived from a survey of 300 tanker truck drivers in Amman (Sigel et al., 2017). It includes fuel, labor, administrative, and maintenance costs per kilometer for the average truck. The overall 95% CI for tanker drivers' reported transportation cost coefficient components used in the JWM ranges from -10.2% to +9.2%. For the sensitivity analyses presented below, we extend the 95% CI factor obtained for the transportation cost coefficient to the relatively smaller rural opportunity cost value of water generated by the Agricultural and Groundwater Modules.

Model sensitivity to demand and price uncertainty: The uncertainty analysis is implemented by varying household and commercial demand function coefficients and tanker offer prices in the coupled model by factors equal to the upper and lower limits of the respective 95% CIs. This requires six JWM-T simulations. An additional two simulations are conducted to assess the combined impacts of (1) low demands and high offer prices, as well as (2) high demands and low offer prices. The resulting variations in household and commercial tanker water prices and purchases are shown in *Supplementary Table S.3*. The largest effects are obtained for the combined uncertainty simulations, resulting in overall tanker water consumption changes of -12.7% (lower limit) to +17.5% (upper limit).

Effect on simulated tanker water market volume: We also compare the size of demand and price uncertainty in the simulated 2015 tanker water market sales volume to license-based estimates of tanker water market size (*Supplementary Figure S.3*). The lowest tanker water sales quantity found in any sensitivity simulation is 51 million m^3 per year. This quantity is within the range between the high and the low estimate based on tanker truck registrations, described in *Supplementary Methods 3, Validation* (41-68 million m^3 per year). The highest tanker water sales quantity found in any sensitivity simulation is 69 million m^3 per year. This quantity is moderately higher than the high registration-based estimate (68 million m^3 per year), but still within the range of the log-normal 95% CI for that estimate (66-71 million m^3 per year; *see Supplementary Methods 3, Validation*).

Supplementary Text 3, Methods 3:

Model validation

Analyses of private TWMs are impeded by an inherent difficulty to obtain direct observations (Garrick et al., 2019; Whittington et al., 1991). The partly informal nature of these markets means that there are only limited public records of their activities. Direct surveys of informal or illegal activities risk exhibiting a downward bias. Jordanian water sector authorities face the same challenge. Tanker trucks require a license and are subject to public health regulations (Sigel et al., 2017). The enforcement of licensing requirements for rural wells, however, is severely limited by the fact that these wells are spread across Jordan and difficult to access (Sigel et al., 2017). Well metering is sparse and the fact that the tariff on groundwater abstractions for tanker water is 50 times higher than that for agricultural abstractions provides a strong incentive against registering a well for tanker water supply (Al-Karablieh and Salman, 2016). The simulation results presented in Fig. 2 of the Article suggest that the quantity of tanker water sold in 2015 across Jordan was 10.7 times as large as officially estimated (Fig. 2.a). Initial evidence for this order of magnitude can be found in a representative survey of commercial establishments in Jordan. The commercial piped water use after losses was 33.7 million m^3 in 2014 (MWI, 2016a). The survey finds that 56% of the establishments representing 59% of all commercial water use rely on tanker supply as their only water source (Sigel et al., 2017), suggesting that the commercial tanker sales volume alone is substantially larger than the total sales volume officially acknowledged. In order to further support these results, we rely on three types of evidence:

3.1. Piped consumption. Firstly, the JWM-T modules producing tanker water demand and supply have been validated in the Supplementary Information to Yoon et al. (2021). The results show a very good fit between modeled and observed piped water consumption values, giving support to the residual tanker water demand, as well as between modeled and observed well water abstractions, determining the tanker water supply availability and opportunity costs.

3.2. Tanker registrations. Secondly, we estimate the range of tanker water sales volumes based on survey data and from vehicle registrations: Public records from the Jordanian Department of Motor Vehicles and Licensing (DMVL) allow us to estimate the range of likely annual tanker water sales quantities. For 2015, these indicate a number of 3,251 active licenses for tanker trucks transporting potable water (Sigel et al., 2017). Annual license fees of US$247 and an obligation to participate in frequent health inspections suggest few if any registered trucks remain unused (Sigel et al., 2017). We multiply these licenses with the average weekly sales quantity from a survey of 300 tanker truck drivers (Sigel et al., 2017), larger than various previous surveys (Raina et al., 2019; Whittington et al., 1991; Wutich et al., 2016; Ahlers et al., 2013; Hailu et al., 2011). A robust Jarque-Bera test (Gel and Gastwirth, 2008) confirms that sales follow a log-normal distribution with a corrected mean of 241 m^3 per truck per week (95% CI [218.3, 265.9] m^3, determined with the Cox modified method; Olsson, 2005). This yields an estimated annual sales volume of 40.8 million m^3 of potable water (95% CI [37.0, 45.1] million m^3). In addition to this, the DMVL registers 2,192 trucks not licensed for potable water. Either these could supply an additional 27.5 million m^3 (95% CI [25.0, 30.4] million m^3) of non-potable water per year for commercial water uses, which would fall under the scope of the TWMs analyzed here, or they could partly transport water between farms. Taking this additional range into account yields an estimated total sales volume of between 40.8 and 68.4 million m^3 per year (37.0 to 75.5 million m^3 with the 95% CIs), 7.4 to 12.4 times that of the official assessment (6.7 to 13.7 times when including the 95% CI range), see *Supplementary Figure S.3*.

3.3. Market attributes. Finally, our ability to capture three attributes of Jordan's TWMs is supported by the findings presented in Fig. 2.b-d of the Article. Importantly for our economic evaluation of Jordan's TWMs, the model results for 2016 are able to capture most prices well compared to observations from a 2016 commercial establishment survey (Fig. 2.b; Sigel et al., 2017). The results significantly overestimate prices for large firms in Irbid and, to a lesser degree, in Amman. Large firms might benefit from an ability to enter large or long-term contracts in ways that the model cannot capture. While market prices are sensitive to many influencing factors, the model is able to closely approximate observed price levels and to capture differences between governorates and size groups. Modeled sales quantities exhibit a very good fit (R^2 = 99%) across space with observed registrations of tanker water trucks from official records, reported in Sigel et al. (2017) (Fig. 2.c). These data likely provide a reliable indicator of the actual number of tanker water trucks in use, since registrations require the high annual fee and regular health inspections mentioned above (Sigel et al., 2017). Fig. 2.c shows that the Amman-Zarqa agglomeration receives 29.9 million m^3 per year, exceeding the quantity abstracted in the Amman-Zarqa basin. This is unsurprising, however, as the agglomeration extends into the neighboring Azraq, Deir-Alla, and Jiza basins. Fig. 2.d illustrates that the inclusion of TWMs in the JWM model allows us to reproduce observed wastewater influent at Jordan's main treatment plant As-Samra to a higher degree. The analysis compares results from a normal historical JWM-T simulation to those from a counterfactual simulation where TWMs are deactivated. Without the additional water consumption from TWMs, simulated fall short of observed influents by 21.8% on average. The inclusion of TWMs reduces this difference to 6.2%, with the remaining deviation mostly attributable to the first year and one outlier event.

<u>Supplementary Text 4, Methods 4:</u>

Future projections

In order to project future TWM developments, we conduct an ensemble of ten simulations until 2050 with the JWM, capturing all five Shared Socio-economic Pathway (SSP) projections for Jordan (Riahi et al., 2007, 2017), climate change under Representative Concentration Pathway (RCP) 4.5 (Yoon et al., 2021; Rajsekhar and Gorelick, 2017), and alternative assumptions about future crop price developments.

The two crop price scenarios use 2000-2014 farm-gate crop price data to project either (a) a continuation of the observed mean crop prices (“constant mean”) or (b) an extension of crop price trends (“trend”), with added price volatility. The price trend is projected with Holt’s double exponential smoothing method (Hyndman et al., 2008, 2018). Price volatility is generated with random draws from a normal distribution, using the standard deviation in the historical data for the constant scenario and the standard deviation from Holt’s method for the trend scenario.

We find that the average tanker water sales quantities across the ten simulations are very close to those obtained with the baseline (“optimistic”) scenario and policy intervention assumptions for the basic JWM described in Yoon et al. (2021), which we use to project and analyze the future value of tanker water and its components. This baseline simulation includes the intermediate climate stabilization of RCP 4.5 and SSP 2 (“Middle of the Road”), as well as a conservative set of future demand policies and supply enhancements used by the Jordanian Ministry of Water and Irrigation (MWI) for planning purposes, which does not include major TWM policy changes or piped supply system improvements. As one deviation from the JWM baseline scenario, we use the alternative assumption that Syrian agriculture recovers, leading to reduced flows in the Yarmouk River (Yoon et al., 2021, *Article and Supplementary Information*).

Supplementary Text 5, Methods 5:

Policy interventions to limit groundwater extractions

Results for the policy interventions presented in Fig. 4 of the Article and assessed in the sections *Results, Public supply improvements* and *Results, Water market policy reform* are generated in JWM-T simulation runs for 2015-2050. The policy interventions are implemented by adjusting the input parameters of the JWM (supply augmentation) or via code scripts, which represent various policy interventions addressing Jordan's TWMs (equitable water distribution, well closures, tanker license cap, and household priority cap). These scripts are added to the JWM as part of the JWM-T extension. Each script updates the rate of a policy factor for the given intervention in every simulation month to target a previously determined countrywide tanker water sales quantity objective (Q^*). In the analyses conducted here, the value of Q^* is set to the total sales quantity estimated for the year 2020, of 58.6 million m³ per year. The individual policy interventions are:

5.1. Supply augmentation. The supply augmentation intervention is simulated as a 300 million m³ water input into the public water conveyance network near Aqaba, phased in during two stages (80 million m³ in 2025, 220 million m³ in 2027). It is implemented by adjusting the capacity parameter of the desalination intervention presented in Yoon et al. (2021). The intervention is based on the earlier plans to build a 230 million m³ seawater reverse osmosis plant on the Red Sea near Aqaba and a conveyor pipeline to deliver the desalinated water to Amman and the populous Northern Governorates, described in Yoon et al. (2021), as well as recent announcements to accelerate the project and expand it to 300 million m³ (Arab News, 2022; EIB, 2022; Petra, 2022).

5.2. Equitable water distribution. This intervention reflects general improvements to efficiency, reliability, and equity of the public water distribution system. The intervention is implemented by allocating water equally among all users and gradually reducing the technical non-revenue water (NRW) percentages across all governorates, representing the shares of water lost through leakages. The intervention allows the system to regain capacity that is otherwise lost to ongoing leaks. Repairing leaks is also important from a resource vantage as most productive aquifers used for urban water supply are located outside the major cities and well depths are often greater than 100 meters (Brückner et al., 2021; Goode et al., 2013). Moreover, private wells are not allowed in Jordan's cities (Rosenberg et al., 2008), largely precluding recovery near the location of leaks. Hence, any recharge to the main aquifers from leakages takes time, exposes groundwater to other forms of loss (e.g., contamination) during the process and requiring duplicative pumping costs to recover once reaching an aquifer. All technical NRW rates are multiplied by a given policy factor r_P, adjusted to meet the policy objective.

5.3. Improved distribution and augmentation. This intervention combines interventions (1) and (2) in one simulation.

5.4. Well closures. The well closure intervention mimics the current Jordanian policy approach of closing a share of known tanker wells (Al-Naber and Molle, 2017; Sigel et al., 2017). This policy is implemented by reducing the quantity offered to the TWM mechanism by each farm agent by an absolute quantity. The quantity is calculated by multiplying that farm agent's average offer quantity for that same month in previous years by a given policy factor r_W. The policy, thereby, affects farm agents in proportion to their past TWM activity.

5.5. Tanker license cap. The license cap intervention reflects the imposition of a quantity constraint on the TWM mechanism in a way that allows for an efficient allocation of the constrained sales quantity. In practice, this constrained optimization result could be approximated by limiting the number of available water tanker licenses. Tanker trucks already face a substantially more stringent monitoring regime than wells (Sigel et al., 2017), as illustrated in *Supplementary Figure S.3*. The accuracy of the intervention could be enhanced by monitoring and potentially regulating the number of trips per vehicle via log books or satellite tracking devices, potentially aided by technological support from other countries. Future advances in remote sensing could further reduce monitoring costs (Zhang et al., 2022). In the model, the intervention is implemented by imposing an additional constraint (r_T) on the TWM optimization, which limits the total sales quantity.

5.6. Household priority cap. The household priority cap implements the same overall capacity constraint on tanker licenses as the tanker cap (Subsection 5.5). It prioritizes household tanker water purchases by imposing caps of different severity on licenses for water deliveries to households and to commercial establishments. Precedents for such a separation can be found in the existing tanker truck fleets for drinking water, agricultural water, and construction water, which have separate licenses and can be identified by different vehicle colors (Sigel et al., 2017).

The modeled intervention builds on the tanker license cap intervention. The constraint on tanker water sales to households (r_{TH}) is determined by multiplying the tanker license cap parameter with a household share coefficient $s_H \in [0, 1]$:

$$r_{TH} = s_H r_T \tag{3}$$

The constraint on tanker water sales to commercial establishments (r_{TC}) is determined as:

$$r_{TC} = \max(0, (r_T - r_{TH})\,) \tag{4}$$

The initial value of s_H is the average ratio of household tanker water sales to total tanker water sales, calculated from a 2015-2020 baseline simulation. Over the course of the simulation, the value of s_H rises in proportion to population.

The factors r_P and r_W and are adjusted each month to minimize the deviation of the past months' total tanker water sales quantity from Q^*. The factor r_T requires no monthly adjustments, since it directly acts as an upper bound constraint on the spatial price equilibrium optimization.

5.7. Note on public water tariff reforms. Reforms of piped water tariffs could support the financial viability of the investments to improve public water supply outlined above (Subsections 5.1-5.3). While tariff reforms are beyond the scope of this study, previous analyses provide insight into their potential: Kubursi et al. (2011) find that water tariffs in Jordan are substantially below the scarcity value of water and fall short covering the operation and maintenance cost of the public water supply system. Al-Saidi and Dehnavi (2019) identify affordability as a key consideration in Jordan's urban water pricing policies. A simulation of alternative tariff structures for Jordan finds that substantial increases cost recovery in residential water tariffs can only be reconciled with affordability and household water security, if Jordan's increasing block tariff structure is reformulated to account for household size (Klassert et al., 2018).

Commercial piped water tariffs in Jordan are used to cross-subsidize other uses, with average rates near the level of tanker water prices (Sigel et al., 2017). Jordan's water authorities, therefore, only have limited leeway to raise commercial water tariffs without risking to lose high-revenue customers (Gerlach and Franceys; Sigel et al., 2017). A separation of household and commercial tanker truck fleets, as described in Subsection 5.6 (household priority cap) might create new opportunities to address this challenge that could be analyzed in future research.

Supplementary Text 6, Results 1:

Public supply improvements

The TWM projections raise the question: Would public supply investments currently considered in Jordan improve water security sufficiently to reduce or at least stabilize TWM demand and externalities? We find that even a large-scale supply augmentation by more than 50% can only stabilize groundwater abstractions if it is combined with network investments achieving a more equitable water distribution.

6.1. Supply augmentation. Water authorities in Jordan have long sought to augment public water supply by building a large-scale desalination plant on the Red Sea, originally combined with a water trading agreement with Israel to get water to Jordan's densely populated north (Whitman, 2019). Recent plans aim to produce 300 million m³ per year of desalinated water by 2027, conveyed from the Red Sea to Amman via pipeline (see *Supplementary Methods 5.1*). Desalination can have substantial negative environmental impacts that would need to be considered in the implementation (Elsaid et al., 2020). In Fig. 4 of the Article we test the resulting supply augmentation in a JWM-T simulation until 2050 and find that it would cause a reduction of tanker water sales below average 2015-2020 levels from 2027 to 2032, after which sales would rise again (Fig. 4.a). Notably, this vast expansion of the public water supply sources by more than 50% (MWI, 2017) would maintain only a moderate impact on TWM sales in 2050, reducing them from 95 to 76 million m³ per year.

6.2. Remaining inequity. Supply augmentation on its own does not address the high inequality in Jordan's public water distribution that causes supply shortages and TWM demand. In the baseline case, the severely vulnerable share of the population, receiving less public water supply than the World Health Organization minimum requirement of 20 liters per person per day, grows to 11% until 2050. The supply augmentation reduces this severe public supply vulnerability below 2%, but does not eliminate it (Fig. 4.c). 15% of households remain substantially vulnerable (Fig. 4.b).

6.3. Equitable distribution. Investing in a more equitable public water distribution system to reduce shortages is a key policy recommendation for addressing informal TWMs (Shah, 2007; Gerlach and Franceys, 2009). We find that Jordan could prevent any further expansion of household tanker water sales beyond average 2015-2020 sales through 2050, if it phased out public supply intermittency, provided equal access to all users, and gradually eliminated leakages (see *Supplementary Methods 5.2*). The investment would reduce the overall growth of uncontrolled annual abstractions from stressed aquifers in 2050 to just +19%, compared to +64% in the baseline case (Fig. 4.a).

Substantially improving the distribution system would naturally be highly beneficial for households, assuming that piped water tariffs remained lower than tanker water prices. An equitable and nearly loss-free distribution system would keep severe public supply vulnerability at zero (Fig. 4.c). Such substantial improvements, however, are difficult to implement in practice, due to high investment needs and because reversing supply intermittency is much more challenging than introducing it (Laspidou and Spyropoulou, 2017). While reduced levels of water losses and theft have been achieved in the past, a complete restoration is likely infeasible.

6.4. Improved distribution and desalination. Combining desalination with a more equitable and efficient public water distribution system would achieve stabilization of tanker water abstractions at present levels (Fig. 4.a) and eliminate severe vulnerability (Fig. 4.c), while only requiring water losses to be reduced to half of their current rate. This would, however, require two highly capital-intensive investment efforts whose feasibility is uncertain. Tariff reforms could support these efforts by enhancing cost recovery in public water supply (see *Supplementary Methods 5.7*).

Supplementary Text 7, Results 2:

Water market policy reform

Unless investments completely alleviate public supply shortages, TWMs will remain part of Jordan’s urban water supply. Can tanker water market reforms contribute to stabilizing TWMs’ groundwater abstractions while maintaining water security?

7.1. Institutional preconditions. Comparative analyses of water markets have established institutional preconditions to facilitate an efficient re-allocation of water under various hydrological and socio-technical contexts (Wheeler et al., 2017; Teytelboym, 2019; Wheeler and Garrick, 2020). For informal TWMs, important preconditions are low transaction costs relative to potential trade gains, a sufficient level of competition, and an absence of substantial water abstraction externalities (Garrick et al., 2019; Wheeler and Garrick, 2020; Garrick et al., 2023). Our finding that tanker water is sold at prices near marginal costs suggests that neither transaction costs nor market power pose substantial barriers to sales on Jordan’s TWMs. Their main inefficiency stems from uncontrolled groundwater abstractions. Recent studies have assessed Jordan's well regulations as ambitious yet challenged by severe enforcement obstacles, and have suggested indirect approaches to improve enforcement (Al Naber and Molle, 2017).

7.2. Improved monitoring and enforcement. We find that such an indirect enforcement has the potential to stabilize groundwater abstractions more cost-effectively than Jordan’s existing enforcement approach. The core of Jordan’s current strategy to implement groundwater regulations is to gradually close known illegal agricultural and tanker wells (Sigel et al., 2017; Al Naber and Molle, 2017). This approach has raised concerns about being particularly inefficient and selectively enforced (Al Naber and Molle, 2017).

We compare this to an example of an indirect enforcement intervention that leverages the existing licensing system for tanker trucks. Tanker trucks, in contrast to tanker wells, are subject to stringent monitoring, including annual registration fees and regular health inspections (Sigel et al., 2017). The intervention enforces a cap on the number of active vehicles to reduce tanker abstractions. While the analysis presented here models the potential impacts of this intervention on TWMs and groundwater abstractions, additional assessments of its practical and political feasibility are needed.

The impacts of the well closure and tanker license cap policies on TWM sales and groundwater abstractions are tested in JWM-T simulations until 2050, presented in Fig. 4 of the Article (see *Supplementary Methods 5.4, 5.5*). We assume that enforcement efforts for each policy are intensified until groundwater abstractions are stabilized at the average 2015-2020 level. Both policies achieve this objective (Fig. 4.a). The license cap, however, is much more cost effective, requiring only 32% of the reduction of the net benefits of TWMs compared to the well closure policy by 2050 (*Supplementary Figure S.4*). Closing known illegal tanker wells means tanker trucks have to rely on fewer licensed wells and travel further out to remaining unlicensed wells, resulting in particularly high costs per m^3 of water supplied (Fig. 4.f and *Supplementary Figure S.5*). This supports the concerns about the inefficiency of the current policy (Al Naber and Molle, 2017).

7.3. Maintaining household water security. While the license cap policy achieves a more cost-effective stabilization of groundwater abstractions, it reduces the tanker water available to vulnerable households by nearly 50% (Fig. 4.e). This could be avoided by allowing water sales to households to grow in proportion to the population. We analyze a modified version of the license cap policy, which prioritizes household water use. It pursues the same groundwater abstraction target as the license cap by separating licenses for sales to households and commercial users, and gradually reducing the latter (see *Supplementary Methods 5.6*).

We find that such a household priority cap policy would have the potential to stabilize groundwater abstractions (Fig. 4.a), while keeping severely vulnerable households' tanker water use near baseline levels (Fig. 4.e) and raising their water access to 97% (Fig. 4.d). It significantly reduces vulnerability (Fig. 4.b-c), while leading to lower transport distances and costs than the general license cap (see *Supplementary Figure S.5*). The reduction in commercial tanker water access under the household priority cap, however, results in 50% greater net benefit losses than under the general license cap (see *Supplementary Figure S.4*). Adjustments to the intervention could balance the objectives of abstraction reduction, household water access, and commercial net benefits differently.

7.4. Feasibility. The extent to which Jordan will be able to address the water security challenges it faces via public supply investments remains uncertain (Yoon et al., 2021). Assessing the feasibility of the market reforms in Jordan's political and institutional environment requires further analysis. The above analysis suggests that market reforms, however, which explicitly account for TWMs' institutional preconditions and their role in extending household water access, can complement public supply investments to enhance the viability of water security objectives.

Supplementary Figure S.1:

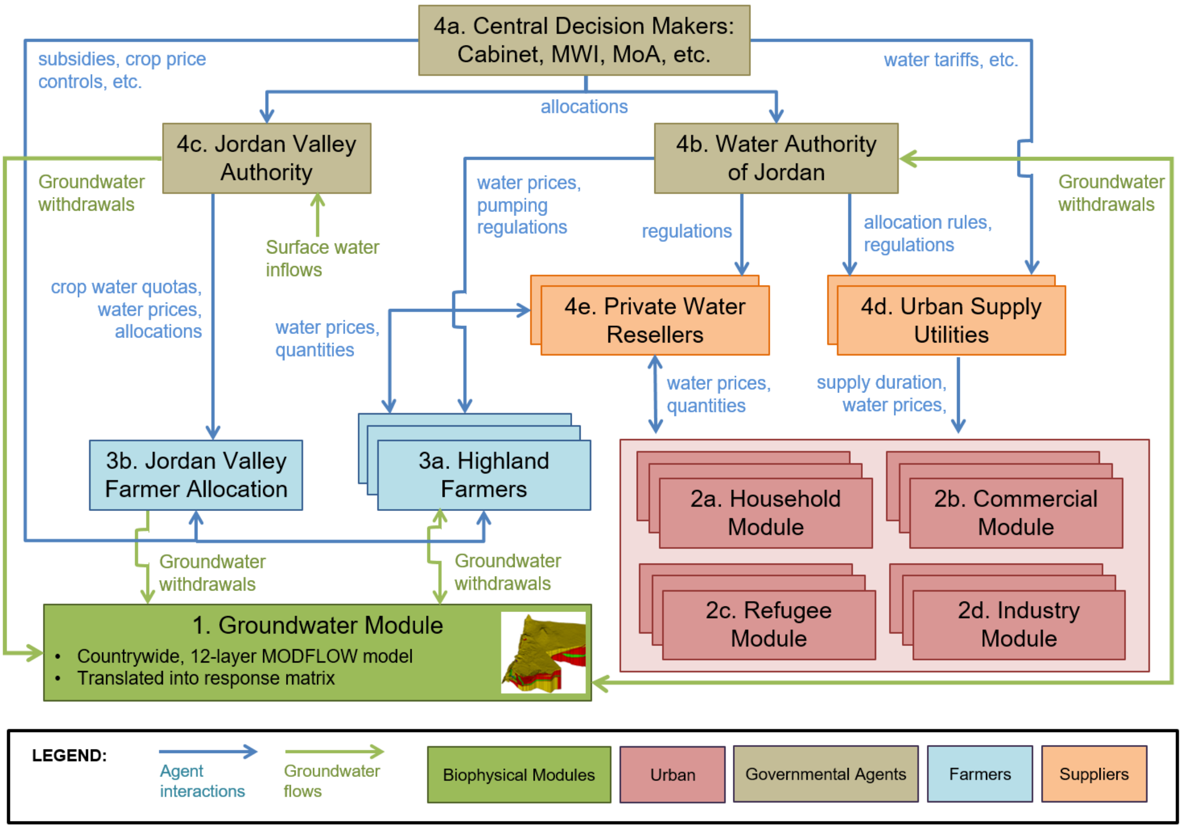

Fig. S.1. Human Modules in the Jordan Water Model. Schematic representation of agent interactions among the Human Modules and of water flows between Human Modules and the Groundwater Module in the *Jordan Water Model* and the *Jordan Water Model for Tanker Water Market Analyses (JWM-T)*, adapted from Yoon et al. (2017). Human Modules represent policies and allocation decisions (Governmental Agents and Suppliers) as well as consumption decisions and impacts (Urban Agents and Farmers). A detailed description of the Modules can be found in Yoon et al. (2021, *Article and Supplementary Information*).

Supplementary Figure S.2:

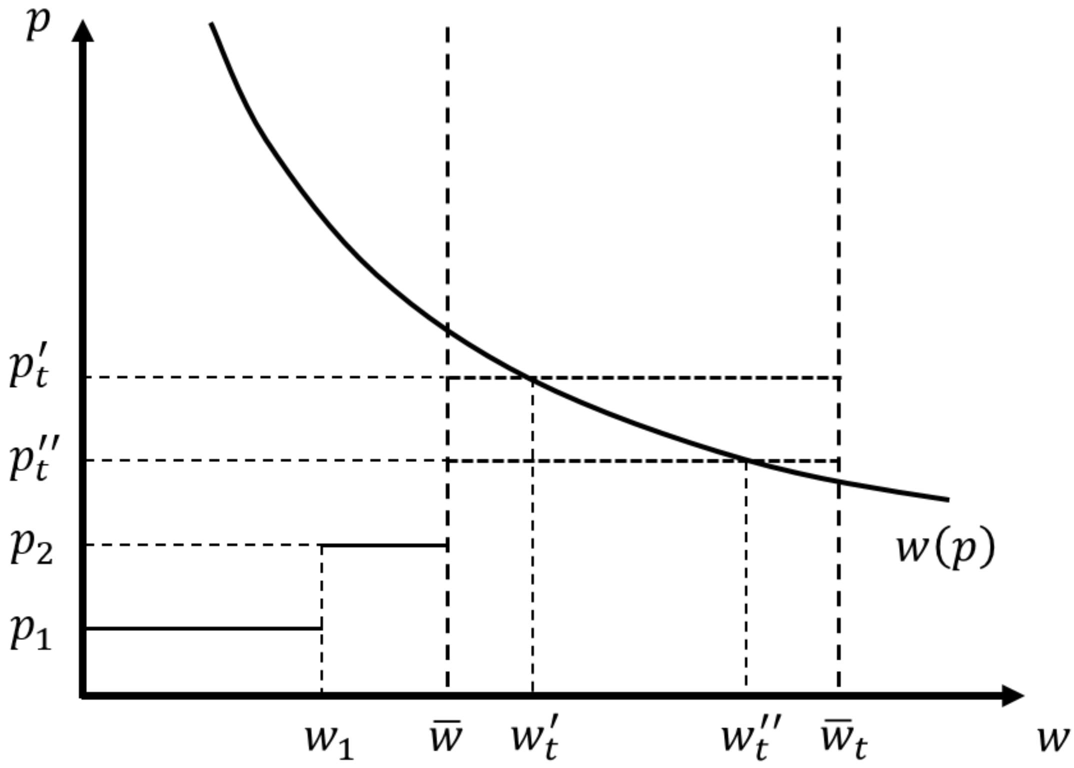

Fig. S.2. Determination of residual tanker water demand in the Jordan Water Model. The plot illustrates the tiered-supply curve approach for consumer choice among multiple water sources (Srinivasan et al., 2010), adapted for the combination of an increasing block tariff for public water supply and tanker water supply present in Jordan (Klassert et al., 2015). The tanker water demand quantity is determined by the demand curve $w(p)$ and the tiered supply curve, where w represents the water consumption quantity, p the water price, w_k is the boundary of tariff block $k \in \{1, 2\}$, and p_k is the tariff rate for block k. Public water supply constraints in Jordan's intermittent water supply system are reflected by $\overline{w}$. The water quantities ($w_t' - \overline{w}$) and ($w_t'' - \overline{w}$) are two examples of residual tanker water demand quantities, resulting from the tanker water prices p_t' and p_t'', respectively.

Supplementary Figure S.3:

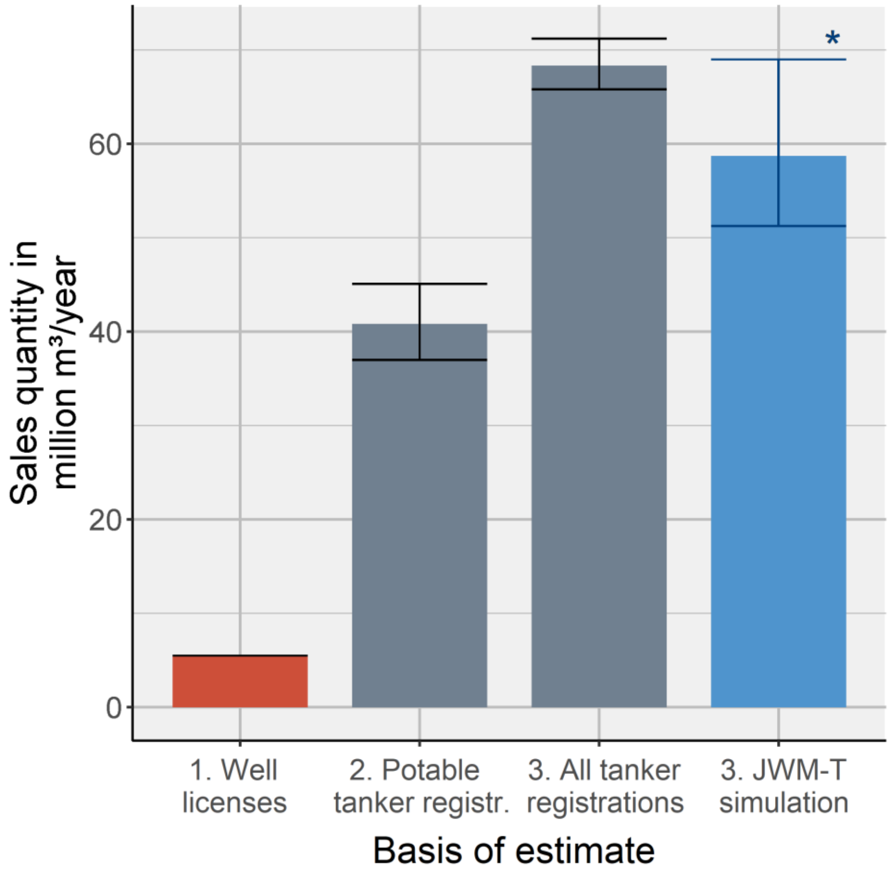

Fig. S.3. Effect of demand and price uncertainty on the simulated tanker water market volume. Simulated tanker water market sales volume in 2015 (blue), compared to well licenses (red), a high estimate based tanker truck registrations (grey, left), and a low estimate based tanker truck registrations (grey, right) (MWI, 2016b; Sigel et al., 2017). Error bars on the registration-based estimates reflect the log-normal 95% confidence interval, see *Supplementary Methods 3, Validation*. *Dark blue error bars on the simulated sales volume indicate the lower and upper limit simulations for combined uncertainty in the demand functions and offer prices, see *Supplementary Methods 2.3, Sensitivity analysis and Supplementary Table 3.* Challenges of a comprehensive uncertainty quantification for coupled human-natural systems models are discussed in *Supplementary Methods 2.3.*

Supplementary Figure S.4:

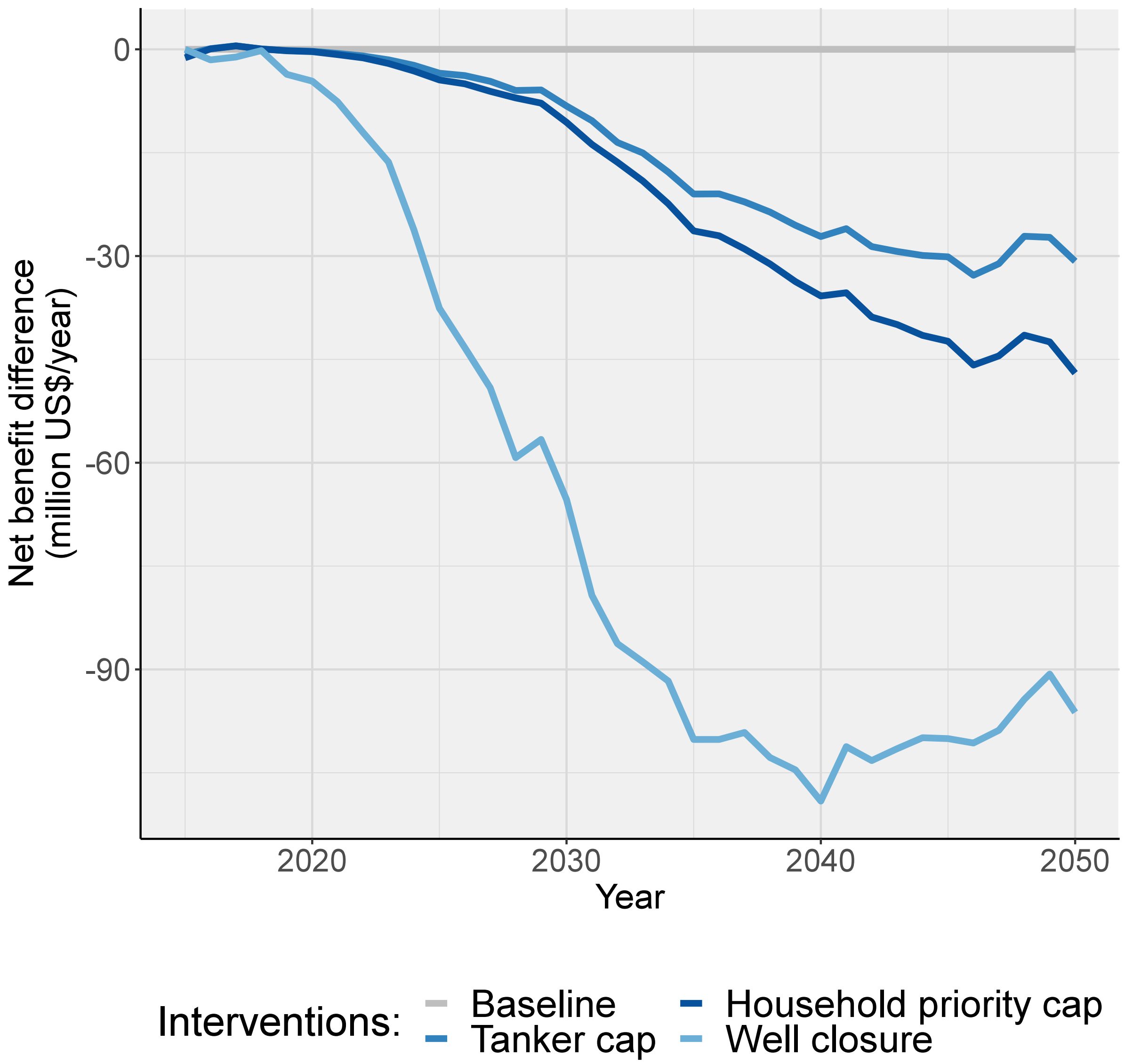

Fig. S.4. Development of net tanker water benefits under three tanker market interventions, relative to baseline. The plot shows the difference in net benefits (consumer surplus plus private and government revenue) between three tanker water market reform interventions and the baseline simulation, based on JWM-T simulations for 2015-2050. Jordan's current policy to close known tanker wells (light blue) reaches a net benefit difference below US$ -90 million per year after 2034, due to its high water cost per m^3 (Fig. 4.f of the Article). The net benefit losses under the household priority cap intervention (dark blue) are 50% higher in 2050 than under the overall tanker license cap (medium blue), due to the higher constraint of sales to businesses under the former. The interventions are described in *Supplementary Methods 5*. All monetary values are in constant 2015 US$.

Supplementary Figure S.5:

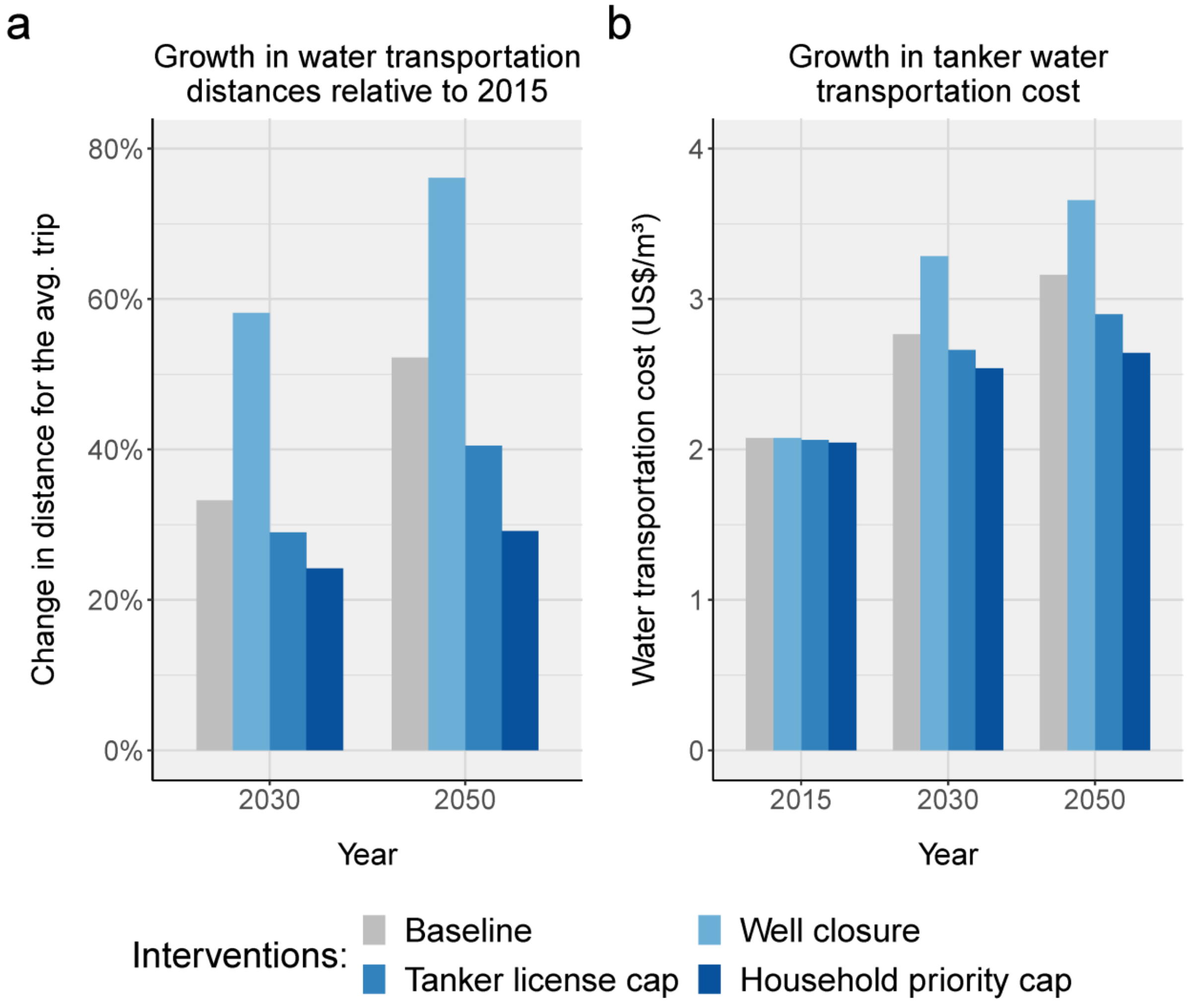

Fig. S.5. Growth of tanker water transportation distances and costs under three tanker market interventions. Bar plots show the increase in tanker water transportation distances relative to 2015 (a) and the resulting transportation costs in 2030 and 2050, compared to 2015 (b) for three tanker water market reform interventions and the baseline simulation, based on JWM-T simulations for 2015-2050. Growing tanker water sales quantities in the baseline simulation lead to an increase of the average tanker water transportation distance by +52%, with a resulting rise in transportation costs from US$2.1 per m^3 in 2015 to US$3.2 per m^3 in 2050. Using Jordan's current policy to close known tanker wells (light blue) to stabilize tanker water abstractions at current levels induces trucks to travel to more remote wells, leading to distance increase of +76% by 2050 and transportation costs of US$3.66 per m^3, despite the smaller sales quantity. Using the tanker license cap (medium blue) or the household priority cap (dark blue) stabilizes tanker water abstractions at current levels, while also reducing increases in the average transportation distances in 2050 to +40% and +29%, respectively. As a consequence, transportation costs only rise to US$2.9 per m^3 under the tanker license cap and US$2.6 per m^3 under the household priority cap. The interventions are described in *Supplementary Methods 5* and *Supplementary Results 7*. All monetary values are in constant 2015 US$.

Supplementary Table S.1:

Table S.1. Econometric residential water demand estimates. Estimates of the natural logarithm of quarterly household water demand from the Discrete Continuous Choice (DCC) model used to inform household agent behavior in the Jordan Water Model, as well as two Ordinary Least Squares (OLS) models applied to the same data for comparison, from Klassert et al. (2018). JOD are constant 2013 Jordanian Dinar. For the JWM household agent parameters, the DCC price and intercept coefficients are adjusted to reflect constant 2015 US$. The income coefficient requires no adjustment as it expresses an elasticity.

Variable	Units	All Years		
		OLS1	**OLS2**	**DCC**
Intercept	-	3.3217*** (0.0343)	1.9951*** (0.0590)	1.4587*** (0.1019)
Price	JOD/m³	0.7798*** (0.0043)	-	−0.4510*** (0.0601)
Log(Income)	JOD/a	−0.0067 (0.0042)	0.1526*** (0.0071)	0.2181*** (0.0125)
Adults	Count	0.0386*** (0.0047)	0.1345*** (0.0081)	0.1852*** (0.0132)
Adults²	Count	−0.0018*** (0.0005)	−0.0084*** (0.0008)	−0.0113*** (0.0012)
Children	Count	0.0085*** (0.0015)	0.0236*** (0.0026)	0.0313*** (0.0038)
Seniors	Count	−0.0124** (0.0045)	0.0286*** (0.0079)	0.0443*** (0.0116)
Married	Boolean	0.0076 (0.0068)	−0.0258* (0.0120)	−0.0423* (0.0167)
Education	Boolean	−0.0169** (0.0060)	−0.0409*** (0.0106)	−0.0542*** (0.0145)
Own house	Boolean	0.0762*** (0.0054)	0.1493*** (0.0095)	0.1673*** (0.0127)
Large house	Boolean	0.0031 (0.0075)	0.1055*** (0.0132)	0.1546*** (0.0195)
Urban	Boolean	−0.1970*** (0.0060)	−0.1951*** (0.0105)	−0.2268*** (0.0157)
N	Count	15,811	15,811	15,811
RSE	-	0.2764	0.4857	-
σ_η	-	-	-	0.3315*** (0.0175)
σ_ϵ	-	-	-	0.3996*** (0.0106)
R^2	-	0.7344	0.1797	-
Log-Likelihood	-	-	-	−10,938.12

Notes: * Significant at α = 0.05, ** at α = 0.01, *** at α = 0.001. Standard errors are listed in parenthesis below the coefficient estimates.

Supplementary Table S.2:

Table S.2. Econometric commercial water demand estimates. Estimates of the natural logarithm of weekly commercial water demand from the Discrete Continuous Choice (DCC) model used to inform commercial agent behavior in the Jordan Water Model, as well as two Ordinary Least Squares (OLS) models applied to the same data for comparison. JOD are constant 2016 Jordanian Dinar. For the JWM commercial agent parameters, the DCC price and intercept coefficients are adjusted to reflect constant 2015 US$.

Variable	Unit	OLS1	OLS2	DCC
Intercept	-	-0.8037 (0.4452)	-2.0099*** (0.4291)	-0.7729 (0.4514)
Price (if Employees >4)	JOD/m³	-0.2196*** (0.0418)	-	-0.2416*** (0.0452)
Price (Employees <=4)	JOD/m³	-0.3185*** (0.0447)	-	-0.355*** (0.049)
Log(Employees)	Count	0.3562*** (0.0467)	0.4695*** (0.0332)	0.3688*** (0.0465)
Summer	Boolean	0.4416*** (0.061)	0.4295*** (0.0636)	0.4372*** (0.0615)
Toilets	Count	0.0052* (0.0021)	0.0046* (0.0022)	0.0048* (0.0021)
Storage	m³	0.0007*** (0.0002)	0.0006*** (0.0002)	0.0007*** (0.0002)
Urban	Boolean	1.1015* (0.4487)	1.3687** (0.4657)	0.9382* (0.4562)
Filtered Water Store	Boolean	1.2125*** (0.1013)	1.1411*** (0.1023)	1.2583*** (0.1029)
Hotel	Boolean	0.8259*** (0.1329)	0.9048*** (0.1363)	0.9115*** (0.1318)
Piped Connection	Boolean	0.4513*** (0.0688)	0.5101*** (0.071)	0.6115*** (0.072)
N	Count	557	557	557
RSE	-	0.7564	0.7564	-
σ_η	-	-	-	0.4912*** (0.128)
σ_ϵ	-	-	-	0.5289*** (0.1151)
R^2	-	0.6049	0.5623	-
Log-Likelihood	-	-	-	1227.505

Notes: * Significant at α = 0.05, ** at α = 0.01, *** at α = 0.001. Standard errors are listed in parenthesis below the coefficient estimates.

Supplementary Table S.3:

Table S.3. Demand and price sensitivity analysis. Sensitivity of 2015 tanker water market outputs to demand and price uncertainty.

Scenario	Input variable change	Total tanker sales	Avg. tanker price	Hhld. tanker sales	Hhld. tanker price	Comm. tanker sales	Comm. tanker price
Hhld. water demand +95% CI	+1.1%	+0.9%	+0.4%	+4.0%	+1.1%	-0.1%	+0.4%
Hhld. water demand -95% CI	-1.1%	-0.8%	+0.4%	-3.9%	+0.9%	+0.2%	+0.1%
Comm. water demand +95% CI	+8.0%	+4.3%	+2.0%	-7.2%	-0.2%	+8.2%	+1.7%
Comm. water demand -95% CI	-7.4%	-4.2%	-2.3%	+7.4%	+0.7%	-8.2%	-2.3%
Tanker offer prices +95% CI	+9.2%	-8.9%	+5.1%	-17.9%	+6.4%	-5.8%	+4.0%
Tanker offer prices -95% CI	-10.2%	+9.9%	-4.1%	+21.3%	-3.0%	+6.1%	-3.6%
Combined uncertainty, upper limit	high demands, low prices	+17.5%	-1.2%	+20.2%	-2.5%	+16.6%	-0.7%
Combined uncertainty, lower limit	low demands, high prices	-12.7%	+2.9%	-12.2%	+5.5%	-12.9%	+2.2%

Notes: Hhld. = Household, Comm. = Commercial

Supplementary Table S.4:

Table S.4. Components of the economic value of tanker water. Modeled components of the economic value of tanker water in 2015, excluding external environmental and resource costs. All monetary values are in constant 2015 US$.

Category	Units	All Consumers	Households	Businesses
Population and no. of businesses	million persons or firms	-	8.1	0.16
Tanker water consumption	million m^3 per year	58.7	14.9	43.8
Tanker share of total water use	% of total water use	14.6%	4.6%	53.3%
Tanker sales revenue	million US$ per year	176	45	132
Gross tanker water value	million US$ per year	317	60	258
Net tanker water benefits	million US$ per year	166	21	145
Tanker water costs	million US$ per year	152	38	113
Gross tanker water value per unit	US$ per m^3	5.4	4.0	5.9
Tanker water benefits per unit	US$ per m^3	2.8	1.4	3.3
- Consumer surplus[a]	US$ per m^3	2.4	1.0	2.9
- Government revenue	US$ per m^3	0.04	0.04	0.04
- Private net revenue	US$ per m^3	0.4	0.4	0.4
Tanker water costs per unit	US$ per m^3	2.6	2.6	2.6
- Agricultural opportunity costs	US$ per m^3	0.5	0.5	0.5
- Water pumping cost	US$ per m^3	0.02	0.02	0.02
- Tanker transport cost	US$ per m^3	2.1	2.1	2.1

[a] Consumer surplus is the aggregate difference between consumers' willingness to pay for water and the price paid.

Supplementary References:

Ahlers, R., Perez Güida, V., Rusca, M., & Schwartz, K. (2013). Unleashing entrepreneurs or controlling unruly providers? The formalisation of small-scale water providers in Greater Maputo, Mozambique. *The Journal of Development Studies, 49*(4), 470-482. https://doi.org/10.1080/00220388.2012.713467

Al-Karablieh, E., and Salman, A. (2016). *Water resources, use and management in Jordan – A focus on groundwater.* IWMI Project Report No. 11. International Water Management Institute (IWMI): Colombo, Sri Lanka. Available online: https://gw-mena.iwmi.org/wp-content/uploads/sites/3/2017/04/Rep.11-Water-resources-use-and-management-in-Jordan-a-focus-on-groundwater.pdf. Accessed on 5 May 2023.

Al Naber, M., & Molle, F. (2017). Controlling groundwater over abstraction: state policies vs local practices in the Jordan highlands. *Water Policy*, *19*(4), 692-708. https://doi.org/10.2166/wp.2017.127

Al-Saidi, M., & Dehnavi, S. (2019). Comparative scorecard assessment of urban water pricing policies – The case of Jordan and Iran. *Water*, *11*(4), 704. https://doi.org/10.3390/w11040704

Arab News (2022, October 22). *Jordan secures $2.2bn financing for water carrier project.* Available online: https://www.arabnews.com/node/2186541/middle-east Accessed on 5 May 2023.

Brückner, F., Bahls, R., Alqadi, M., Lindenmaier, F., Hamdan, I., Alhiyari, M., & Atieh A. (2021). Causes and consequences of long-term groundwater overabstraction in Jordan. *Hydrogeology Journal 29,* 2789–2802. https://doi.org/10.1007/s10040-021-02404-1

European Investment Bank (EIB, 2022, April 27). *Aqaba-Amman Water Desalination and Conveyance.* Project Reference: 20190712. Available online: https://www.eib.org/en/projects/pipelines/all/20190712 Accessed on 5 May 2023.

Elsaid, K., Kamil, M., Sayed, E. T., Abdelkareem, M. A., Wilberforce, T., & Olabi, A. (2020). Environmental impact of desalination technologies: A review. *Science of the Total Environment*, *748*, 141528. https://doi.org/10.1016/j.scitotenv.2020.141528

Garrick, D., Balasubramanya, S., Beresford, M., Wutich, A., Gilson, G. G., Jorgensen, I., ... & Mendoza, K. V. (2023). A systems perspective on water markets: barriers, bright spots, and building blocks for the next generation. *Environmental Research Letters*, *18*(3), 031001. https://doi.org/10.1088/1748-9326/acb227

Garrick, D., O'Donnell, E., Moore, M. S., Brozovic, N., & Iseman, T. (2019). *Informal water markets in an urbanising world: Some unanswered questions.* World Bank Report No. AUS0000606. World Bank Group: Washington, D.C. Available online: http://documents.worldbank.org/curated/en/358461549427540914/Informal-Water-Markets-in-an-Urbanising-World-Some-Unanswered-Questions. Accessed on 5 May 2023.

Gel, Y. R., & Gastwirth, J. L. (2008). A robust modification of the Jarque–Bera test of normality. *Economics Letters*, *99*(1), 30-32. https://doi.org/10.1016/j.econlet.2007.05.022

Gerlach, E., & Franceys, R. (2010). Regulating water services for all in developing economies. *World Development, 38*(9), 1229-1240. https://doi.org/10.1016/j.worlddev.2010.02.006

Goode, D. J., Senior, L. A., Subah, A., and Jaber, A. (2013). *Groundwater-level trends and forecasts, and salinity trends, in the Azraq, Dead Sea, Hammad, Jordan Side Valleys, Yarmouk, and Zarqa groundwater basins, Jordan.* U.S. Geological Survey, (USGS), Open-File Report 2013-1061. USGS: Reston, VA. Available online: https://pubs.usgs.gov/of/2013/1061/ Accessed on 5 May 2023.

Hailu, D., Rendtorff-Smith, S., & Tsukada, R. (2011). *Small-scale water providers in Kenya: Pioneers or predators.* United Nations Development Programme (UNDP): New York, NY. Available online: https://www.undp.org/publications/small-scale-water-providers-kenya-pioneers-or-predators. Accessed on 5 May 2023.

Hyndman, R., Koehler, A. B., Ord, J. K., & Snyder, R. D. (2008). *Forecasting with exponential smoothing: the state space approach.* Springer Science & Business Media: New York, NY. https://doi.org/10.1007/978-3-540-71918-2

Hyndman, R. J., & Athanasopoulos, G. (2018). *Forecasting: principles and practice.* OTexts. Available online: https://otexts.com/fpp3/. Accessed on 5 May 2023.

Klassert, C., Sigel, K., Gawel, E., & Klauer, B. (2015). Modeling residential water consumption in Amman: The role of intermittency, storage, and pricing for piped and tanker water. *Water, 7*(7), 3643-3670. https://doi.org/10.3390/w7073643

Klassert, C., Sigel, K., Klauer, B., & Gawel, E. (2018). Increasing block tariffs in an arid developing country: A discrete/continuous choice model of residential water demand in Jordan. *Water, 10*(3), 248. https://doi.org/10.3390/w10030248

Kubursi, A., Grover, V., Darwish, A.R., Deutsch, E. (2011). *Water Scarcity in Jordan: Economic Instruments, Issues and Options.* The Economic Research Forum (ERF) Working Paper 599; ERF: Cairo, Egypt. Available online: https://ideas.repec.org/p/erg/wpaper/599.html Accessed 5 May 2023.

Laspidou, C., and Spyropoulou, A. (2017). Chapter 3: Root causes and implications of IWS. In: B. Charalambous and C. Laspidou (eds.): *Dealing with the Complex Interrelation of Intermittent Supply and Water Losses.* Pp. 17-27. IWA Publishing: London, UK. https://doi.org/10.2166/9781780407074

Ministry of Water and Irrigation (MWI) (2016a). *National water strategy 2016-2025.* MWI: Amman, Jordan. Available online: http://faolex.fao.org/docs/pdf/jor156264E.pdf Accessed 5 May 2023.

Ministry of Water and Irrigation (MWI) (2016b). *Annual report 2015.* MWI: Amman, Jordan. Available online: https://jordankmportal.com/resources/annual-report-2015 Accessed 5 May 2023.

Ministry of Water and Irrigation (MWI) (2017). *Jordan water sector – Facts and figures 2017.* MWI: Amman, Jordan. Available online: https://www.mwi.gov.jo/ebv4.0/root_storage/ar/eb_list_page/%D9%82%D8%B7%D8%A7%D8%B9_%D8%A7%D9%84%D9%85%D9%8A%D8%A7%D9%87_%D8%AD%D9%82

%D8%A7%D8%A6%D9%82_%D9%88%D8%A7%D8%B1%D9%82%D8%A7%D9%85_-2017.pdf Accessed 5 May 2023.

Nauges, C., & Whittington, D. (2009). Estimation of water demand in developing countries. *World Bank Research Observer, 25*, 263–294. https://doi.org/10.1093/wbro/lkp016

Olsson, U. (2005). Confidence intervals for the mean of a log-normal distribution. *Journal of Statistics Education*, *13*(1). https://doi.org/10.1080/10691898.2005.11910638

Open Access Micro Data Initiative (OAMDI). (2014). *Harmonized Household Income and Expenditure Surveys (HHIES), Version 2.0 of Licensed Data Files, HEIS 2002–2013, Department of Statistics (DOS).* Economic Research Forum (ERF): Cairo, Egypt, 2014. Available online: http://erfdataportal.com/index.php/catalog/HHIES Accessed on 5 May 2023.

Petra (2022, December 18). *Jordan secures €200mln EIB loan to finance Aqaba-Amman water carrier project.* Petra – Jordan News Agency. Available online: https://petra.gov.jo/Include/InnerPage.jsp Accessed on 5 May 2023.

Potter, R. B., & Darmame, K. (2010). Contemporary social variations in household water use, management strategies and awareness under conditions of 'water stress': The case of Greater Amman, Jordan. *Habitat International, 34*(1), 115-124. https://doi.org/10.1016/j.habitatint.2009.08.001

Raina, A., Zhao, J., Wu, X., Kunwar, L., & Whittington, D. (2019). The structure of water vending markets in Kathmandu, Nepal. *Water Policy*, *21*(S1), 50-75. https://doi.org/10.2166/wp.2019.181

Rajsekhar, D., & Gorelick, S. M. (2017). Increasing drought in Jordan: Climate change and cascading Syrian land-use impacts on reducing transboundary flow. *Science Advances*, *3*(8), e1700581. https://doi.org/10.1126/sciadv.1700581

Renzetti, S. (2015). Non-household water demand: the industrial and commercial sectors. In: Grafton, Q., Daniell, K. A., Nauges, C., Rinaudo, J. D., & Chan, N. W. W. (eds.). *Understanding and managing urban water in transition.* Pp. 297-310. Springer: Dordrecht, Netherlands. https://doi.org/10.1007/978-94-017-9801-3_14

Riahi, K., Grübler, A., & Nakicenovic, N. (2007). Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technological Forecasting and Social Change*, 74(7), 887-935. https://doi.org/10.1016/j.techfore.2006.05.026

Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'neill, B. C., Fujimori, S., ... & Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change, 42*, 153-168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Rosenberg, D. E., Talozi, S., & Lund, J. R. (2008). Intermittent water supplies: Challenges and opportunities for residential water users in Jordan. *Water International, 33*, 488–504. https://doi.org/10.1080/02508060802474574

Salman, A., Al-Karablieh, E., & Haddadin, M. (2008). Limits of pricing policy in curtailing household water consumption under scarcity conditions. *Water Policy, 10*(3), 295-304. https://doi.org/10.2166/wp.2008.040

Shah, T. (2007). Issues in Reforming Informal Water Economies of Low-Income Countries in India and Elsewhere. In: van Koppen, B, Giordano, M and Butterworth, J (eds.): *Community-Based Water Law and Water Resource Management Reform in Developing Countries*. Pp. 65-95. Oxfordshire, UK: CAB International. https://doi.org/10.22004/ag.econ.138046

Sigel, K., Klassert, C., Zozmann, H., Talozi, S., Klauer, B., & Gawel E. (2017). *Urban water supply through private tanker water markets: An empirical market analysis of Amman, Jordan.* UFZ Report 02/2017. Helmholtz Centre for Environmental Research – UFZ: Leipzig, Germany. https://nbn-resolving.de/urn:nbn:de:gbv:3:2-141140

Srikrishnan, V., Lafferty, D. C., Wong, T. E., Lamontagne, J. R., Quinn, J. D., Sharma, S. ... & Lee, B. S. (2022). Uncertainty Analysis in Multi-Sector Systems: Considerations for Risk Analysis, Projection, and Planning for Complex Systems. *Earth's Future, 10*(8), e2021EF002644. https://doi.org/10.1029/2021EF002644

Srinivasan, V., Gorelick, S. M., & Goulder, L. (2010). Sustainable urban water supply in south India: Desalination, efficiency improvement, or rainwater harvesting? *Water Resources Research, 46*(10). https://doi.org/10.1029/2009WR008698

Teytelboym, A. (2019). Natural capital market design. *Oxford Review of Economic Policy, 35*(1), 138-161. https://doi.org/10.1093/oxrep/gry030

Vásquez Lavín, F. A., Hernandez, J. I., Ponce, R. D., & Orrego, S. A. (2017). Functional forms and price elasticities in a discrete continuous choice model of the residential water demand. *Water Resources Research, 53*(7), 6296-6311. https://doi.org/10.1002/2016WR020250

Water Authority of Jordan (WAJ) (2015). *Water Distribution Program: Summer 2015.* MWI: Amman, Jordan.

Wheeler, S. A., & Garrick, D. E. (2020). A tale of two water markets in Australia: lessons for understanding participation in formal water markets. *Oxford Review of Economic Policy*, *36*(1), 132-153. https://doi.org/10.1093/oxrep/grz032

Wheeler, S. A., Loch, A., Crase, L., Young, M., & Grafton, R. Q. (2017). Developing a water market readiness assessment framework. *Journal of Hydrology*, *552*, 807-820. https://doi.org/10.1016/j.jhydrol.2017.07.010

Whitman, E. (2019). A land without water. *Nature*, *573*(7772), 20-23. https://doi.org/10.1038/d41586-019-02600-w

Whittington, D., Lauria, D. T., & Mu, X. (1991). A study of water vending and willingness to pay for water in Onitsha, Nigeria. *World Development*, *19*(2-3), 179-198. https://doi.org/10.1016/0305-750X(91)90254-F

Worthington, A. C. (2010). Commercial and industrial water demand estimation: Theoretical and methodological guidelines for applied economics research. *Estudios de economía aplicada, 28*(2), 237-258. Available online: https://www.redalyc.org/articulo.oa?id=30120357002. Accessed on 5 May 2023.

Wutich, A., Beresford, M., & Carvajal, C. (2016). Can informal water vendors deliver on the promise of a human right to water? Results from Cochabamba, Bolivia. *World Development*, 79, 14-24. https://doi.org/10.1016/j.worlddev.2015.10.043

Yoon, J. (2017). *Evaluation of Water Security in Jordan using a Multi-Agent Hydroeconomic Model*. Dissertation, Stanford University. Available online: https://stacks.stanford.edu/file/druid:qg946vz7395/Jim%20Yoon%20Dissertation-augmented.pdf. Accessed on 5 May 2023.

Yoon, J., Klassert, C., Selby, P., Lachaut, T., Knox, S., Avisse, N., Harou, J., Tilmant, A., Klauer, B., Mustafa, D., Sigel, K., Talozi, S., Gawel, E., Meddelin-Azuara, J., Bataineh, B., Zhang, H., Gorelick, S.M. (2021). Coupled human-natural system analysis of freshwater security under climate and population change. *Proceedings of the National Academy of Sciences (PNAS) 118*(14), e2020431118. https://doi.org/10.1073/pnas.2020431118

Zhang, Z., Wang, C., Song, J., & Xu, Y. (2022). Object Tracking based on satellite videos: A literature review. *Remote Sensing*, *14*(15), 3674. https://doi.org/10.3390/rs14153674

Zozmann, H., Klassert, C., Sigel, K., Gawel, E., & Klauer, B. (2019). Commercial tanker water demand in Amman, Jordan – A spatial simulation model of water consumption decisions under intermittent network supply. *Water*, *11*(2), 254. https://doi.org/10.3390/w11020254