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Connecting changes in Euphrates River flow to hydropattern of the Western Mesopotamian Marshes

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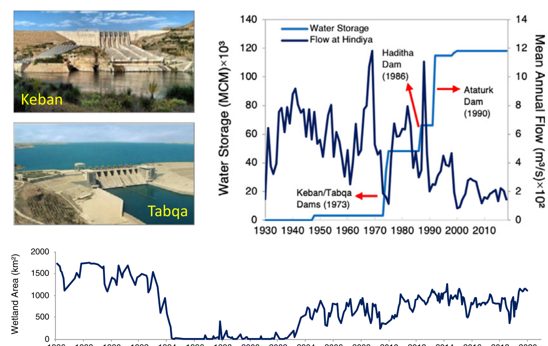
HIGHLIGHTS

- Mesopotamian Marshlands restoration relies on Euphrates River (ER) flow (Q).
- Upstream dams have severely reduced ER Q and altered river and wetland hydropattern.
- Post-restoration, western Al-Hammar marsh area is 47% lower than before drainage.
- 70 m^3/s of canal inflow required to restore 1000 km^2, equivalent to 200 m^3/s ER Q
- River-marsh connection critical for restoration of unique social-ecological system

GRAPHICAL ABSTRACT



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ABSTRACT

The Mesopotamian Marshlands are the largest wetland system in the Middle East. Historically, these marshes served as the floodplains of the Tigris and Euphrates rivers, and they are currently connected to these rivers via surface water feeder canals. Historically, the Mesopotamian marshes received consistent flood pulses during the spring season from March to May. In recent decades, however, several large dams have been constructed in the Tigris and Euphrates basins for irrigation purposes and power generation, severely altering the flow regime, which along with other direct anthropogenic activities, has severely degraded the marsh ecosystem. This work quantifies changes in the riverine flow regime and how they have affected the hydro-pattern of the western Mesopotamian marshes (focusing on the western Al-Hammar marsh) and describes the role of hydrological drivers that are important for marsh restoration. The total area of the Al-Hammar marshes has been reduced from an average of 2800 km^2 before 1970 to a minimum of 240 km^2 in recent decades, concomitant with reductions in annual average Euphrates River flow (at Hit) from 967 to 602 m^3/s and marked flow regime alteration. While climate warming and reduced precipitation were observed in the basin, changes in the fundamental precipitation-flow relationship implicate infrastructural changes (upstream dams) as the primary reason for these changes. This analysis quantified how flow variability under historic and contemporary conditions have affected wetland area and other hydro-pattern characteristics and suggests that at an annual average of least 70 m^3/s of water deliveries to the western Mesopotamian marsh are required to restore 1000 km^2 of wetland area. Our hope is that this focus on the river-marsh connection will help inform predictive models and scenario analysis for restoration of this unique social-ecological system.

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1. Introduction

The Mesopotamian Marshlands (MM) are the largest freshwater wetland ecosystem in the Middle East, covering 15,000 km^2 to 20,000 km^2 of permanent and seasonal wet habitats (water, vegetation, and mudflats) during the flood season (Alwash et al., 2004; Al-Hilli et al., 2009; Chen et al., 2012). These vast marshes include the Al-Hawizeh, Al-Qurnah (Central), and Al-Hammar Marshes, which are fed by the Tigris and Euphrates Rivers (Fig. 1). The MM historically served as a critical ecological corridor between Africa and Eurasia

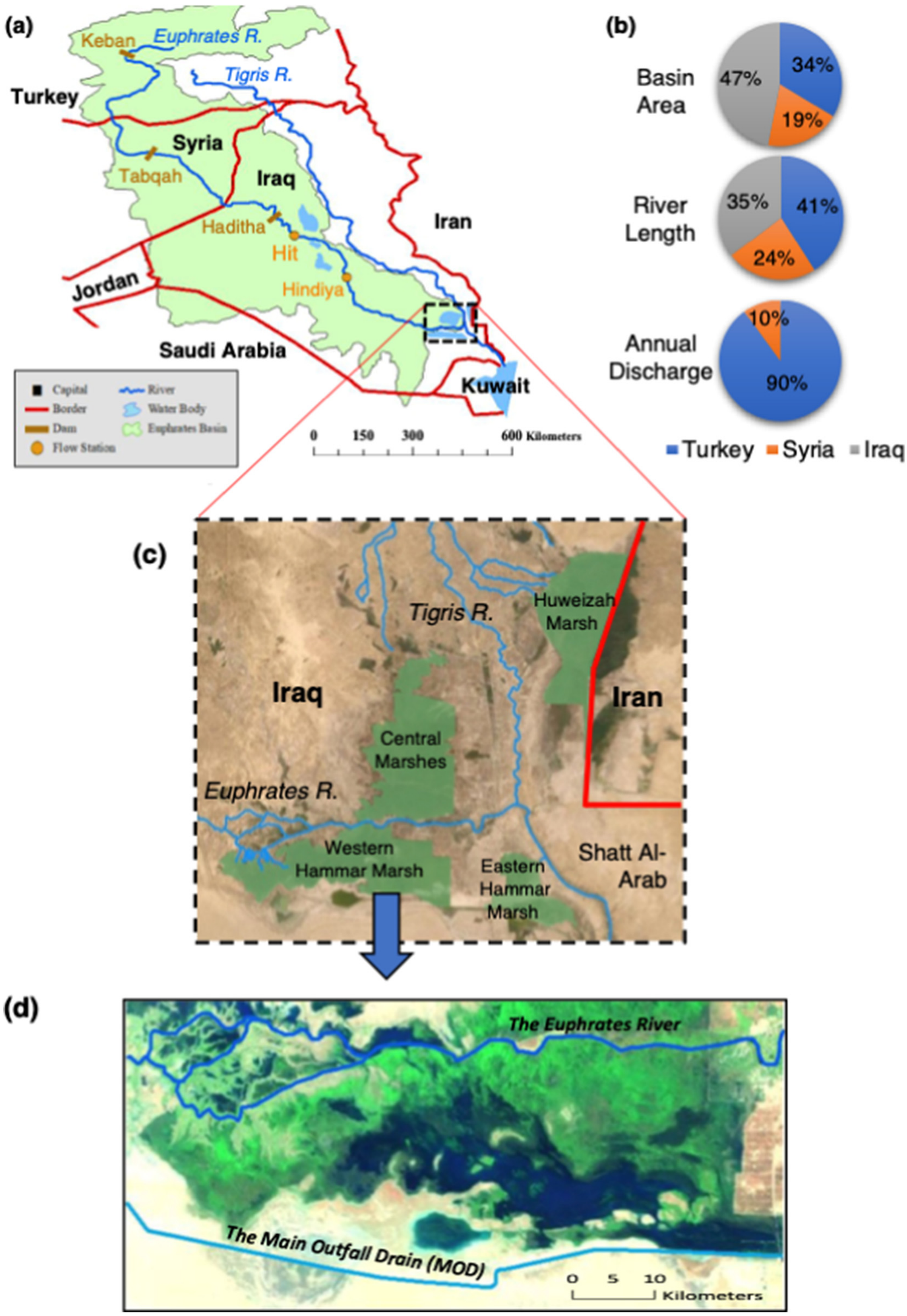

Fig. 1. Study site: (a) the Euphrates River basin; (b) portion of Euphrates River basin area, river length, and flow generation in each riparian country; (c) regional layout of the Mesopotamian Marshes; and (d) boundary of the Western Hammar marsh, referred to as the Western Mesopotamian Marshes (WMM) showing location of feeder canals and the main outfall drain (MOD).

(UNEP, 2006) and supported very high biodiversity, including numerous threatened species, especially birds and reptiles (Garstecki and Amr, 2011). The MM have also served as the home of ancient civilizations (Alwash et al., 2004; Partow and Jaquet, 2005). Until recently, the marshes supported the Madan people, commonly referred to as the Marsh Arabs, descendants of the Sumerians who lived in this area as much as 5000 years ago. The Madan adapted and thrived in the marshlands, using reeds as building material, catching fish and hunting waterfowl, and raising water buffalo to produce milk and butter, maintaining a lifestyle illustrated in ancient Sumerian tablets (Kubba, 2011). Before 1990, there were about 500,000 Marsh Arabs in the marshlands. After the Gulf War in 1991, almost all flow of the Euphrates and Tigris Rivers was diverted away from the marshes, drying 97% of the Central Marshes, 94% of the Al-Hammar Marsh, and 65% of the Al-Hawizeh marsh (UNEP, 2006) (Fig. 2). As a consequence, nearly all aquatic flora and fauna were extirpated, and an estimated 200,000 Marsh Arabs became refugees in Iraq and Iran (Partow and Jaquet, 2005).

Since 2003, restoration efforts have sought to return water to the western Mesopotamian marshes (WMM) (specifically the western Al-Hammar marsh), resulting in the inundation of wide areas of the

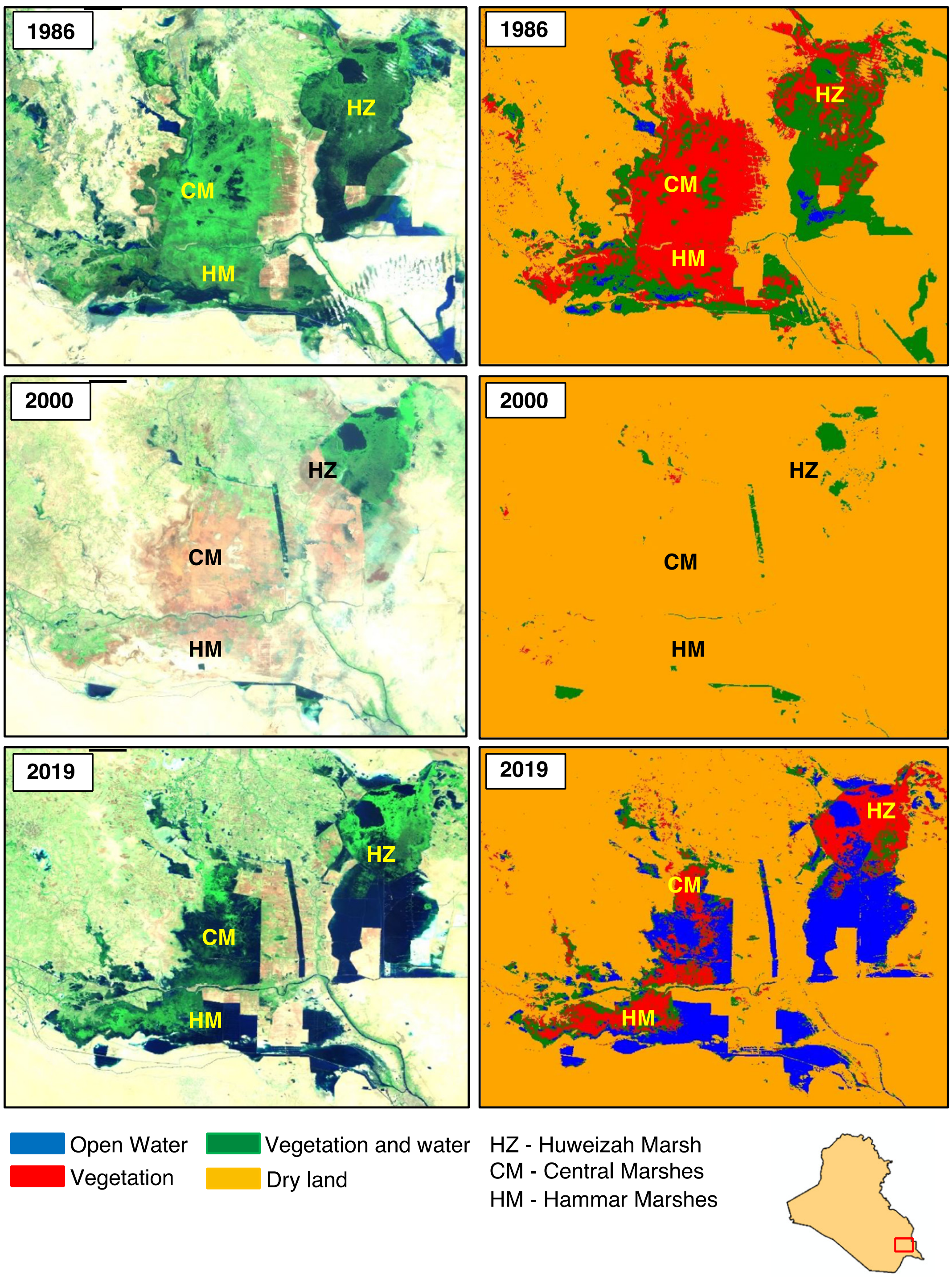

Fig. 2. Satellite images (left) and classification (right) of the Mesopotamian Marshes for three different periods: pre-drainage (May 1986), desiccation (May 2000), and post-restoration (September 2019).

WMM and a conversion of many desiccated and agricultural lands back to their original state as marshland (UNEP, 2006). Overall, hydrological restoration has been successful in supporting the return of native flora, which in turn provide habitat for many of species of fish, birds, and mammals. For example, 159 bird species have returned since reflooding, including 34 of species conservation concern and 8 globally threatened species (Salim et al., 2009). Despite these successes, restoration has been constrained by limited water availability in the Euphrates River. Historic and ongoing reduction in Euphrates River flow has led to a decreasing volume of water being delivered to the WMM via "feeder canals". Consequently, the restoration of the WMM is primarily dependent on the rate and pattern of Euphrates River flow, which is affected by climate and human modifications across the watershed.

The watersheds of the Euphrates basins include, from upstream to downstream, Turkey, Syria, and Iraq (Fig. 1a). The majority of flow in the Tigris and Euphrates Rivers comes from precipitation in Turkey (Medzini and Wolf, 2006), which receives an average of 1000 mm of rainfall per year, compared to 300 mm and 150 mm in Syria and Iraq, respectively (Medzini and Wolf, 2006). The management and development of the Tigris and Euphrates Rivers has greatly expanded in all three riparian countries in recent decades to meet increasing human demands, such as agricultural, domestic, and industrial water use. This work focuses on the Euphrates River, which is the main water source for the WMM that serve as the Euphrates River floodplain in the lower basin. The Euphrates is the third largest river in the Middle East, with total basin area of 444,000 km^2 (Klaphake et al., 2005; Al-Ansari, 2016). Iraq accounts for 47% of the basin area but is estimated to contribute close to 0% of the river's annual discharge (Klaphake et al., 2005; Hager and Regime, 1990). In contrast, Turkey, with 34% of the basin area, provides approximately 90% of the annual discharge, and Syria, with 19% of the basin area, contributes approximately 10% (Fig. 1b) (Klaphake et al., 2005). The mean annual discharge of the Euphrates River at Hit is 1000 m^3/s (Klaphake et al., 2005) and varies widely (from <200 m^3/s to >2000 m^3/s over the period of record) depending on the magnitude and timing of precipitation in upstream countries (UN-ESCWA and BGR, 2013). Iraq thus derives most of its fresh water of the Euphrates River from Turkey and Syria, making it a tremendously vulnerable downstream user. Iraq mainly uses this fresh water for irrigation, hydropower, domestic use, and more recently to restore flow to the WMM (Fig. 1d) (Hager and Regime, 1990; Albarakat et al., 2018).

Despite its position as the final consumer of Euphrates River water, Iraq was the first of the riparian countries to construct water control structures, including the Hindiya barrage in 1913 and the Ramadi barrage in 1950 (Hager and Regime, 1990). Since the 1970s, however, the number of dam construction projects and reservoir operations have increased greatly in all three riparian countries. The result has been changes in the flow regime, flood patterns, and annual mean flow of the Euphrates River, with significant negative impacts on the ecology of the basin and especially the downstream marshes (Mohamed et al., 2012; Almaarofi, 2015). In 1973–1975, the Keban dam in Turkey and the Tabqa dam in Syria were both operated, and their reservoirs filled (Fig. 3a) (UN-ESCWA and BGR, 2013; Medzini and Wolf, 2006). As a result, flow in the Euphrates River at the Iraq-Syria border dropped from 920 m^3/s to 197 m^3/s in 1975 (Medzini and Wolf, 2006). In addition to this severe reduction in flow magnitude, the reservoirs have had more active storage, and their operation has shifted the flow of the Euphrates River from natural, pulsed regime to a more steady, regulated flow (Fig. 3b).

In 1973 Syria also implemented the Euphrates Valley Project to irrigate 640,000 ha, generate electricity, and regulate seasonal flooding (Klaphake et al., 2005). In 1992, Turkey implemented the Southeastern

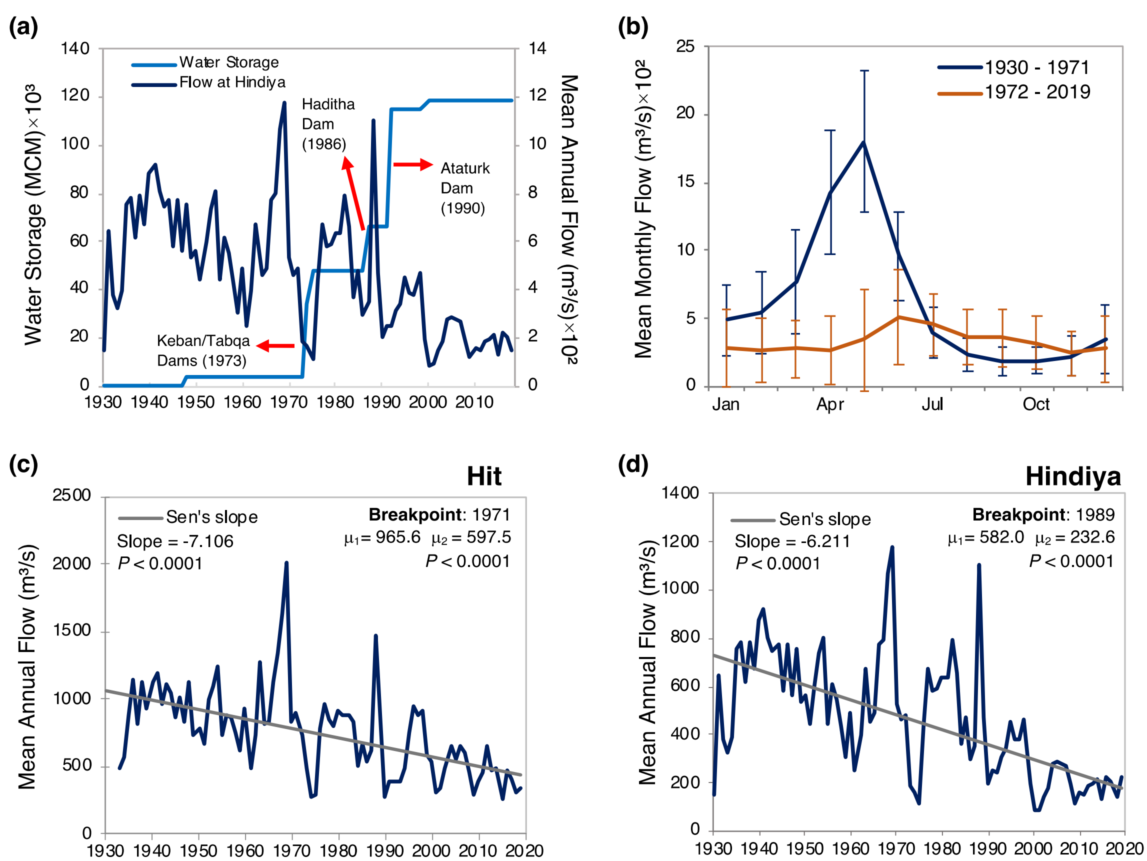

Fig. 3. Hydrological changes in the Euphrates River from 1930 to 2019. (a) Accumulated reservoir storage in the basin plotted with mean annual flow at the Hindiya station; (b) hydrograph of the mean monthly flow at Hindiya station separated into "natural" and "regulated" flow regimes , before and after 1971, respectively; (c, d) breakpoint and trends (slope) of the mean annual flow at the Hit and Hindiya gauging stations.

Anatolia Project (GAP), which includes 21 large dams with 19 hydropower plants on the Tigris and Euphrates to irrigate about 1.7 million hectares and generate 26 billion kWh annually (Medzini and Wolf, 2006; Klaphake et al., 2005). As a result of this extensive upstream dam construction, Iraq is one of the most water stressed countries in the world (Al-Ansari, 2013; World Bank Group, 2020) and becoming even more so with changing climate and increasing upstream water use. By some estimates, the Euphrates in Iraq is in danger of running completely dry by 2040 (Al-Ansari, 2013).

Given these extreme changes in water supply and management, the objectives of this research were to: 1) quantify changes in the flow regime of the Euphrates River; 2) identify the role of dams versus climate on these observed changes; and 3) illustrate how altered flow regimes affect the hydropattern of the WMM. Additionally, this work aimed to establish a target for the minimum Euphrates River flow necessary to inundate the WMM based on relationships built from hydroclimate and remote sensing data. We hypothesized that dam construction and water development projects have been the primary driver of changes in annual water flow and hydrologic regime, with decreasing rainfall as a secondary, but important factor. Further, we expect that current Euphrates River flow rates are insufficient to support restoration of this vital ecological, social, and cultural resource. By testing these hypotheses, this study significantly advances our understanding of the major drivers of disturbance and recovery in this globally important social-ecological system and identifies specific targets for improved restoration outcomes.

2. Methods

2.1. Study area

The western Mesopotamian marsh (WMM) is situated south of the Euphrates River in Al-Nasiriyah and is fed by canals from the river into the marsh (Fig. 1d). Historically, the WMM had a total area of 3000 km^2 (Partow, 2001). The current size of the WMM is approximately 1200 km^2 of frequently inundated area, but this area varies widely from season to season (Chen et al., 2012). The main cover classes of the WMM include water, mudflats, and herbaceous vegetation, which consists of both seasonal and permanent marshes. The marsh is mainly composed of reeds, grasses, and other floating and submerged vegetation, which serve as nursery areas for many wildlife species (Patience and Klemas, 1993). *Phragmites australis* (common reed), *Typha domingensis* (cattail) and *Schoenoplectus litoralis* are dominant within the marsh, while the upland border consists mostly of shrubs, such as *Tamarix brachystichas* and *T. ramosissima* (Alwan, 2006) and agricultural plantations of date palms. Additionally, other aquatic vegetation species are common species within the marsh, such as hornwort (*Ceratophyllum demersum*), eel grass (*Vallisneria* sp.) and pondweed (*Potamogeton lucens spp.* (Al-Ansari et al., 2012). In the 1980s, portions of the WMM were drained for oil exploration, and the path of the Euphrates River was changed via construction of levees. Taken together, these changes caused the WMM to be separated into two distinct sections: the eastern and the western Al-Hammar marshes (Fig. 1d). Critically, the WMM dried up entirely for the period from 1992 to 2003 after flow diversion, extirpating nearly all flora and fauna, as well as the Marsh Arabs, who fled.

Since April 2003, the WMM has been restored by delivering water from the Euphrates River via feeder canals, as well as from the Main Outfall Drain (MOD) via the Al-Kamissyah Canal since 2010. The MOD is the largest agriculture drainage water project in Iraq and discharges about 200 m^3/s of brackish water into the Arabian Gulf (Engineering Consulting Bureau, 2010). A portion of this flow has been used to hydrate the WMM to compensate for the ongoing decline in Euphrates River flow. The WMM has also experienced massive human modifications (i.e. dikes and drainage networks) that severely affected marsh hydro-pattern during the active drainage period, and many of this infrastructure still exists, impeding flows and changing the water dynamic to this day. Accordingly, in some locations, uncontrolled (and unmeasured) flows from dike breaches made by the local Madan inhabitants were made to increase the duration of inundation within the WMM, attenuate drought conditions, and provide suitable habitat for marsh grasses and water buffaloes.

Despite restoration efforts, the WMM remains in the worst condition of all the Mesopotamian Marshes (Khafaji et al., 2012; Hamdani, 2014) for several reasons, including: 1) changes in Euphrates River hydrology due to upstream dam operation and reduced watershed rainfall; 2) the construction of levees and massive drainage networks in the WMM itself; and 3) severe water quality degradation due to the use of brackish water from the MOD (total dissolved solids, TDS, >10,000 mg/l in 2009) as an alternative water resource to the WMM. Additionally, rising salinity concentrations in the WMM result from high evaporation in the region (which also increases salinity in the Euphrates River) and a lack of marsh outlets, which prevents flushing of salts from the system, motivating additional study to understand how much water is needed to restore ecosystem function.

2.2. Data sources

The data used in this project includes hydrological, climate, and remotely sensed data. Hydrological data were obtained from the Iraqi Ministry of Water Resources National Center for Water Resources Management (NCWRM) and Center for Restoration Iraqi Marshes and Wetlands (CRIMW). The data from NCWRM included monthly measurements of Euphrates River flow for the Hit and Hindiya gauging stations (Fig. 1a) from 1930 to 2019, while the CRIMW included monthly measurements of the feeder canals flow of WMM from 2009 to 2019 and monthly measurements of the MOD flow from 2010 to 2019. Climate data included annual precipitation and temperature for the riparian countries obtained from the World Bank, which uses reanalysis data from 1901 to 2016 that was derived from 15 Global Circulation Models (GCMs) (World Bank Group, 2020). Remote sensing analyses used satellite data from NASA missions Landsat 5 and 7, which were obtained and analyzed using Google Earth Engine (GEE).

2.3. Hydroclimate data analysis

Hydroclimate data were analyzed using statistical analyses of homogeneity to detect significant change-points and Mann-Kendall (MK) trend tests to assess trends over time. Specifically, MK tests were used to detect monotonic trends and quantify the linear rate of change (slope), and homogeneity tests were used to detect the date of potential change-points in the means of hydroclimate data (Villarini et al., 2011; Salarijazi, 2012). The probability of detecting change-points depends on how large changes are relative to variance (Bosch and Hewlett, 1982; Zang and Liu, 2013; Pohlert, 2018). The position and significance of change-points were analyzed using Pettitt's test, a nonparametric test that requires no assumption about data distributions (Pettitt, 1979) and is applied to detect a single change-point in continuous data (Pohlert, 2018). Homogeneity and MK tests were conducted in Microsoft Excel using the XLSTAT tool (Addinsoft, 2019) and analyzed over the full period of record (1930–2019). Analyses were performed on flow data from two stations in Iraq and on rainfall and temperature data from Turkey, Syria, and Iraq to better understand the relationships between observed changes in watershed climate and Euphrates River flow. To develop precipitation-flow relationships, mean annual flow at the Hit and Hindiya stations were regressed against area-weighted annual precipitation from upstream contributing areas; these areas were also used to calculate specific discharge (i.e., flow divided by watershed area).

2.4. Remote sensing of wetland area

Two approaches were used to estimate wetland area change using remotely sensed data. The first approach extracted wetland area using a supervised classification algorithm code in the Google Earth Engine (GEE) platform. For the supervised classification, multi-temporal satellite images were classified on a per-pixel basis from 1984 to 2019 using GEE. Pre-processing steps were applied to decrease atmospheric impacts, and the GEE cloud-free algorithm (Zurqani et al., 2018) was used to build a cloud-free composite of the study area. The Classification and Regression Trees (CART) algorithm (Shelestov et al., 2017) was used to classify images by pixel, and classifiers were built from a set of training data to represent non-inundated uplands and three main wetland categories: vegetation, open water, and mixed vegetation and water. In this study, the total wetland area was defined as the sum of these three coverages. Training sites were selected based on those areas clearly identified in all sources of images. Five or more training sites for each classifier were digitized for pure pixels, which have been identified based on the hydrologic zones within the marsh's boundary as following: 1) the open water classifier was in the deep water pool (1 m or more in depth); 2) mixed vegetation and water classifiers were in the shallow water bench (5 to 50 cm deep); and 3) the vegetation classifiers were in the shallow water fringe (0 to 5 cm deep) (U.S. EPA, 2008; Hoag et al., 2014). Classification performance was assessed by calculating the overall accuracy and kappa coefficient (κ) using a confusion matrix (Gonzlez and Bitterman, 1964; Stehman, 1996).

The second approach to understanding wetland area change used the normalized difference vegetation index (NDVI) to illustrate the overall trajectories of degradation and recovery in the wetland (Ramsey et al., 2009; Ramsey et al., 2011) and qualitatively support results from the supervised classification. NDVI is used to measure aboveground biomass and primary productivity and has been applied for quantifying both terrestrial (Özyavuz, 2010; Herbei et al., 2015) and wetland vegetation (Xu et al., 2018). NDVI takes the form:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + \mathrm{R}}$$

where NIR is the near-infrared band, and R is the red band (vegetation reflects NIR and absorbs R wavelengths). The range of NDVI is from -1 to $+1$, and the vegetated surfaces tend to have positive values, while the non-vegetated surfaces, such as bare soil has zero and open water features have zero or negative values (Tuxen et al., 2008). Average NDVI was calculated for each available scene over the WMM area bounded by the largest flood extents in the pre-drainage (1984–1992) and post-restoration (2004 to 2019) periods. We also tested the ability of average NDVI to reflect changes in wetland area by regressing the two against each other. For both analyses, a total of 195 scenes were 100% available and sufficiently cloud-free to produce area estimates and NDVI values over the period from 1984 to 2019.

2.5. Hydropattern analysis

Following Poff et al. (1997), we characterized five elements of hydropattern in the WMM, including: 1) magnitude, characterized by annual median, maxima, and minima in marsh area; 2) timing, quantified as the annual dates of minimum and maximum marsh area; 3) duration, assessed as the duration in each year that wetland area was below the 25th percentile (small inundated area) and above the 75th percentile (large inundated area) in each period; 4) frequency, represented here by the number of reversals in marsh area in a year; and 5) rate of change in marsh area during the rising and falling limbs of the hydrograph. Hydropattern elements were calculated for the pre- and post-restoration periods to quantify the type and magnitude of changes between the two periods. We limited our analyses to the period from 1986 to 1992 (pre-drainage) and 2004 to 2019 (post-restoration) to avoid drainage and transitional periods; for all comparisons, the null hypothesis was that hydropattern elements were unchanged between these two periods. Hypothesis testing was conducted using R statistical software (R Core Team 2019), using a significance level (α) of 0.05. We used Shapiro-Wilks tests to check for data normality (Villasenor and Estrada, 2009) and accordingly applied either student *t*-tests or non-parametric Wilcoxon signed rank tests (Smucker et al., 2007) to assess differences in hydropattern elements between pre-drainage and post-restoration periods.

3. Results

3.1. Hydroclimate data analysis

Homogeneity tests applied over the full period of record (1930–2019) identified a statistically significant change-point in Euphrates River flow at the Hit and Hindiya gauging stations. Statistically significant change-points ($P < 0.001$) were identified in 1971 and 1989 at the Hit and Hindiya stations, respectively (Figs. 3c,d). Similarly, MK tests identified a significant decline in Euphrates River flow at both the Hit and Hindiya stations. Homogeneity tests for temperature showed significant change points in all three riparian countries in the 1990s, with increases of about 1 °C in each case (Figs. 4a-c). No significant change points in annual precipitation were detected for Turkey or Syria (Figs. 4d,e), however a significant decrease in rainfall was detected in Iraq, also in the 1990s (Fig. 4f). Mann-Kendall tests generally mirrored these findings, with significantly increasing temperature trends in all three countries (Fig. 4 a-c). However, while there was no significant trend in rainfall both in Turkey and Iraq (Figs. 7d, f), MK tests detected significant rainfall declines in Syria (Fig. 4e).

Figs. 5 shows precipitation-flow relationships for the Hit and Hindiya stations with data into separated “natural” (pre-1971) and “regulated” (post-1971) periods identified by breakpoint analysis for Hit. Notably, 1974 marks the year in which Keban and Tabqa dams were operated for the upper Euphrates basin, and these changes resulted in decreased flow and reduced flood peaks due to regulation (Fig. 3). At both stations, the natural flow regime was characterized by a relatively strong relationship between annual precipitation and flow ($R^2 = 0.45$ and 0.46 for the Hit and Hindiya stations, respectively), with slopes of 0.41 and 0.24 indicating that 41% and 24% of area-weighted watershed precipitation was realized as flow at the two stations, respectively. For context, Euphrates River flow during this time period was relatively.

high (mean annual flow of 967 and 638 m^3/s at the Hit and Hindiya stations, respectively). In contrast, the precipitation-flow relationship in the regulated era (post-1971) had much weaker correlations ($R^2 = 0.02$ for both stations) and lower slopes (0.07 and 0.05), indicating a massive reduction in water delivery and extreme shift in the Euphrates River flow regime. Mean annual flow at Hit and Hindiya in the regulated period were 605 and 330 m^3/s, respectively.

3.2. Wetland area and NDVI

Supervised classification of images for wetland area extraction was highly accurate, with overall accuracy and κ both ranging from 0.98 to 0.99 (Table 1). Time series of estimated monthly wetland area are shown in Fig. 6, along with NDVI, Euphrates River flow and the combined inflow measured from the feeder canals and the MOD. When looking at area and NDVI, three distinct periods are apparent: pre-drainage (1986–1992), desiccation (1993–2003), and post-restoration (2004–present). In the pre-drainage period, WMM area averaged 1470 km^2, with a maximum of 1744 km^2 (including an extended period of extreme flooding from 1987 to 1989). Minimum wetland area was 1077 km^2 in 1992, but seasonal lows in late summer (August to September) were experienced in most years. Mean Euphrates River flow at the Hindiya station was 400 m^3/s during this period.

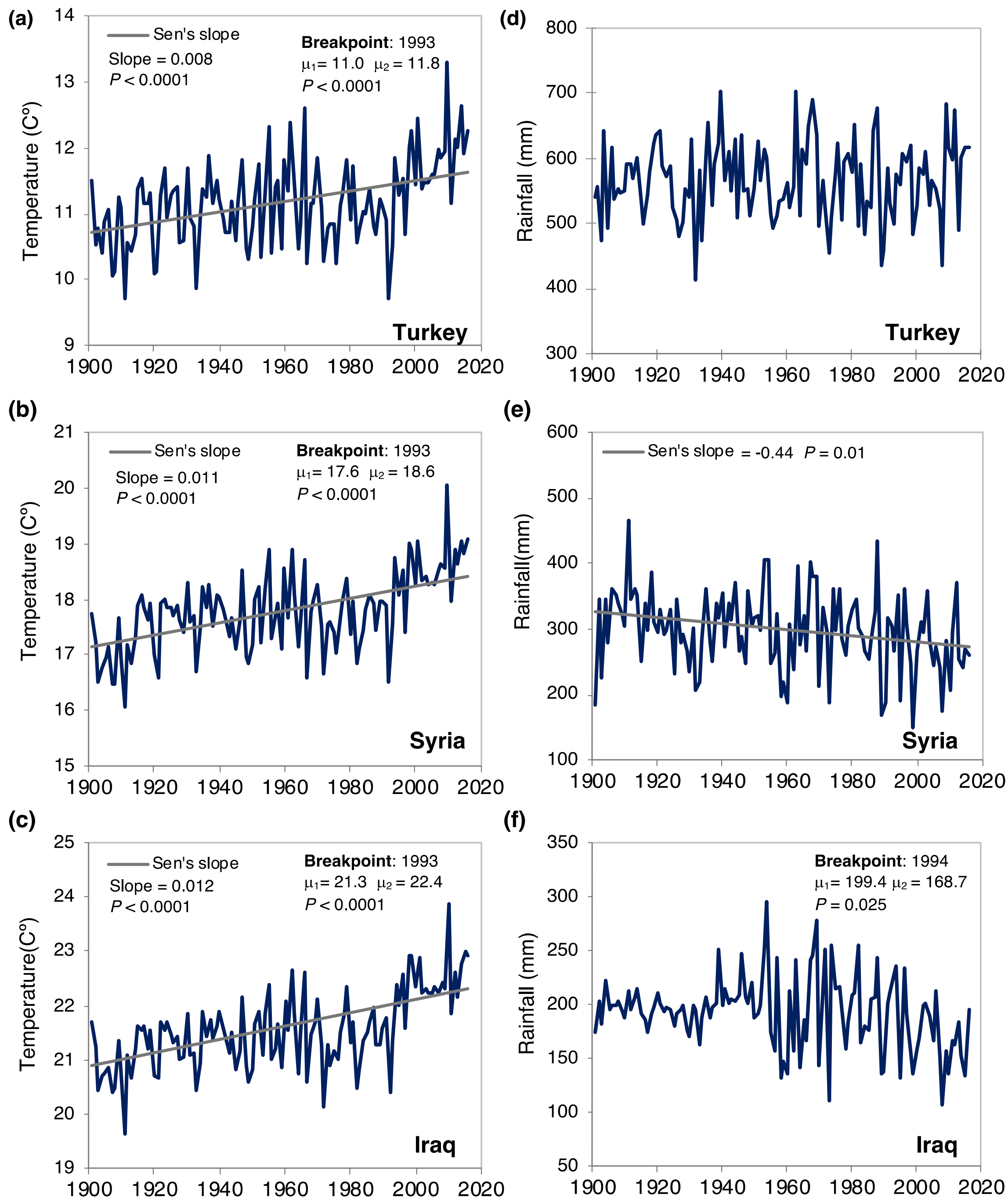

Fig. 4. Significant breakpoints (BP) and trends (slope) in temperature (a-c) and rainfall (d-f) for Turkey, Syria, and Iraq from 1901 to 2016.

Marsh drainage began in 1991, but it took several years before the marsh converted completely to dryland around May 1994. After this point, wetland area remained at or close to zero, with only small excursions concomitant with wet seasons. In the early post-restoration phase (2004 to 2008), marsh area averaged 646.5 km^2, with a clear seasonal pattern of marsh area varying from approximately 300 km^2 in the dry season (April to October) to approximately 900 km^2 in the wet season (November to March). During the drought of 2009, wetland area and flow rate in the Euphrates both reached their lowest values (240 km^2 and 90 m^3/s, respectively) (Figs. 6 a, c). After 2010, an increase in wetland area is apparent, when Euphrates River flow began to be supplemented by water from the MOD (Fig. 6c). Notably, the seasonal pattern of areal variation becomes less clear at this time since about 20 m^3/s of MOD water was being added to the marsh, particularly in summers to compensate for evaporation losses. During this time, the average wetland area increased to 860 km^2, with a minimum of 360 km^2 in the dry season of 2018 and a maximum of 1258 km^2 in the wet season of 2014 (Fig. 6a).

NDVI revealed strong seasonal variation in greenness (Fig. 6b), with maximum values during the growing season from April to September and minimum values in the dormant season from October to March. The exception to this pattern was during the desiccation period, when NDVI remained consistently low, as expected. Notably, the seasonal NDVI variation apparent in the pre-drainage and post-restoration periods was not present from our estimates of wetland area, which included vegetated, open water, and mixed coverages. Indeed, we found

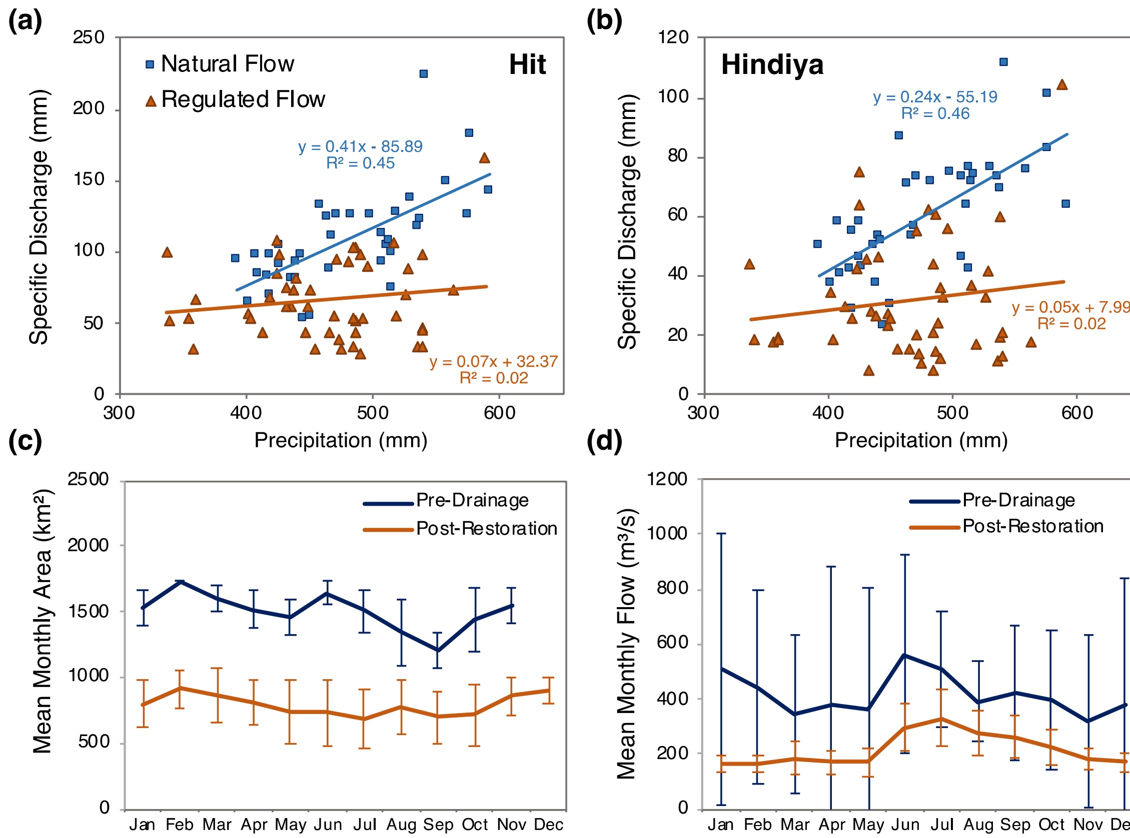

Fig. 5. Euphrates River flow changes and influences on the Western Mesopotamian Marsh (WMM). (a, b) Mean annual Euphrates River specific discharge at Hit and Hindiya vs. area-weighted upstream precipitation in the natural and regulated periods (i.e., before and after 1971). (c, d) Monthly variation in WMM area and combined Euphrates River and MOD flows in the pre-drainage period (1986–1994) and post-restoration period (2003–2019.

negative correlations between NDVI and total wetland area ($R = -0.29$), NDVI and water area ($R = -0.50$), and NDVI and mixed area ($R = -0.46$), driven by low values of NDVI for open water and mixed pixels. In contrast, the relationship between NDVI and vegetated area was positive ($R = +0.43$). Overall, there were significant decreases in wetland area ($P < 0.0001$) and Euphrates River flow ($P < 0.0001$) between the pre-drainage and post-restoration periods, but NDVI did not significantly differ ($P = 0.534$).

3.3. Relationship between flow and wetland area

Variation in monthly WMM area and Euphrates River flow (augmented by the MOD from 2010 to 2019) showed that wetland area was higher and less variable in the pre-drainage relative to the post-restoration period, while flow was higher and more variable in the pre-drainage period (Fig. 5c, d). In other words, high flows in the pre-drainage period, even if variable across years, were sufficient to consistently inundate larger wetland areas. In the post-restoration period, flows were more consistent, but low in magnitude, leading to low and variable wetland inundation area. Fig. 7 summarizes the relationships among mean annual WMM area, mean annual Euphrates River flow, and flows delivered from feeders (from 2009) and the MOD (from 2010). Before drainage, Euphrates River flow explained two-thirds of the variance in WMM area, but this relationship was insignificant during both the desiccation period (as expected) and the full post-restoration period (Fig. 7a). Separating the post-restoration flow-area relationship into periods before and after MOD flow augmentation reveals two distinct relationships, however, with higher areas for the same flow after 2010 due to MOD augmentation (Fig. 7b). Regressing area directly against measured flow deliveries from feeder canals and the MOD for the period when these data are available yielded a strong positive relationship (Fig. 7C), with consistently high wetland areas (above 1000 km^2) at annual flow deliveries above ~70 m^3/s. Flow deliveries from feeder canals, which are approximately equal in magnitude to MOD flows, were positively correlated with Euphrates flow (Fig. 7d).

3.4. Changes in WMM hydropattern

Average Euphrates flow was 51.4% lower in the post-restoration period (2004–2019) compared to the pre-drainage era (1986 to 1992), a significant decline ($P < 0.0001$). More specifically, the early restoration period (2004 to 2009) had fresh water supply from Euphrates with

Table 1
Accuracy assessment of the supervised classification.

Hydrologic period	Overall accuracy	Kappa coefficient	Satellite	Layers	Path/Raw	Grid size (m)
Pre-drainage	0.987	0.982	Landsat 5 TM Collection 1 Tier	7	167/39	30
Desiccation	0.987	0.982	Landsat 5 TM Collection 1 Tier	7	167/39	30
Post-restoration	0.990	0.986	Landsat 7 Collection 1 Tier 1	8	167/39	30

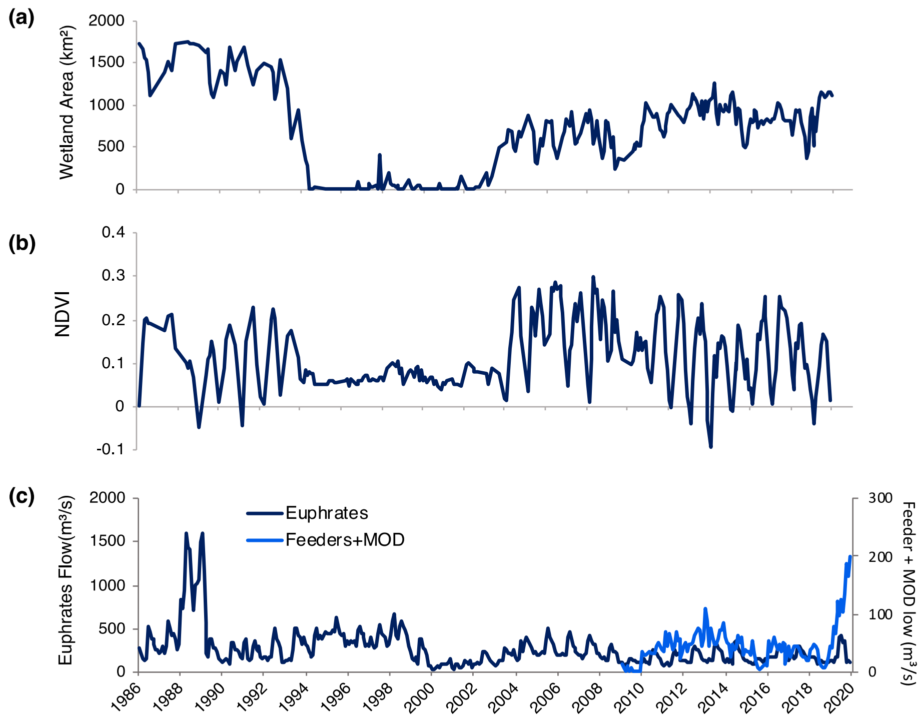

Fig. 6. Time series of (a) wetland area, (b) mean Normalized Difference Vegetation Index (NDVI), and (c) Euphrates River (at Hindiya) and supplemental flow (feeders plus MOD) from 1986 to 2019.

average flow from feeder canals of about 25 to 40 m^3/s, but after 2010 flow increased to about 50 m^3/s with additional flow supplied from the MOD (Al Khafaji et al., 2012). Associated with these changes, we found significant differences between the pre-drainage and post-restoration periods for only 2 out of 5 hydropattern elements analyzed: wetland area and frequency of reversals (Table 2). Specifically, mean wetland area was lower in the post-restoration period (764 km^2) compared to pre-drainage (1452 km^2); median annual area minima and maxima were also significantly lower in the post-restoration period (507 and 956 km^2) than the pre-drainage period (1234 and 1718 km^2). Frequency, as measured by number of reversals, also showed a significant increase in the post-restoration period, from 2.4 to 5.25 reversals per year (Table 2).

The seasonal timing of minimum and maximum wetland area were both statistically unchanged between the two periods. The median dates of area minima were days 227 ($\pm$50) and 208 ($\pm$80) in the pre-drainage and post-restoration, respectively, while median area maxima occurred on days 141 ($\pm$97) and 142 ($\pm$117). We also found no significant differences in area duration below the 25th percentile ($P = 0.41$) and above the 75th percentile ($P = 0.49$), with only a small decrease in the duration of small inundation area from 104.1 to 80.7 days and an decrease from 83.1 to 76.2 days for high inundation area between the pre-drainage and post-restoration, respectively. Finally, the rate of change in wetland area showed an increase ($P = 0.102$) on the rising limb (from 2.05 $\pm$ 1.34 to 3.30 $\pm$ 1.19 km^2/day in the pre-drainage and post-restoration periods, respectively) and no difference on the falling limb ($P = 0.408$) (Table 2).

4. Discussion

4.1. Flow regime of the Euphrates River

Historically, Euphrates River flow was driven by the seasonality of rainfall and snowmelt in the watershed. This “natural” flow regime was characterized by strong flood pulse (Fig. 3b) and generally high flows (Fig. 3c), which are a primary driving force for productivity and biotic interactions in river-floodplain systems (Junk et al., 1989). In contrast, the regulated flow regime has considerably lower flows and muted intra-annual variation, driven largely by upstream dams, which store large volumes of water for development and irrigation projects and regulate water releases. Change-point analyses identified the beginning of this regulated flow regime in 1971, near the time when two of the basin's largest dams began construction in Turkey (Keban dam) and Syria (Tabqah dam) (Fig. 3). As a consequence, the flow regime of the lower Euphrates River has been drastically altered and flow reduced, and many of the functions of its natural floodplain have been lost. At the same time, water storage in reservoirs has increased substantially (Fig. 3a) to meet water demand in different sectors, such as power generation, agriculture, flood control, and flow diversion. Consequently, the observed hydrologic alteration represents a formidable challenge for the restoration of the Mesopotamian marshes, which require consistent flood pulses to maintain the hydrology, productivity, and wildlife of the marsh.

Climate factors also had significant changes during the long-term period of record, with significant increases in temperature in all three riparian countries (Figs. 4 a-c) and significant change point and decline in rainfall in Iraq (Fig. 4e). While rainfall declines can partially explain reduced Euphrates River flows, changes in the fundamental nature of the precipitation-flow relationship (Figs. 5a,b) implicate infrastructural changes in the watershed. Specifically, changes in the precipitation-flow relationship in pre-dam and post-dam periods for Hit and the Hindiya gauging stations support the idea of a drastic anthropogenic shift in 1970s as the primary driver of flow changes at both stations after 1971. Specifically, the highly positive slope and relatively strong correlation between precipitation and flow in the “natural” flow period are both lost in the “regulated” era (Figs. 5 a,b). This means that changes in rainfall in the current day are only weakly associated with changes in flow due to water storage in reservoirs. Most concerningly perhaps is the fact that approximately 41% of the upstream basin's rainfall was delivered to Iraq in the period before 1971 (i.e., the slope of the

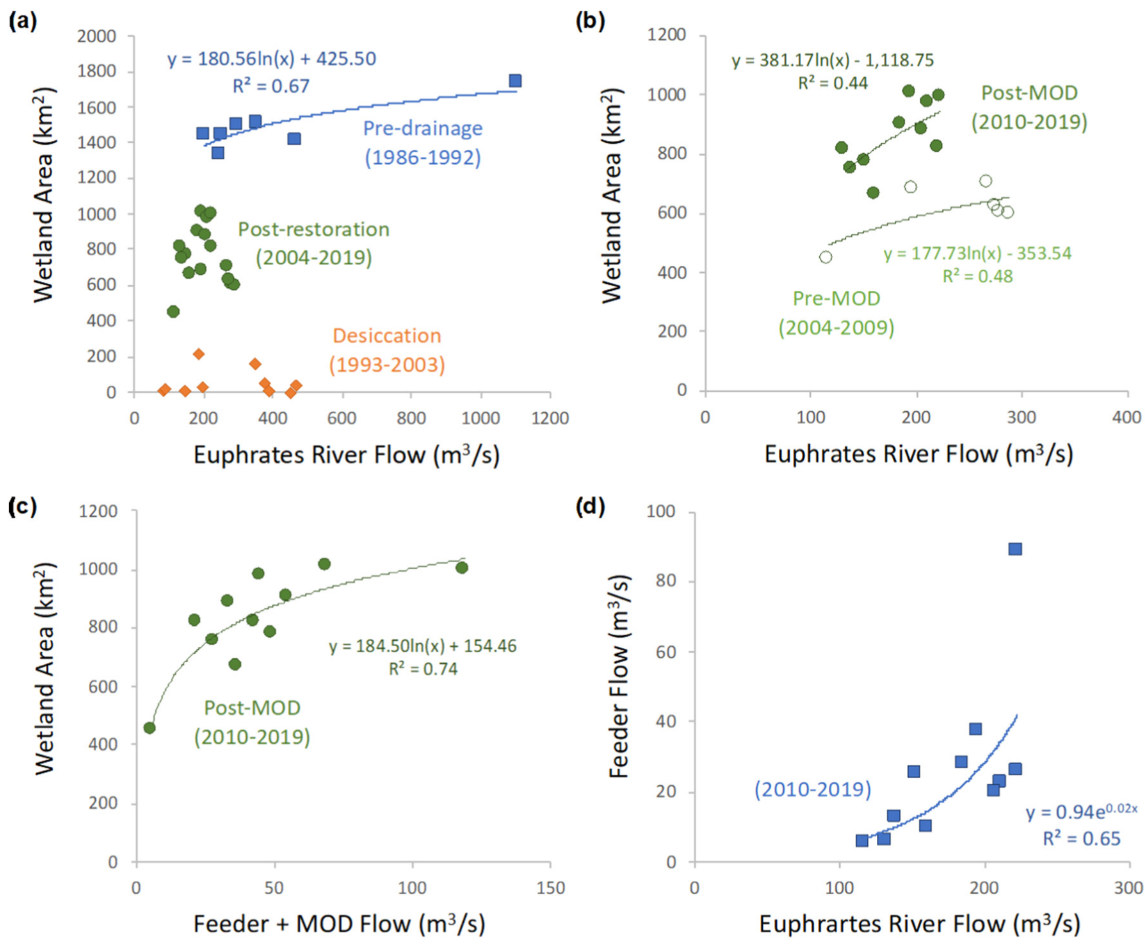

Fig. 7. Relationship between mean annual wetland area and Euphrates River flow at Hindiya over the entire period of record (a) and separating the post-restoration phase into periods with and without MOD augmentation (b). After restoration, the sum of inflows from feeders and the MOD from 2010 to 2019 (the period for which these data are available) correlate well with mean annual wetland area (c), and feeder flow is strongly associated with flow in the Euphrates over the same period (d).

rainfall-specific discharge in Fig. 5a); that percentage dropped to 7% in the regulated period (Fig. 5b), an 82% reduction. As a result, there has been a sharp reduction in flow and a huge shift in the flow regime of the Euphrates from a natural to a regulated flow regime since 1971. Additional changes in the flow regime driven by a changing climates and growing number of dams are expected in the future.

Most critically, Euphrates River flows have significantly declined (Figs. 3c, d), and the temporal pattern of high and low flows, which are important in the seasonal stability of communities, complexity, and community diversity, have become more regulated (Fig. 3b). The inflow of the WMM was strongly dependent on the flow rate of the Euphrates River, especially given low direct precipitation and minimal groundwater inputs (Al-Ansari et al., 2012). During this time (1930–1970), average monthly flows of the Euphrates at Hindiya were 1240 m^3/s in the flood season (March to June) and 328 m^3/s in the non-flood season (July to February) (Fig. 3b). Under the regulated regime (1971–2019), the average monthly flow dropped to 350 m^3/s in the flood season and 325 m^3/s in the non-flood season (a reduction of 72% in flow during flood season). Hence, the regulated flow regime has severely reduced and muted the flood pulse, which is a significant structuring mechanism via its effects on materials transport, food resources, biotic interactions, and microhabitat distributions (Richter et al., 1996).

Table 2
Hydro-pattern elements of the WMM during pre-drainage and post-restoration periods. Significant changes are indicated in bold.

Hydro-pattern element	Limits	Pre-drainage	Post-restoration	*P*-value
Area (km^2)	Minimum	1271(±214)	541(±188)	**<0.0001**
	Average	1484(±117)	766(±156)	**<0.0001**
	Maximum	1687(±76)	978(±139)	**<0.0001**
Timing (day of year)	Minimum	227(±50)	208(±80)	0.755
	Maximum	141(±97)	142(±117)	0.864
Duration (days)	25 percentiles	104.1(±66)	80.7(±90)	0.418
	75 percentiles	83.1(±113)	76.2(±101)	0.494
Reversals/year	Average	2.71(±1.48)	5.25(±1.68)	**0.005**
Rate of change (km^2/day)	Rise rate	+2.05(±1.34)	+3.30(±1.19)	0.102
	Fall rate	−2.73(±1.34)	−3.30(±1.46)	0.408

4.2. Changing structure of the WMM

The hydrology and ecology of the WMM can be separated into three distinct phases that emphasize the significance of surface hydrological connection between the Euphrates River and the marsh, and how it has changed over this period: pre-drainage (before 1992), drainage (1993 to 2003), and post-restoration (2004 to present). The pre-drainage period represents the period when the marsh was intact and served as the natural floodplain of the Euphrates River. This condition sustained a healthy freshwater ecosystem that supported high vegetation species richness (Al-Saadi and Al-Mousawi, 1988), including 104 aquatic and semi-aquatic plants (Alwan, 2006); more than 80 bird species (Al-Ansari et al., 2012), including endangered species of migratory birds (Canada-Iraq Marshlands Initiative, 2010); production of 60% of the fish consumed in Iraq (Partow, 2001); and shelter and livelihoods of about 500,000 of the Marsh Arabs, who lived in and around the Marshes (Dellapenna, 2007; Canada-Iraq Marshlands Initiative, 2010). During this period, the wetland recorded its highest area (over the period from 1986 to 2019 for which we estimated area) with an annual average area about 1740 km^2 in 1988 (Fig. 6a).

In late 1991, the regime of Saddam Hussein initiated a systematic plan to drain the marshes through construction of impoundments and drainage canals in the marshes. Therefore, the vast majority of the marsh dried up from 1994 to 2003, with the exception of about 10% of the area fed by water sources in Iran (UN, 2011). During this phase, the WMM was completely desiccated, representing one of the worst environmental catastrophes of the 20th century (Partow, 2001). During this time, areas of the desiccated marsh were used to support agricultural development through two "reclamation" projects. The Al-Malha (30,500 ha) and Al-Shafi (12,200 ha) projects included constructed irrigation networks to irrigate new agricultural lands and orchards (CRIMW, 2007). Some of these irrigation networks are now being used as feeder canals to restore the WMM. During desiccation, the estimated WMM area was very small, but not zero (Fig. 6a), likely due to the fact that vegetation characteristics of planted crops and some natural vegetation are sufficiently similar to wetland vegetation to be included in the classification.

The post-restoration period began in April 2003, when dikes along the Euphrates and its tributaries were breached or removed by the marsh inhabitants, causing large wetland areas with high vegetation cover to return. Remotely-sensed area and NDVI showed that much of the WMM experienced some level of restoration (Figs.6a, b), however it is important to note that maximum annual wetland areas in the post-restoration period are considerably lower than those in the pre-drainage period (Table 2). This reduction is due at least in part to infrastructural changes within the wetland (berms, dikes, and agricultural development) that have reduced the total possible area of inundation. We also found a higher variation in mean monthly wetland area in the post-restoration period (Fig. 5c) for a variety of possible reasons, including: 1) continuing flow reduction in the Euphrates, which caused inconsistent flow delivery to the WMM; 2) the use of alternative water resources, such as brackish water (TDS >5000 ppm) from Main Outfall Drain canal (MOD) and (untreated) wastewater from surrounding cities and villages to compensate for the reduction in the Euphrates water, which changed hydroperiod hydrodynamics in the WMM (Al Hamdani, 2014); and 3) the lack of an operational plan to restore the WMM (for example, there are few existing outlets to the WMM, which coupled with the high evaporation rate has caused hyperaccumulation of salt).

Despite these challenges, the overall mean area in the post-restoration period was about 785 km^2 and the maximum was 1258 km^2, leading to an abundance of aquatic vegetation species. For example, Alwan (2006) recorded 27 species of aquatic plants had returned to the Mesopotamian marshes after the reflooding in 2003 (Alwan, 2006). Additional flows from the MOD and municipal wastewater did result in increased area after 2010 (Fig. 6a), though at the expense of water quality. Despite generally positive trends in recovery, the post-restoration period has experienced high fluctuations in inundated area and vegetation cover because of seasonality, flow reduction, and water quality degradation. For example, in May 2009, the reduction in the average flow of the Euphrates at Hindiya to 90 m^3/s caused considerable reduction in wetland area and growing season NDVI, potentially indicative of a drought-induced plant die-off (Fig. 6b).

4.3. Hydropattern of the restored WMM

Alteration of the Euphrates River flow regime has affected many wetland ecological processes regulated by magnitude, frequency, duration, timing, and rate of change of inundation (LeRoy Poff et al., 1989; Richter et al., 1996). The considerable variation in the WMM area (representing magnitude) were driven by Euphrates River flow rate variation, local meteorology (i.e., low rainfall, high and seasonal evapotranspiration), and water management (drainage, restoration, flow augmentation). While there was a positive correlation between average annual wetland area and average annual Euphrates River flow in the post-restoration period (Fig. 7b), this relationship was better explained using measures of direct flow deliveries from feeder canals and the MOD (Fig. 7c), with approximately 70 m^3/s of direct deliveries required to consistently achieve wetland areas near 1000 km^2 (Fig. 7c). Critically, flows of this magnitude were associated with mean annual Euphrates River flows greater than 200 m^3/s as measured at Hindiya. Reductions in wetland area in the post-restoration period were large and significant, both for mean and minima/maxima (Table 2). Reduced wetland area translates to reduced habitat provisioning, lower primary and secondary production, and potentially reduced bird, fish, and mammal community structure that are influenced by changes in vegetation and habitat types (Gorman and Karr, 1978). For example, fish species richness also dropped between these two periods, from 106 species of freshwater and migrant marine species recorded prior to the 1990s to a maximum of 52 species after restoration (Abed et al., 2009).

Regarding timing, WMM area and NDVI both had a periodic seasonal cycle (Fig. 6a, b), with area minima in summers (August and September) due to extremely high evaporation (245 cm/year; Richardson et al., 2005) and area maxima in winters (February and March) when river flow is high and evaporation is low. As noted above, NDVI maxima correspond to the growing season (April to September) despite declines in wetland area in this season; in other words, NDVI and WMM are not in synch, limiting the use of this spectral index for wetland area estimation. Overall, seasonal patterns in the timing of area minima and maxima were not significantly different between the two periods (Table 2), suggesting that ecological processes associated with flood pulse timing such as aquatic organism life cycles, stress avoidance, habitat access, and migratory cues (Richter et al., 1996; Brock et al., 2003; Nasirian and Salehzadeh, 2019) may be maintained. Similarly, there were no significant changes in the duration of area above/below the 25% and 75% area percentiles, suggesting that the restored marshes support areas with hydroperiods that resemble the pre-drainage state, even if their area has been reduced.

While overall NDVI was not significantly different between the two periods (Table 2), the relatively "smooth" periodic NDVI oscillations in the earlier period were more jagged in the latter period. This was reflected in a significantly higher number of reversals in WMM area (our measure of frequency) in the post-restoration period (Table 2), likely due to active water management via feeder canals and supplemental sources. We note, however, that there were more and longer image gaps in the pre-drainage period, which could artificially reduce the number of reversals observed during this time. Higher numbers of hydrologic reversals in pulsed wetlands have been associated with reduced foraging opportunities and nest failure for wading birds (Sklar et al., 2009); reduction in fish recruitment (Nelson, 2015); and negative effects on obligate wetland vegetation (Aguiar et al., 2018). Increases in rates of change in wetland area on the rising limb in the post-restoration period, while not quite statistically ($P = 0.102$), were relatively large (from a mean of 2.05 to 3.30 km^2/day in the pre and post periods, respectively, a 60% increase) (Table 2). In other words, the transitional period between the dry and wet seasons is much shorter in the present day, potentially disrupting the lifecycle of wetland vegetation (Middleton, 1999; Kaplan et al., 2010) and stranding terrestrial organisms as waters rise (Richter et al., 1996).

Finally, while not explicitly estimated in this study, we note that water depths measured in previous studies support the idea of hydrologic restoration, at least in portions of the marsh. For example, during the pre-drainage period, the average water depth within the marsh was 0.5 and 2 m in dry and wet seasons, respectively (UNEP, 2006), while post-restoration the average water depth was 1 to 1.25 m, with maxima of 2.5 to 2.6 m (Al-Quraishi, 2006; Abdulraheem, 2015). While water depths have recovered in some areas, the changing the water regime described here, as distinct from measured water depth, can affect the composition and diversity of macrophyte communities (Casanova and Brock, 2000; Nicol et al., 2003) and their distribution (Rea and Ganf, 1994; Boar, 2006), with wide-ranging effects on water quality, soils, and other wetland organisms.

5. Conclusions

The proliferation of dam construction in Turkey, Syria, and Iraq, combined with the influence of climate, have converted the Euphrates River regime from natural flow to regulated flow since 1971. In Iraq, the annual Euphrates River flow has declined by 38% and 46% at the Hit and Hindiya stations, respectively since the 1930s. In terms of climate change, there were statistically significant increasing trends in the temperature for Turkey, Syria and Iraq and statistically significant decreasing trends in rainfall for Syria during the same period. More recently, there has also been a statistically significant 51% reduction in the monthly average Euphrates River flow between the pre-drainage (1986 to 1992) and post-restoration periods (2003 to present), indicating a continued, recent decline since the mid-1980s. Average WMM area has shrunk by about 47% between these periods. The estimated flow required to restore 1000 km^2 of wetland area is an annual average of about 70 m^3/s delivered through feeder canals and the MOD, which corresponds to periods when Euphrates River flow at Hindiya exceeded 200 m^3/s. While we found significant differences in the number of hydrologic reversals in the post-restoration period, other hydro-pattern metrics related to timing, duration, and rate of change were statistically similar to pre-drainage values, suggesting the potential for many ecological functions to be restored.

This study presents a framework for considering how direct anthropogenic changes (e.g., marsh drainage, upstream dam construction) and the effects of climate change (increased temperatures, decreased rainfall) combine to affect wetland ecosystem integrity. As climate change continues to threaten water availability in both human and natural systems, it will become even more important to understand ecosystem water needs and robustly attribute the causes of hydrological alteration to aquatic ecosystems. Going forward, two major challenges for successful restoration of the Mesopotamian Marshes are addressing ongoing water quality issues, especially related to increased salinity and wastewater inputs, and implementing water agreements with riparian countries to ensure the availability of adequate fresh water.

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CRediT authorship contribution statement

Ali K. Al-Quraishi: Conceptualization, Methodology, Writing – original draft. **David A. Kaplan:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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