RESEARCH ARTICLE

How war, drought, and dam management impact water supply in the Tigris and Euphrates Rivers

Mejs Hasan, Aaron Moody, Larry Benninger, Heloise Hedlund

Received: 28 November 2017 / Revised: 2 April 2018 / Accepted: 20 June 2018 / Published online: 12 July 2018

Abstract The fast-paced conflicts in the Middle East can disrupt management and supply of water, particularly on dams and barrages along the Tigris and Euphrates rivers that have experienced threats or changes in sovereignty. Water supply is also under pressure from upstream water management, drought, and structural decline. In this research, we used a satellite-based algorithm, the normalized difference water index (NDWI), to monitor changes in the extent of surface reservoirs (1985–present). We compared the timeline of reservoir fluctuations with the timeline of events related to conflicts, droughts, and dam management. Our results show that the most sudden changes in water supply occurred during events related to conflict, but conflict was not often a cause of the greatest absolute changes to reservoir area. Though not as precise as on-the-ground information, satellite data can give insights to water supply when conflict has disrupted the flow of information or restricted on-the-ground data collection.

Keywords Conflict · Euphrates · NDWI · Satellites · Tigris · Water

INTRODUCTION

The yearly supply of water that a river delivers is a result of many factors including climate, watershed characteristics, and water management. Engineering projects for flood control and hydropower alter ecology, flow, and sediment deposits, as do water withdrawals for domestic, farming, and industrial use (Vörösmarty et al. 2010).

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s13280-018-1073-4>) contains supplementary material, which is available to authorized users.

One human activity with potentially great consequences for river systems is armed conflict. Damage to water systems was documented during conflicts in Kosovo, Afghanistan, and other places (UNEP 1999; UNEP 2003). Water infrastructure like dams can be directly targeted by airstrikes (MacQuarrie 2004). Displacement, explosions, and movement of heavy equipment increase dust that then settles on rivers and accumulates in reservoirs (Moridnejad et al. 2015). Conversely, conflict sometimes leads to better water quality. For example, reservoir salinity can improve if agriculture is disrupted and reduces irrigation return flows (UN-ESCWA and BGR 2013; Eklund et al. 2016). Abandoned farms can free water otherwise consumed by crops, increasing river flow (Müller et al. 2016).

Satellite data can shed light on such changes. Satellite sensors capture optical signatures of water that stand in contrast to desert sand, vegetation, and cities, thereby delineating the water-surface area (Gao 1996; McFeeters 1996). Different approaches have been tested for delineating inland water bodies, often with high accuracy both regionally and globally (Pekel et al. 2016; Klein et al. 2017).

In this paper, we use satellite data to explore the effects of conflict and other factors on the Tigris and Euphrates Rivers, which flow through Turkey, Syria, and Iraq. The Tigris and Euphrates allow countries like Iraq, comprised largely of desert, to enjoy abundant water resources compared to some neighboring countries (UN-ESCWA and BGR 2013). Both rivers are fed by snowmelt from Turkey's Taurus Mountains and Armenian highlands. The Tigris is also fed by the Zagros Mountains in Iran. Snowmelt normally occurs between April and June (MacQuarrie 2004). Dams along the Tigris and Euphrates collect snowmelt in reservoirs to prevent flooding, generate hydropower, and supply irrigation canals (Table 1;

Table 1 Dams and barrages along the Tigris and Euphrates. Dams ignored, due to small size, include Baath on the Euphrates (storage capacity of 0.09 km³) and Goksu (0.06 km³) on the Tigris. Capacities and years from Altinbilek (2004)

River	Dam	Country	Year completed	Capacity (km ³)
Tigris				
	Mosul	Iraq	1985	11.1
	Kralkizi	Turkey	1997	1.92
	Batman	Turkey	1998	1.18
	Dicle	Turkey	1997	0.60
	Devegecidi	Turkey	1972	1.18
Euphrates				
	Haditha	Iraq	1984	8.2
	Tishrine	Syria	1999	1.9
	Tabqa	Syria	1975	11.7
	Karkamis	Turkey	1999	0.16
	Birecik	Turkey	2000	1.22
	Ataturk	Turkey	1992	48.70
	Karakaya	Turkey	1987	9.58
	Keban	Turkey	1975	31
Other Euphrates water diverters/storage areas				
	Ramadi Barrage	Iraq	1955	–
	Lake Habbaniya	Iraq	1948	3.3
	Lake Razaza	Iraq	1951	26
	Lake Therthar	Iraq	1954	72.8
	Falluja Barrage	Iraq	1985	–

Altinbilek 2004). During droughts, the water supply in these reservoirs can fall sharply (Trigo et al. 2010).

The recent history of armed conflict around the Tigris and Euphrates Rivers includes the 1980–1988 Iran–Iraq War; the 1990–1991 Gulf War; the 2003–2011 progression of violence marked by the United States invasion and occupation of Iraq, and sectarian fighting; episodes of isolated airstrikes; and ongoing civil wars and insurgencies since around 2012. Obtaining information from stressed war zones can be difficult. This paper applies a formal analysis of satellite data to approximate water supply and compare the different ways that natural, engineering, and conflict stressors affect the Tigris and Euphrates. We focus on locations that have borne at least one direct episode of conflict: Mosul Dam on the Tigris River, and Haditha Dam, Falluja Barrage, and Ramadi Barrage, all on the Euphrates River. We evaluate how changes in water supply compares to government and news reports of conflict-driven change, as well as documentation of drought. We did not test these conflict–water relationships in a quantitative or statistical sense, or broaden the view to examine cooperation–water relationships. But this study may set the stage for a more

statistically rigorous analysis of water–climate–cooperation events as possible future research.

MATERIALS AND METHODS

Study area

Mosul and Haditha Dams were built in 1985 and 1986 to provide hydropower and irrigation (Table 1; Fig. 1a; Altinbilek 2004). Approximately 140 km south-east from Haditha Dam stands a series of gates and locks (Ramadi Barrage and Falluja Barrage) through which authorities can manipulate how much water continues down the Euphrates, and how much is instead diverted to peripheral water routes (Kassim et al. 2006). One of these routes, the Warar Canal, extends south from the Ramadi Barrage, and channels excess spring floods into lakes devoted to irrigation, recreation, and wildlife (Fig. 1c). The first of these lakes, Lake Habbaniya, has two outflow canals: one diverts water back to the Euphrates, and the other carries water south into Lake Razaza (Kassim et al. 2006).

Upstream of Mosul Dam, the Tigris is relatively undeveloped, with five smaller Turkish dams established. The flow of the Euphrates, on the other hand, is restricted by three Syrian dams and five Turkish dams upstream of Haditha Dam in Iraq (Fig. 1a). Most of the largest dams were inaugurated during the 1970s–1980s. The turn of the millennium ushered in a period of small-sized dam-building in Turkey and Syria.

The Turkish headwaters of the rivers develop in areas that receive upwards of 800–1000 mm of precipitation per year (MacQuarrie 2004). Further south, four local rain gages around the Tigris River near Mosul Dam recorded average rainfall of 325 mm year^{−1} between 1990 and 2009 (Zakaria et al. 2012). Southern Syria and Iraq receive about 75–150 mm year^{−1} (MacQuarrie 2004). Precipitation along the Tigris and Euphrates has declined recently, to the point that some researchers consider the region under a prolonged drought since 1999 (UN-ESCWA and BGR 2013). The two most serious periods of low precipitation occurred during the hydrological years (October–September) of 1998–2000 and 2007–2009 (Trigo et al. 2010), with another period occurring 2013–2014 (Electronic supplementary material, Fig. S1c).

Among conflicts that directly affected the Tigris/Euphrates water supply (Table S1), a notable example is the militant capture of Mosul Dam in August 2014. The capture was accompanied by a threat to destroy the dam and flood downstream Baghdad (Milner 2014). In fact, a visual inspection of the head of Mosul Dam Lake pre- and post-battle shows dramatic changes in lake-surface area

Fig. 1 Map of the study area. Map **a** shows the Tigris and Euphrates rivers as they wend their way through Iraq to the Persian Gulf, and the major dams, with an inset map showing the location on a world map. The dotted lines indicate the watersheds of the two rivers. The satellite imagery is a most-recent-pixel-value composite of Landsat images between January 1 and September 15, 2014, timed so that the most recent pixels were cloud-free. The Tigris and Euphrates vector layers were obtained from a river and lake shapefile produced by Natural Earth. The watersheds were determined through maps (UN-ESCWA and BGR 2013) and shapefiles from the World Resource Institute. Map **b** shows a close-up of Mosul Dam, and the section of the Tigris River used to approximate discharge (burgundy polygon). Map **c** expands the black box on Map **a** to show a close-up of the lakes, barrages, and canals between Ramadi and Falluja in the Anbar Province. It also shows the sections of the Euphrates River (burgundy polygons) upstream of Ramadi Barrage, and downstream of Falluja Barrage, used to approximate discharge. These Landsat images were retrieved from Google Earth Engine

Fig. 1 continued

(Fig. 2). However, quick visual inspections may be misleading, so we therefore applied a formal analysis.

Data

The data we needed to complete this analysis included information on the amount of water in the reservoirs studied; discharge information along the Tigris and Euphrates; precipitation data; and information on when conflicts and droughts occurred.

We used Landsat calibrated, ortho-rectified, top-of-the-atmosphere (TOA) reflectance images to measure water-surface area of rivers and reservoirs, because this was our indicator of water supply and how it changed in response to war, drought, or management (Table S2; Fig. S2 for row/path information, image distribution over time). Landsat imagery dates from 1984, and is set at $30 \times 30 \text{ m}^2$ pixel resolution retrieved from different U.S. satellite sensors (Thematic Mapper from Landsats 4 and 5, Enhanced Thematic Mapper + from Landsat 7, and Operational Land Imager from Landsat 8). These sensors and their satellite orbits have been designed to provide continuity in the data products so that imagery over the

entire data archive can be readily combined over time (Hui et al. 2008).

We validated our results with finer $10 \times 10 \text{ m}^2$ resolution multi-spectral Sentinel-2 images over Mosul and Haditha reservoirs. These Sentinel-2 images come from eleven different months between 2015 and 2016. For each reservoir, we found 10 cloud-free Sentinel-2 images captured within 2 days of a Landsat image, or 20 images in all.

We used satellite-based altimeters to fill gaps in the Landsat record. Mosul reservoir has altimetry data collected by the Ocean Surface Topography Mission since 2008 (NASA 2008; Birkett and Beckley 2010). Haditha reservoir altimetry dating from 2002 was collected by TOPEX/Poseidon and ENVISAT satellites (Crétaux et al. 2011).

We used established studies to identify time of major droughts based on meteorological, hydrological, and agricultural evidence (Trigo et al. 2010), as well as estimates of rainfall from the PERSIANN Climate Data Record. The PERSIANN record dates from 1982 and provides daily precipitation based on a combination of satellite data, modeled outputs, and rain gage data (Ashouri et al. 2015). We wanted this data to assess how drought affected reservoir water quantity.

Fig. 2 The head of Mosul Dam illustrated in Landsat 8 imagery, on **a** June 9, **b** July 11, **c** August 12, and **d** September 13, 2014 shows rapid changes in the water-surface area of the reservoir. Militants captured the dam on August 8, and relinquished control on August 16

Fig. 2 continued

We had access to archived monthly discharge records from several Iraqi river stations, though no data more recent than 2005 (Saleh 2010). This data granted insight into water management practices, as well as allowing us to extrapolate to more recent estimates of discharge.

Our approach focused on the surface area of various water bodies, rather than the total volume. Most of the reservoirs were filled before satellite-based topographic information became globally available, and we also lacked cross-sections of the rivers, information essential for deriving volume. We did have access to 1983 and 2011 depth-height-surface area data from Mosul reservoir (Issa 2015).

The repeat period for Landsat data is 16 days, and gaps in the data record due to clouds or missing data can extend for month-long stretches. Thus, floods or quick changes that occurred entirely within a repeat period cannot be captured (Yamazaki et al. 2015; Klein et al. 2017). We used all possible images, but accept that a conspiracy of sensor absence or clouds would thwart complete data on quickly-occurring extreme events.

We used news articles, reports, and books depicting events back to 1990 to build our timeline of various conflict flashpoints.

Methods

We assembled a Landsat database in Google Earth Engine for each day on which high-quality images captured the entirety of each reservoir of interest between 1984 and 2016 (Table S2). Using the cloud.score functionality in Google Earth Engine, we masked out all pixels exceeding a cloud score of 0.25 (¼ of the pixel is cloud contaminated) and used images for which less than 1% of pixels were cloud-masked out.

We measured water-surface area by applying the normalized difference water index (NDWI) (McFeeters 1996). NDWI is a normalized difference of the green and near-infrared Landsat bands ($[\text{near-infrared} - \text{green}] / [\text{near-infrared} + \text{green}]$). Image pixels scoring above a threshold were classified as water (Klein et al. 2014). A threshold was determined by first creating two polygons for each reservoir, one entirely over land and one over water. Average NDWI, and the standard deviation, was calculated for the water polygon and the land polygon. The land and water distributions were separated by a gap whose magnitude varied from image to image; we placed the land–water threshold within the gap (Fig. S3). Water in rivers and along shorelines, being shallower than reservoirs and susceptible to containing bottom reflectance, had NDWI values on the lower tail of the water distribution. Thus we adjusted the threshold for every image to include as much of the lower tail as possible without trespassing onto the

land distribution. We applied the following formula to achieve this goal:

$$T = \frac{[\bar{x}_w - (\bar{x}_L + n * S_L)]}{S_w - 1} \quad ([1])$$

where $\bar{x}_w$, $\bar{x}_L$, S_w , and S_L represent the mean values and standard deviations of the land and water distributions, T is the number of standard deviations below the water mean where the threshold is placed, and n is an adjustable value that can be set to achieve the best visual match. The value of n changed depending on the brightness of the image, and ranged from 2 to 11.

We converted the resulting number of water pixels into square kilometers, which represented the lake-surface area on the given day of each image. Using this information, the rate of change per day was calculated between successive images (except those separated by years-long gaps). The number of data-points per reservoir varied based on the number of cloud-free images available. For example, Mosul reservoir had 22 non-consecutive years with data, sixteen of which had at least five data-points, while Haditha reservoir had 27 years with data, twenty of which had at least five data-points. We defined years-long gaps as being at least 1.5 years. The frequency of these gaps also varied by reservoir; Mosul had five, Haditha had one. With two exceptions, all remaining data intervals for Mosul and Haditha were less than 1 year. For intervals that lasted several months, we accepted that the rate of change in lake-surface area gives less specific information. We removed contaminated data, such as a July 2009 sandstorm that obscured Haditha reservoir. We converted the 1983 and 2011 Mosul reservoir depth-height-surface area data into regression equations used to estimate total water volume from that reservoir's lake-area.

To fill in Landsat record gaps, we regressed altimeter water-level data with Landsat-based lake-surface area for Mosul and Haditha reservoirs. We used these linear regressions to estimate surface area from water-level data when Landsat images were not available.

When validating our data, we randomly generated 22 validation coordinates each for the twenty Landsat images paired with a Sentinel-2 image. This meant a total of 440 validation points, which allowed for at least 50 validation points in each of our two classifications (water or land; Congalton and Green 2009). Twenty-four points were discarded because the corresponding Sentinel image did not extend to that particular coordinate. The remaining 416 validation points were randomly distributed over the reservoirs, desert, mountain shadows, and shorelines (Fig. S4). From these points, we calculated our accuracy in correctly classifying all real-world water as water on the satellite images (user's accuracy), and our accuracy in not misclassifying real-world land as water on the satellite

Table 2 Error matrix and accuracy results

Sentinel reference data	User's accuracy		
	Water	Land	Total
Landsat classification			
Water	50	0	50
Land	1	365	366
Total	51	365	416
Producer's accuracy	98.04%	100%	Total: 99.75%

images (producer's accuracy) (Table 2). We also include the kappa coefficient which adjusts accuracy estimates to correct for the random chance of assigning the correct labels.

To get general discharge trends after the official records end in 2005, we substituted river-surface area. River-surface area is often a suitable indicator of discharge so we tested whether this was true on the Tigris and Euphrates (Bjerklie et al. 2003). We compared the historically recorded discharges to same-month river-area derived from Landsat images at selected river reaches. We selected the river reaches by picking a section right next to the dam or barrage whose discharge we wanted to recreate. Each stretch of river was also chosen such that no canal or tributary joined or separated from the river in the middle of the stretch to keep the sourcing consistent. We tested four sections of river downstream of Mosul dam, and four sections upstream, downstream, and in between Haditha Dam, Ramadi Barrage, and Falluja Barrage.

RESULTS

Extreme events

Both Mosul and Haditha reservoirs, over the entire period of record, have a surface area generally ranging between 300 and 400 km² (Fig. 3). Haditha mean lake-area was 302 km². Mosul mean lake-area before 2004 was 351 km² (9.8 km³, based on 1983 Mosul bathymetry), while post-2004, it declined to 313 km² (around 7.2 km³, based on 2011 Mosul bathymetry) (Fig. 3b).

We identified the lake-area values that were beyond two standard deviations from mean reservoir area. Lake-surface area fell to levels below this range twice for Haditha reservoir (multi-month stretches in 2009 and 2015), and thrice for Mosul (February 1991, March 2011, December 2015) (Fig. 3; Table 3). Lake-surface area never exceeded the upper bound of this range for either reservoir. Likewise, we categorized rates of lake-area change as substantial if they occurred beyond three standard deviations from mean rates (Fig. 4). Three deviations were chosen to eliminate high rates

occurring repeatedly between May and July, which we assumed were caused by spring floods. Five occasions fit this standard: at Mosul reservoir in August 1990, February 1991, and March–April 2011, and at Haditha reservoir in February 1991 and June 2014 (Table 3).

Classification error

We calculated user's and producer's accuracy ranging from 98 to 100% for all classes (Table 2), and a kappa coefficient of 98.9%. Land and water are highly distinguishable categories, and our formula that set the land–water threshold individually for each image also accounts for the high accuracy.

Altimeters for gaps

The altimeter-Landsat correlation for Mosul reservoir was $r^2 = 0.90$; for Haditha, it was $r^2 = 0.99$ (Fig. S5). We decided to therefore only use the altimetry data for Haditha reservoir, because we could depend that the estimates produced from it would be nearly identical to estimates we would have derived from Landsat images, and the transitions between the two sets of estimates would be unnoticeable. We used linear regression to convert height estimates during Landsat gap years into lake-surface area estimates.

River-surface area for discharge

Some river stretches correlated to discharge better than others. On the Euphrates, the best correlations were found on the stretch of river just upstream of Ramadi Barrage (correlation of 0.73 with Husayba station) and a stretch just downstream of Falluja Barrage (correlation of 0.64 with Hindiya station) (Fig. 1c). The two sections in between Ramadi and Falluja Barrages did not correlate strongly, likely because the water flow is too regulated between the two barrages. For Mosul discharge station, a stretch of river located about 70 km downstream was most strongly correlated to discharge ($r = 0.79$; Fig. 1b). This is likely because the Mosul discharge station (located right at Mosul dam) is actually upstream of a second regulatory dam (Adamo and Al-Ansari 2016). This extra layer of human management could be why river extents tested within the area of the regulatory dam and the city of Mosul itself did not correlate well with river discharge. We used river-surface area in the designated areas to look at general trends in discharge, rather than for generating specific estimates.

Droughts

Haditha reservoir underwent a 72% decline in surface area between May 2007 and October 2009 (Fig. S6d). This

Fig. 3 Surface area of Haditha (a) and Mosul (b) reservoirs. Haditha estimates are based on Landsat and altimetry data; Mosul only on Landsat. Lines of significance are two standard deviations from the mean. Background colors indicate: red = conflict; gray = upstream dam-building; tan = droughts. Close-ups of significant changes in water supply are provided in Fig. S6

occurred during a major drought, and as the upstream Keban, Ataturk, and Tabqa reservoirs declined between 4 and 11%. During the 2013–2014 drought, those same three upstream reservoirs declined by 5–13%, but supplies were replenished during the following year until they were at 95–111% of their original pre-drought levels. Concurrently, surface area at Haditha reservoir dropped by 62% (Fig. S6e).

Conflicts

The First Gulf War, occurring between August 1990 and February 1991, saw rapid changes in lake-surface area. Between August 18–26, 1990, the Mosul reservoir lost an average of 3.3 km² of surface area per day, in total falling from 372 to 346 km² (Figs. S6a, S7a, S8a,b). In volume terms based on 1983 Mosul bathymetry, this represented a

Table 3 Main episodes of substantially high or low water supply situations, or substantial changes in water supply, along the Tigris and Euphrates

Substantially high or low lake-areas			Substantial rates of change in lake-area		
Dam	Year	Most likely cause	Dam	Year	Most likely cause
Haditha	2009	Drought	Haditha	February 1991	Conflict
Haditha	2015	Drought	Haditha	June 2014	Conflict
Mosul	Feb 1991	Conflict	Mosul	August 1990	Conflict
Mosul	March 2011	Averting dam failure	Mosul	February 1991	Conflict
Mosul	December 2015	Averting dam failure	Mosul	Spring 2011	Unknown

decline from 10.8 to 9.6 km³. During the same span of days, the downstream Lake Therthar increased at a rate of 2.73 km² day⁻¹. Over the next 5 months, Mosul reservoir continued losing surface area, at an average rate of 0.5 km² day⁻¹. Then, came another plunge: between January 25 and February 10, 1991, the reservoir lost about 3.4 km² day⁻¹ of lake-surface, for a final surface area of 215 km², and a volume of 3.3 km³. At the same time (January 17–February 10, 1991), Haditha reservoir lost an average of 2.5 km² of lake-surface per day, a loss of 21% in three weeks (Figs. S7c, S8c,d).

Between June 25 and July 11, 2014, a time consumed by both militant battles and drought, Haditha reservoir lake-surface area declined at a rate of 2.0 km² day⁻¹, a substantial rate of loss only otherwise exceeded by the drainage of Haditha Dam in February, 1991 (Fig. S7d). Around the same time, flooding was clearly visible between the towns of Falluja and Abu Ghraib. The land area affected had only 3.8 km² water-surface on February 26, but increased to 92.6 km² by the next available non-cloudy data point, May 17 (Fig. S9). By June 2, the wet area receded to 37.0 km², then 11.9 km² by June 18, and remained below that point for the rest of the year.

Other instances of substantial water loss or gain

Mosul reservoir experienced an increase of 4.0 km² day⁻¹ in surface area between March 29 and April 14, 2011, and then of 2.2 km² day⁻¹ between April 14 and May 16, 2011 (Fig. S7b). Mosul reservoir also reached substantially low levels in March 2011 and December 2015, at a time when

wet-season management of the dam was changing to avoid its failure (Fig. S6b,c).

Relations to other reservoirs

By examining scatter plots of the major upstream reservoirs versus downstream Mosul and Haditha reservoirs (Fig. 5; Table 4), we found that same-day surface areas were typically positively correlated within individual years. These high correlations ($r \geq 0.85$) suggest that within a single year, regional climate conditions drove water availability evenly over all reservoirs: if one reservoir increased, the same driving factor caused an increase in the others. There are a few exceptions with poor or negative correlations (2002; 2011 and 2015 between Haditha and all upstream reservoirs, and especially so with Syrian reservoirs). From year to year, the slopes of the Mosul-Turkish reservoir comparisons were remarkably similar, although after 2002, they became flatter (Fig. 5a). Yearly Euphrates correlations were more prone to high scatter.

DISCUSSION

Seasonality

In general, both Mosul and Haditha reservoirs followed a steady pattern of spring flooding-induced peaks, followed by contraction over the summer and fall. The pattern was steadier for Mosul reservoir than Haditha, likely because it had fewer and smaller dams upstream. Mosul reservoir reached peak surface area most commonly in June, and occasionally as late as July or as early as May. These peaks diminished either due to downstream releases, evaporation, or irrigation usage until the lake reached its smallest surface area generally in October, sometimes in November or December. Our results showed no evidence that the timing of the June peak size had changed.

Yearly peaks at Haditha reservoir were not consistent, even during non-drought times. The peaks occurred as early as February, and sometimes as late as November. The yearly timing of the smallest lake size was equally varied. It appears releases from upstream dams regulate lake-area as well as seasonal precipitation.

Droughts and conflicts

When lake-surface area changed very quickly and substantially, the most closely associated event was often conflict; but if substantial changes occurred over a long period of time, the associated event was usually drought or dam management (Table 4).

Fig. 4 Rates of change in reservoir lake-area of Haditha (a) and Mosul (b) reservoirs. Lines of significance are three standard deviations from the mean. Background colors indicate: red = conflict; gray = upstream dam-building; tan = droughts. Close-ups of significant rates are provided in Supplemental Fig. 4

For example, Haditha reservoir-surface area fell substantially during the three drought periods. But the median rate at which it fell ranged from -0.35 to $0.06 \text{ km}^2 \text{ day}^{-1}$. These rates are far less extreme than rates in both Haditha and Mosul reservoirs during the first Gulf War. These Gulf War declines were so sudden they suggested a dam breach, but in fact, a UN report confirmed that dam managers had partially drained the reservoirs as a precaution in case the

dams failed during attack (Aga Khan 1991). Each drainage occurred just before the main periods of warfare: August 1990 when Iraq invaded Kuwait, and January–February 1991 when Iraq was driven out. The concurrent increase in Lake Therthar, downstream of Mosul reservoir, suggests at least some of the water released was funneled there.

At the same time, not all conflicts produced rapid changes in lake-area. One example is the U.S. invasion of

Fig. 5 Scatter plots of reservoir size, upstream sums versus Mosul (on the Tigris; **a**) and Haditha (on the Euphrates). We separated the Haditha graph by the Syrian (**b**) and Turkish (**a**) upstream dams. Only years with at least three points are shown. To maximize data-points, we included only the largest reservoirs on the Euphrates (Keban, Karakaya, Ataturk, and Tabqa). Using all Euphrates reservoirs resulted in identical plots, but with fewer points

Iraq between March 19 and May 1, 2003, and subsequent occupation and battles, one of the most destructive of which occurred at Falluja near Haditha (Traub 2006). Rates of change in the Haditha lake-surface ranged from a loss of $0.80 \text{ km}^2 \text{ day}^{-1}$ to a gain of $0.99 \text{ km}^2 \text{ day}^{-1}$ between March 2003 and March 2006. Mosul reservoir also exhibited stable rates of lake-surface change throughout spring 2003, based on available data. The precautions taken prior to combat during the first Gulf War are not in

evidence. We speculate that it was harder to make plans for a conflict-driven by another power's decisions, rather than one's own instigations.

The same steadiness in water supply is true of the August 8, 2014 militant attack on Mosul Dam, and the fight to retake it a week later (Adamo and Al-Ansari 2016). In spite of bombardments and chaotic availability of dam workers (Adamo and Al-Ansari 2016), the rates of change in lake-surface area were not substantial. The greatest rate of loss in lake-area, $1.16 \text{ km}^2 \text{ day}^{-1}$, occurred between August 12 and September 13. Mosul reservoir has experienced sharper rates of decrease during peaceful summers (Fig. 4b). The median rate of lake-area change, based on the six usable Landsat 8 images retrieved between June 9 and September 13, was $-0.46 \text{ km}^2 \text{ day}^{-1}$. Exactly 24 years before these battles, Mosul reservoir was experiencing its sharpest rate of surface area decline preparatory to the first Gulf War; yet the clashes of 2014 raged without any of the same preparations, perhaps pointing either to the surprise of the attack, or a change in strategy by dam managers.

Some recent flare-ups in Iraq featured heavy fighting in Falluja and Ramadi between January 2014 and June 2016 (Cockburn 2014; Milner 2014; BBC 2015; BBC 2016; BBC 2017; Fig. 1c). These cities both have a barrage controlling water flow on the Euphrates. The battles featured airstrikes and the exchange of barrage control between government and militant forces multiple times. Despite this, the actual military campaigns (January 2014, September 2014, May 2015, January 2016, May–June 2016) were not associated with substantial changes in the river-area upstream of Ramadi Barrage, downstream of Falluja barrage, or between the two barrages.

Reportedly, militants manipulated the Ramadi and Falluja Barrages to block water from continuing downstream along the Euphrates on multiple occasions. One report suggested that they diverted water at Ramadi Barrage in June 2015 through the Warar Canal into Lake Habbaniya (Gander 2015). However, no substantial increase in these water bodies was detected at this time. The surface area of Lake Habbaniya fell steadily throughout 2015 until September, broken by a slight uptick in June, but not enough to lastingly alter the trajectory. Other reports of barrage manipulations were met with similarly routine water-surface conditions. Perhaps the manipulations were short-lived and contained between Landsat overpasses. Some only lasted days (von Lossow 2016).

The sole evidence we found on Landsat imagery of militant water manipulations was the flooded land between Falluja and Abu Ghraib during spring, 2014. This coincided with closure of Falluja Barrage. The surfeit of water removed from the Euphrates rushed into an irrigation canal which burst its banks (von Lossow 2016).

Table 4 Correlations between dam lake sizes. Correlations after the Syrian Civil War began are outlined in red. R refers to the correlation; n refers to the number of dates for each year on which usable images were available for all reservoirs. *These correlations rounded up to 1

Year	Haditha + Turkish upstream dams		Haditha + Syrian upstream dams		Syrian + Turkish dams, Euphrates		Haditha + all upstream dams		Mosul + Turkish upstream dams	
	<i>r</i>	<i>n</i>	<i>r</i>	<i>n</i>	<i>r</i>	<i>n</i>	<i>r</i>	<i>n</i>	<i>r</i>	<i>n</i>
2000			0.987	4					0.999	4
2001			0.899	4		1		1		
2002	− 0.590	5	0.753	5	− 0.742	4	0.925	4	0.992	3
2006	1.00*	3	0.934	4	0.992	3	0.999	3	0.968	4
2007	0.964	6	0.944	5	0.973	5	0.939	5	0.995	3
2009			0.978	4		2		2	0.961	6
2011	− 0.410	3	− 0.540	3	0.989	3	− 0.431	3	0.564	6
2013	0.931	10	− 0.158	11	− 0.230	10	0.892	10	0.775	8
2014	0.853	5	0.063	11	− 0.262	5	0.959	5	0.714	5
2015	0.137	6	− 0.792	8	− 0.627	6	− 0.604	6		
2016	0.984	5	0.353	7	0.420	4	0.965	4	0.972	6

The Iraqi government also manipulated water for conflict. A substantial decline of Haditha reservoir occurred during June and July, 2014, alongside a substantial increase in river area downstream of Haditha Dam. The government planned this mass release to swell the Euphrates River and impede militants, fresh from victories across Iraq, from attacking Haditha (Rubin and Nordland 2014). To avoid further flooding near Falluja and Abu Ghraib, the excess water was presumably diverted into Lake Habbaniya, and from there into Lake Razaza (Fig. 1c). Lake Razaza increased in surface area from 329 to 579 km² between June 18 and August 5, 2014.

Upstream dams

Several dams were built in the 1990s. Comparing pre-1992 to post-2000 lake-surface areas, we found that Mosul lake-area remained constant throughout the constructions (Fig. 3b). Haditha reservoir likewise did not substantially decline in size directly following dam-building, but afterwards, droughts had a disproportionate effect on Haditha compared to upstream reservoirs. This implies that droughts combined with water management affect the farthest downstream dam the most. Iraqi marshes situated at the farthest downstream point of the Tigris and Euphrates also contracted during droughts (Al-Handal and Hu 2014).

Reservoir sizes on the same river were generally correlated within a single year. Exceptions sometimes occurred when snowmelt expanded the upstream reservoirs, while evading Haditha; or when a delayed pulse expanded Haditha late in the summer while the other reservoirs

contracted. Syrian dams also did not follow the patterns of other dams after the Syrian Civil War began in 2011 (Fig. 5b). Either Haditha/Syrian reservoirs were no longer correlated, or they were negatively correlated, meaning that as Syrian dams expanded, Haditha contracted (Table 4). This perhaps reflects the weakening of Iraqi-Syrian agreements for sharing Euphrates water as other issues took precedence (UN-ESCWA and BGR 2013). As of February 2013, all three Syrian Euphrates dams were controlled by militants renowned for flouting international conventions (von Lossow 2016).

Managing for dam failure

The sustained decline in median Mosul reservoir levels after 2006 probably reflects the deliberate decrease in volume held by the reservoir to deal with potential dam failure (Adamo and Al-Ansari 2016; Filkins 2017). This potential failure is also behind dam managers releasing water over the winter in anticipation of incoming snowmelt (Filkins 2017). Perhaps this explains why the lake-area shrank to notably low levels in March 2011 and December 2015. The reservoir area remained low for a brief span of time (unlike the prolonged depressions seen in Haditha during droughts) and rebounded following snowmelt.

Uncertainties

There is one substantial change in lake-area which we could not account for: the sharp increase experienced by Mosul reservoir between March 29 and May 16, 2011. Snowmelt might account for some of the increase, but no

other snowmelt period was similar. The temperatures in spring 2011 were not unusually warm in the Mosul Dam watershed compared to other years (Fig. S10). We did not have evidence that downstream water release from Mosul Dam was cut off in 2011; nor that upstream reservoirs suddenly lost surface area; nor that conflict might have driven these high increases in the Mosul reservoir. There was no outright civil war occurring in Iraq at the time. The Syrian Civil War was mostly restrained to civil disobedience and protests until July 2011, and centered around Damascus and the south of the country—far from the Tigris River border that northern Iraq and Syria share.

Reverse pathway of water to conflict

While this paper dealt exclusively with how conflict affects water resources, other scholars have addressed the converse issue: how water resources—usually a scarcity of them—can cause conflict (Link et al. 2016). This has occurred in the Tigris and Euphrates basin, for example, the Iraq-Syria troop build-ups following the 1975 filling of the Tabqa Dam (Beschoner 1992). At the same time, there is a growing field studying the extent to which water-based disputes can lead to cooperation (Bring and Sjöberg 2017).

Many frameworks have been proposed to describe pathways and outcomes by which water scarcity leads to conflict or cooperation (Link et al. 2016). In the same way, in this paper we have shown that the mechanisms by which conflict affects water resources are also very varied. Decisions to manipulate water resources as a result of conflict can come during actual military action, or pre-empt it. Not all tensions between transboundary rivers lead to conflict; neither does all conflict leave a clear imprint on water resources. The links between water and conflict are often specific to the particular context.

CONCLUSIONS

Our results suggest that conflict was associated with most rapid fluctuations in reservoir-surface area, but not with the greatest absolute changes (Video S1). This is evident at Haditha reservoir, and may come to affect Mosul reservoir if proposed upstream projects, such as Turkey's Ilisu Dam, are completed (UN-ESCWA and BGR 2013). Reservoir-surface areas were generally correlated yearly along a single river, with the exception of Syria's since the onset of the Syrian conflict. Broader climate factors seemed to affect all these lakes together. We recommend further monitoring of the water situation on these rivers, as ongoing wars, population increases, and possible declines in future water supply due to climate change may increase scarcity. Satellite monitoring could contribute to an

international framework for peaceful adjudication of water resources, and for monitoring the effects of drought, conflict, and management on water resources.

Acknowledgments The authors would like to acknowledge Nadhir Al-Ansari of Luleå University of Technology for his helpful email communications while researching and writing this paper.

REFERENCES

- Adamo, N., and N. Al-Ansari. 2016. Mosul Dam full story: Safety evaluations of Mosul Dam. *Journal of Earth Sciences and Geotechnical Engineering* 6: 185–212.
- Aga Khan, S. 1991. *Report to the Secretary-General dated 15 July 1991 on humanitarian needs in Iraq prepared by a mission led by Sadruddin Aga Khan*. United Nations, Document S/22799, New York, USA.
- Al-Handal, A., and C. Hu. 2014. MODIS observations of human-induced changes in the Mesopotamian Marshes in Iraq. *Wetlands* 35: 31–40. <https://doi.org/10.1007/s13157-014-0590-6>.
- Altinbilek, D. 2004. Development and management of the Euphrates-Tigris basin. *International Journal of Water Resources Development* 20: 15–33. <https://doi.org/10.1080/07900620310001635584>.
- Ashouri, H., K. Hsu, S. Sorooshian, D. Braithwaite, K. Knapp, L. Cecil, B. Nelson, and O. Prat. 2015. PERSIANN-CDR: Daily precipitation climate data record from multi satellite observations for hydrological and climate studies. *Bulletin of the American Meteorological Society* 96: 69–83. <https://doi.org/10.1175/BAMS-D-13-00068.1>.
- BBC. 2015. Ramadi battle: IS prepares to defend seized Iraqi city. Retrieved 1 August, 2016, from <http://www.bbc.com/news/world-middle-east-32791448>.
- BBC. 2016. IS conflict: Iraqi forces “retake most” of Falluja. Retrieved 21 June, 2017, from <http://www.bbc.com/news/world-middle-east-36557092>.
- BBC. 2017. Islamic state and the crisis in Iraq and Syria in maps. Retrieved 20 June, 2017, from <http://www.bbc.com/news/world-middle-east-27838034>.
- Beschoner, N. 1992. *Water and instability in the Middle East*. London: Adelphi Papers, Brassey's Ltd.
- Bjerklie, D., S. Lawrence Dingman, C. Vorosmarty, C. Bolster, and R. Congalton. 2003. Evaluating the potential for measuring river discharge from space. *Journal of Hydrology* 278: 17–38. [https://doi.org/10.1016/S0022-1694\(03\)00129-X](https://doi.org/10.1016/S0022-1694(03)00129-X).
- Birkett, C., and B. Beckley. 2010. Investigating the performance of the Jason-2/OSTM radar altimeter over lakes and reservoirs. *Marine Geodesy* 33: 204–238.
- Bring, A. and E. Sjöberg. 2017. Complex climate effects on cooperation and disputes in transboundary river basins. University of Utah, Department of Economics Working Paper No. 2017-2, Salt Lake City, Utah.
- Cockburn, P. 2014. The harm before the storm: army battles to expel resurgent al-Qa'ida from Iraq. Retrieved 21 June, 2017, from <http://www.independent.co.uk/news/world/middle-east/the-harm-before-the-storm-army-battles-to-expel-resurgent-al-qa-ida-from-iraq-9040155.html>.
- Congalton, R., and K. Green. 2009. *Assessing the accuracy of remotely sensed data: Principles and practices*, 2nd ed. Boca Raton: Taylor & Francis Group.
- Créteaux, J., W. Jelinski, S. Calmant, A. Kouraev, V. Vuglinski, M. Bergé-Nguyen, M. Gennero, F. Nino, et al. 2011. SOLS: A lake

- database to monitor in the Near Real Time water level and storage variations from remote sensing data. *Advances in Space Research* 47: 1497–1507. <https://doi.org/10.1016/j.asr.2011.01.004>.
- Eklund, L., A. Persson, and P. Pilesjö. 2016. Cropland changes in times of conflict, reconstruction, and economic development in Iraqi Kurdistan. *Ambio* 45: 78–88. <https://doi.org/10.1007/s13280-015-0686-0>.
- Filkins, D. 2017. Before the flood. Retrieved 20 January, 2017, from <http://www.newyorker.com/magazine/2017/01/02/a-bigger-problem-than-isis>.
- Gander, K. 2015. Isis use water as a weapon in Iraq, by shutting dam on the Euphrates River. Retrieved 2 August, 2016, from <http://www.independent.co.uk/news/world/middle-east/isis-use-water-as-a-weapon-in-iraq-by-shutting-dam-on-the-euphrates-river-10295763.html>.
- Gao, B. 1996. NDWI—A normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment* 58: 257–266. [https://doi.org/10.1016/S0034-4257\(96\)00067-3](https://doi.org/10.1016/S0034-4257(96)00067-3).
- Hui, F., B. Xu, H. Huang, Q. Yu, and P. Gong. 2008. Modelling spatial-temporal change of Poyang Lake using multitemporal Landsat imagery. *International Journal of Remote Sensing* 29: 5767–5784. <https://doi.org/10.1080/01431160802060912>.
- Issa, I. 2015. Sedimentological and hydrological investigation of Mosul Dam Reservoir. PhD Thesis. Luleå, Sweden: Luleå University of Technology.
- Kassim, T., H. Al-Saadi, and R. Farhan. 2006. Vertical distribution of phytoplankton in Habbaniya Lake, Iraq. *Marsh Bulletin* 1: 19–31.
- Klein, I., A. Dietz, U. Gessner, A. Galayeva, A. Myrzhakmetov, and C. Kuenzer. 2014. Evaluation of seasonal water body extents in Central Asia over the past 27 years derived from medium-resolution remote sensing data. *International Journal of Applied Earth* 26: 335–349. <https://doi.org/10.1016/j.jag.2013.08.004>.
- Klein, I., U. Gessner, A. Dietz, and C. Kuenzer. 2017. Global WaterPack—A 250 m resolution dataset revealing the daily dynamics of global inland water bodies. *Remote Sensing of Environment* 198: 345–362. <https://doi.org/10.1016/j.rse.2017.06.045>.
- Link, P., J. Scheffran, and T. Ide. 2016. Conflict and cooperation in the water-security nexus: a global comparative analysis of river basins under climate change. University of Hamburg, Working Paper CLISEC-31, Hamburg, Germany.
- MacQuarrie, P. 2004. Water security in the Middle East: Growing conflict over development in the Euphrates-Tigris Basin. PhD Thesis. Dublin, Ireland: Trinity College.
- McFeeters, S.K. 1996. The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing* 17: 1425–1432. <https://doi.org/10.1080/01431169608948714>.
- Milner, A. 2014. Mosul Dam: Why the battle for water matters in Iraq. Retrieved 17 June, 2017, from <http://www.bbc.com/news/world-middle-east-28772478>.
- Moridnejad, A., N. Karimi, and P. Ariya. 2015. Newly desertified regions in Iraq and its surrounding areas: Significant novel sources of global dust particles. *Journal of Arid Environments* 116: 1–10. <https://doi.org/10.1016/j.jaridenv.2015.01.008>.
- Müller, M., J. Yoon, S. Gorelick, N. Avisse, and A. Tilmant. 2016. Impact of the Syrian refugee crisis on land use and transboundary freshwater resources. *Proceedings of the National Academy of Sciences of the United States of America* 113: 14932–14937. <https://doi.org/10.1073/pnas.1614342113>.
- National Aeronautics and Space Agency. 2008. Ocean Surface Topography Mission/Jason-2 Mission Overview. Retrieved 29 June, 2017, from https://www.nasa.gov/mission_pages/ostm/overview/index.html.
- Pekel, J., A. Cottam, N. Gorelick, and A. Belward. 2016. High-resolution mapping of global surface water and its long-term changes. *Nature* 540: 418–422. <https://doi.org/10.1038/nature20584>.
- Rubin, A. and R. Nordland. 2014. Sunni militants advance toward large Iraqi dam. Retrieved 4 July, 2017, from <https://www.nytimes.com/2014/06/26/world/middleeast/isis-iraq.html>.
- Saleh, D. 2010. Stream gage descriptions and streamflow statistics for sites in the Tigris River and Euphrates River Basins, Iraq. U.S. Geological Survey, Data Series 540, Reston, Virginia.
- Traub, J. 2006. *The Best Intentions: Kofi Annan and the UN in the Era of American World Power*, 1st ed. New York: Farrar, Straus and Giroux.
- Trigo, R., C. Gouveia, and D. Barriopedro. 2010. The intense 2007–2009 drought in the Fertile Crescent: Impacts and associated atmospheric circulation. *Agricultural and Forest Meteorology* 150: 1245–1257. <https://doi.org/10.1016/j.agrformet.2010.05.006>.
- UN-ESCWA and BGR (United Nations Economic and Social Commission for Western Asia, Bundesanstalt für Geowissenschaften und Rohstoffe). 2013. Inventory of Shared Water Resources in Western Asia. Beirut, Lebanon.
- United Nations Environment Programme. 1999. The Kosovo conflict—Consequences for the environment and human settlements. Nairobi, Kenya.
- United Nations Environment Programme. 2003. Afghanistan: Post-Conflict Environmental Assessment. Nairobi, Kenya.
- von Lossow, T. 2016. Water as weapon: IS on the Euphrates and Tigris. Stiftung Wissenschaft und Politik, Comments 3, Berlin, Germany.
- Vörösmarty, C., P. McIntyre, M. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, S. Bunn, et al. 2010. Global threats to human water security and river biodiversity. *Nature* 468: 334–334. <https://doi.org/10.1038/nature09549>.
- Yamazaki, D., M. Trigg, and D. Ikeshima. 2015. Development of a global ~ 90 m water body map using multi-temporal Landsat images. *Remote Sensing of Environment* 171: 337–351. <https://doi.org/10.1016/j.rse.2015.10.014>.
- Zakaria, S., N. Al-Ansari, M. Ezz-Aldeen, and S. Knutsson. 2012. Rain water harvesting and supplemental irrigation at Northern Sinjar Mountain, Iraq. *Geoscience Research* 3: 100–108.

AUTHOR BIOGRAPHIES

Mejs Hasan (✉) is a recent Ph.D. graduate from the University of North Carolina, Chapel Hill. Her research interests include monitoring water supply through satellite imagery.
Address: Department of Geological Sciences, UNC, 104 South Road, Mitchell Hall room 309, Campus Box #3315, Chapel Hill, NC 27599-3315, USA.
e-mail: mejs@live.unc.edu; mejs.unc@gmail.com

Aaron Moody is an Associate Professor in Geography at the University of North Carolina, Chapel Hill. His research interests include ecology and remote sensing.

Address: Department of Geography, UNC, Carolina Hall room 211, Campus Box #3200, Chapel Hill, NC 27599-3200, USA.
e-mail: aaronm@email.unc.edu

Larry Benninger is a Professor in Geology and Marine Sciences at the University of North Carolina, Chapel Hill. His research interests include low-temperature geochemistry and sedimentary processes.

Address: Department of Geological Sciences, UNC, 104 South Road, Mitchell Hall room 323, Campus Box #3315,, Chapel Hill, NC 27599-3315, USA.
e-mail: lbenning@email.unc.edu

Heloise Hedlund is a recent graduate in Geography and Environmental Science at the University of North Carolina, Chapel Hill.

Address: Department of Geography, UNC, Carolina Hall, Campus Box #3200, Chapel Hill, NC 27599-3200, USA.
e-mail: heloisee@live.unc.edu