

Unexpected growth of an illegal water market

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Scarce and unreliable urban water supply in many countries has caused municipal users to rely on transfers from rural wells via unregulated markets. Assessments of this pervasive water re-allocation institution and its impacts on aquifers, consumer equity and affordability are lacking. We present a rigorous coupled human–natural system analysis of rural-to-urban tanker water market supply and demand in Jordan, a quintessential example of a nation relying heavily on such markets, fed by predominantly illegal water abstractions. Employing a shadow-economic approach validated using multiple data types, we estimate that unregulated water sales exceed government licences 10.7-fold, equalling 27% of the groundwater abstracted above sustainable yields. These markets supply 15% of all drinking water at high prices, account for 52% of all urban water revenue and constrain the public supply system's ability to recover costs. We project that household reliance on tanker water will grow 2.6-fold by 2050 under population growth and climate change. Our analysis suggests that improving the efficiency and equity of public water supply is needed to ensure water security while avoiding uncontrolled groundwater depletion by growing tanker markets.

Urban water supply systems face growing difficulties to extend their services to a rapidly expanding population^{1–3}, while their freshwater resources become increasingly scarce and extreme events proliferate^{4,5}. An estimated 941 million urban residents globally⁶ already bear the costs of intermittent piped water supply^{7,8}. Formal and informal tanker water markets (TWMs) have emerged as a private mechanism for reallocating water from rural uses and ecosystems to urban uses via tanker trucks, providing a valuable remedy for gaps in public supply

and sometimes the only available source of water^{9,10}. At the same time, they are criticized for selling drinking water at unaffordable prices^{11,12}, fostering uncontrolled groundwater pumping^{13,14}, causing excessive transportation emissions¹⁵ and constraining public water networks' ability to recover costs^{14,16}. There is a wide range of findings that is often case-specific on whether TWMs improve water security⁹, whether their benefits outweigh their negative impacts^{11,17} and whether they could be improved by regulation^{9,15}.

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Informal TWMs are essential to water security in major cities worldwide, such as Chennai, Nairobi and Mexico City, and there is a growing recognition of the importance of understanding them^{9,14,18,19}. Yet they remain underrepresented in the literature²⁰ and have so far not benefited from similar modelling advances as other informal trading activities^{20,21}. Assessments of TWMs' water security contribution and negative impacts have been impeded by obstacles inherent in data collection about informal institutions that aim to avoid costly licences, regulations or sanctions for sourcing water illegally¹⁴. Informal markets have the potential to allocate scarce water resources efficiently and sustainably^{22,23}, but limited data availability can obscure whether their market structure permits sufficient competition. If not, higher prices can reduce the affordability and accessibility of tanker water^{9,24}. While some analyses suggest that TWMs can be competitive due to low barriers of entry^{25,26}, the overall evidence is mixed^{9,14,18}. Knowledge of TWMs' degree of informality or illegality is necessary to determine the extent to which they impose unregulated impacts on society and its water resources⁹. Previous simulation studies have focused on identifying demand-side factors that can explain the emergence of TWMs^{27,28}. Integrated supply- and demand-side analyses of TWMs that provide insights into their market structure and degree of informality are missing. The water security contribution of informal TWMs, their impacts on groundwater abstractions, their response to regulation and their reliability in future water crises remain open questions^{9,14}.

We develop a rigorous coupled human and natural systems modelling approach to answer these questions. Shadow-economic insights linking informal TWM activities to observable costs and demands²⁹ allow us to overcome the data scarcity challenge characterizing these markets. Jordan is a quintessential example of a country relying heavily on tanker water from illegal sources to cope with highly intermittent public water supply³⁰. We apply a country-wide spatial price-equilibrium mechanism³¹ within a coupled human and natural system model³² to simulate how the unmet demands of Jordan's urban water users, represented by 1,823 agents, road transportation distances, groundwater dynamics and the rural opportunity costs of water interact to determine sales on Jordan's legal and illegal TWMs across space. Aquifer impacts and rural well owners' pumping costs are captured by a three-dimensional numerical groundwater model, reflecting how competition between public and private water pumping shapes tanker water sales patterns over time. Agricultural production models calculate the rural opportunity costs of water. Results are validated using three types of independent data. The approach developed allows for comprehensive analyses of informal water supply institutions in present, future and counterfactual settings.

We find that Jordan's TWMs exhibit a high degree of illegal activity, with unregulated sales exceeding government licences 10.7-fold. We project that household reliance on TWMs will grow 2.6-fold by 2050. TWM growth cannot keep pace with population pressures, however, as the number of residents receiving less than 40 litres per person per day (l.p.d.) of public supply increases fivefold, and tanker water reliance among that population falls from 92% to 64%. Groundwater abstractions by TWMs are expected to grow by 62%, imposing further pressure on stressed aquifers. Improving the efficiency and equity of public water supply could largely avoid these developments. Absent that, even a large-scale investment generating 300 million m³ yr⁻¹ of desalinated water would only reduce future tanker sales from 95 to 76 million m³ yr⁻¹. The growth of TWMs is a warning sign of the declining capacity of public supply systems to meet United Nations Sustainable Development Goal 6. Until public supply provides adequate water access for all, policies affecting informal water supply institutions should account for their critical contribution to urban water security.

Results

Capturing illegal tanker water markets

We capture the spatial characteristics (Fig. 1), total market size and market attributes (Fig. 2) of Jordan's legal and illegal TWMs by extending a coupled human and natural system model, the Jordan Water Model (JWM)³², to overcome the data scarcity challenge characterizing these markets (JWM for TWM Analyses, JWM-T).

Jordan relies on dwindling groundwater and surface water resources supplying 366 million m³ yr⁻¹ (73%) and 134 million m³ yr⁻¹ (27%) of urban water supply, respectively³³. Per capita water availability is projected to fall below 50% of its current level by 2100 (ref. 32). Water utilities in Jordan have long adopted scheduled supply interruptions to ration scarce freshwater resources and limit water losses³⁴. Public water supply is provided 36 h per week on average, ranging from 6 to 168 h per week³². Households and businesses across Jordan use storage tanks and tanker water deliveries to cope with public supply intermittency, low piped network pressure and limited connection size³⁵. Tanker trucks source their water predominantly from rural wells. Legal tanker water abstractions require a well license and the payment of a tanker water pumping charge of US\$0.25 m⁻³ (ref. 36). We define illegal TWMs as those selling water abstracted without a license or in excess of an existing license, thus avoiding pumping charges and circumventing groundwater management efforts. Jordan initiated a campaign to gradually close illegal agricultural and tanker wells in 2013, but the majority of illegal wells remain operational due to monitoring and enforcement challenges^{36,37}.

Figure 1 reveals how unmet urban water demands (Fig. 1a), transport distances (Fig. 1b) and rural opportunity costs of water (Fig. 1c) shape sales prices and quantities on Jordan's legal and illegal TWMs (Fig. 1d), according to a baseline JWM-T simulation for 2015.

Figure 2 shows the JWM-T results regarding the size and the degree of illegality of Jordan's TWMs, as well as a comparison of key attributes of these markets to data. Our simulation for 2015 results in a total volume of tanker water sales across Jordan of 59 million m³ yr⁻¹ (Fig. 2a,c). That value is well within the range of sales values of 41 to 68 million m³ yr⁻¹ derived from the number of tanker truck registrations (Supplementary Methods 3 and Supplementary Fig. 3) and further validated on the basis of three market attributes (Fig. 2b–d). The simulated sales exceed the official Water Authority of Jordan (WAJ) data on licensed tanker well abstractions of 5.5 million m³ yr⁻¹ by a factor of 10.7 (ref. 38). This means that an estimated 91% of all tanker water is obtained from illegal sources. Jordan has reformed its well regulations multiple times, but WAJ faces substantial enforcement obstacles, including the high personnel requirements to monitor wells dispersed throughout the highlands and intimidation by well owners³⁷. While Jordan's tanker trucks generally have licences, well owners have strong incentives not to report unlicensed or excessive abstractions to avoid high tanker water pumping charges and fines^{36,39}.

WAJ's underestimation of the illegal markets' size also implies that their impacts on groundwater sustainability have not yet been fully considered in groundwater management. Total groundwater abstraction in Jordan is estimated to be 619 million m³ yr⁻¹ (ref. 33). All groundwater basins face abstraction rates beyond sustainable yields, totalling 215 million m³ yr⁻¹ in 2015 (ref. 40), resulting in an average groundwater level decline of 3.5 m yr⁻¹ (ref. 32). Total tanker water sales correspond to 27% of that overabstraction. The Amman–Zarqa basin faces the highest overabstraction in the country of 79 million m³ yr⁻¹ beyond the sustainable yield. Water sales are also highest in that basin at 27 million m³ yr⁻¹, equivalent to 34% of the overabstraction (Fig. 2a).

A comparison of the remaining three attributes of Jordan's TWMs shows that the JWM-T is able to capture the real-world behaviour of this partly illegal institution (Fig. 2b–d). Similar to a study of Chennai's TWMs²⁸, we find that the JWM-T can explain both spatial and temporal variations in tanker water sales (Fig. 2c,d) on the basis of residual tanker water demands and local water availability. In addition, our

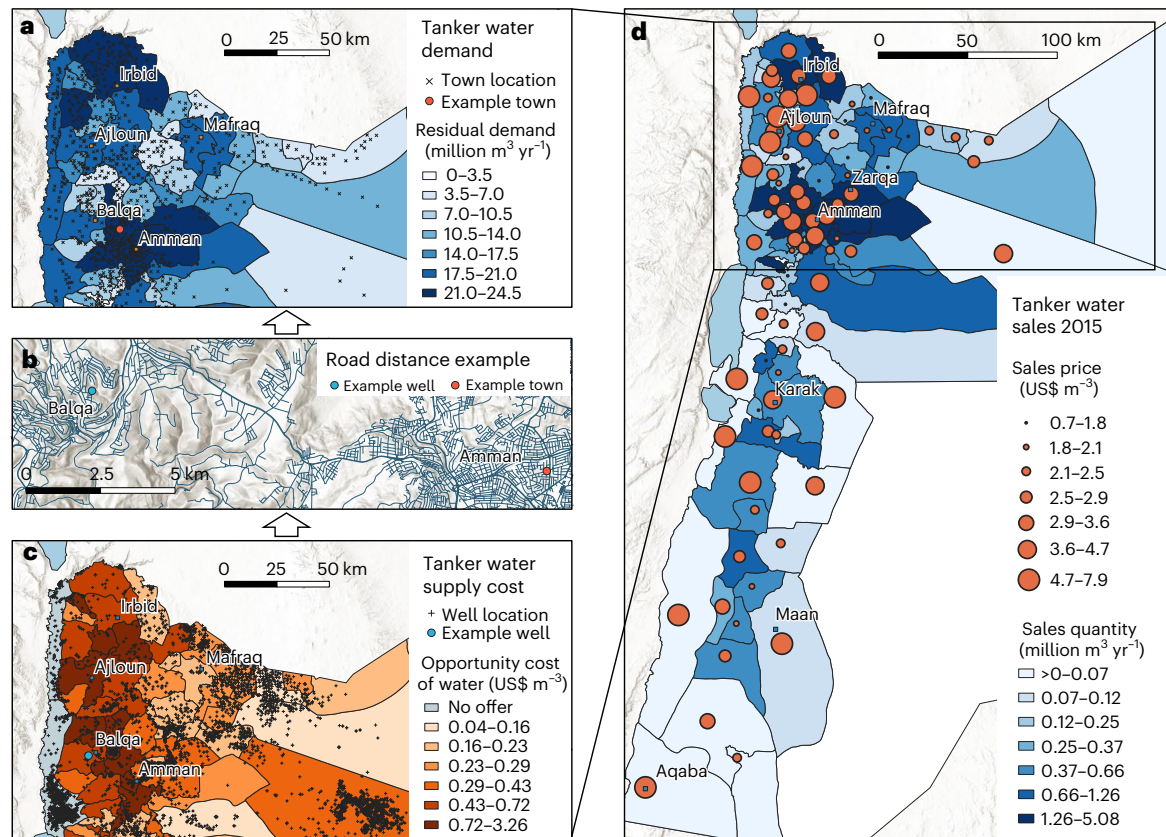


Fig. 1 | Spatial characteristics of modelled tanker water markets across Jordan in 2015. **a, c, d.** The JWM-T determines the set of feasible sales between consumer and agricultural agents in Jordan's 89 subdistricts that maximizes their private surplus (**d**) by simulating consumers' residual tanker water demands (**a**) and agricultural opportunity costs (**c**). **b.** Illustration of the road distances taken into account by the model to calculate transport costs between the well and town locations shown in **a** and **c**. Results are from a baseline JWM-T simulation for 2015. **d.** Large sales quantities along with moderately high prices occur around the central Amman–Zarqa agglomeration and Irbid, higher prices around Ajloun, comparatively large sales quantities around Mafraq and hardly any tanker water sales in Aqaba. Prices around Amman–Zarqa and Irbid are explained by high demands (**a**). Amman–Zarqa is the main population centre. In Irbid, the arrival of Syrian refugees in 2011–2015 has strained local piped water supply capacities. High local opportunity costs (**c**) and long mountain roads impeding access to

affordable tanker water (**b**) explain the higher prices around Ajloun. By contrast, the area around Mafraq, with its large number of wells and low opportunity costs, exhibits particularly low tanker water prices. As a result, some subdistricts around Mafraq show higher sales quantities than those around Ajloun, despite having comparable demands. Tanker water sales expand south to the towns and villages between Karak and Maan. At the southern border of Jordan, the coastal city of Aqaba receives continuous piped water supply from the Disi Aquifer and thus purchases almost no tanker water. The model and its data sources are described in Methods. All monetary values are in constant 2015 US\$. Map data include World Hillshade tiles by Esri, USGS, Airbus DS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community. Credit: basemaps in **a–d**, ESRI and contributors; roads in **b**, OpenStreetMap contributors.

results show that explicitly modelled agricultural opportunity costs and transport costs derived from a spatial market optimization contribute to explaining the distribution of tanker water sales. As further evidence of the JWM-T's ability to capture TWMs' behaviour accurately, we find a good fit of modelled tanker water prices to observations from a 2016 commercial establishment survey (Fig. 2b)³⁶. Importantly, these results support our survey-based assumption that Jordan's TWMs are characterized by a high degree of competitiveness for water sales both from well owners to vendors and from vendors to consumers (Methods, Spatial price-equilibrium optimization). This counters a common perception that TWMs are characterized by market power³⁹. Jordan's TWMs price water at marginal cost, which indicates that they compensate for the deficiencies of the public supply system in an economically efficient manner. This does not, however, preclude the possibility that TWMs cause adverse externalities.

The role and impacts of tanker water markets in Jordan

An economic evaluation of the baseline simulation for 2015 shows that Jordan's TWMs have high costs but also fulfil a critical role in the water supply system. Water from legal and illegal TWMs accounts for 15% of

total urban water use and 53% of all commercial water use by businesses except heavy industry (Supplementary Table 4). At an average price of US\$3.0 m⁻³ in constant 2015 US\$, tanker water is about 4.8 times as expensive as piped water. For households benefiting from inexpensive blocks in the piped water tariff structure, this ratio can be much larger, making tanker water substantially less affordable than piped water. The high price means that TWMs generate US\$176 million yr⁻¹ in revenue, 8% more than all of Jordan's public water suppliers combined, while providing only 15% of the total water supply to households and firms. Due to the presence of TWMs, Jordan's public utilities have to limit the rates they can charge for high-volume users and businesses to cross-subsidize essential uses or risk losing customers^{14,16,36}. If public water suppliers were able to attract part of this revenue, those funds could be used for improving Jordan's deficient public supply infrastructure.

However, since Jordan's TWMs sell water at marginal costs, their negative impacts are a direct consequence of water demands unmet by the public supply system. Of the tanker water expenditure, 86% goes to transportation costs (69%), mainly for fuel³⁶, agricultural opportunity costs and pumping costs. These costs amount to US\$152 million yr⁻¹,

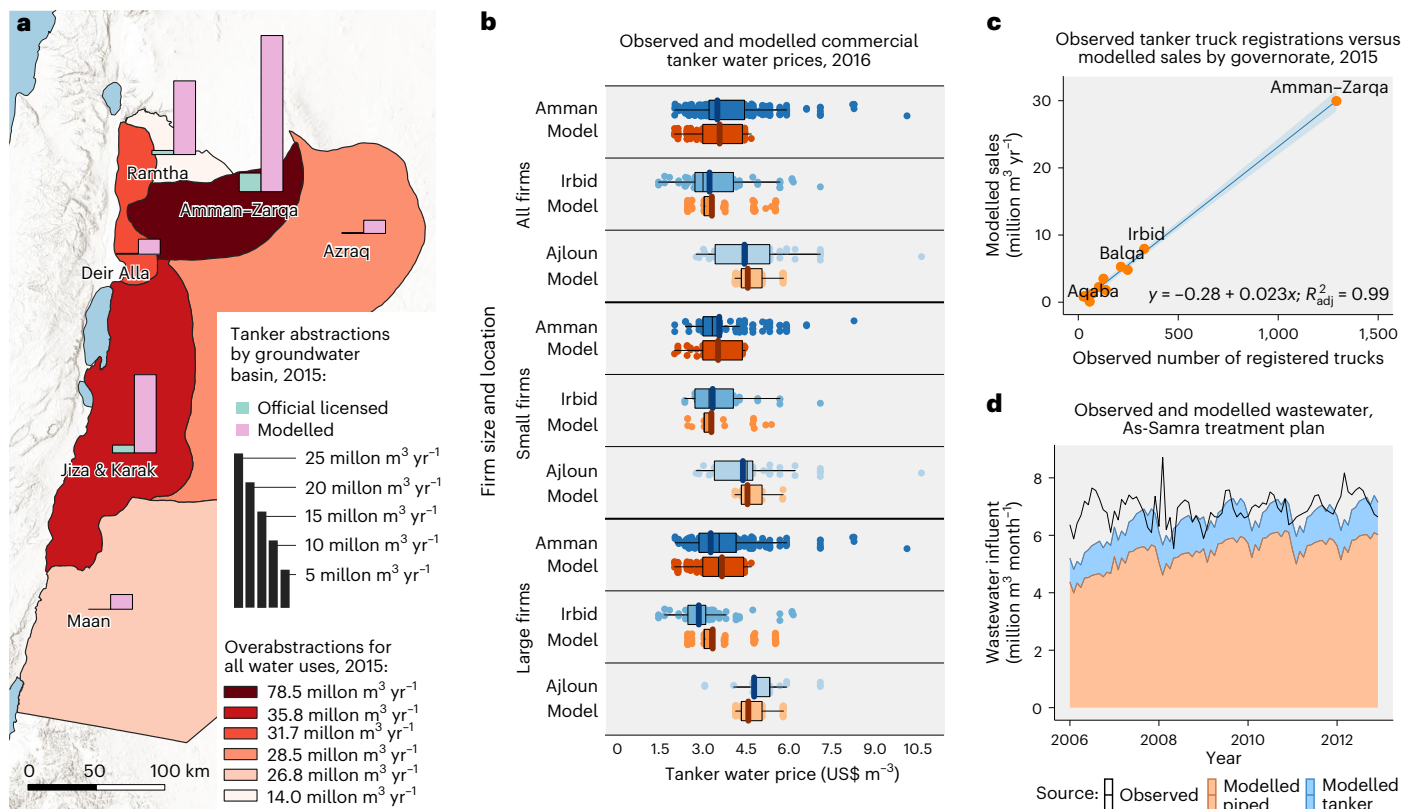


Fig. 2 | Comparing four tanker water market attributes with observed data.

a, Modelled annual tanker water abstraction quantities for 2015 far exceed officially licensed abstraction quantities in all six monitored groundwater basins. This result is supported by the comparison of the other three attributes with observed data (and by additional analyses described in Supplementary Methods 3). **b**, The fit of modelled agent-level prices (orange dots) to observations (blue dots) from a 2016 survey of commercial establishments in Amman ($n = 98/234$ for small/large firms), Irbid ($n = 26/65$) and Ajloun ($n = 47/18$) (ref. 36). Box plots (showing the median, first and third quartiles and whiskers of $\pm 1.5 \times$ the interquartile range) and means (dark blue and red bars) are weighted by sales quantities. **c**, The fit of modelled sales quantities to official potable water tanker truck registration data for 2015 ($R^2 = 99\%$; 95% confidence bands shown in light blue)³⁶. **d**, A comparison

of modelled wastewater quantities from two 2006–2012 simulations with and without tanker water with observed monthly wastewater influent at Jordan's main treatment plant, As-Samra, for the same period. Without the wastewater from tanker water consumption, the simulated quantities are on average 21.8% lower than the observed quantities. This gap is reduced to just 6.2% once the wastewater from tanker water consumption is included, with the remaining deviation occurring mostly in the first year and one outlier event. All monetary values are in constant 2015 US\$. Map data in **a** include World Hillshade tiles by Esri, USGS, Airbus DS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community. Credit: basemap in **a**, ESRI and contributors.

while the net benefits generated are US\$166 million yr⁻¹. Of the net benefits that TWMs generate, 85% are conveyed to consumers. The remaining net benefits accrue to sellers (14%) and to the government as taxes (<1%).

The high fuel costs of tanker water also reflect the fact that tanker trucks provide a technically inefficient means of transporting water. Transporting water via truck requires about three to seven times as much energy as generating freshwater by reverse osmosis, adding about 17.6 kWh m⁻³ on top of the required well pumping energy costs (Methods, Energy use and comparison of water supply modes). While this high energy intensity seems sensible when avoiding acute water shortages or servicing remote areas, transporting a large share of drinking water by road has negative implications for greenhouse gas emissions.

Water pumping costs are less than 1% of tanker water costs, suggesting current electricity tariffs and abstraction charges for private wells^{36,37,41} fall far short of the full societal costs of groundwater abstractions. Comprehensive estimates of the environmental and resource cost of groundwater pumping in Jordan are missing. Rapidly falling groundwater tables, however, indicate that these societal costs are high compared with many other parts of the world³². Total TWm sales, equivalent to 27% of all overabstraction, contribute substantially to that impact.

TWms have considerable negative impacts on groundwater and on the climate. Like the private costs of tanker water, however, these impacts are a symptom of public water supply deficits.

Growth projections for Jordan's illegal tanker water markets

Evaluating the trade-offs between the positive and negative impacts of TWms will become more pressing in the future as the factors that have led to their emergence intensify under population growth and climate change. Here we make use of the ability of our approach to not just estimate the size of TWms, but also to simulate their evolution over time. We conducted an ensemble of ten simulations until 2050 with the JWM-T, capturing all five shared socioeconomic pathway (SSP) projections for Jordan⁴², climate change under representative concentration pathway 4.5 and two alternative assumptions about future crop price developments (Fig. 3).

We find that the current trajectory of Jordan's water sector leads to a substantially increased role of its legal and illegal TWms. Tanker water sales to all consumers grow from 59 to 95 million m³ yr⁻¹ between 2015 and 2050 (Fig. 3a). Household reliance on tanker water increases 2.6-fold, from 4.6% to 12% (Fig. 3b). The total net benefits of water sales rise to US\$313 million yr⁻¹ in 2050 (Fig. 3c). The value of tanker sales

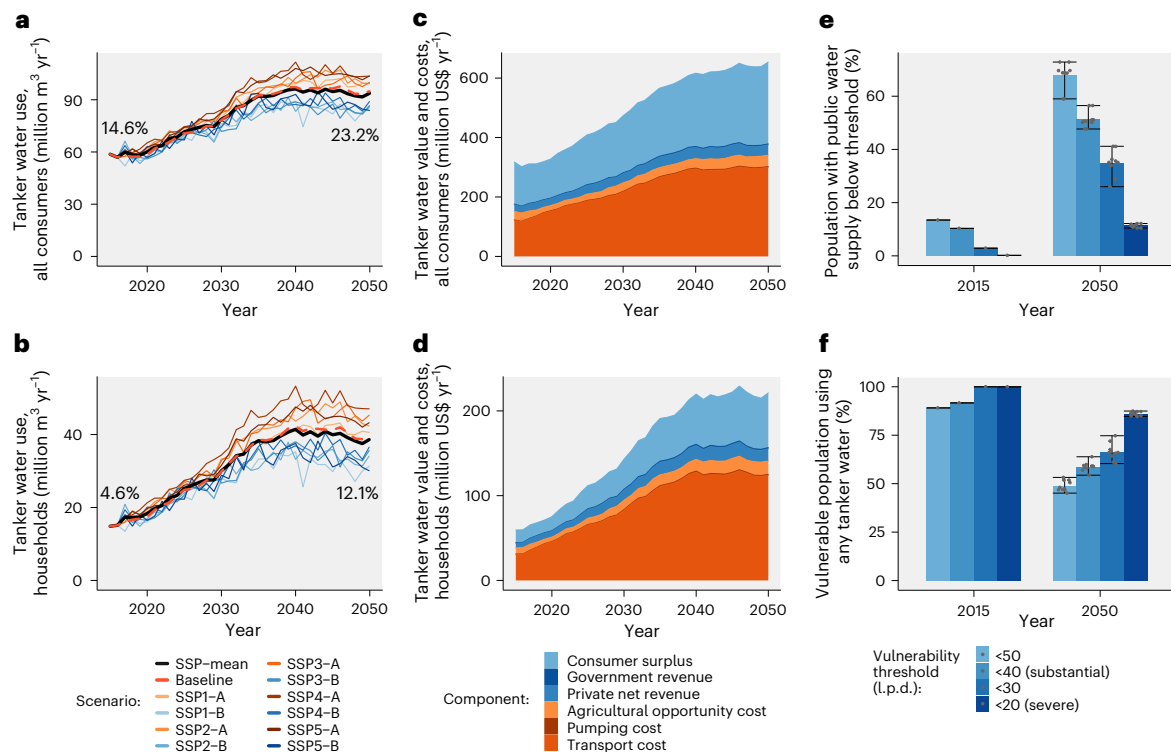


Fig. 3 | The growing size, value and costs of Jordan's tanker water markets.

Ensemble simulations show the growing economic role of TWMs. **a, b**, Projected tanker water use and share of total water use for all consumers (**a**) and for households (**b**). Across ten combinations of the five SSPs and two crop price scenarios (Methods, Future projections and policy interventions), total tanker sales increase, on average, from 58.7 to 94.9 million $\text{m}^3 \text{yr}^{-1}$ between 2015 and 2050. The share of tanker water in total water consumption rises from 14.6% to 23.2%. For households, the share of tanker water consumption grows 2.6-fold, from 4.6% to 12.1%. Analyses of TWMs' economic value use a baseline simulation closely resembling the ensemble averages in **a** and **b**. **c, d**, Tanker water value and costs for all consumers (**c**) and for households (**d**). Across all water uses, we project that the total net benefits generated by tanker water sales will increase by a factor of 1.9, from US\$165.8 to US\$313.3 million yr^{-1} between 2015 and 2050.

The private net revenue accruing to well owners grows by a factor of 1.5, consumer surplus (defined as the aggregate difference between consumers' willingness to pay for water and the price paid) by a factor of 1.9 and total costs of tanker water provision by a factor of 2.2. For households, the total value increases by a factor of 3.7, private net revenue by a factor of 2.5, total costs by a factor of 3.7 and consumer surplus by a factor of 4.3. **e, f**, The population vulnerable to public supply shortages increases (**e**) and the share of that population using tanker water to mitigate their vulnerability decreases (**f**). Dots indicate the individual values for the ten simulations, solid bars indicate the mean values and error bars indicate the minimum and maximum values. All monetary values are in constant 2015 US\$. Environmental and resource externalities are not included in the costs but analysed separately. A, constant mean crop price scenario; B, crop price trend scenario.

to households rises faster than their costs (Fig. 3d) as tanker water is increasingly employed for essential uses.

Along with TWMs' economic value, tanker water prices and transport distances also increase substantially. Average tanker water prices are projected to rise from US\$3.0 m^{-3} currently to US\$4.0 m^{-3} in 2050 across Jordan as a whole and from US\$3.2 to US\$5.2 m^{-3} in 2050 in the capital city of Amman. A key factor in this increase is local groundwater drawdown. The JWM-T is able to simulate how over-pumping under Amman causes groundwater levels to drop locally, making it economically preferable for tanker trucks to travel farther from the city to source their water supply (Extended Data Fig. 1). These substantial increases in costs and energy use constitute a downside of heavy reliance on TWMs.

As costs rise, the 2.6-fold expansion of TWMs' share in household water supply fails to keep pace with the increasing public supply shortages. The substantially vulnerable population with less than 40 l.p.d. of public water supply grows fivefold (Fig. 3e) while the share of that population purchasing tanker water declines from 92% to 64% (Fig. 3f).

Public supply improvements

The TWM projections raise the question of whether public supply investments currently considered in Jordan would improve water security sufficiently to reduce or at least stabilize TWM demand

and externalities. We test investments in supply augmentation and improved water distribution in JWM-T simulations until 2050 (Fig. 4 and Supplementary Methods 5.1–5.3).

Even the largest desalination investment under consideration (300 million $\text{m}^3 \text{yr}^{-1}$), which expands public supply by more than 50%, would reduce TWM abstractions in 2050 by just 19 million $\text{m}^3 \text{yr}^{-1}$. Compared with the 2015–2020 average (57.8 million $\text{m}^3 \text{yr}^{-1}$), abstractions grow by +64% (95 million $\text{m}^3 \text{yr}^{-1}$) without desalination versus +31% (76 million $\text{m}^3 \text{yr}^{-1}$) with desalination (Fig. 4a). The reason is that household vulnerability (Fig. 4b,c) and tanker water demand (Fig. 4d,e) remain high unless supply augmentation is complemented by investments in a more equitable and efficient water distribution system.

Combining both investments would stabilize tanker abstractions (Fig. 4a) and mitigate nearly all vulnerability (Fig. 4b). This would, however, require two highly capital-intensive investment efforts whose feasibility is uncertain. Further analyses of public supply improvements are provided in Supplementary Results 1.

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 policy reforms contribute to stabilizing TWMs' groundwater abstractions while maintaining water security?

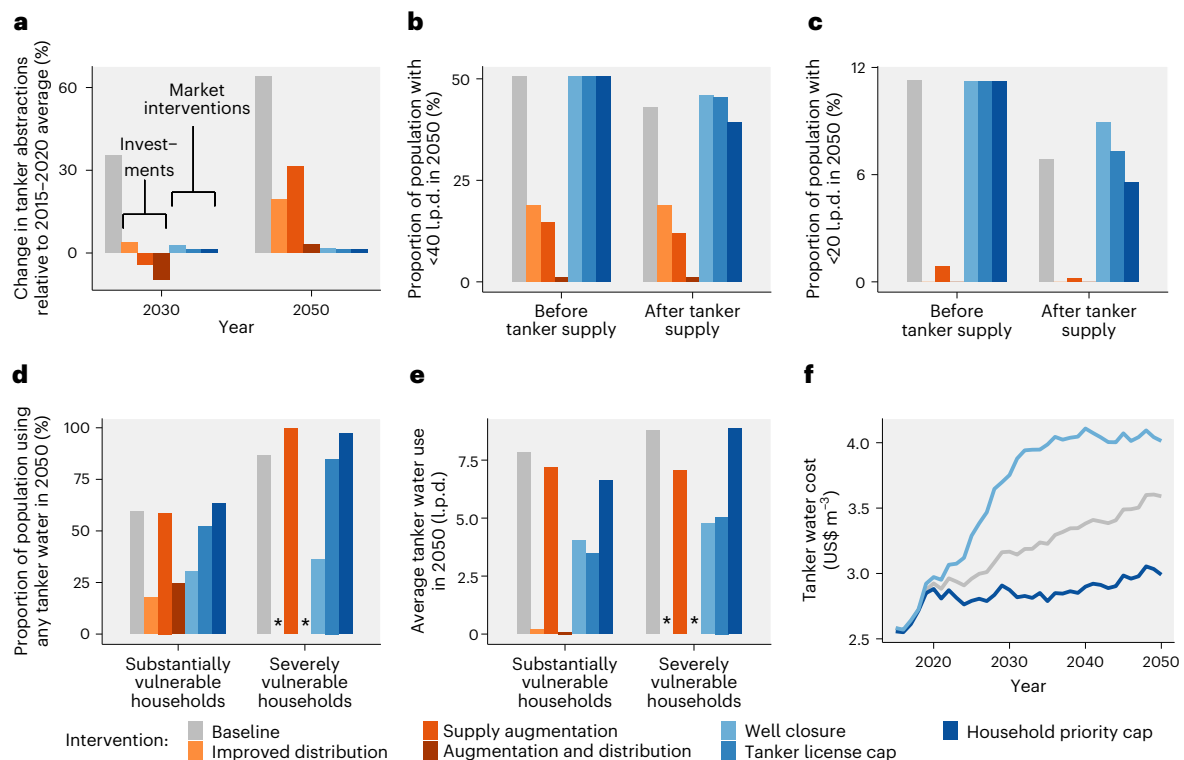


Fig. 4 | Evaluation of six tanker market interventions until 2050. Results from JWM-T simulations of six tanker market interventions for 2015–2050 (Supplementary Methods 5). **a**, Change in tanker groundwater abstractions. Large investments improving the public water distribution system or augmenting supply through desalination substantially mitigate the growth of groundwater abstractions for TWMs compared with a no-policy baseline. Under supply augmentation, tanker water abstractions still grow by +31% by 2050, compared with +64% under the baseline. Implementing both public supply investments simultaneously or TWM reform interventions (well closure, tanker license cap, household priority cap) stabilizes abstractions near average 2015–2020 levels until 2050. **b, c**, Public supply investments reduce substantial water vulnerability of households in 2050, defined as those receiving less than 40 l.p.d. (**b**), and largely prevent severe vulnerability in 2050, defined as those receiving less than 20 l.p.d. (**c**), by making piped water more accessible.

Market interventions allow TWMs to mitigate vulnerability at rates similar to the baseline, with the exception of a substantial increase in severe vulnerability under a stricter enforcement of Jordan's current well closure policy. **d, e**, Well closure also lowers the share of vulnerable households that enhance their water supply by purchasing tanker water in 2050 (**d**) and both well closure and the tanker license cap reduce vulnerable households' average tanker water use in 2050 by about 50% (**e**). The household priority cap maintains tanker water use at levels closer to the baseline. **f**, Closing known illegal tanker wells raises the costs per cubic metre of water sold, compared with the baseline. The household priority cap provides a more efficient way of reducing groundwater abstractions, leading to lower costs. This also results in higher overall net benefits of tanker water provision (Supplementary Fig. 4). All monetary values are in constant 2015 US\$. Asterisks (*) indicate non-applicable categories.

Comparative analyses of water markets have established institutional preconditions to facilitate an efficient re-allocation of water under various hydrological and sociotechnical contexts^{22,23,43}. 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^{14,20,22}. 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 enforcement³⁷.

We use the JWM-T to compare two indirect enforcement interventions to Jordan's existing approach (Fig. 4 and Supplementary Methods 5.4–5.6). Jordan's current strategy to mitigate tanker abstractions is to gradually close known illegal wells ('well closure')^{36,37}. The first indirect enforcement intervention leverages the existing tanker licensing system³⁶ to cap the number of active vehicles and reduce abstractions ('tanker license cap'). A modified intervention prioritizes household water use by separating licences for sales to households from those for sales to commercial users ('household priority cap').

The former grow in proportion to population while the latter are reduced to control abstractions.

All three policies manage to stabilize groundwater abstractions at current levels until 2050 (Fig. 4a). However, closing known illegal tanker wells requires tankers to travel farther out to additional wells that did not previously sell tanker water, resulting in high costs per cubic metre of water supplied (Fig. 4f) and making tanker water unaffordable for many vulnerable households (Fig. 4d). The license cap avoids this increase in transportation distances and stabilizes groundwater abstractions in a more cost effective manner (Supplementary Figs. 4 and 5).

Vulnerable households have greater access to tanker water under the license cap (Fig. 4d), but the cap reduces their average tanker water use by half (Fig. 4e). The household priority cap avoids this shortcoming while keeping costs low (Fig. 4f) but comes at the cost of economic losses for commercial users (Supplementary Fig. 4). Adjustments to the intervention could balance the objectives of abstraction reduction, household water access and commercial net benefits differently.

Assessing the feasibility of these market reforms in Jordan's political and institutional environment requires further analysis. The preceding 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. Additional analyses of these policies are provided in Supplementary Results 2.

Discussion

We estimate that TWMs in Jordan sold 10.7 times as much water as officially acknowledged in 2015, implying a much greater reliance of water users on this informal institution than previously known. The results confirm concerns about TWMs: their sales quantity of 59 million m³ yr⁻¹ is equivalent to 27% of groundwater overabstraction, hampering government efforts to manage aquifers sustainably. TWMs attract about 52% of the total funds Jordanian households and firms spend on water while delivering only 15% of their water supply. Of tanker sales, 75% serve commercial water use by businesses. The funds TWMs attract are spent on a technically inefficient supply mode that uses 69% of their revenue for transport costs and causes unnecessary carbon emissions.

However, TWMs also provide an essential lifeline for households in intermittent water supply systems. Of households with less than 40 l.p.d. in Jordan, 92% use tanker water. Tanker water prices are on average 4.8 times as high as piped water tariffs, raising concerns about the affordability of drinking water and inequity between households with and without sufficient piped water access. We find that TWMs in Jordan price water at marginal costs and that they convey 85% of the net benefits they generate to consumers. They are competitive markets, and their high prices and negative impacts are a direct consequence of the inability of public water supply to meet all demands.

We project that the share of tanker water in household water use will grow 2.6-fold by 2050. Tanker water prices will rise further due to local groundwater depletion and expanding transport distances. This limits TWMs' ability to mitigate the fivefold increase in the population receiving less than 40 l.p.d. of public water supply, and the share of that vulnerable population using tanker water falls from 92% to 64%. The total net benefits of TWMs still rise from US\$166 to US\$313 million yr⁻¹ during 2015–2050 while tanker water is employed for increasingly essential water uses. TWMs are projected to transport 95 million m³ of water per year in 2050, exacerbating the conflict between (1) TWMs' unregulated groundwater abstractions and negative climate impacts and (2) their positive role in generating economic value and extending household water access.

Restrictive policies, such as Jordan's current approach to regulate TWMs by closing illegal tanker wells, can stabilize groundwater abstractions at current levels but have the unintended consequence of severely impeding TWMs' role in improving the water access of vulnerable households. Public water supply investments would more directly address the cause for TWM abstractions. Notably, even Jordan's recent plans for large desalination investments would only moderately reduce the demand for tanker water if public water access remains highly unequal. Combining recent large-scale desalination with a more equitable and efficient distribution, however, would be highly effective in curbing tanker water demand while also improving water access and affordability. Achieving this would require extensive additional investments to break the vicious circle of intermittency and leakages in public supply⁷. This barrier is difficult to surmount, as evidenced by the limited progress to date^{30,44}.

Even in the absence of viable public supply improvement options, we find that closing illegal tanker wells reduces TWMs' benefits more than other options to limit their groundwater impacts. Closing illegal wells has been an important part of Jordan's efforts to curb agricultural groundwater overabstraction, but transferring that approach to TWM policy is unexpectedly detrimental to water access. The existing tanker registration system offers a potential basis for regulating the extensive water sales to businesses. This could provide a more viable approach to control groundwater abstractions without curtailing the smaller yet essential TWM supply to households. The analysis shows that policy

design can enhance water security by explicitly considering illegal TWMs' critical contributions to household water access.

Informal water supply institutions are increasingly relevant to nearly one billion urban residents facing water supply intermittency⁶. This study develops an approach for analysing informal water supply institutions within coupled human and natural systems models, applicable to TWMs in cities around the world such as Mexico City, Karachi, Beirut and Mumbai^{14,18}. The case of Jordan is emblematic for an unfolding water crisis exacerbated by unreliable urban water supply³². Our results show that these factors can cause informal institutions to provide a substantial share of urban water supply and an even larger contribution to household water access. Improving the understanding and governance of informal water supply institutions is, therefore, essential for future urban water security.

Methods

Here we develop a new approach to simulating informal TWMs, building on a coupled hydro-economic multi-agent system (MAS) model, the JWM³². Adopting an integrated hydro-economic modelling perspective allows us to better understand the dynamics of economic systems under environmental constraints⁴⁵. Integrated MAS models are especially suitable for gaining insights into complex hydro-economic⁴⁶ and socio-hydrological systems⁴⁷ and closely coupled human and natural systems, such as Jordan's water sector, in particular⁴⁸. Both integrated hydro-economic models in general⁴⁹ and specifically MAS models have been successfully applied to simulate water markets⁵⁰, transportation networks⁵¹ and other decentralized supply systems. References 27,28 developed a first coupled human–environment system model capturing TWMs in Chennai.

The JWM models water resource availability with a set of hydro-logic models, including a countrywide 12-layer MODFLOW-based groundwater model, inputs from SWAT run-off models and a water supply network model³², implemented in the Pynsim modelling framework⁵². Water allocation decisions are represented by a number of institutional modules, including (1) a central water authority, responsible for strategic water-sector decisions, including reservoir releases, (2) a WAJ agent, managing groundwater well extractions and water conveyance between governorates and (3) local piped water utilities, distributing water within governorates. Water consumption behaviour is captured by 1,823 water user agents, representing households, refugee households and commercial establishments in all 89 subdistricts of Jordan. During simulations, the JWM captures monthly dynamic feedbacks between surface and groundwater abstraction decisions by water supply network operators and 84 farm agents on the one hand and declining groundwater levels on the other, allowing us to represent the trajectory of the highly coupled human–water system that is Jordan's water sector. This approach enables us to better understand future implications of Jordan's TWMs regarding their economic and water security contribution as well as their impacts on groundwater sustainability, greenhouse gas emissions and affordability.

For the TWM analyses conducted here, an extension of the JWM, the JWM-T, is developed. The JWM-T includes a more precise transport cost simulation based on road distances, a calculation of the energy requirement of TWMs and the ability to simulate additional policy interventions, specifically addressing TWM activities, which are described in the subsequent sections. A summary of the JWM data inputs of particular relevance to this analysis and of the added JWM-T data inputs is provided in Supplementary Methods 1.

Informal water market simulation approach

To model legal and illegal TWMs across Jordan despite the inherent data scarcity^{14,25}, we use a conceptual approach of indirect measurement developed for assessing informal and shadow-economic activities in general²⁹. This approach relies on the fact that informal or illegal economic activities rarely exist in isolation but are linked to formal

activities in terms of both inputs and outputs. In the context of measuring overall informal economic activities, common examples of indirect approaches include identifying discrepancies in currency or energy demand²⁹. In Jordan, measurable indirect factors that influence illegal TWMs include (1) the fact that tanker water is demanded as a substitute for piped water wherever piped water is rationed, (2) the fact that rural freshwater sources are so scarce that there is a direct trade-off between selling water to tanker trucks and using it for agricultural production, (3) groundwater levels determining pumping costs and (4) road transportation distances and costs. These four factors determine the market demand and supply for tanker water. The modules representing these factors are presented in the subsequent sections.

Residual water demand of households and businesses

We operationalize the market demand for tanker water as a residual demand for water after the available piped water supply has been exhausted. This rests on the fact that in Jordan, private wells are not available to water users within cities, whereas other sources, such as bottled water, are used for drinking purposes only and thus are not large enough quantitatively to make a substantial difference to residual water demand³⁵. The JWM-T accounts for so-called non-revenue water, consisting of leakages and unbilled piped water uses (Supplementary Methods 1). Consumers' residual demand for tanker water is determined by combining a tiered supply curve approach^{53,54} with econometric demand function estimates⁵⁵ and data on local scheduled supply interruptions that constrain the consumption of piped water (Supplementary Methods 1 and 2). Household characteristics and water use are obtained from Jordan-wide household expenditure and income surveys for the years 2006, 2008, 2010 and 2013 ($n = 15,858$) (ref. 56). Commercial establishment characteristics and water use rely on our previous survey of Amman, Irbid and Ajloun ($n = 341$) (ref. 36). Supplementary Methods 1 summarizes how survey data and annual data from other sources are combined to provide model inputs to the JWM³². For a consumer with given socioeconomic characteristics, this approach gives us the quantity of tanker water demanded by that customer as a function of the tanker water price. Equation (1) defines the functional form of the demand function for households as well as commercial establishments⁵⁵.

$$q_t(p_t) = \exp\left(\beta_p p_t + \sum_i \beta_i x_i\right) - q_0. \quad (1)$$

Here, q_t refers to the consumption of tanker water in cubic metres per household or establishment per day, p_t refers to a given price for tanker water, β_p is the price coefficient, x_i refers to all non-price demand function parameters (for example, household size, income, establishment employees), β_i refers to all non-price demand function coefficients and q_0 is the piped water consumption. Due to its lower price and higher quality, piped water is assumed to be prioritized over tanker water.

Opportunity costs of rural groundwater abstractions

The price of tanker water depends on the marginal resource opportunity costs (MROC) of water, defined as the marginal value of water at its source, varying across space and time^{57,58}. Here these MROC of water at rural wells are determined by a positive mathematical programming (PMP) model⁵⁹, optimizing crop production on the basis of farm-gate prices, costs and local groundwater availability for each of the 84 agricultural production agents represented in the JWM-T³². Farm characteristics and production are obtained from agricultural census data for 2006 (ref. 60) and agricultural survey data for 2007 and 2013 (ref. 61). Well production and yield data are based on a US Geological Survey well survey ($n = 8,200$)⁶². Since irrigated agriculture is constrained by scarce rural freshwater sources, we assume that water sold on the tanker market could always be used for agriculture. Local agricultural

profitability, therefore, determines the opportunity costs of tanker water. The minimum price a farm agent is willing to accept for selling tanker water, or reservation price, thus, is equal to the net revenue of the least profitable, marginal crop plus the groundwater pumping cost. Equation (2) defines the objective function of the seasonal cropping optimization problem solved by each subdistrict's farm agent³²:

$$\begin{aligned} \max(\pi) &= \sum_i (p_i y_i - c_i w_i - k_i - \alpha_i - \beta_i x_i) x_i, \\ \text{subject to } \sum_i x_i &\leq \bar{X} \text{ and } \sum_i w_i x_i \leq \bar{W}. \end{aligned} \quad (2)$$

Here, x_i refers to the area allocated to each crop i in dunum (a Jordanian unit of area equal to 1,000 m²), $\bar{X}$ is the total arable land available in the subdistrict, w_i is the net irrigation requirement of each crop, indicating the seasonal irrigation water quantity in cubic metres per dunum required to grow that crop after accounting for local rainfall, and $\bar{W}$ is the maximum irrigation water quantity in cubic metres per season that can be abstracted from ground- and surface water sources in the subdistrict. p_i is the producer price of crop i in US\$ per ton, y_i is the yield in tons per dunum, c_i is the water cost in US\$ per cubic metre, including local pumping energy costs based on the current groundwater pumping head and water abstraction tariffs, k_i is the non-water input cost in US\$ per dunum, including inputs such as labour, machinery, pesticides and fertilizers, and α_i and β_i are PMP calibration coefficients. After solving the PMP optimization problem, the minimum price at which a given farm is willing to sell tanker water is calculated as the water pumping cost plus the net revenue of the least profitable crop actually grown in US\$ per cubic metre. In each simulation month, pumping costs are updated on the basis of groundwater levels, consequent pumping lift is determined by the spatially distributed numerical groundwater model that is integrated into the JWM, and the maximum abstraction quantity $\bar{W}$ is reduced proportionately if wells in a subdistrict run dry³². Specifically, the maximum abstraction quantity linearly declines starting at an upper threshold groundwater level until reaching zero when groundwater levels hit the bottom of the aquifer or well.

Spatial price-equilibrium optimization

Besides the agricultural opportunity cost of water at its rural source, the price of tanker water is also determined by the transportation costs required to get the water to the customer. It is, therefore, dependent on the customer's location. In the hydro-economic TWM model of refs. 27,28, the agricultural opportunity, pumping and transportation costs determining tanker water prices were calculated exogenously. The available tanker water quantity was assumed to be locally unconstrained, implying that prices are not influenced by competition between local demands. The spatial price-equilibrium approach and the endogenous calculation of MROC used here represent an important methodological innovation, allowing us to (1) capture the various costs determining tanker water sales much more precisely, (2) analyse the market structure of Jordan's TWMs and the distribution of the value generated between consumer and producer surplus and (3) simulate the dynamics of Jordan's TWMs under future and counterfactual scenarios, accounting for dynamic interactions among changing demands, groundwater levels and agricultural opportunity costs of water across the country.

We capture the spatial influence of competition among urban demands, agricultural opportunity costs and transportation costs on TWMs in Jordan by applying a spatial price-equilibrium approach³¹ within the JWM³². The spatial price-equilibrium approach simulates a perfectly competitive market with transportation costs by determining a set of feasible sales between consumer and agricultural agents' locations that maximizes total private surplus. The assumption of a highly competitive market is supported by a survey of tanker water truck drivers ($n = 300$) (ref. 36) indicating a market structure with a large number

of small firms and low barriers to entry and by the validation analyses described in Supplementary Methods 3. For the JWM-T extension, we determine road distances between average locations of wells and towns across Jordan^{62–64} calculated with the Google Distance Matrix API (application programming interface)⁶⁵. Transport costs per cubic metre by kilometre are estimated from the survey data collected by ref. 36, including fuel costs, wages and a contribution margin required for truck maintenance or replacement. The spatial price-equilibrium model is defined as a private surplus maximization problem with local supply constraints and transportation costs, representing perfectly competitive TWMs (equation (3))³².

$$\begin{aligned} \max(W) &= \sum_i \sum_j \int (p_i(q_i) - t^c d_{ij} - p_j^r) q_{ij}, \\ \text{subject to } q_{ij} &\leq \bar{q}_j. \end{aligned} \quad (3)$$

Here, W is the total private surplus generated by TWMs. The willingness to pay (p_i) of household or firm i for tanker water in US\$ m⁻³ is a function of the variable allocation of tanker water (q_i) in m³ user⁻¹ d⁻¹; q_{ij} is the quantity of water transferred from a given farm j to a given water user i in m³ d⁻¹; d_{ij} is the road distance between a given farm j and water user i in kilometres; t^c is tanker truck transportation cost in US\$ m⁻³ km⁻¹; p_j^r is the reservation price of water at farm j in US\$ m⁻³; and $\bar{q}_j$ is the local water constraint. We apply the Python Optimization Modeling Objects (Pyomo) optimization framework^{66,67} with the Interior Point Optimizer (IPOPT) solver⁶⁸ to solve this optimization problem.

Model validation

Employing the spatial price-equilibrium approach within a coupled human–natural systems framework enables the JWM-T to integrate the abstraction, transportation and sale of water on Jordan's legal and illegal TWMs. Model validation analyses conducted to support the approach on the basis of survey data, tanker truck registrations and wastewater influent records are presented in Supplementary Methods 3.

Energy use and comparison of water supply modes

To determine the energy intensity of tanker water transport, we use the road distances calculated by the spatial price optimization and an energy use factor based on energy requirements for heavy truck transportation (equation (4)).

$$E = \phi \sum_i \sum_j d_{ij} q_{ij}. \quad (4)$$

Here, E is the total energy use by TWMs in kWh d⁻¹, ϕ is the energy requirement for heavy truck transportation per m³ km⁻¹ (ref. 69), and q_{ij} and d_{ij} are defined as in the preceding subsections.

We rely on the following considerations to compare the energy intensity of tanker water transport with that of the piped water network. The public water supply system in Jordan's highlands, where all major cities are located, uses on average 7.51 kWh to produce and deliver one cubic metre of piped water⁴⁴. This includes substantial energy costs for pumping water from the Jordan Valley into the highlands, conveying water across long distances and desalination^{39,41}. By comparison, the average in the Jordan Valley, where no major elevation needs to be surmounted, is just 0.27 kWh m⁻³ (ref. 44). It is striking that the average energy intensity of water supply in the highlands is higher than the 3–7 kWh m⁻³ required for seawater reverse osmosis⁷⁰. Our model estimates that tanker trucks across Jordan travel on average 13.1 km from their water source to their customers, or 26.2 km to travel back and forth, adding about 17.6 kWh m⁻³ on top of well pumping energy costs.

Future projections and policy interventions

We conduct an ensemble of ten simulations until 2050 with the JWM-T to project future TWM developments, capturing all five SSP

projections for Jordan⁴², climate change under representative concentration pathway 4.5 and two alternative assumptions about future crop price developments. A detailed description is provided in Supplementary Methods 4. The implementation of three TWM policy reform options and three public supply investment interventions introduced in the JWM-T is presented in Supplementary Methods 5.

Inclusion and ethics in global research

Local researchers were involved in all steps of the process of preparing the research presented, including study design, study implementation and authorship. The research is locally relevant and has been defined in collaboration with local partners and stakeholders. Ahead of the research, all roles and responsibilities were agreed upon among collaborators. Local experts were trained in using the JWM in a companion project aimed at capacity building. We have included local and regional research relevant to our study in the citations.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data inputs required to execute the Jordan Water Model (JWM) and the JWM for Tanker Water Market Analyses (JWM-T) extension are available at the Stanford Data Repository: <https://doi.org/10.25740/zw908ds8394>. Additional hydrologic and infrastructure data used to calculate some of the model inputs and parameters are available from the corresponding author upon request and consultation with the relevant national authorities who own the data. Additional socioeconomic data used in developing the JWM are available from the Economic Research Forum: <http://erfdataportal.com/index.php/catalog>. Raw business and tanker truck survey data used are not publicly available to protect confidentiality, although summary statistics are provided in ref. 36.

Code availability

The code of the Jordan Water Model (JWM) and the JWM for Tanker Water Market Analyses (JWM-T) extension is available for download at the Stanford Data Repository: <https://doi.org/10.25740/zw908ds8394>.

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Author contributions

C.K., J.Y., B.K., E.G. and S.M.G. conceptualized the study. C.K., J.Y., K.S., B.K., S.T., T.L., P.S., S.K., N.A., A.T., J.J.H., D.M., J.M.-A., B.B., H.Z., E.G. and S.M.G. contributed to research design. C.K., J.Y., T.L., P.S., S.K., N.A., J.M.-A. and H.Z. implemented the model. C.K., J.Y., K.S., B.K., S.T. and D.M. collected data. C.K., J.Y. and S.M.G. wrote the article. C.K., J.Y., K.S., B.K., S.T., T.L., P.S., S.K., N.A., A.T., J.J.H., D.M., J.M.-A., B.B., H.Z., E.G. and S.M.G. reviewed and improved the analyses and the article.

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Competing interests

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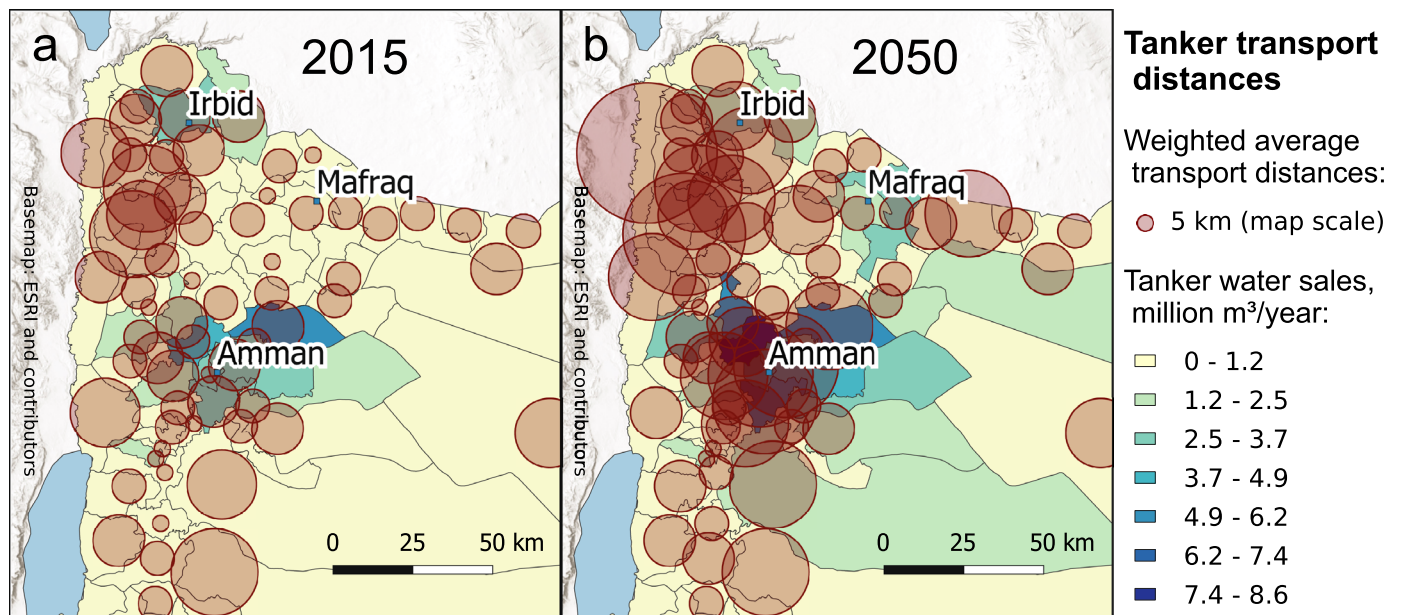
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Extended Data Fig. 1 | Increasing tanker water transport distances. Circles display the average simulated tanker water transport distances at the map scale for the years (a) 2015 and (b) 2050, weighted by the sales quantity, based on a baseline JWM-T simulation. The coloration of each subdistrict reflects the total annual tanker water quantity sold. The average transport distance almost doubles from 13.1 to 19.9 km one-way between 2015 and 2050, corresponding to an average 39.8 km round trip for each delivery, raising the energy requirement from about 17.6 kWh per m³ to about 26.8 kWh per m³ (see Methods, Energy use and comparison of water supply modes). Transport distances see an especially

pronounced increase in the mountainous Northwestern corner of Jordan, which is surrounded by deep valleys to the north and west, and other high-demand urban centers to the south and east. In Amman, this distance even grows from 13.1 to 25.5 km, corresponding to an average travel distance of 51 km per round trip for each delivery and an estimated 34.3 kWh per m³. Map data include World Hillshade tiles by Esri, USGS, Airbus DS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap, and the GIS user community. Credit: basemaps, ESRI and contributors.

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Software and code

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Data collection No software was used to collect data.

Data analysis The Jordan Water Model code used for data analysis is available for download at the Stanford Data Repository (<https://doi.org/10.25740/zw908ds8394>) including all data required to execute the model.

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All data inputs required to execute the Jordan Water Model (JWM) and the JWM for Tanker Water Market Analyses (JWM-T) extension are available at the Stanford Data Repository: <https://doi.org/10.25740/zw908ds8394>. Additional hydrologic and infrastructure data used to calculate some of the model inputs and parameters are available from the corresponding author upon request and consultation with the relevant national authorities who own the data. Additional socio-economic

data used in developing the JWM are available from the Economic Research Forum: <http://erfdportal.com/index.php/catalog>. Raw business and tanker truck survey data used are not publicly available to protect confidentiality, though summary statistics are provided in Sigel et al. (2017).

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Study description A country-wide coupled human and natural system model of Jordan's water sector and freshwater resources, the Jordan Water Model (JWM; Yoon et al., 2021, <https://doi.org/10.1073/pnas.2020431118>) is extended and used for a quantitative simulation analysis of the role of illegal water markets in Jordan's water supply system including their impacts, to their expected future developments, and available policy responses.

Research sample No new primary data was collected for this study. The coupled human and natural system model combines various existing hydrologic, climate, and socio-economic datasets to simulate developments in Jordan's water system (see Supplementary Methods 1 and Yoon et al., 2021, Supplementary Information). The data used is representative of the country of Jordan and covers the period of 2006 to 2015. Analyses after 2015 combine historical data and country-specific projections from the five Shared Socioeconomic Pathways (Riahi et al., 2017, <https://doi.org/10.1016/j.gloenvcha.2016.05.009>), as well as regional climate projections (Rajsekhar and Gorelick, 2017, <https://doi.org/10.1126/sciadv.1700581>), to simulate future developments at the subdistrict level.

Sampling strategy The existing datasets used by the JWM were collected based on various sampling techniques. The survey datasets in particular used stratified sampling methods building on previous census and survey data to ensure representativeness across geographical zones and categories.

Data collection No new primary data was collected for this study.

Timing and spatial scale The illegal water market analyses cover the whole country of Jordan at the level of 89 subdistricts and the years 2006 to 2050.

Data exclusions No data were excluded from the analyses.

Reproducibility Results can be reproduced with the code and data provided in the Stanford Data Repository (see Data Availability and Code Availability statements).

Randomization Not applicable, as this is a modeling study based on existing datasets.

Blinding Not applicable, as this is a modeling study based on existing datasets.

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