

Impact of the Syrian refugee crisis on land use and transboundary freshwater resources

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Edited by Peter H. Gleick, Pacific Institute for Studies in Development, Environment, and Security, Oakland, CA, and approved November 1, 2016 (received for review August 27, 2016)

Since 2013, hundreds of thousands of refugees have migrated southward to Jordan to escape the Syrian civil war that began in mid-2011. Evaluating impacts of conflict and migration on land use and transboundary water resources in an active war zone remains a challenge. However, spatial and statistical analyses of satellite imagery for the recent period of Syrian refugee mass migration provide evidence of rapid changes in land use, water use, and water management in the Yarmouk–Jordan river watershed shared by Syria, Jordan, and Israel. Conflict and consequent migration caused ~50% decreases in both irrigated agriculture in Syria and retention of winter rainfall in Syrian dams, which gave rise to unexpected additional stream flow to downstream Jordan during the refugee migration period. Comparing premigration and postmigration periods, Syrian abandonment of irrigated agriculture accounts for half of the stream flow increase, with the other half attributable to recovery from a severe drought. Despite this increase, the Yarmouk River flow into Jordan is still substantially below the volume that was expected by Jordan under the 1953, 1987, and 2001 bilateral agreements with Syria.

remote sensing | Landsat | reservoir | conflict | irrigation

Disputes over scarce water resources rarely escalate into full-blown wars (1–4), but the impact of drought on water resources and agricultural land use is severely impacting the Middle East. The effect is most apparent in the current Syrian civil war, where poor governance and overreliance on intensive irrigation diminished the country's ability to cope with a severe drought (5, 6). That drought, which hit the Middle East between 2006 and 2008 (6–8), had a detrimental effect on freshwater resources with consequent human impacts. The Syrian civil war was sparked by riots in the southern city of Dara'a (5), located in the Yarmouk River basin, a subbasin of the Jordan River watershed, which is shared with Jordan and Israel. Poor crop yields in Syria led to the collapse of the agricultural sector and large-scale migration to urban areas, contributing to economic hardship, political instability, and ultimately, armed conflict (5). The ensuing war caused a massive migration of Syrian refugees to neighboring countries, largely in 2013. The combined effect of conflict-related power outages and migration out of southern Syria is clearly visible in night-light images (Fig. 1C) that reflect population changes in the small cities and villages in the area (9). Data from the United Nations High Commission on Refugees (10) suggests that in excess of 369,000 people were driven out of the Syrian portion of the Yarmouk basin, an estimate that excludes the large number of unregistered refugees.

This migration put major stress on Jordan's infrastructure, including its water resources (11), a heavy burden for a country ranked among the most water-scarce in the world even before the refugee influx (12). However, the refugee crisis also coincided with an unexpected, rapid increase in flow in the Yarmouk River from Syria to the Al-Wehda reservoir on the Syria–Jordan border (Fig. 1), which feeds Jordan's water supply system. The Yarmouk River is the primary tributary to the lower Jordan River and a strategic transboundary freshwater resource. The river has historically been the largest natural surface water source available to Jordan, providing a significant portion of the country's surface water supply. The Al-Wehda dam, along the Jordan–Syria border, became

operational in 2007. The reservoir captures much of the Yarmouk flow, serving as a significant water storage facility for Jordan. In the past several decades, the Yarmouk watershed upstream of the Al-Wehda dam has been extensively exploited by Syria with the construction of 21 dams to enable intensive agricultural irrigation, resulting in substantial flow decreases to downstream Jordan and Israel (Fig. S1D). After 2012, inflow records at Al-Wehda reservoir show a sudden reversal in this declining flow trend, an unexpected increase as rainfall declined between 2012 and 2014 (Fig. 1). However, there is a clear correspondence between the flow increase and the number of refugees migrating out of the Syrian side of the basin (Fig. 1). This correspondence suggests a potential relationship between civil conflict, land use, and water consumption in Syria, with consequent changes to the hydrological response.

This study explores the impact of armed conflict and consequent Syrian refugee migration on land use and freshwater resources. We show that the abrupt increase in transboundary river flow is a consequence of rapid upstream changes stemming from the Syrian civil war. Results indicate that the Syrian conflict and refugee crisis caused a substantial decline in agricultural land use and irrigation water use, and a significant alteration in the management of the Syrian stored water supply system, which ultimately resulted in increased flow to downstream Jordan.

Water Resources Assessment in a War Zone

Reliable land use and hydrological data are essential to investigate the changes in Syria on transboundary river flow to Jordan, but collecting data in an active war zone is a major challenge. Satellite data are increasingly exploited during situations requiring rapid collection of data in environments that are difficult to access, such as for disaster response and emergency mapping (13). Here, we use satellite imagery to investigate causal relations between changes in land use and water resources during an armed conflict.

Significance

The notion that sudden impacts on shared international waters can be detected and quantified, even in a war zone, is important to scientists and policy makers, who have been stifled in the past by inaccessibility to such regions and the consequent inability to collect relevant data. Our study uses satellite imagery of war-torn Syria, showing how conflict and migration caused sudden reductions in Syrian agricultural land use and water use. An unexpected effect of the conflict was increased flow in the Yarmouk River to Jordan, which nonetheless remains one of the world's most water-poor nations. The study illustrates that conflict and human displacement can significantly alter a basin's water balance with dramatic effects on the transboundary partitioning of water resources.

Author contributions: M.F.M., J.Y., and S.M.G. designed research; M.F.M. performed research; M.F.M. and N.A. analyzed data; and M.F.M., J.Y., S.M.G., and A.T. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1614342113/-DCSupplemental.

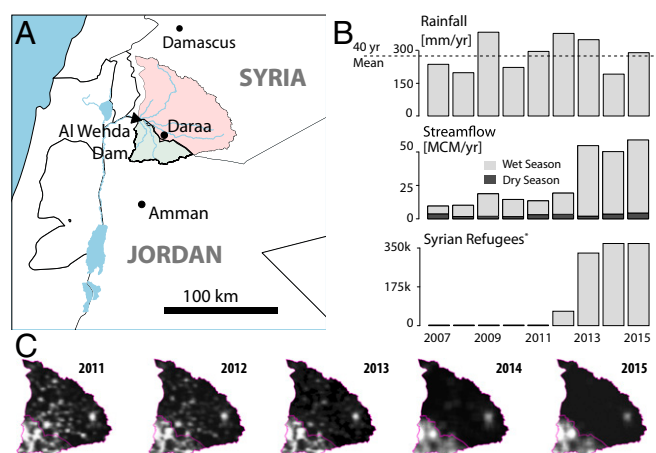


Fig. 1. Yarmouk river flow increase coincides with refugee migration. (A) Map of the Yarmouk basin upstream of the Al-Wehda dam, with the Syrian and Jordanian parts of the basin (red and green), and the Al-Wehda dam, where stream flow is measured. (B) Time series of annual precipitation spatially averaged over the Yarmouk basin (Top, with long-term average represented as a dashed line), annual discharge volumes measured at Al-Wehda disaggregated by wet (October to May) and dry (June to September) seasons (Middle), and the cumulative number of registered refugees from the Syrian part of the basin (Bottom). (C) Annual average night-light intensity images of the Yarmouk region, from the Defense Meteorological Satellite Program Operational Line Scanner (DMSP-OLS) and Visible Infrared Imaging Radiometer Suite (VIIRS) satellite, illustrate the timing and magnitude of refugee migration out of the Syrian part of the basin. There is a clear decrease in night-light intensity in Syria when comparing images across three periods: (i) in 2011, before the war; (ii) in 2013, during the peak of refugee migration from Jordan to Syria; and (iii) in 2014–2015, during which the rate of migration decreases. In contrast, night-light intensity in Jordan during this entire 5-y period remained relatively constant. VIIRS images for 2014 and 2015 were downsampled and adjusted to match the resolution and average intensity (in the Jordanian portion of the basin) of DMSP-OLS images used for previous years.

We use Landsat 7 images to quantify temporal changes in Syrian land use and water reservoir storage. To test the causal effect of the refugee crisis on land and water resources, we compare changes observed in Syria with corresponding changes observed in nearby regions where irrigation and dam management were unaffected by the refugee crisis. This differences-in-differences approach (14) uses two non-Syrian regions as controls: (i) the Jordanian side of the Yarmouk basin to assess changes in irrigated agricultural land use (Fig. 2) and (ii) the Israeli-controlled Golan Heights to evaluate changes in water reservoir management (Fig. 3). These two neighboring regions are expected to have similar rainfall, land use, and reservoir storage variations as in the Syrian Yarmouk, but they primarily differ in that they have not experienced a massive emigration of refugees. The validity of using these regions as controls is supported by remote sensing observations (Figs. S1C and S2). The causal effect of migration on irrigated land areas and reservoir storage volumes is evaluated statistically by relating premigration and post-migration changes in Syria to changes in the control regions over the same periods. The analysis takes 2013 as a cutoff, which is the year when most refugees migrated (Fig. 1). Using this cutoff allows us to identify specifically the impacts of migration, and disentangle migration from other potential effects of the conflict that started in 2011.

Effect of Migration on Land Use

To evaluate the impact of migration on land use, irrigated land area was estimated at 30-m resolution using Landsat 7 multi-spectral satellite imagery. Vegetation indices commonly exploit the unique property of photosynthetic pigments to absorb red and emit near-infrared wavelengths of the electromagnetic spectrum. The Normalized Difference Vegetation Index (NDVI) measures increases in chlorophyll content, which is inversely related to water stress (15). We classified vegetation as irrigated

cropland for those areas with high NDVI values during summer months (June to September) when precipitation is negligible. We further distinguished summer-irrigated crops from evergreen vegetation by evaluating the difference between median cloud-free NDVI values in the spring (January to May) and summer, bias-correcting to account for temporal variation in NDVI due to changing soil and atmospheric conditions (Materials and Methods). In Fig. 2, we generated maps of irrigated crop areas for the Jordanian and Syrian portions of the Yarmouk basin between 2000 and 2015 (see Fig. S2 for all years and Table S1 for confusion matrices). Irrigated areas increased in both countries between 2000 and 2006, followed by an abrupt drop during the following years, which corresponds to a regional drought. In Syria, irrigated area declined considerably after 2012, coinciding with the flight of Syrian refugees (Figs. 1B and 2A and B). Notably, the post-2012 drop was much greater in Syria than in Jordan, suggesting that conflict and the flight of refugees caused a major reduction in farming and associated reduction in irrigation water use in Syria. Irrigation in Jordan remained unaffected by the influx of refugees, who settled predominantly in camps and cities outside of the Yarmouk basin. Using temporal changes in irrigated area in Jordan as a counterfactual scenario, results show a statistically significant [90% confidence interval (CI)] 47% decrease in irrigated land in southern Syria caused by the refugee crisis that started in 2013 (Table 1, column 1; interaction coefficient). This effect remains robust to systematic remote sensing classification errors, as discussed in Supporting Information. In contrast, no significant change was detected on the Jordanian side of the basin, as seen in the nonstatistically significant coefficient for the time dummy. The effect ceases to be statistically significant when setting 2011 and 2012 (when the civil conflict started) as cutoff years, respectively, instead of using 2013 (when most refugees migrated). This finding suggests that the changes in land use are more likely attributable to refugee migration than to other conflict-related causes.

Effect of Migration on Reservoir Levels

In addition to land use impacts, we investigated the relationship between refugee migration and Syrian reservoir management.

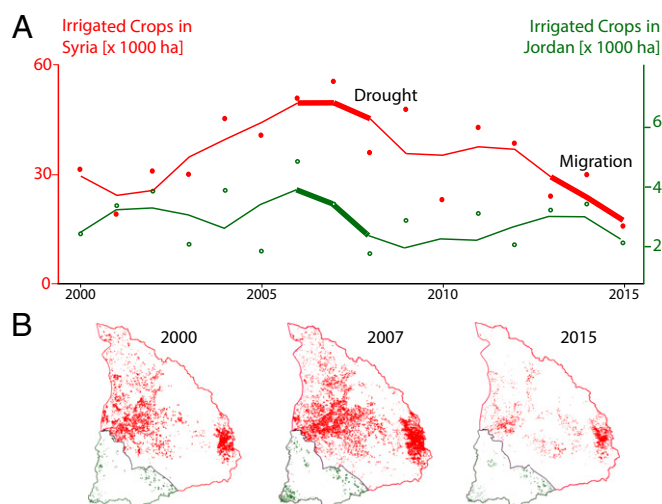


Fig. 2. Remote sensing detection of irrigated regions. (A) Time series graphs of annual extent of irrigated areas in the Yarmouk basin, excluding irrigated olives, for Syria (red) and Jordan (green). Dots ($n = 16$) represent point estimates obtained from Landsat 7 imagery and used in the statistical analyses. Lines are obtained by a local polynomial regression fit (span = 0.5) to reduce observation errors and illustrate land use trends. Decreases in irrigated land surface corresponding to the 2006–2008 drought are clearly visible for both countries, whereas a second significant drop occurs only in Syria after 2012, during refugee migration. (B) Maps of irrigated areas for 2000, 2007, and 2015 (1 pixel = 30 × 30 m) illustrate the extent of the change in land use.

Table 1. Ordinary least squares regression coefficients for the differences-in-differences analysis reveal a significant negative effect of the refugee crisis (interaction coefficient) on irrigation and reservoir storage

Independent variable	Dependent variable		
	Log irrigated area		Log reservoir storage
	No olives	With olives	
Country dummy (Syria)	2.633*** (0.144)	1.703*** (0.100)	0.793*** (0.094)
Time dummy (post-2013)	0.074 (0.235)	0.013 (0.164)	-0.049 (0.152)
Interaction coefficient	-0.640* (0.333)	-0.390# (0.232)	-0.678*** (0.215)
Intercept	7.877*** (0.102)	9.345*** (0.071)	2.096*** (0.070)
Counterfactual scenario	Jordan	Jordan	Golan Heights
Observations	32	32	378
R ²	0.931	0.922	0.185

Exponentially transformed regression coefficients can be interpreted as relative changes in outcomes. SEs are shown in parentheses. # $P < 0.11$; * $P < 0.1$; ** $P < 0.05$; *** $P < 0.001$.

Based on monthly cloud-free Landsat 7 composite images, we identified 21 Syrian-controlled surface water reservoirs in the Yarmouk basin, upstream of the Al-Wehda dam, and estimated the surface area of the 11 largest reservoirs for each month over the 2000–2015 period. These reservoirs account for 93% of Syrian storage capacity used for irrigation in the Syrian part of the Yarmouk basin upstream from the Al-Wehda dam. We estimated storage volumes from reservoir extents by relating topographic information from a high-resolution digital elevation model [Advanced Spaceborne Thermal Emission and Reflection Global Digital Elevation Model (ASTER GDEM), version 2] to local flooding frequencies observed on Landsat 7 images. All of the reservoirs included in the analysis are used for seasonal irrigation storage and were completely empty at least once during the Landsat coverage period (2000–2015), so this procedure allowed complete filling curves to be determined individually for each dam (Fig. S3), as described in *Supporting Information*.

As a control, a similar analysis was conducted for the eight reservoirs operated by Israel in the Golan Heights. The effect of the 2006–2008 drought is apparent with a minimum in reservoir storage in both Syria and Israel (Fig. 3). Storage increased in both areas as the region recovered from drought during 2009–2012, before decreasing again during the low rainfall period of 2013–2015. This final decrease in stored water, however, was notably more substantial in Syria than in the Golan Heights, which suggests that Syrian reservoir storage was largely affected by changes in the country's water management practices during the conflict. This effect is corroborated by a comparative difference analysis that revealed a statistically significant (99% CI) 49% decrease in reservoir storage in Syria for the 2013–2015 refugee migration period compared with the reservoir storage decrease in the Golan Heights, where no detectable change has been found during the same period (Table 1, column 3).

Attribution of Transboundary Flow Increases

Finally, we evaluated the impacts of the refugee migration along with associated land use and reservoir storage changes on the hydrological response of the watershed. Measured inflows into the Al-Wehda reservoir on the Jordan border reveal a 340% increase in the annual flow after the onset of the refugee crisis (2013–2015) compared with the baseline period (2006–2012). We used regression analysis and water balance calculations to disentangle the effects of conflict-related changes in water demand, and the watershed's natural recovery from the 2006–2008 drought (Fig. 4A).

Results suggest that drought recovery and decreased winter flow retention are responsible for 72% of the flow increase during the refugee migration period. Recovery from the 2006–2008 drought accounted for ~30% of the flow increase, as revealed by a substantial increase in 4-y precipitation averages (Fig. S4C). As for

flow retention, the analysis of Landsat 7 imagery also showed that Syrian dams retained considerably less runoff during the refugee migration period (2013–2015) compared with prior years. These changes predominantly occurred during the wet season (October

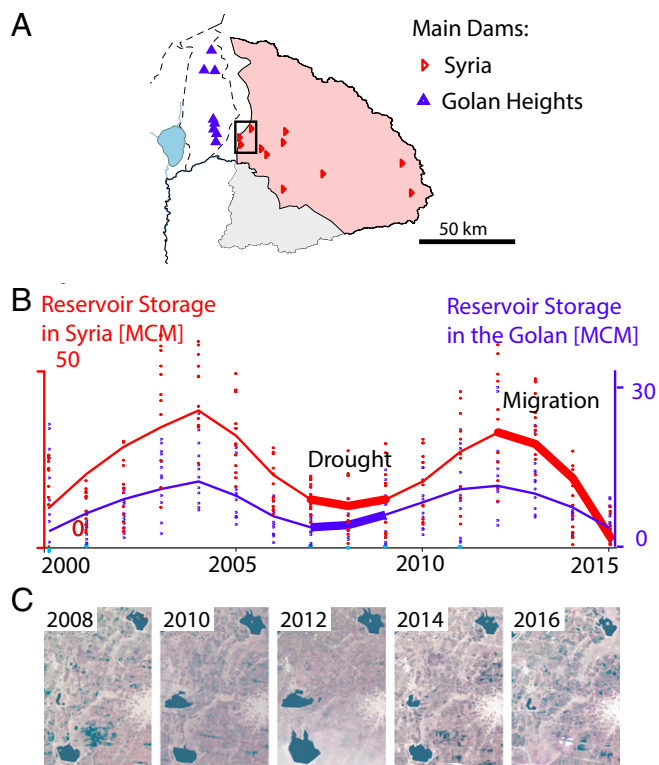


Fig. 3. Remote sensing detection of reservoir storage. Time series estimates of water volume stored in the major reservoirs are presented for the Upper Yarmouk basin in Syria (A, red) and the Golan Heights (B, blue) ($n = 189$ for each region). Lines represent average annual storage, and monthly estimates are represented as dots. The effect of the 2006–2008 drought is visible for both regions as a local minimum in dammed-reservoir storage volume. A second decrease in reservoir storage was detected in both regions after 2012, but the decrease is significantly more dramatic in Syria, from which refugees fled. (C) Changes in reservoir storage are illustrated with satellite images of the westernmost reservoirs of southern Syria. The Landsat 7 images were taken at the end of the wet season (March and April) and are overlain by Normalized Difference Water Index water extent estimates (dark regions).

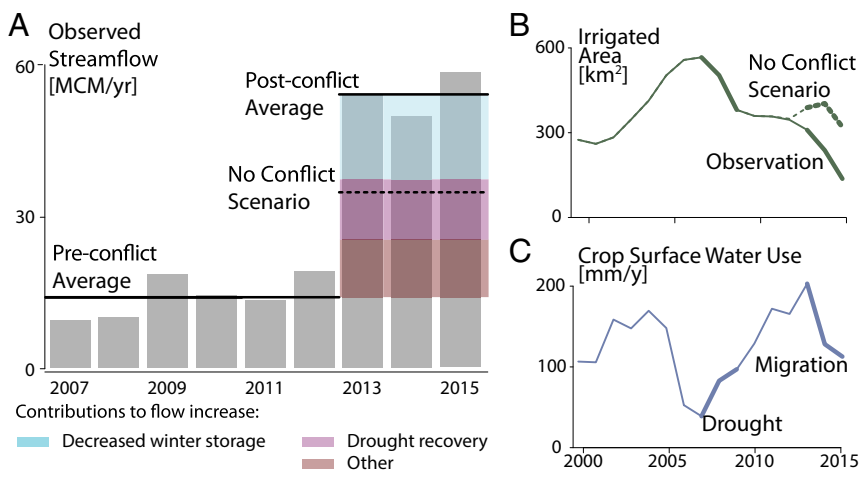


Fig. 4. Contributions to transboundary stream flow increase. (A) Annual stream flow volume observed into the Al-Wehda reservoir (gray bars). Averages for the 2007–2012 and 2013–2015 periods (solid black line) show a significant increase in runoff during the Syrian refugee migration. The graph is overlain by areas representing the proportions of flow increase related to reservoir management (blue) and drought recovery (purple) as determined by the winter water balance regressions (Table 2). Residual flow change remaining unexplained by the observed covariates is represented in brown (*Supporting Information*). (B) Time series of irrigated area ($n = 16$), with annual estimates from Landsat imagery (solid) and a counterfactual scenario with no conflict-related migration (dashed). (C) Aggregated water volume stored in reservoirs each year ($n = 16$), normalized by the area of irrigated land. The resulting water consumption rates represent the portion of crop water demand met by stored surface water.

to May), when the largest portion of the stream flow increase occurred (Fig. 1B). The decreased retention of wet-season floods during the refugee migration period accounts for another 42% of the observed flow increase reaching Jordan. Syrian dams are used to store winter runoff for summer irrigation, so the decreases in both reservoir storage and irrigated cropland during the refugee flight from Syria, as observed in Landsat 7 imagery, are likely related. This narrative is confirmed by the regression results presented in Table 2, which show that river flow is strongly correlated to refugee migration, even when controlling for short-term and long-term rainfall contributions (column 2). However, that correlation disappears when including changes in reservoir storage (ΔS_+) in the dependent variable (Table 2, column 3). This finding suggests that the correlation between river flow and refugee migration is primarily related to changes in winter reservoir storage. A detailed discussion of the causes of changes in Yarmouk River runoff is provided in *Supporting Information*.

Despite their effects on stream flow, these changes in reservoir management practices are not entirely attributable to the impacts stemming from the Syrian conflict. Changes in reservoir storage were also detected in the Golan Heights, which serves as a control region (Fig. 3), and appear to be correlated to the changes in annual rainfall displayed in Fig. S1C. Similarly, winter reservoir storage is not the only pathway through which water management can affect the flow of the Yarmouk. For instance, the refugee crisis caused a significant decrease in irrigation demand, which likely increased the portion of reservoir releases making it back from irrigation canals to the stream during the summer. To identify the effect of the conflict on stream

flow, we inspected land-use observations from the Jordanian side of the basin to construct a counterfactual scenario describing irrigation in Syria if the refugee crisis had not occurred (Fig. 4B). A counterfactual stream flow scenario was then constructed using annual crop demands for surface water estimated from satellite imagery (Fig. 4C) to determine the volume of water that would have been lost to irrigation had the refugees not migrated (*Materials and Methods*). It is noteworthy that unlike other irrigation sources (e.g., groundwater), surface-irrigation water would have otherwise resulted in runoff flowing into Jordan and would have been observed at the Al-Wehda gauge if not used for irrigation in Syria. Assuming a local average crop water use of $700 \text{ mm}\cdot\text{y}^{-1}$ (16), crop water use estimations presented in Fig. 4C suggest that only about 7–35% of irrigation demand is supplied by stored surface water, with the remainder being supplied by groundwater, surface water imports (Fig. S5), and direct precipitation. These ratios are in line with other published estimates of agricultural water use in the region, as discussed in *Supporting Information*. Despite the small relative contribution of surface water to irrigation volume, the flow counterfactual scenario suggests that about 48% of the stream flow increase between the two periods (2006–2012 and 2013–2015) is attributable to the rapid migration of Syrian refugees and subsequent abandonment of irrigated agriculture. Compared with the counterfactual scenario, the observed stream flow represents a 150% increase in the annual flow into the Al-Wehda reservoir along Jordan’s northern border (Fig. 4A).

These results suggest that the Syrian conflict and subsequent refugee migration caused stream flow to increase by primarily affecting

Table 2. Ordinary least squares regression coefficients for the winter water balance suggest that reductions in winter storage in Syrian reservoirs explain the substantial increase in stream flow observed during the refugee crisis

Independent variable	Dependent variable: winter flow (October–May), $\text{MCM}\cdot\text{mo}^{-1}$		
	$Q + \Delta S$	Q	$Q + \Delta S$
Controls for refugee migration	No	Yes	Yes
Refugees, 10^5 persons		1.160*** (0.195)	0.217 (0.527)
Rain, $\text{mm}\cdot\text{y}^{-1}$	0.024*** (0.003)	0.014*** (0.004)	0.024*** (0.003)
Lagged rain 4-y average, $\text{mm}\cdot\text{y}^{-1}$	0.066** (0.031)	0.020 (0.025)	0.055 (0.050)
Intercept	−9.855** (3.988)	−3.694 (3.594)	−8.507 (6.175)
Observations	81	81	81
R^2	0.501	0.491	0.502

Q , observed winter flow at Al Wehda; ΔS , remotely sensed increase in reservoir storage volume. Standard errors in parentheses are clustered by water year (October 1 to September 30). The winter water balance equation is described in *Supporting Information*. * $P < 0.1$; ** $P < 0.05$; *** $P < 0.01$.

irrigation demand and reservoir management practices within the basin. The abnormal recent decrease in Syrian water retention detected on satellite imagery (Fig. 3) is substantiated by anecdotal evidence from the field, which points toward the underuse or decommissioning of dams due to targeted military operations (17) and poor operational management (18). In effect, as of 2015, most dams in the basin were controlled by rebel forces that lacked the proper information, technical knowledge, energy access, and institutional cohesion to manage reservoirs in an efficient and coordinated manner (18). This situation, along with decreased institutional capacity that might have prevented illegal well drilling after the beginning of the conflict, likely contributed to an increased relative reliance on groundwater versus surface water to supply the irrigated agriculture that remained in the region (18). This observation is consistent with our remote sensing analysis showing a decreasing relative contribution of surface water to crop irrigation on a per area basis after 2013 (Fig. 4C). However, this increased relative reliance on groundwater versus surface water is counteracted by an overall decrease in irrigated area, making it unclear whether total groundwater withdrawals have increased or decreased due to the war. In addition, the effect of the conflict on cropping patterns and domestic water use, both of which affect total groundwater use, remains uncertain.

Increases in summer runoff are insignificant [<2 million cubic meters (MCM) per year for the four summer months] compared with the rise of wet-season runoff after 2013 ($48 \text{ MCM}\cdot\text{y}^{-1}$ for nonsummer months), which dominates the change in total annual transboundary flow volume as apparent in Fig. 1. This finding indicates that changes in base flow (contributed by groundwater) are insignificant in terms of explaining the increase in surface water runoff highlighted in our analysis. Furthermore, the slight increases in summer flows are also insignificant compared with historical summer flows observed in decades past, before intensive water development by the Syrians. This finding suggests that changes in groundwater extraction or groundwater recharge patterns due to the war have not resulted in substantial groundwater system recovery or a significant increase in transboundary base flow contribution in the short term.

Summary and Implications

The Syrian portion of the Yarmouk basin, which is a major subbasin of the Jordan River, has been the epicenter of an ongoing, devastating civil war involving the migration of hundreds of thousands of Syrian refugees. This study sheds light on the indirect effects of that conflict on freshwater resources through the impacts of refugee migration, land use change, and wartime changes in water management practices. The analysis revealed that a 47% reduction in irrigated land area in the Syrian portion of the Yarmouk basin and a 49% decrease in reservoir storage are attributable to the conflict and subsequent migration. These changes, in turn, account for 48% of the 3.5-fold increase in transboundary surface water flow to Jordan observed from the 2006–2012 premigration period to the 2013–2015 postmigration period. Although the relation between upstream water use and downstream water availability has been studied for transboundary watersheds (19), we are not aware of any study that has quantified transboundary water resource changes resulting from the indirect impacts of an armed conflict. Such impacts are difficult to quantify due to lack of data access in an active war zone. In the absence of ground data, we rely on satellite remote sensing analysis to deduce the impacts of conflict on land use and reservoir management. The analysis reveals that armed conflict resulted in significant changes to land use and water management in Syria, and, ultimately, in an unexpected increase in transboundary flow to neighboring Jordan, a severely water-scarce country receiving many of the refugees escaping the war.

It is noteworthy that in the near term, the unintended “spillover” effect to Jordan represents a modest irrigation water benefit that minimally offsets the immediate freshwater needs of hundreds of thousands of Syrian refugees received by Jordan. The Yarmouk inflows are conveyed from the Al-Wehda dam for irrigation in the Jordan Valley rather than to the eastern highlands, where the vast majority of the urban population, including the

Syrian refugees, reside. In the long term, should the observed reduction in Syrian irrigated agriculture persist, the recent increase in transboundary flows would have a positive impact on Jordan’s overall water resource availability, because the Yarmouk flows in excess of $25 \text{ MCM}\cdot\text{y}^{-1}$ could be used by Jordan, per the 1994 bilateral agreement between Jordan and Israel (20). Even then, however, such an increase would only reflect a slight shift back toward flow volumes expected by the Jordanians under the 1953, 1987, and 2001 bilateral agreements with Syria (21–23).

The case study of the Syrian civil war and its impact on the Yarmouk basin’s water resources reveals the potential interactions between human displacement, land use change, and reservoir management for a region undergoing conflict. Although much research has focused on either the impacts of water scarcity on conflict (1, 4) or the direct effect of violence on water infrastructure (24), our analysis shows that human conflict can also significantly alter the basin-scale water balance with potentially important water supply ramifications for water users in the basin. This work also illustrates how innovative methodologies combined with remote sensing data can be used to evaluate hydrologic and land-use dynamics in a conflict zone, and more generally for the acquisition of critical information for water management in unstable, inaccessible, or noncooperative settings.

Materials and Methods

Remote Sensing. Rainfall in the Yarmouk basin is highly spatially variable and strongly affected by local topography (25). We used a remote sensing precipitation product [Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks (PERSIANN)-CDR (26)] to resolve spatial trends and estimate precipitation in Syria, where rain gauge data are unavailable. PERSIANN-CDR is available as a global 1.5° -resolution gridded product of monthly precipitation (1983 to present) and is freely accessible on Google Earth Engine (27). We used Google Earth Engine to compute a time series of spatially averaged monthly precipitation estimates over the entire basin, bias-correcting based on local gauge data (as described in [Supporting Information](#)).

We detected irrigated crops using monthly NDVI images (15) that were computed using the top of atmosphere (TOA) (28) reflectance composite of Landsat 7 imagery (bands 3 and 4), which we bias-corrected to account for temporal fluctuations in atmospheric and soil conditions ([Supporting Information](#)). We classified irrigated areas by segmenting dry-season NDVI images (29) using thresholds that were determined by manual adjustment using visual inspection of high-resolution background imagery provided in Google Earth Engine (Fig. S6). Several recent studies have successfully applied remote sensing techniques to assess lake volumes based on vegetation (30, 31) and water (32) indices. The Modified Normalized Difference Water Index (MNDWI) (32) uses the green and medium infrared bands of Landsat 7 images at 30-m resolution to detect open water, which we found to detect open water in the Yarmouk basin more reliably than the NDVI used in other studies (30, 31). MNDWI images computed from weekly cloud-free Landsat 7 TOA reflectance composites were used to determine the monthly extent of the 11 largest reservoirs upstream of the Al-Wehda dam at the Jordan border. These reservoirs, listed in [Table S2](#), are all located in Syria and account for 93% of Syrian capacity used for irrigation in the Syrian portion of the Yarmouk basin. Open-water pixels were detected by applying a threshold on MNDWI images, and classified pixels were corrected for image-stripping defects ([Supporting Information](#)) and aggregated to form monthly composite images of maximum water extent. Reservoir volumes were finally obtained by constructing filling curves based on remotely sensed topographic data (ASTER GDEM2) and flooding frequencies determined from Landsat imagery ([Supporting Information](#)). The approach was tested on the Al-Wehda reservoir, for which in situ storage observations are available from the Jordanian Ministry of Water and Irrigation (Fig. S7).

All remote sensing procedures used to quantify rainfall, irrigated crop area, and reservoir storage were successfully validated against local in situ observations, as described in [Supporting Information](#).

Change Attribution. We use a differences-in-differences strategy (14) to identify the causal effect of the refugee crisis on changes in land use and reservoir management practices. The approach was implemented in a statistical framework by regressing the outcomes (measured in all regions in all periods) against a regional dummy (Syria or the control region), a time dummy (before or after the refugee crisis), and their interaction. For the purpose of our analysis, we model the refugee crisis as a shock occurring immediately before the calendar year 2013, and consider log-transformed outcomes in the regressions. This model allows exponentially transformed regression coefficients to be interpreted as relative changes in outcomes. The causal interpretation of these results hinges on the

assumption that irrigated land use and reservoir storage have similar trajectories in Syria and their respective control region, which did not experience a refugee crisis. Under these conditions, any factor affecting irrigated land use or reservoir management that is specific to Syria but does not change concurrently with refugee migration or that may change during the refugee crisis but at a rate that is uniform across the regions is netted out during the estimation. This assumption is strongly supported by remote sensing observations obtained for each region, which show time series of irrigated land area and stored water volume that have similar shapes for each log-transformed outcome before 2013 (Fig. S8).

We consider the monthly water balance to relate the changes in irrigation practices to the substantial increase of the Yarmouk River flow at the Al-Wehda gauge that occurred simultaneously with the refugee migration. During the wet winters, reservoirs are predominantly used for flood abatement purposes and to retain water for summer irrigation; dams are located on stream channels, so any runoff water that is not retained in reservoirs directly flows as runoff and reaches the Al-Wehda gauge at the outlet of the basin. We expressed the direct relation between reservoir storage and stream flow runoff in a water balance equation (Supporting Information), and used the linear regression framework to test whether the large increase in winter river flow during rapid refugee migration was explained by changes in winter retention volumes in Syrian reservoirs. To do so, monthly estimations of the number of refugees fleeing the Syrian portion of the Yarmouk basin were determined using data from the United Nations High Commission on Refugees (Fig. S9), as described in Supporting Information.

Finally, to construct a counterfactual scenario for irrigation, we first performed a panel regression analysis to estimate the effect of refugee migration on

irrigated land in the Syrian Yarmouk. This relation allowed us to estimate irrigated area in the Syrian Yarmouk in a hypothetical scenario that assumes the migration of refugees did not occur (Fig. 4B). We then estimated crop use of stored surface water based on remotely sensed observations of reservoir storage and irrigated land areas (Table S3), as described in Supporting Information.

ACKNOWLEDGMENTS. We thank Deepthi Rajsekhar for estimates of water import volumes. We also thank the Stanford Woods Institute for the Environment and the UPS Foundation for their support. Hydrological data were provided by Jordan's Ministry of Water and Irrigation. Landsat data are distributed by the Land Processes Distributed Active Archive Center (LP DAAC), located at US Geological Survey (USGS)/Earth Resources Observation and Science (EROS) Center (lpdaac.usgs.gov), and were accessed and processed using Google Earth Engine. The ASTER GDEM data product was retrieved from the online Global Data Explorer tool, courtesy of the National Aeronautics and Space Administration LP DAAC, USGS/EROS Center (gdex.cr.usgs.gov/gdex/). VIIRS Day/Night Band Cloud Free Composites and DMS-OLS Nighttime Lights version 4 were obtained courtesy of the Earth Observation Group, National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Center (ngdc.noaa.gov/eog/). PERSIANN monthly precipitation data were accessed on Google Earth Engine, courtesy of the Climate Data Record program of the NOAA. This work was supported by the National Science Foundation (NSF) under Grant GEO/OAD-1342869 (to Stanford University). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF. Postdoctoral fellowship support was provided by the Swiss National Science Foundation.

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