

## CLIMATE CHANGE EFFECTS

# Increasing drought in Jordan: Climate change and cascading Syrian land-use impacts on reducing transboundary flow

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In countries where severe drought is an anticipated effect of climate change and in those that heavily depend on upstream nations for fresh water, the effect of drier conditions and consequent changes in the transboundary streamflow regime induced by anthropogenic interventions and disasters leads to uncertainty in regional water security. As a case in point, we analyze Jordan's surface water resources and agricultural water demand through 2100, considering the combined impacts of climate change and land-use change driven by the Syrian conflict. We use bias-corrected regional climate simulations as input to high-resolution hydrologic models to assess three drought types: meteorological (rainfall decrease), agricultural (soil moisture deficit), and hydrologic (streamflow decline) under future scenarios. The historical baseline period (1981–2010) is compared to the future (2011–2100), divided into three 30-year periods. Comparing the baseline period to 2070–2100, average temperature increases by 4.5°C, rainfall decreases by 30%, and multiple drought-type occurrences increase from ~8 in 30 years to ~25 in 30 years. There is a significant increase in the contemporaneous occurrence of multiple drought types along with an 80% increase in simultaneous warm and dry events. Watershed simulations of future transboundary Yarmouk–Jordan River flow from Syria show that Jordan would receive 51 to 75% less Yarmouk water compared to historical flow. Recovery of Syrian irrigated agriculture to pre-conflict conditions would produce twice the decline in transboundary flow as that due to climate change. In Jordan, the confluence of limited water supply, future drought, and transboundary hydrologic impacts of land use severely challenges achieving freshwater sustainability.

## INTRODUCTION

The effects of global climate change are known to have important, often adverse consequences on regional environmental security as well as on social well-being, conflict, and transboundary migrations, especially water security in arid regions. The time scale of these changes, however, is sufficient to allow transformations of land use and transboundary river flows, both of which are sensitive to the nature of droughts and pose challenges to freshwater management. The distributional conflicts over transboundary waters will intensify in the future due to increasing water needs as populations compete for ever-dwindling resources. This is significant in arid regions and, more specifically, in the Middle East, where the added pressure of climate change on limited water resources is further exacerbated by anthropogenic disasters. The coupled effects of climate change–induced droughts and conflict-induced land-use changes on transboundary waters are often left unexplored.

We consider Jordan as a case in point. Jordan's water security is already being affected by a multitude of factors. Jordan lies in the heart of the Middle East (Fig. 1A); is functionally landlocked with a minimal coastline; is surrounded by Syria, Saudi Arabia, Israel, and Iraq; and is among the most water-poor nations in the world. Its drying climate, population increases through a succession of shocks of refugees, and disadvantaged downstream location on the Yarmouk–Jordan River system increase the vulnerability of the nation's freshwater resources (1). Specifically, Jordan is facing a deepening multipronged freshwater crisis, exacerbated by a long-term decline in rainfall (2), declining groundwater levels (3), and regional conflict and immigration (4–6). Jordan's per capita water availability has decreased from 3600 m<sup>3</sup>/year in 1946 to 135 m<sup>3</sup>/year in the present (7, 8), putting the nation far below the 500 m<sup>3</sup>/year level of “absolute scarcity” (9).

Two major historical factors are largely responsible for the worsening freshwater supply crisis in Jordan: (i) The country has depended on most of its surface waters from Syria and Israel via the transboundary Yarmouk–Jordan River, and (ii) the overuse of its groundwater resources has increased to approximately 200% of its sustainable capacity (10). Even newly developed groundwater resources will not last. Since 2013, Jordan's largest city, Amman, depends partly on groundwater from a transboundary fossil aquifer shared with Saudi Arabia. Increasing groundwater depletion is expected to approach the noneconomic pumping level by the end of this century (11).

Jordan is adversely affected by unilateral water development projects by Syria in the Upper Yarmouk basin as well as by Israel in the Upper Jordan River and Golan Heights. Both Syria and Israel have retained significant control over headwaters of the Jordan and Yarmouk Rivers. Despite agreements with these countries, Jordan received only around 119 and 92 million m<sup>3</sup> (MCM)/year from Yarmouk water and Lake Tiberias (also known as the Sea of Galilee or Lake Kinneret) in 2004 and 2005, respectively, which accounts for only 10% of the total flow in the upper Jordan and Yarmouk Rivers (12). Fortunately, the 1994 agreement between Israel and Jordan allows Jordan to store 20 MCM/year during the winter in Lake Tiberias for later use during summer months.

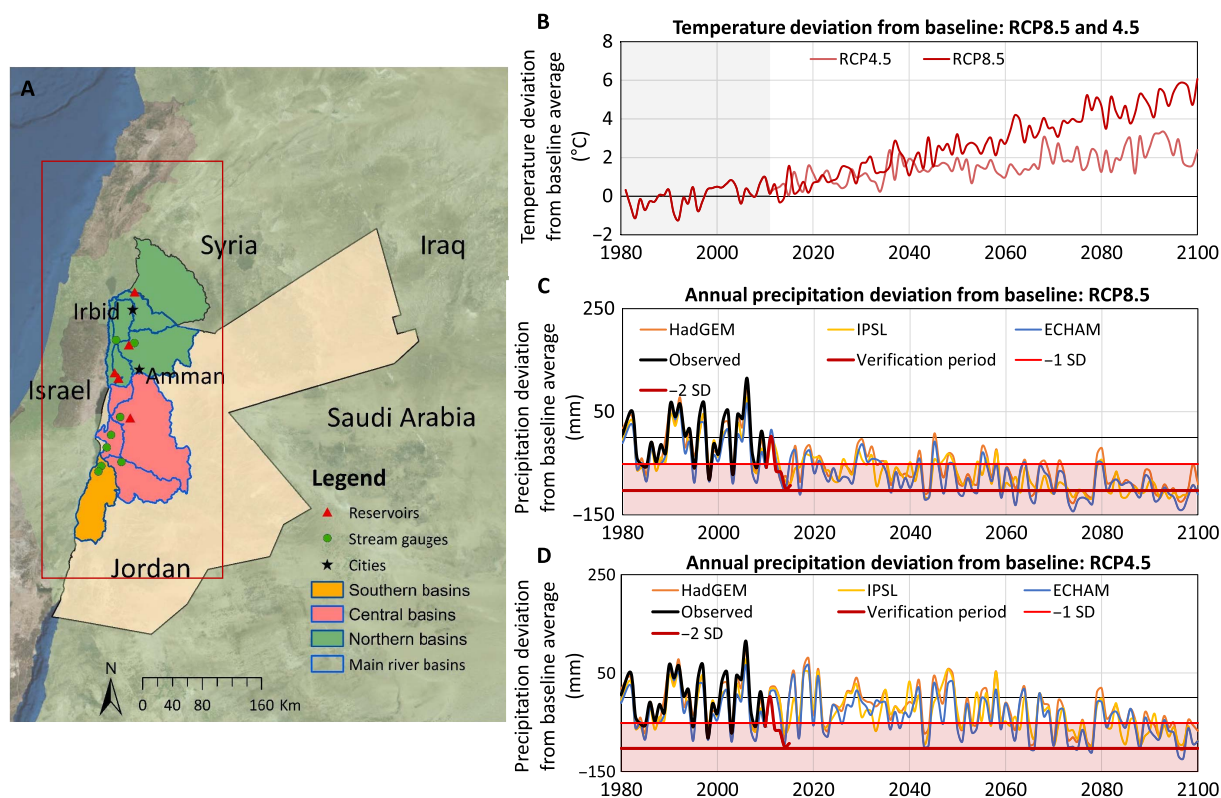
Syrian water use and its numerous dams that capture flow in the Yarmouk basin are of particular importance because they have critical influences on reducing river discharge that remains for Jordan and Israel. However, it is noteworthy that Israel, Jordan, and the Palestinian Authority overcame political obstacles in transboundary water allocation by signing a bilateral agreement green-lighting the construction of a Red Sea–Dead Sea pilot water transfer program, with desalinated water transferred to Israel in exchange for additional water provided to Jordan to supply Amman. Full execution of the Red-Dead program beyond the pilot stage is the next-step essential option to partially alleviate some of the stress imposed by the current and future water demands in Jordan. Recently, pressure on Jordan's freshwater resources has stemmed from

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**Fig. 1. Major river basins and projected climate change in Jordan.** (A) Map of Jordan with the major surface water basins color-coded according to the regional basin groups they belong to and locations of the major cities, reservoirs, and stream gauges. (B) Temperature deviation from the baseline period average for RCP4.5 and RCP8.5 scenarios. The gray shaded area represents the baseline period (1981–2010). Although Jordan is expected to experience an increase of 2°C in the annual average temperature by 2071–2100 under RCP4.5, a significant increase of 4.5°C is expected under RCP8.5. (C) Annual precipitation (essentially the same as the winter precipitation because summers are devoid of rainfall) deviation from the baseline period average under RCP8.5. Any deviation that falls below the –1 SD level from the average is considered to indicate a dry year, as represented by the red shaded area. If, for a given year, the annual average precipitation falls below the –2 SD level, then it is considered to be an extremely dry year. The plotted time series include the bias-corrected precipitation simulations for the three chosen climate models (HadGEM, ECHAM, and IPSL) for 1981–2100 and the observed precipitation (1981–2015). The distribution mapping–based bias correction for the climate simulations was based on the observations during the baseline period (1981–2010). The verification period (2011–2015) is a comparison between bias-corrected climate simulations and the observed precipitation post-baseline period. (D) Annual precipitation deviation from the baseline period average for RCP4.5.

a sudden population increase during 2011–2015 in large measure due to its rapid acceptance of more than 1.3 million refugees, of which 1 million were Syrian, compared to a native Jordanian population of 8.2 million (13). Given the crucial role of Jordan in maintaining the stability of the Middle East and the threat to the nation's water security, we present an analysis of the potential impacts of future droughts and climate change on the nation's freshwater resources. We then explore the additional future potential impact of Syrian land-use change as a result of recovery from the ongoing war as it affects transboundary river flow to Jordan.

In recent years, there have been growing concerns worldwide about the increased incidence of drought events due to climate change. However, despite its widespread impact on multiple sectors, drought responses have remained poorly coordinated (14). This can be attributed to the fact that droughts are an enigma in many respects when compared to other natural disasters. Because the effects of drought often accumulate slowly over a considerable period of time and may linger for years after the termination of the event, the onset and end of drought are difficult to determine, thus making it challenging to properly define drought duration (15–17). Therefore, drought management warrants an approach that treats all of the underlying associated vulnerabilities to people, agriculture,

and the environment (18, 19). Of particular importance is the analysis of simultaneous occurrence of multiple drought types (20).

Despite its elevated state of water insecurity, the impacts of droughts and climate change on Jordanian water resources have not been extensively studied. There is limited scholarly literature on drought occurrence, evolution, and how drought characteristics might change in Jordan. Previous research (21–23) studied the cyclic nature of meteorological droughts in various small watersheds in Jordan. As an extension to this, more recent studies (24, 25) analyzed both the current and future meteorological droughts in Jordan using global circulation models. Studies of the Middle Eastern region in general suggest an expected decline in winter precipitation by about 11.5% and rise in annual mean temperatures by about 2.1°C by 2060 (26–28). Large-scale climate variability related to meteorological drought, particularly La Niña impacts, in the Middle East has also been studied (29).

All of these previous studies restricted their analyses to meteorological droughts (low precipitation). However, droughts affecting agriculture and river flow have serious and often longer-lasting impacts on both food and water security, although these problems typically follow the onset of meteorological droughts. Merely considering meteorological drought as an indicator of freshwater and agricultural

vulnerability provides an incomplete picture that may be too optimistic. Jordan cannot afford to be overly sanguine about the devastating consequences of droughts given preexisting regional vulnerabilities due to conflicts, immigration, dependence on transboundary river flow, and limited mitigation options (30).

Here, we investigate two key aspects of Jordan's freshwater vulnerability related to droughts. First, we consider multiple manifestations of future high temperature in conjunction with low precipitation by exploring three types of drought: meteorological drought reflecting a decline in precipitation, agricultural drought representing the deficit in soil moisture (soil water under nondeficit conditions is required for crops), and hydrologic drought as measured by reduced streamflow. The latter two drought types indicate the potential additional manifestations of precipitation deficit, rising temperature, and land-use change. To quantify the effects of agricultural and hydrologic droughts that directly affect Jordan under climate change, we simulate rainfall-runoff processes in each major drainage basin in the country based on future projections of temperature and precipitation obtained from regional climate models. We consider two climate change scenarios: RCP4.5 (optimistic case) and RCP8.5 (business as usual).

Our analysis relies only on those particular regional climate model results that satisfactorily reproduce historical precipitation measurements and are consistent with El Niño–Southern Oscillation (ENSO) behavior (table S1). The hydrologic simulations of each basin in Jordan (including one major basin extending into southern Syria) provide estimates of the duration, frequency of occurrence, and severity of agricultural and hydrologic droughts. These hydrologic simulations were then aggregated by averaging over the study region (Fig. 1A) to provide a general quantitative picture of drought evolution in significantly populated Jordan and southern Syria. Spatial impacts on flow in rivers and soil moisture deficit throughout Jordan showing the drought impacts in each region are presented in Results.

Second, we investigate the combined impact of climate change–induced future hydrologic droughts and land-use changes in upstream Syria on Jordanian water resources. The Yarmouk River lies in a major transboundary basin shared with Syria and is the largest tributary to the Jordan River (Yarmouk–Jordan River system). This is important because significant transboundary flow in the Yarmouk River from Syria has served as a major freshwater source for Jordan Valley agriculture and public supply for Amman, Jordan's largest city. For decades, Syria has built dams to retain water and used the Yarmouk basin's surface water for agricultural irrigation, allowing little flow to reach its downstream neighbor, Jordan (31). For the first time, we inspect combined impacts of future droughts and the return to prewar conditions of irrigated agriculture that was abandoned in southern Syria in 2013 resulting from the recent Syrian uprising.

The effect of Syrian conflict on Syrian land use and transboundary flow in the Yarmouk River, and subsequent impact on Jordan, was the topic of a recent remote sensing and statistical analysis (31). Our investigation builds upon and differs from that effort as we analyze the combined impacts of climate change and the Syrian conflict on transboundary river flow from Syria to Jordan during the remainder of the 21st century, by relying on simulations of hydrologic processes rather than statistical analysis only applied to the historical period. We analyze two post-conflict scenarios affecting Yarmouk flow: (i) “continuing conflict” is the case in which Syria continues in a state of reduced irrigated agriculture due to conflict, fewer farmers, and disrepair of irrigation infrastructure, and (ii) “recovery to pre-conflict status” wherein, after 2025, Syria returns to its prewar state of irrigated agriculture. In both cases, Jordan receives

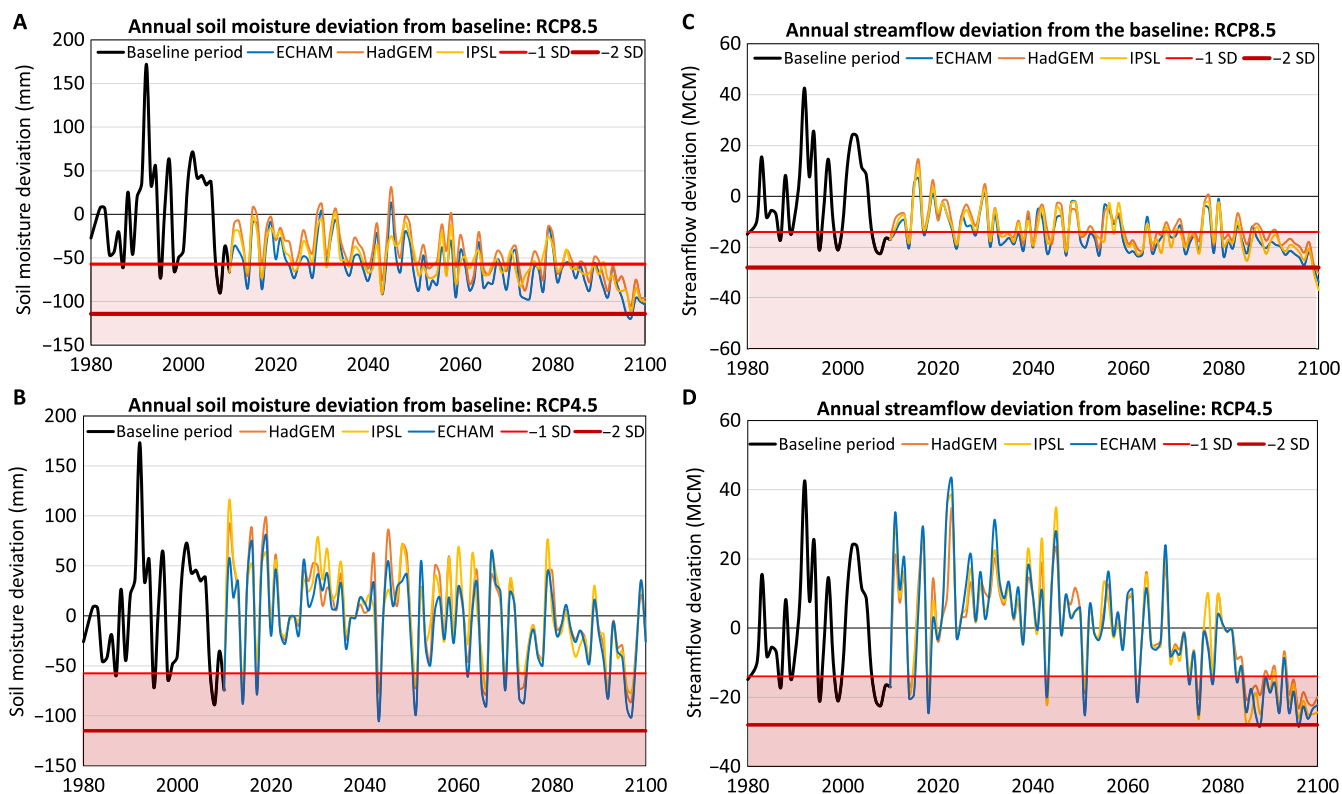
a small fraction (about one-third) of transboundary flow than it relied upon in the prewar period 1980–2010. In addition, in both cases, the changes in upstream agricultural water use are quantified using our hydrologic model, which accounts for changes in agricultural land-use patterns and Syrian reservoir releases.

## RESULTS

Droughts are multi-attribute events characterized by properties such as duration, frequency of occurrence, and severity. We quantify droughts on a monthly time scale in terms of levels of SD from the baseline average, with each sequential level reflecting a greater drought magnitude. If, for each drought type, the variable of interest (precipitation, soil moisture, or streamflow) falls below  $-1$  SD from the baseline average for a continuous period of one or more months, then it is defined as a drought event. Drought frequency of occurrence during a 30-year period is reported as the number of months of drought events. As an annual summary, we also report the number of dry years in each 30-year period with annual precipitation, average soil moisture, and average streamflow falling below  $-1$  SD from the baseline annual average. The duration of a drought event is the number of months during which the monthly deviation falls below  $-1$  SD from the baseline average. Severity of each drought event reflects its magnitude and is the sum of monthly SD levels falling below  $-1$  SD. We present results for all four 30-year time periods in our figures. These figures show the progression of climate impacts on droughts over the century. Our comparison of the 2071–2100 end of century period to the 1981–2010 baseline period illustrates how drought properties are likely to change with (RCP4.5) and without (RCP8.5) climate change policy intervention (32).

We analyze future winter season (October to May) drought as a function of low precipitation, soil moisture deficit, and reduced streamflow based on comparison of results from the three climate models meeting the criteria that each model must satisfactorily replicate the baseline period precipitation and temperature. Under the influence of climate change during the “business-as-usual” RCP8.5 scenario that assumes a future with no policy action and increasing greenhouse gas concentrations, Jordan is expected to experience a 30% decline in annual winter precipitation and a  $4.5^{\circ}\text{C}$  increase in annual average temperature by 2071–2100 (Fig. 1, B and C). The effect of changes in precipitation and temperature will be further manifested in the form of changes in variables such as soil moisture and streamflow. Under RCP8.5, Jordan is likely to experience a 28 and 58% decline in soil moisture and streamflow, respectively, resulting in agricultural and hydrologic droughts (Fig. 2, A and C).

Results for the “business-as-usual” case show a significant increase in drought occurrence and severity. For meteorological drought, we find that the number of years that receive annual precipitation less than  $-1$  SD from the baseline period progressively increases from 7 of 30 years (7 years in 1981–2010 or 23% of years) in the baseline period to 28 of 30 years (94% of years) during 2071–2100. Similarly, although the baseline period did not experience a precipitation deficit that falls below  $-2$  SD, 15 of the 30 years (50% of years) during 2071–2100 are likely to experience extreme precipitation deficit, falling below  $-2$  SD (Fig. 1C). Agricultural and hydrologic droughts also show a moderate increase in occurrence and severity. The number of years with annual soil moisture deficit falling below  $-1$  SD increases from 6 (20% of years) during 1981–2010 to 23 years during 2071–2100 (76% of years), with only 1 of 30 years (3% of years) seeing an extreme soil moisture deficit (Fig. 2A). Similarly, a streamflow deficit that falls below  $-1$  SD



**Fig. 2. Increasing agricultural and hydrologic drought conditions.** (A) Annual soil moisture deviation from the baseline period average for RCP8.5. (B) Annual soil moisture deviation from the baseline period average for RCP4.5. (C) Annual streamflow deviation from the baseline period average for RCP8.5. (D) Annual streamflow deviation from the baseline period average for RCP4.5. The red shaded region indicates the dry zone. The two red lines indicate 1 and 2 SD levels below the baseline period average.

progressively increases from 9 years during the baseline period (30% of years) to 25 years during 2071–2100 (86% of years). The number of years likely to experience an extreme streamflow deficit increases from zero during the baseline period to two during 2071–2100 (7% of years) (Fig. 2C).

We find that the increase in occurrence of –1 and –2 SD droughts coincides with a substantial increase in the number of years with positive temperature anomalies from 13% during the baseline period to 100% during 2071–2100 (Fig. 3A). A positive temperature anomaly is defined as an annual average temperature departure from the baseline average that is greater than 1 SD. The probability of years having simultaneous drought (precipitation, soil moisture, and streamflow) and a positive temperature anomaly increases from less than 10% to more than 90% toward the end of the 21st century when compared to the baseline period (Fig. 3B).

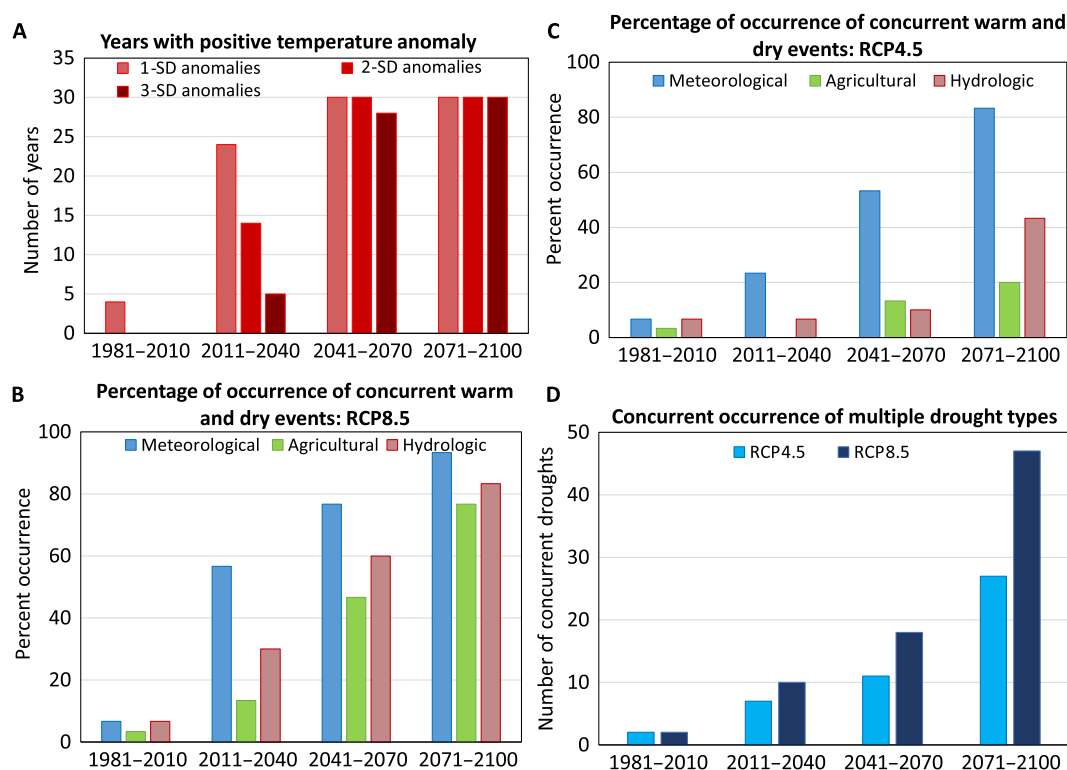
Overall, the number of drought events (in any form) and the average drought duration (months) are significantly greater for RCP8.5 than for RCP4.5 (Fig. 4). Under RCP4.5, the future maximum drought severity is lower than the baseline period maximum drought severity during 2011–2070. However, the frequency of drought occurrence is greater than that of the baseline period. This is an indication of the emergence of a higher rate of occurrence of “moderate” drought events ( $-1.5 < SD < -1$ ) in the near future under RCP4.5.

The major basins within Jordan fall into three groups: northern (Yarmouk, Jordan Valley, and Zarqa), central (Dead Sea wadis, Wadi Mujib, and Wadi Hasa), and southern (Wadi Mujib). Spatially, frequency of drought occurrence, duration, and maximum severity show an increase from north to south (Fig. 5, A to C). From north to south,

the duration of meteorological drought events increases from 2 to 3 months, and meteorological drought severities increase from 26 to 37%.

However, considering meteorological droughts alone underestimates the impacts on streamflow and agriculture. For example, by 2071–2100, compared to the baseline period, the northern basins, which contain the major river tributaries, cities, and agricultural areas, we note that (i) the frequency of occurrence of hydrologic and agricultural droughts doubles, whereas meteorological drought increased by 60%, and (ii) agricultural drought duration increases from 2 to 5 months/year, whereas meteorological drought increases from 2 to 4 months/year. In addition, northern basin agriculture takes a longer time to recover from drought than the rest of Jordan. Agricultural drought duration increases by 3 months in the north versus 1.5 to 2 months in the central and southern regions, respectively.

In addition to the expected increase in the future number of dry events, the number of wet events (when precipitation, soil moisture, or streamflow is more than +1 SD from the baseline) is also expected to decline during the 21st century (Fig. 6). This is evident under RCP8.5, wherein there is a clear decline over time in all the wet event properties (duration, frequency of occurrence, and maximum severity of wet events), thus indicating a dual impact of climate change in simultaneously reducing the wet events and increasing the dry events. The sporadic wet events are likely to occur toward the end of the 21st century and strictly fall in the moderate category ( $<1.5$  SD), with the climate models predicting a likelihood of zero monthly occurrences of receiving “severe” or extreme rainfall ( $>1.5$  or 2 SD) based on the baseline period in the second half of the 21st century (fig. S1).



**Fig. 3. More warm years and concurrent warm and dry periods.** (A) Number of years with a positive temperature anomaly that is greater than 1, 2, and 3 SD levels from the baseline period average for RCP8.5. (B) Percent chance of occurrence of high temperature ( $>1$  SD) and different drought types for RCP8.5. (C) Percent chance of occurrence of high temperature ( $>1$  SD) and different drought types for RCP4.5. (D) Number of events resulting in concurrent occurrence of multiple drought types for each 30-year time slice.

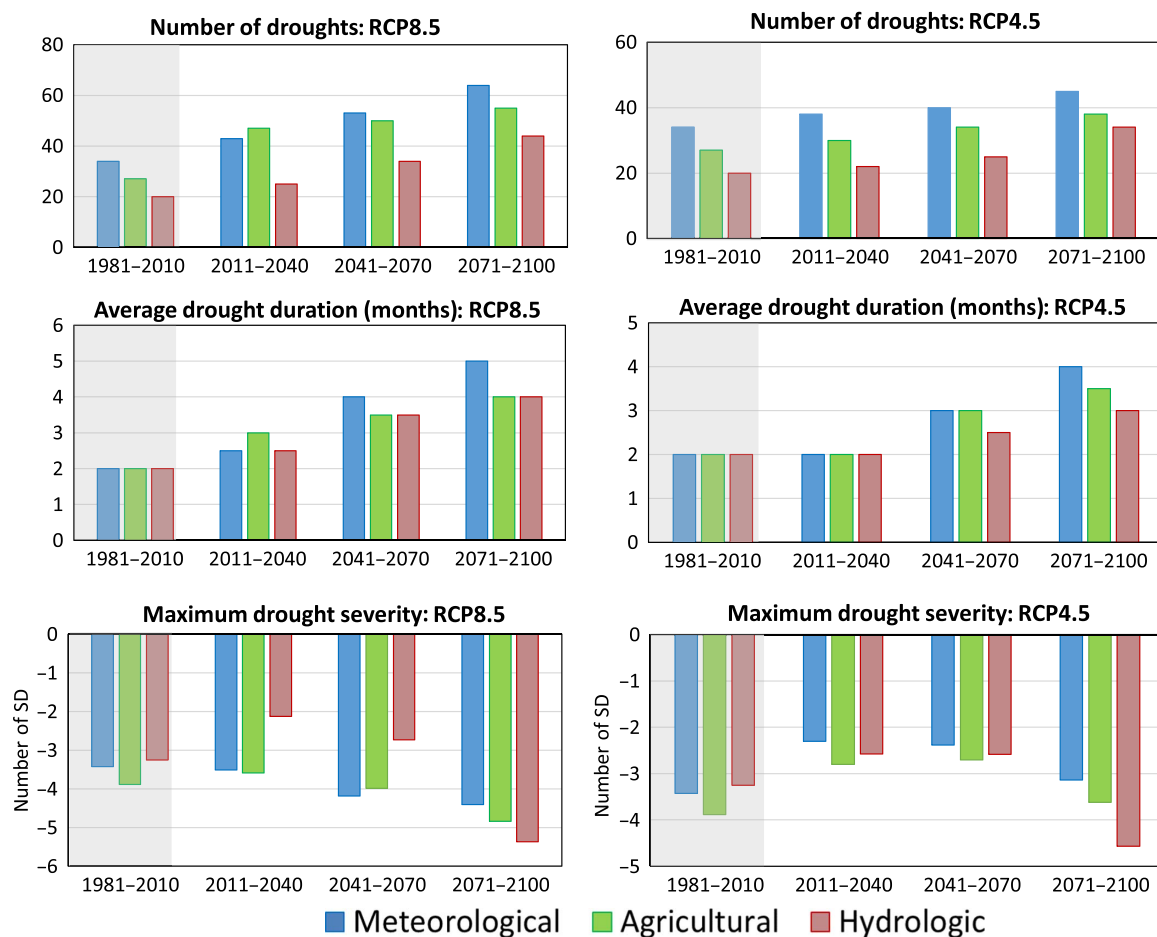
Under RCP4.5, Jordan is likely to experience a gradual decline in the occurrence of extremely wet months. Compared to the baseline period, under RCP4.5, the chance of occurrence of an extreme precipitation event ( $>2$  SD) reduces by 85%, and the chance of occurrence of a severe precipitation event ( $>1.5$  SD) reduces by 73% during 2071–2100 (fig. S1). The effect of increased warming and the subsequent reduction of the wet events in the case of soil moisture and streamflow are experienced at a slower pace, and even under RCP8.5, the region is likely to see months with streamflow and soil moisture values higher than 1.5 to 2 SD, until 2070 (Fig. 6 and fig. S1).

Although inconsistent climate variability across independent climate models or between models and observations is not surprising (33), we find that the variance of the future projections of the multimodel mean is  $\sim 35\%$  smaller than that in precipitation, soil moisture, and streamflow during the baseline period (Figs. 1, C and D, and 2, A to D). The decline in variance is more evident in RCP8.5, which is consistent with significantly lower occurrence of wet events under this scenario. This reduced variance does not appear to be due to bias correction as suggested by a 5-year period (2011–2015), during which we validated the bias-corrected precipitation versus observed precipitation (Fig. 1, C and D).

An examination of the probability density functions (PDFs), reflecting levels of drought severity for meteorological, agricultural, and hydrologic droughts, depicts a shift over time toward drier conditions under RCP8.5 (2071–2100) when compared to the baseline period (Fig. 7, A to C). This shift signifies an increase in drought occurrence and severity in the future. The right (wet) tail of the PDFs for RCP8.5 is flattened, indicating low probability of occurrence of wet events for precipitation, soil moisture, or streamflow. The PDFs for RCP4.5 (2071–2100) also show a temporal shift toward drier conditions, although to a lesser extent.

The consistent negative shift in the probability distributions for all three types of droughts under future scenarios suggests a higher level of aridity and drought persistence. First, for meteorological drought, the mean of both RCP8.5 and RCP4.5 PDFs shows a shift toward drier conditions and a decline in variance as reflected in the relatively flatter right tail in comparison to the PDF for the baseline period, indicating a lower probability of occurrence of wet events. Second, for agricultural drought, the PDF for RCP4.5 has an elongated right (wet) tail, with a slight negative shift in the mean and a higher variance when compared to the baseline period PDF (Fig. 7, A to C). Under RCP4.5, the probability of the region experiencing near-normal soil moisture conditions is similar to the baseline period, with a slightly higher probability of occurrence of both dry and wet extreme events. The density function for agricultural droughts under RCP8.5 has a negative shift in the mean and lower variance when compared to RCP4.5 and the baseline period, thus indicating the possible need for higher irrigation requirements in the future. Third, the hydrologic drought density functions for RCP8.5 and RCP4.5 experience a moderate shift toward the drier side, although to a lesser extent when compared to meteorological and agricultural droughts. The variance for the baseline period and future scenarios is quantified for all three drought types and agrees with the above inferences (Fig. 7).

In addition to the increase in probability of occurrence of individual drought types in the future, there is a higher incidence rate of multiple drought types occurring contemporaneously. Evaluation of extreme events like droughts by considering a univariate (single drought type) indicator could lead to significant underestimation of the actual hazard posed by concurrent multiple drought-type events. Simultaneous co-existence of multiple forms of drought leads to compound extreme



**Fig. 4. Drought properties for RCP4.5 and RCP8.5.** Droughts are defined by the number of events, average duration, and maximum severity for each 30-year time slice. The gray shaded area represents the baseline period (see figs. S1 and S2 for details).

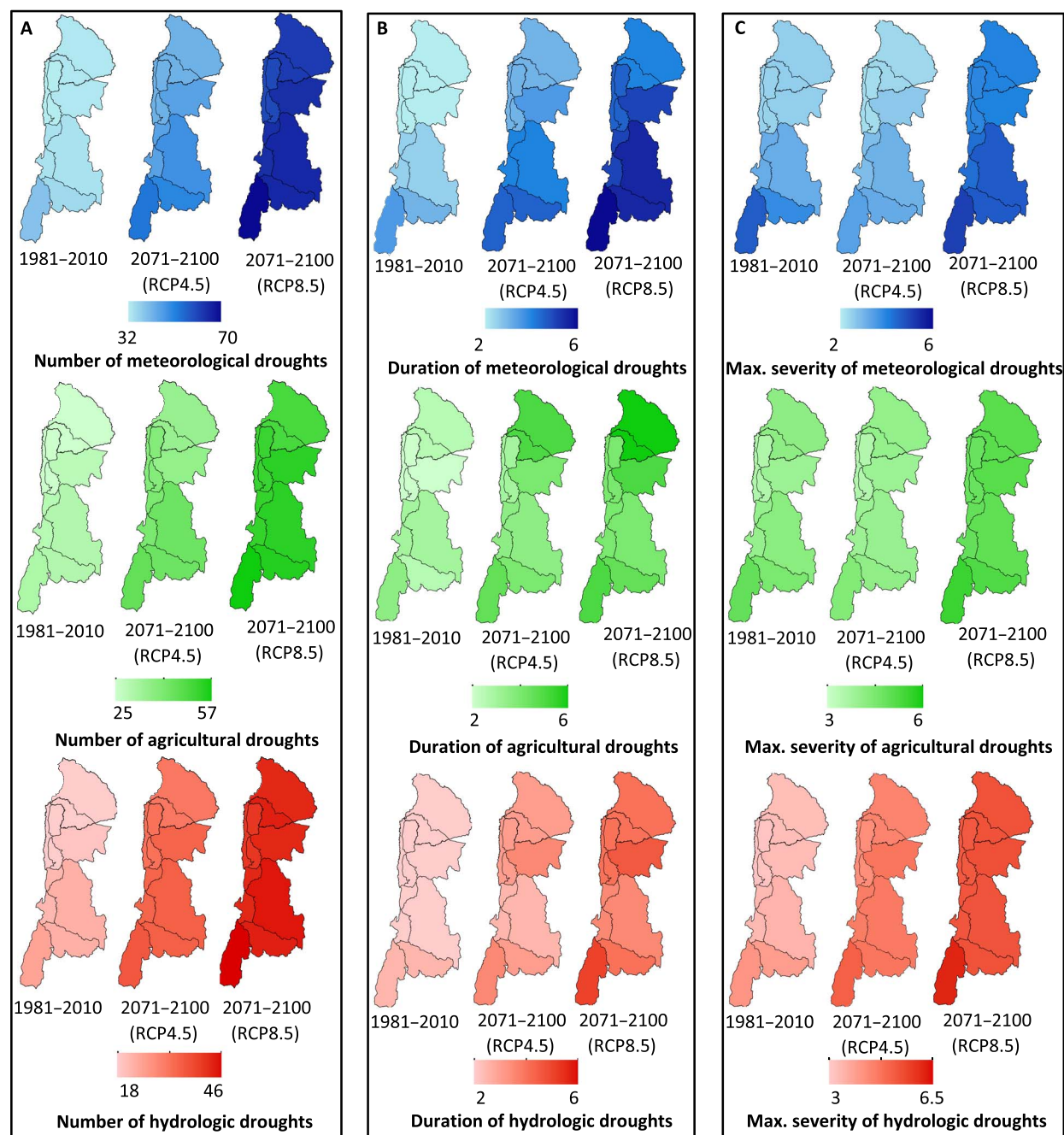
events having a significant impact (34). We find that the probability of concurrent occurrence of all three drought types is expected to significantly increase from only 2 collective events during the baseline period to 27 and 47 collective events under RCP4.5 and RCP8.5, respectively, during the 30-year period (2071–2100) (Fig. 3D).

The likelihood of increased incidence of droughts and an increasingly warmer, drier future has important implications for Jordan's freshwater resources. The agricultural sector is the country's largest water user (about 64% of total supply), and because of the rapidly depleting groundwater resources in the region, the nation's irrigation demand largely relies on surface water and treated wastewater (3). With decreased natural runoff as a consequence of increased warming and irrigation demand, we find a significant anticipated reduction in the flows into the major reservoirs within the country (fig. S3) under the RCP8.5 scenario. King Talal dam and Al-Wehda dam, which constitute the two major reservoirs in the country with a combined capacity of 188 MCM, are likely to experience a reduction in annual inflow of 31 and 65%, respectively, by the end of the 21st century. The rest of the reservoirs with a combined capacity of 45 MCM are also likely to experience a decline in annual inflows.

Jordan receives water from the Yarmouk River, the largest and most important tributary of the Jordan River, with an annual average flow of around 400 to 500 MCM (35). Flow into Jordan is controlled by the Al-Wehda dam. The Al-Wehda reservoir not only is the nation's largest

with a capacity of 110 MCM but also is located at the Jordan-Syria border and serves as the centerpiece of the 1987 transboundary water-sharing agreement between the two nations. However, since the construction of Al-Wehda dam in 2005, the annual flow into the reservoir steadily declined from 150 to 15 MCM by 2011. This is largely due to the increase in upstream water use and diversions via a number of Syrian dams and reservoirs, the development of which ran counter to the intent of various water treaties with Jordan. The transition period from 2006 to 2011 is important because it represents the time after which the Al-Wehda dam officially started functioning in accordance with the Jordan-Syria water agreement of 1987 and right before the decline in agricultural land use following the onset of the Syrian crisis. The reservoir inflows started rising in 2013, which can be attributed to the (i) recent Syrian uprising that led to a decline in the irrigated land in the Syrian portion of the Yarmouk basin and (ii) recovery from a multiyear drought (31).

We analyzed the annual inflows to the Al-Wehda reservoir under four plausible scenarios, which are combinations of climate change and agricultural land-use change in Syria (Fig. 8A). Our analysis was limited to the first half of the 21st century (2015–2050) because the future of the region is quite uncertain. Two of the four plausible scenarios revealed important results discussed presently. First, under the continuing conflict scenario, we assume that the current reduction in irrigated agricultural land area generated by the Syrian conflict remains

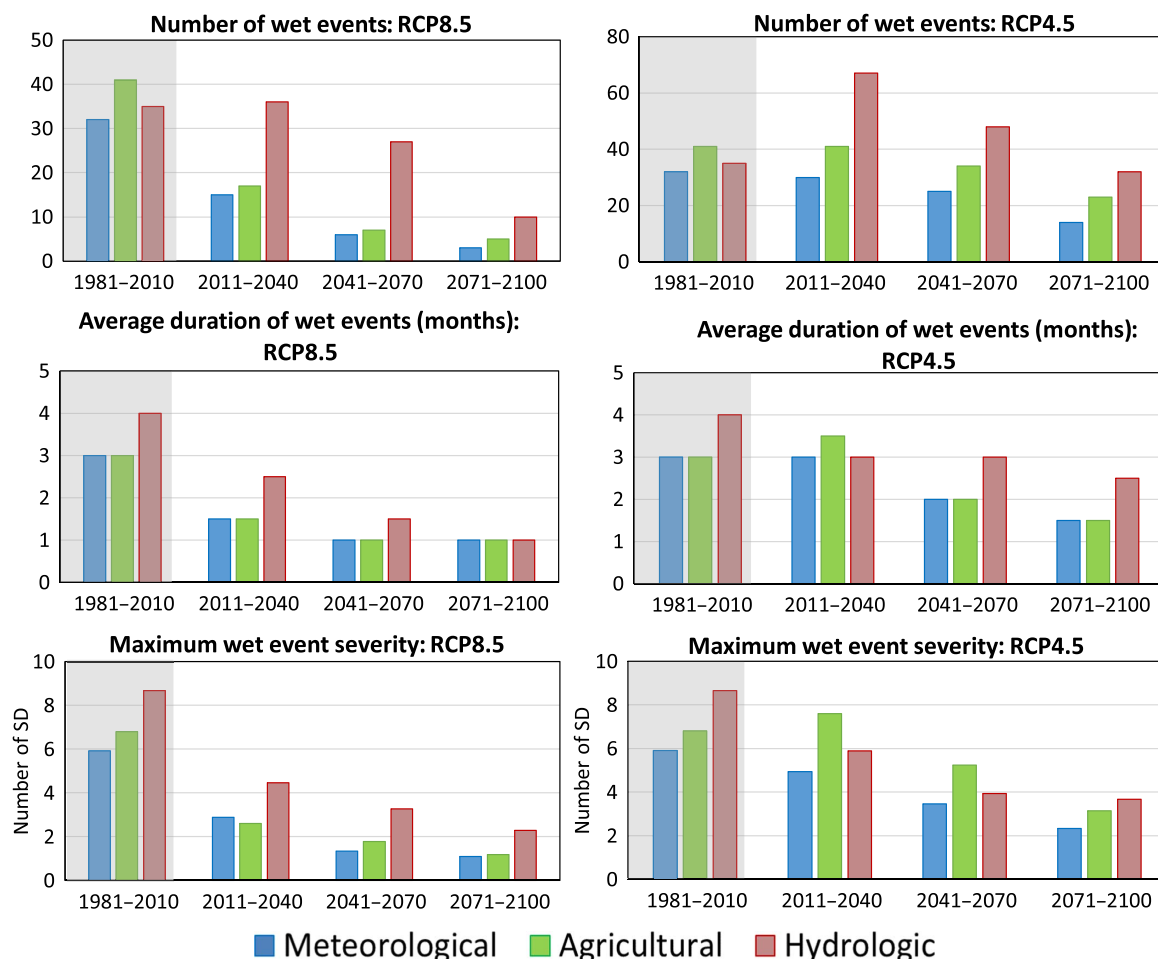


**Fig. 5. Progression of multiple drought types in each river basin.** Spatial maps of the (A) number, (B) duration in months, and (C) maximum drought severity (of a single event) of meteorological, agricultural, and hydrologic droughts during the baseline period, 2071–2100 (RCP4.5), and 2071–2100 (RCP8.5), respectively. The blue, green, and red maps represent meteorological, agricultural, and hydrologic droughts, respectively. We define a drought event as a continuous period of one or more months with precipitation, soil moisture, or streamflow less than  $-1$  SD from the baseline average. The drought duration is in months (see Fig. 1A to identify the locations of basins).

unchanged until 2050 and is sufficiently represented using the 2014 post-conflict agricultural land-use map (Fig. 8D). Second, under the recovery to pre-conflict status land-use scenario, Syrian irrigated agriculture is assumed to recover to the pre-conflict state in 2025 and is sufficiently represented using the 2009 land-use map (Fig. 8E). The irrigated land area under the recovery to pre-conflict scenario is 50% more than the irrigated land area under the continuing conflict scenario (Fig. 8, D and E, and table S2).

We compare the inflow into the Al-Wehda reservoir in the future to the baseline period (1981–2010) transboundary Yarmouk river flow to Jordan. Note that the Al-Wehda dam was not constructed until 2005. Comparison of future annual average transboundary streamflow to Jordan with respect to the baseline period under the above scenarios reveals two-key potential future impacts (Fig. 8A):

1) The continuing conflict scenario represents the best-case scenario for Jordan in terms of receiving transboundary flow from



**Fig. 6. Wet event properties for RCP4.5 and RCP8.5.** When the variable of interest falls above +1 SD from the baseline average, it is considered as a wet event. Wet events are defined by the number of events, average duration, and maximum severity for each 30-year time slice. The gray shaded area represents the baseline period. The severity of each wet event is defined as the sum of monthly deviations of the variable of interest exceeding +1 SD from the baseline period over a continuous period of one or more months (see figs. S1 and S2 for details). Duration of a wet event is defined as the number of months of a continuous period over which the monthly deviation of the variable of interest is above +1 SD.

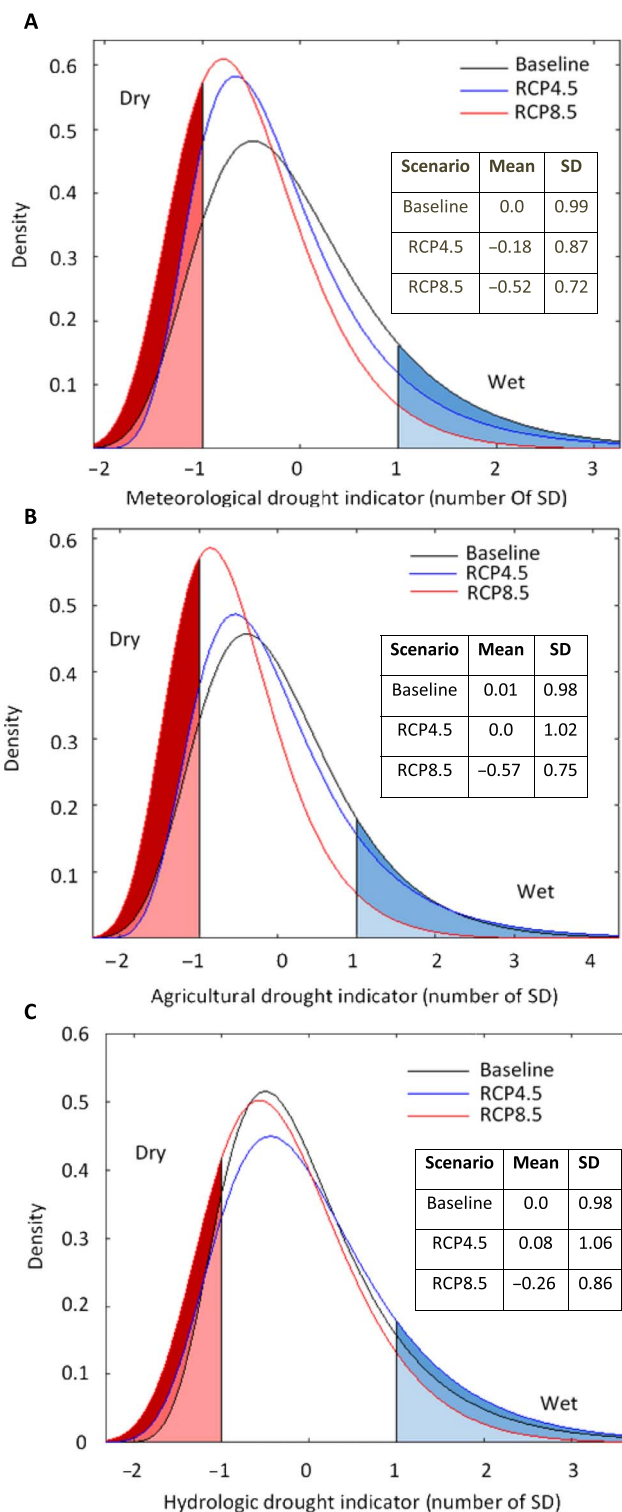
Syria. Under reduced Syrian agriculture and moderate climate change impacts represented by RCP4.5, our hydrologic simulations suggest an average inflow of 62 MCM/year to the Al-Wehda reservoir during 2016–2050. Even under this best-case future scenario, Jordan is likely to experience 51% less inflow compared to what it received during the baseline historical period (127 MCM/year during 1981–2010). Groundwater formerly fed the Yarmouk River, but excessive groundwater abstraction in Syria (36), combined with the construction of multiple Syrian dams and changing climate, results in a “permanent” reduction in the basin’s water yield under this scenario.

2) The recovery to pre-conflict status land-use scenario is the best case for Syria but is the worst case in terms of transboundary river supply for Jordan. Under pre-conflict irrigated agriculture in Syria and more severe climate change impacts represented by RCP8.5, our hydrologic simulations show that after 2025, Jordan would experience little flow in the Yarmouk River. This is due to resumption of greater irrigated agriculture in upstream Syria, lower future precipitation, and higher temperatures leading to more severe and frequently occurring droughts. It is significant to note that under this scenario, average an-

nual inflow into the Al-Wehda reservoir would be 32 MCM/year, which represents a 75% reduction in inflow compared to the baseline historical period (127 MCM/year).

The other two scenarios, RCP8.5 continuing conflict and RCP4.5 recovery to pre-conflict status, are intermediate ones that fall between the best-case and worst-case scenarios discussed above. The annual average transboundary flows into Jordan are estimated to be 47 and 43 MCM/year under RCP8.5 continuing conflict and RCP4.5 recovery to pre-conflict status scenarios, respectively, during 2016–2050. These values are about one-third of the baseline period average annual transboundary flow during the baseline period (127 MCM/year).

To determine the independent impacts of conflict-driven land-use changes and climate change on flow generation as shown in Fig. 8A, we separately analyzed the (i) difference in inflows to Jordan when comparing the recovery to pre-conflict status and continuing conflict scenarios under the same climate change scenario (either RCP4.5 or RCP8.5) and (ii) difference in inflows when comparing climate change scenarios RCP4.5 and RCP8.5 holding land-use change constant (Fig. 8, B and C). The analysis indicated that the ongoing Syrian uprising and



**Fig. 7. Probability distributions show shift toward drier conditions.** Kernel density functions of the (A) meteorological drought indicator, (B) agricultural drought indicator, and (C) hydrologic drought indicator for the baseline period, RCP4.5, and RCP8.5, respectively. The red shaded portion of the density functions indicate dry events, and the blue shaded portion of the density functions indicate wet events. The time periods considered are 1981–2010 for the baseline period and 2071–2100 for RCP4.5 and RCP8.5 scenarios. The pdfs are obtained using a well-established nonparametric kernel density estimation approach (52).

the resulting change in agricultural land use have over twice the impact on average annual streamflow generation than climate change (table S3, A and B) and is supported by the following results:

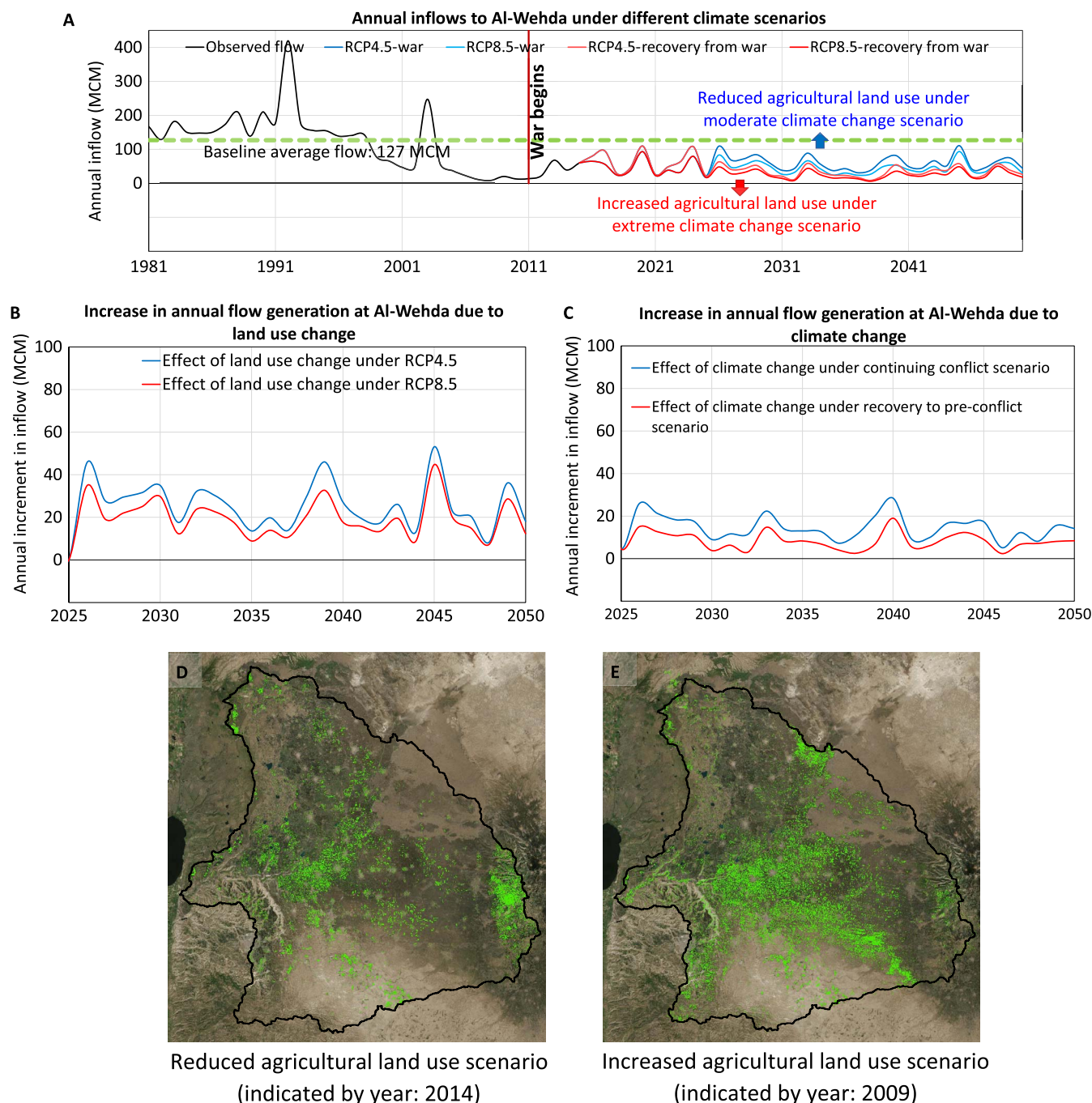
1) The reduction in flow to Jordan caused by the recovery in southern Syrian agriculture is twice that due to climate change. In this context, by “reduction” in flow, we mean the difference in flow caused by either (i) the different climate scenarios while keeping the land-use scenario constant or (ii) the different land-use change scenarios while keeping the climate scenario constant. To specifically consider the independent impact of conflict-driven reduction in Syrian agricultural land use on inflows to Jordan, we take the difference in flows between the scenarios RCP8.5 continuing conflict scenario and RCP8.5 recovery to pre-conflict scenario, and the difference between RCP4.5 continuing conflict scenario and RCP4.5 recovery to pre-conflict scenario. In this case, we find that, during 2026–2050, there is an average annual decline of 26 and 20 MCM in inflow from Syria to Jordan under RCP4.5 and RCP8.5, respectively. However, looking at the effect of climate change alone on flow generation, we see that the average decline in annual flow generation is only 15 and 8 MCM under the continuing conflict and recovery to pre-conflict scenarios, respectively.

2) The maximum decline in annual inflows into Jordan due to the independent impact of land-use change alone is two times as great as the maximum decline in flow due to the independent impact of climate change. Comparing the continuing conflict versus the recovery to pre-conflict land-use scenarios under the constant climate scenario, we found that the maximum decline in inflow to Jordan from Syria is 53 and 45 MCM/year, respectively, whereas the impact of climate change alone, while keeping the land use constant, on maximum decline in inflow is only 28 and 19 MCM/year for RCP4.5 and RCP8.5, respectively (table S3, A and B).

## DISCUSSION

Water security assessments spanning future decades would greatly benefit from reflecting on the joint impacts of multiple drought types and human-induced land-use change. These impacts are especially worth considering for the 278 transboundary waterways (37) associated with shared watersheds occupying nearly half of the world’s land (38). Future water security concerns are critical in arid countries reliant on transboundary freshwater resources and where the combined effects of future droughts and human-induced land-use changes are likely to continue. We quantify these combined effects of land-use change and future climate change-induced precipitation (meteorological drought) on streamflow (hydrologic drought) and irrigated land (agricultural drought). Although our analyses focus on Jordan and its upstream riparian neighbor, Syria, where land use has changed markedly since 2013 (31), our approach is highly relevant to other countries in which regional and global changes might produce similar cumulative impacts on water resources and agricultural land.

From a broad perspective, our results suggest that climate change analyses focusing only on precipitation deficit in transboundary flow systems underestimate potential impacts in water-stressed regions for two reasons. First, although the effect of declining precipitation is no doubt the major driving factor for all three types of droughts considered in the Jordan-Syria system, declines in streamflow and soil moisture, which are critical to freshwater supply and agriculture, are driven not only by lower precipitation but also by significantly higher temperature and evapotranspirative demand plus land-use change. Second, downstream riparian nations are extremely susceptible to the cascading impacts of multiple drought types. For example, streamflow in a downstream nation



**Fig. 8. Transboundary flow reduced due to climate and land-use changes.** (A) Annual projected inflow in MCM to Al-Wehda dam under different climate and conflict scenarios. (B) Increase in annual flow generation at Al-Wehda dam due to land-use change. (C) Increase in annual flow generation at Al-Wehda dam due to climate change. (D) Land-use map for year 2014 indicating the reduced irrigated agricultural land use under continuing conflict scenario. (E) Land-use map for year 2009 indicating the increase in irrigated agricultural land use under recovery to pre-conflict scenario. The green shaded region indicates the irrigated agricultural land area. The annual incremental flows were calculated by taking the difference between the continuing conflict and recovery to pre-conflict scenarios and RCP4.5 and RCP8.5, respectively, to identify independent impacts of conflict and climate change.

(such as Jordan) may decline because of the drought there, but flow can also further diminish because of the impact of meteorological drought in the upstream riparian nation plus the indirect effect on runoff suppression in the upstream riparian nation (for example, Syria) due to soil moisture deficit (agricultural drought) and consequent increases in irrigation demand.

A comprehensive set of high-resolution process-based watershed models developed for Jordan and southern Syria proved to be essential to quantifying the effect of future climate change on Jordan through drought impacts within its boundaries and in upstream Syria. Comparing Jordan's surface water resources today to those under climate change at the end of the century, our hydrologic simulation results suggest a

reduction of 40% (204 to 122 MCM under RCP8.5) in total streamflow generated from all major watersheds. Drought within Jordan accounts for 56% of this decline, with the remaining 44% due to transboundary drought effects in Syria, assuming that agricultural land use reverts to historical pre-conflict conditions after 2025. The cascading effect of soil moisture deficit in Syria on this decline in streamflow to Jordan is 31% (26 MCM/year) because the upstream river flow is diverted to supply irrigated agriculture, thereby reducing transboundary flow to the south.

Our work advances methods and understanding of the evolution of multiple drought types under future climate scenarios that cause reductions in freshwater supply in critically dry Jordan, which is also affected by upstream riparian land-use change. First, we present a systematic assessment of the baseline historical period behavior of climate models for drought analysis as an essential step for strategic selection of a realistic subset of future model projections. Our approach eliminates the most implausible models for this region—those that do not reproduce the historical precipitation record. Of the 10 Coupled Model Inter-comparison Project phase 5 (CMIP5) climate models, only 3 met statistical criteria for acceptability and are the only ones consistent with both the selection criteria and ENSO behavior. The selected models were shown to be consistent with the latter portion of the historical record not used in the model culling process. Models that were inconsistent with the historical precipitation data remained so during the consistency-check period. Although this check period was brief, it was one showing a sudden marked drought.

Second, we analyze future meteorological droughts but go beyond that to consider agricultural droughts (soil moisture deficit) and hydrologic droughts (decline in streamflow). Assessment of agricultural and hydrologic droughts was based on a set of high-resolution regional data-driven process-based watershed models covering 95% of both the populated area and agricultural regions of Jordan. For all three drought types, we quantify temporal behavior of drought occurrence duration, frequency severity, and concurrence of events. Our results suggest (i) the emergence of a drier, hotter future climate with consequent declines of 30% in precipitation, 28% in soil moisture, and 58% in streamflow during the late century (2070–2100) that fall well outside the climatological conditions experienced during the baseline historical period (1981–2010); (ii) that the concurrence of all three drought types during the late century increases to 27 and 47 monthly events (RCP4.5 and RCP8.5) from only 2 concurrent events during the baseline period; (iii) that the average variance of all three drought types during the late century is ~35% lower than the variance during the baseline period, which is likely due to the occurrence of far fewer wet events; (iv) that the two largest dammed reservoirs in Jordan are likely to see a reduction in annual inflow of 31 and 65%, respectively, by late century; and (v) that spatial and temporal drought analyses indicate that the northern basins, which contain most of Jordan's population and agricultural activities, are twice as likely to experience either agricultural or hydrologic droughts by the end of the 21st century under extreme climate change compared to the baseline.

Third, in addition to climate change, the potentially long-lasting (multidecadal) effects of land-use change in Syria is shown to affect the magnitude and timing of streamflow in the transboundary Yarmouk basin that supplies water to Jordan. Most notably, when accounting for the plausible recovery to pre-conflict status in the future, the decline in streamflow entering Jordan due to an increase in Syrian agricultural land use to pre-conflict levels is twice that attributable to climate change.

Future freshwater sustainability in Jordan will likely be threatened by increased future water consumption generated by an increasing

population and refugee influxes, following a punctuated population growth pattern observed since 1948. Future adaptation to extreme droughts in Jordan will be an immense challenge. The projected negative impacts of more severe droughts of greater duration calls for essential alternatives, such as fresh water supplied by desalination associated with the Red Sea–Dead Sea project and improved transboundary water-sharing agreements with neighboring countries. Regional cooperation among riparian countries resulted in an agreement signed by Jordan, Israel, and the Palestinian Authority. This agreement enables the Red Sea–Dead Sea pilot project to move forward and, along with potential future full implementation of the project, is an essential positive step toward beginning to alleviate water scarcity through mid-century. However, given worsening hydrologic and agricultural droughts, transboundary river flow that depends on Syrian agricultural land use, refugee-driven population growth, and groundwater depletion, enormous obstacles remain for Jordan to achieve a secure and sustainable freshwater supply.

## MATERIALS AND METHODS

Analysis of meteorological, agricultural, and hydrologic droughts requires measured or estimated monthly precipitation, soil moisture, and streamflow, respectively. Streamflow considered for measuring hydrologic drought is the flow out of the basin, which, in most cases, would be a reservoir inflow. These flow values were the basis for evaluation of hydrologic drought. For the baseline period (1980–2010), daily gridded precipitation from the global meteorological forcing data set at a resolution of 0.25° was temporally aggregated to obtain monthly precipitation data and was subsequently used for the meteorological drought analysis (39, 40). This data set is a blend of reanalysis data and observations, primarily used for driving land surface models. The data set was chosen after performance analysis by comparing against observed rainfall at 10 station locations within Jordan. Visual inspection through comparison of monthly time series plots, autocorrelograms, empirical cumulative distribution function (CDF) plots, and other statistical metrics (root mean square error, Pearson  $R^2$ , and two-sample  $t$  tests at 5% significance level) were used to ensure that the reanalysis data set for the baseline period is satisfactorily representing the regional precipitation pattern. The results of the analysis are provided in figs. S4 to S7 and table S4 (A to C). Results indicate that by all measures, the Princeton reanalysis data set was able to reliably represent precipitation within an error margin of 10 mm/month and a high Pearson  $R^2$  (average of 0.93 across all the stations considered for performance analysis). However, the reanalysis data set is undoubtedly prone to errors related to spatial interpolation and complex (steep) topography of the region, such as locations 2 and 10. The baseline period gridded precipitation data served as the benchmark for the correction of bias in the 21st century precipitation projections obtained from regional climate model simulations.

Although the climate models are capable of providing information, with some confidence, on how the climate is likely to evolve in future, because of their coarse spatial and temporal scale of operation, they are incapable of capturing the effects of natural processes such as flow in streams, evaporation from land and water surfaces, evapotranspiration from crops and vegetation, groundwater movement and recharge, and artificial processes such as irrigation or reservoir storage. All of these processes affect the regional hydrology and hence require a coupling of climate models with a physically based regional hydrologic model to perform climate change impact assessment on regional hydrology and natural disasters such as agricultural or hydrologic droughts.

A land surface rainfall-runoff model was used to obtain monthly simulations of soil moisture and streamflow for agricultural and hydrologic drought analysis [in this case, Soil Water Assessment Tool (SWAT)]. SWAT is a distributed parameter hydrologic model that estimates the water balance within a watershed by using daily meteorological variables, topography, land use, vegetation, and soil characteristics as inputs (41). Daily time series of precipitation, temperature, wind speed, and relative humidity obtained from the global meteorological forcing data set (39, 40) was used to run SWAT. Land-use maps used as inputs were based on Landsat 8 satellite images, topography maps were obtained from the Shuttle Radar Topography Mission (42), and soil characteristics were derived using the Food and Agricultural Organization global soil maps (43). SWAT uses Manning's equation to compute open-channel flow. Streamflow through the channel network is routed using a variation of the kinematic wave model (Muskingum method). Flows into the major reservoirs were simulated in the model, and values were checked against observed inflows. The reservoir outflows were based on rules developed on the basis of inflow and reservoir storage change data. Details regarding SWAT data requirements and model description are given in table S5 (A and B).

The preparation of land-use map from Landsat imagery for Syria was based on an unsupervised classification protocol, wherein the pixels were gathered in a defined number of clusters depending on the reflectance for each wavelength. The clusters were then manually associated to land-use classes, and a "temperature" analysis was carried out to differentiate between irrigated and rainfed areas. Goward *et al.* (44) had shown that the surface temperature ( $T_s$ ) declines with the increase in soil moisture and is negatively correlated with normalized difference vegetation index. Hence,  $T_s$  would be an encouraging indicator of irrigation (45).  $T_s$  was calculated on the basis of a split window algorithm detailed by Du *et al.* (46). The differentiation between irrigated and rainfed areas was done on the basis of the temperature difference between cropped soil and surrounding bare soil, with a negative temperature anomaly being an indicator for irrigation. The irrigated land-use classes primarily include fruit trees (citrus, apple, and grapes), summer and winter vegetables (lettuce, eggplant, cauliflower, and tomato), and olives (partly rainfed and partly irrigated, and differentiated on the basis of temperature analysis). The source of irrigation can be either surface water or groundwater. The irrigated crop areas falling within a 5-km buffer zone from reservoirs or streams are assumed to be irrigated using surface water, and the remaining through groundwater. Irrigated water use was estimated using CROPWAT (47) and remote sensing approaches by merging crop-evapotranspiration data estimates with sequential maps of irrigated crops. Our results were evaluated by comparing them to those of Al-Bakri *et al.* (48), who conducted a similar study for the northern Jordan portion of the Yarmouk basin and provided monthly estimates of irrigated water use for different crop classes. Our results for the different irrigated crop classes were within 5% of those of Al-Bakri *et al.* (48) (table S6).

SWAT modeling was carried out for the study region (35.5° to 37°E and 30° to 33°N), which contains six major watersheds in Jordan where 95% of the country's population resides (Fig. 1A), plus the southernmost portion of Syria, which constitutes a large portion of the Yarmouk transboundary basin. SWAT model parameters for each basin were calibrated on the basis of the observed monthly stream gauge data (Fig. 1A, fig. S8, and table S7). Monthly simulations of streamflow and soil moisture at 1-m depth obtained as SWAT model outputs were used for agricultural and hydrologic drought analysis.

Figure S8 and table S7 show the results of calibration and validation for locations within each of the major basins in Jordan. SWAT model calibration parameters include curve number, evaporation compensation factor, baseflow recession factor, groundwater "revap" coefficient, threshold depth of water in shallow aquifer for initiation of return flow, and deep percolation. Both manual calibration and optimization algorithms in SWAT-CUP (Calibration and Uncertainty Program) were used. Details regarding the above calibration parameters, their physical implications, and routines can be found in the SWAT user manual (41). The calibration results showed a Pearson  $R^2$  of  $0.86 \pm 0.08$ , Nash-Sutcliffe efficiency of  $0.72 \pm 0.16$ , and percent bias of  $3.12 \pm 5.61$ . A portion (30%) of the simulation time period was used for validation of the calibrated model and shows statistics similar to those obtained for calibration.

Regarding the future, two climate change scenarios considered encompass a plausible future range of conditions: (i) RCP4.5 is considered to be the "optimistic" scenario, which assumes that greenhouse gas concentrations stabilize by mid-century due to policy intervention, and (ii) RCP8.5 is considered to be the "business-as-usual" scenario, which assumes that greenhouse gas concentrations follow an increasing trajectory until the end of the 21st century. Meteorological properties, including temperature and precipitation, for the 21st century projections were based on dynamically downscaled regional climate model simulations at a resolution of 50 km from the Coordinated Regional Climate Downscaling Experiment (CORDEX) project (49). CORDEX is an integrated data portal for providing downscaled global and regional climate model simulations derived from CMIP5. We restricted the analysis of the future by considering an "intelligent" subset of the CMIP5 climate models that performed well in successfully replicating the climatology during the baseline historical period (tables S1 and S8) rather than taking an ensemble average of all the CMIP5 models, many of which did not reproduce historical precipitation observations. The replication criterion was assessed in terms of the Pearson's  $R$ , absolute error, percent bias, and an ENSO score (table S8). The selection criteria ensure that the chosen models satisfactorily represent the regional climatic characteristics, including ENSO that can affect Jordan's climatology. Three climate models were chosen on the basis of these selection criteria: HadGEM, IPSL, and ECHAM. Temperature was reproduced well by all models (fig. S9B). However, precipitation was not. Those precipitation models selected were bias-corrected using a distribution mapping approach based on the observed precipitation for the baseline period (1981–2010) (see figs. S9A to S10, A to G, and table S9). Comparison of observed precipitation to the bias-corrected precipitation for a verification period (2011–2015) suggests that the bias-corrected precipitation for this period from selected models follows RCP4.5 and RCP8.5 (Fig. 1, C and D). The bias-corrected monthly values of precipitation per basin based on observed precipitation values during the baseline period 1981–2010 were extended to include the future scenarios of RCP4.5 and RCP8.5.

Given the strong seasonality in the region's climatology that manifests as zero or near-zero precipitation during the summer months, we consider only the rainy season (October to May) when analyzing drought properties. Summers are so dry and devoid of rainfall that we do not consider droughts during June to September. In the case of hydrologic droughts, the source of flow, if any, is groundwater baseflow and timed releases of treated wastewater or reservoir storage accumulated during winter. Because of many years of excessive pumping and consequent depletion of groundwater resources, the baseflow contribution to summer flows is negligible (50, 51). Similarly, the soil moisture levels during

summer months will be largely controlled by artificial supply through irrigation, which again depends on the winter storage. Hence, the drought metrics do not consider summer months for analysis. During this rainy season, any month is considered to be under drought if monthly precipitation, soil moisture, or streamflow falls below at least 1 SD from the baseline period average. We consider the event to be a moderate drought if the variable of interest exceeds  $-1$  SD of the baseline period, a severe drought if it exceeds  $-1.5$  SD, and an “extreme” drought if it exceeds  $-2$  SD (table S10).

For the baseline period, monthly gridded precipitation from the global meteorological forcing data set at a resolution of  $0.25^\circ$  (39, 40) and SWAT model simulations of soil moisture and streamflow at the smaller, sub-basin, hydrologic response unit scale were computed for each basin and used for analysis of meteorological, agricultural, and drought properties. On the basis of the observations or model simulations, we calculate (i) the baseline average value over 1981–2010, (ii) the deviation of the variable of interest value from the baseline average (fig. S2), (iii) classification of drought events based on the extent of deviation expressed relative to the SD in the baseline period, and (iv) drought properties consisting of duration, frequency of occurrence, and maximum severity. For the 21st century simulations, we compare all three drought properties for each 30-year period to the baseline period to facilitate evaluation of the progression of regional climate change for each drought type.

For the analysis of the impact of land-use changes in upstream Syria under the influence of the recent conflict on Jordan’s water resources, SWAT model for the Yarmouk basin (transboundary basin shared by Jordan and Syria) was driven under four future scenarios extended until 2050. These scenarios serve as a combination of climate change and land-use change scenarios:

1) RCP4.5 and “continuing conflict state—reduced irrigated agriculture”: This scenario assumes moderate emissions and reduced irrigated agriculture in upstream Syrian parts of the Yarmouk basin due to the impact of the continuation of the Syrian conflict, leading to migration of Syrian farmers and decline in agricultural land-use acreage. The land-use maps developed for different years based on Landsat 8 images indicated a peak in irrigated agricultural area before the beginning of the Syrian uprising in 2011. At present, under the influence of the Syrian conflict, the irrigated agricultural land area is reduced by 33% compared to the pre-conflict years (table S2). This scenario assumes that the agricultural land-use area remains at this reduced state (as indicated by the 2014 land-use map) until 2050. The behavior of the upstream Syrian reservoir releases is assumed to be represented by average monthly releases during the post-conflict period 2012–2015.

2) RCP8.5 and “continuing conflict state—reduced irrigated agriculture”: This scenario assumes extreme emissions and reduced irrigated agriculture in upstream Syria (indicated by the 2014 land-use map) until 2050. The behavior of the upstream Syrian reservoir releases is assumed to be represented by average monthly releases during the post-conflict period 2012–2015.

3) RCP4.5 and “pre-conflict state—recovery of irrigated agriculture”: This scenario assumes moderate emissions and a recovery to pre-conflict agricultural land use in upstream Syria after 2025. Hence, from present to 2025, the agricultural land-use area is reduced because of the effect of conflict (indicated by the 2014 land-use map). After 2025, Syria is assumed to recover from the conflict and return back to the increased agricultural land area corresponding to the pre-conflict years (indicated by the 2009 land-use map). The behavior of the upstream Syrian reservoirs is assumed to be represented by average monthly releases

during the post-conflict period 2012–2015 until 2025 and during 2025–2050, and the upstream Syrian reservoir releases are assumed to be represented by average monthly releases during the pre-conflict period 2000–2011.

4) RCP8.5 and “pre-conflict state—recovery of irrigated agriculture”: This scenario assumes extreme emissions and a recovery to pre-conflict agricultural land use in upstream Syria after 2025. The agricultural land-use area is assumed to stay at a reduced level due to the impact of conflict until 2025 (indicated by the 2014 land-use map) and after 2025 and is assumed to improve and return back to the pre-conflict level that is 50% more (indicated by the 2009 land-use map). The behavior of the upstream Syrian reservoirs is assumed to be represented by average monthly releases during the post-conflict period 2012–2015 until 2025 and during 2025–2050, and the upstream Syrian reservoir releases are assumed to be represented by average monthly releases during the pre-conflict period 2000–2011.

## SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/3/8/e1700581/DC1>

- table S1. List of climate models considered for subset selection.
- table S2. Agricultural land-use area for Yarmouk under different conflict scenarios.
- table S3A. Flow generation to Jordan under different land-use change scenarios.
- table S3B. Flow generation to Jordan under different climate change scenarios.
- table S4A. Performance metrics for the reanalysis data at the 10 station locations.
- table S4B. Summary statistics of the difference between reanalysis and observed monthly precipitation for all the 10 stations in Jordan.
- table S4C. Two sample *t* test for monthly precipitation at the 10 stations.
- table S5A. SWAT model inputs and sources.
- table S5B. Land-use maps used for different scenarios.
- table S6. Validation of estimated irrigation water requirement in the Yarmouk basin.
- table S7. Results of monthly streamflow calibration and validation.
- table S8. Climate model selection criteria.
- table S9. Bias correction statistics.
- table S10. Drought and wet event classification.
- fig. S1. Scatterplots for extreme event severity (wet and dry) for meteorological, agricultural, and hydrologic droughts under RCP4.5 and RCP8.5.
- fig. S2. Monthly drought indicator values for meteorological, agricultural, and hydrologic droughts under RCP4.5 and RCP8.5.
- fig. S3. Trends in the annual reservoir inflows in the future under RCP8.5 plotted on Jordan’s relief map.
- fig. S4. Performance analysis of reanalysis data set.
- fig. S5. Comparison of empirical CDF for observed and reanalysis monthly precipitation at the 10 stations.
- fig. S6. Correlograms for observed and reanalysis monthly precipitation time series at the selected stations.
- fig. S7. Box plots showing difference between reanalysis and observed monthly precipitation.
- fig. S8. Calibration and validation results for SWAT monthly streamflow simulations.
- fig. S9. Distribution mapping technique and climate model performance in simulating temperature during baseline period.
- fig. S10. Effect of bias correction of precipitation at monthly and annual scales.
- fig. S11. Comparison of observed and bias-corrected climate model precipitation for all rainy season months for a randomly selected grid.

References (53–62)

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