Assessment of water resources in Yarmouk River Basin using geospatial technique during the period 1980-2020 postprint

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Abstract

It is common knowledge that Yarmouk River Basin (YRB) is shared between Jordan and Syria. Management of YRB trans-boundary water resources is attracting increasing interest because it is a strategic water resource for the riparian countries. Actually, lack of sharing information regarding hydrological flows and basin' s water management between partners' countries makes it difficult to distinguish between natural and man-made factors affecting the water body. Therefore, this study seeks to address and assess the main on-site changes that exert on YRB. Geospatial technique and arithmetic equations were combined to carry out an assessment of the changes on water resources in YRB. Data, information and field measurements of the basin were aggregated, compiled and presented to determine the extent of changes during the period 1980-2020. Remarkable findings showed that precipitation amount in the basin significantly declined during the period 1980-2020 in particularly after the year 1992. Pumping rate of groundwater was 550$×$103 m3/a, exceeding the basin' s safe yield. Draw down of static groundwater level over time approached the value of -3.2 m/a due to the over abstraction in the aquifer body. Additionally, the evaporation rate reached more than 99% in some regions in the basin. Moreover, the number of private wells has increased from 98 wells in 1980 to 126 wells in 2020, showing the excessive extraction of groundwater. These findings indicate that the study area is subjected to a considerable groundwater depletion in the near future due to extensive abstraction, continuous drilling of illegal wells and decreased annual precipitation under the shadow of the rapid population growth and continuous influx of refugees. Therefore, decision makers-informed scenarios are suggested in the development of water resource portfolios, which involves the combination of management and infrastructural actions that enhance the water productivity of the basin. Further studies are recommended to evaluate the on-site changes on water resources in YRB in collaboration with riparian countries and to establish monitoring system for continuous and accurate measurements of the basin.

Full Text

Preamble

Assessment of Water Resources in Yarmouk River Basin Using Geospatial Techniques During the Period 1980-2020

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Abstract: The Yarmouk River Basin (YRB) is shared between Jordan and Syria. Management of YRB’ s trans-boundary water resources is attracting increasing interest because it represents a strategic water resource for the riparian countries. However, lack of information sharing regarding hydrological flows and water management between partner countries makes it difficult to distinguish between natural and man-made factors affecting the water body. Therefore, this study seeks to assess the main on-site changes affecting YRB by combining geospatial techniques and arithmetic equations. Data, information, and field measurements from the basin were aggregated, compiled, and analyzed to determine the extent of changes during 1980-2020. Remarkable findings showed that precipitation in the basin declined significantly during this period, particularly after 1992. Groundwater pumping rates reached 550$\times10^{3}$ m^{3}/a, exceeding the basin’ s safe yield. Drawdown of static groundwater level over time approached -3.2 m/a due to over-abstraction in the aquifer body. Additionally, evaporation rates exceeded 99% in some regions. Moreover, the number of private wells increased from 98 in 1980 to 126 in 2020, demonstrating excessive groundwater extraction. These findings indicate that the study area is subject to considerable groundwater depletion in the near future due to extensive abstraction, continuous drilling of illegal wells, and decreased annual precipitation, compounded by rapid population growth and continuous refugee influx. Therefore, decision-maker-informed scenarios are suggested for developing water resource portfolios that combine management and infrastructural actions to enhance basin water productivity. Further studies are recommended to evaluate on-site changes on water resources in YRB in collaboration with riparian countries and to establish a monitoring system for continuous and accurate measurements.

Keywords: assessment; geospatial technique; on-site changes; water resources; Yarmouk River Basin

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1 Introduction

Jordan is a country with very scarce water resources, ranked as the second most water-deprived country in the world. The supplied and consumed water amounts are 126 L and 71 L per capita per day, respectively (Ministry of Water and Irrigation (MWI), 2016a). Currently, Jordan’ s population growth rate is 1.94%, which is comparatively high (Awawdeh et al., 2019). This situation has been aggravated by a huge refugee influx in the last decade. Groundwater consumption exceeds replenishment by more than 60%, with 6 out of 12 major groundwater basins being over-extracted (MWI, 2019). Furthermore, climate change forecasts project a significant decrease in current and future precipitation, which will aggravate water shortages especially in arid regions (Duan et al., 2021). Thus, renewable water resources are expected to decline in the future. Regarding water balance, Jordan had only 992$×10^{6}$ m^3 of total water resources available, while total water demand was 1401$×10^{6}$ m^3 (MWI, 2016a).

The Yarmouk River Basin (YRB) is shared between Jordan and Syria. Upstream diversion and construction of Syrian dams since 1968 in the upper reaches of YRB have reduced the river flow available to Jordan by 85%. Moreover, groundwater over-abstraction in the Syrian part of the basin also explains much of the changes in streamflow (Avisse et al., 2020). The strategic importance of YRB is attributed to its role as one of the major sources of groundwater and surface runoff in Jordan and the main source of water for the King Abdullah Canal. Thus, YRB is considered the backbone of development in the Jordan Valley. The study area is important for three reasons: (1) it is a typical agricultural watershed in Jordan; (2) intensive human activities have been identified as primary contributors to sedimentation within the basin; and (3) it has been selected by the government for upland conservation practices to reduce sedimentation.

According to Jordan’s water strategy for 2016-2025, the deficit in available water resources from YRB was approximately 41% in 2016 (MWI, 2016b). However, the water deficit amount in 2019 was 10$×10^{6}$ m^3, given a safe yield of 40$×10^{6}$ m^3 and total water abstraction of 50$×10^{6}$ m^3 (MWI, 2019), representing one of the highest relative deficits compared to other basins. Depletion of flows from major springs feeding the Yarmouk River and abstraction from wells for irrigation purposes will result in long-term reduction in the river’ s baseflow and consequent water table dropping in shallow aquifers (Salameh, 2004; Obeidat et al., 2019).

Salameh (2004) revealed that Jordan’ s water supply from the Yarmouk River is at high risk due partially to climate change and expanded utilization. Bunning et al. (2016) discussed water assessment methods in drylands and identified that the extent and performance of water resources management alongside analyzing impacts of drought or over-exploitation are of concern. Moreover, previous studies have explained what are called on-site changes on water resources, which are considered by spatial location, effectiveness on water resources, and fate of water resources in the study area. Analyzing these changes and updating relevant information are highly important for determining the actual status and trends of water resources in a basin in terms of water quantity and hydrological regime (Duan et al., 2020; Meran et al., 2020).

The aim of the present study is to analyze the main on-site changes affecting YRB during 1980–2020 by assessing surface water hydrology, evaluating groundwater resources, and suggesting water management scenarios. Geospatial techniques and arithmetic equations were combined to carry out this assessment. Data, information, and field measurements from the basin were collected, compiled, and analyzed to determine the extent of changes during this period. Based on anticipated findings, different scenarios may be concluded and discussed with decision makers to diminish impacts on water resources and reduce risks. This study addresses spatial system-wide changes across different aspects of water resources assessment in the basin.

2.1 Study Area

YRB in northern Jordan (Fig. 1 [Figure 1: see original paper]) is a transboundary basin shared between Jordan and Syria. The Yarmouk River originates on the southeastern slopes of Mount Hermon in Syria. The main channel of the Yarmouk River forms the boundary between Syria and Jordan for 40 km, while its southern part partially forms the border between Jordan and Palestine. The central and southeastern parts of YRB are described as smoothly contoured semi-desert land that falls toward the Jordan Rift Valley, forming inclined cliffs and gorges (Obeidat et al., 2019). Elevation ranges from 1200 m at the highest ridges near Ajloun (Ras Munif) to -200 m near Adasiya in the Jordan Rift Valley.

The average flow of the Yarmouk River was 495\$×10^{6}\$ m^3/a in the 1950s (Hoff et al., 2011) and has been decreasing since then to reach 83\$×10$^{\{6\}-99\times10}${6}\$ m^3/a presently (Abdulla and Al-Shurafat, 2020). The total catchment area is 6780 km^2, with the majority in Syria and the remainder (approximately 1160 km^2) in the upstream of YRB in Jordan. The area is mostly agrarian land with some small industrial zones. During floods, small amounts of wastewater runoff reach the river. The Yarmouk River has permanent baseflow as well as considerable flood flows, originating primarily from precipitation in winter and supplemented by spring discharges. The basin has a semi-arid Mediterranean climate in the west and an arid climate in the east. The precipitation gradient is obvious across the west-east direction, where mean annual precipitation ranges from 500 mm in the west (Samar weather station) to 133 mm in the east (Hosha weather station). Minimum mean temperatures are 12.3°C in the lowlands (Jordan Rift Valley) and maximum is 23.1°C in the highlands (MWI, 2016c; Obeidat et al., 2019). It is typical to construct dams as an adaptation approach to increase water supply for mitigating anticipated shortages. Therefore, Al-Wehada Dam was constructed on the Yarmouk River in the border area of Jordan and Syria for drinking and irrigation purposes in 2004. However, water from the dam is used for irrigation due to water quality and quantity considerations as it collects winter floodwater from YRB and springs.

2.2 Data Collection

Hydrogeological and meteorological data were obtained from the Ministry of Water and Irrigation (MWI) and Jordan Meteorological Department (JMD), including but not limited to geologic information, hydrogeological data, groundwater and surface water data, and climatic data (daily temperature, relative humidity, hourly sunshine, wind velocity and direction, monthly average precipitation, and potential evaporation). The data and measurements collected are mostly associated with locations and were represented as discrete values stored by their exact geographic location as vector data.

Additionally, a digital elevation model (DEM) from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) with 30 m$×$30 m resolution was obtained from the US Geological Survey website (US Geological Survey, 2021). This study focused on achieving water resources appraisal through analyzing different changes on groundwater and surface water resources that affect the hydrological regime in the basin. The manual by Bunning et al. (2016) explained significant changes on water resources. Accordingly, the present study identified the most prominent on-site changes in the study area according to their potential, including: change in surface water availability (streamflow amount including mainly base flow and flood flow), change in groundwater availability (abstraction, monitoring wells, and depth to water table), and expansion in water extraction from growing numbers of private or unlawful wells. Subsequently, these changes were processed through a developed quantitative water resources assessment approach as discussed in the next section.

2.3 Data Processing

The raw data representing the changes were analyzed, processed, and validated using a developed approach as demonstrated in Figure 2 [Figure 2: see original paper]. Data were processed using different methods. The collected data on abstraction and monitoring wells, YRB boundaries, climatic and streamflow parameters were prepared and processed using ArcGIS v10.7.1 software to produce exemplified maps, while precipitation, evaporation, and climatic parameter data were handled by mathematical equations to compute evaporation rates and mean areal precipitation for the entire YRB surface. These data were interpolated using ArcGIS v10.7.1 software. The data layers were graphically combined using analytical operators (overlay analysis) and processed into diagrammatic representations as maps to attain sound interventions for water resources management in the basin.

The sub-basins of YRB were delineated using Geographic Information Systems (GIS; Fig. 3 [Figure 3: see original paper]). A DEM was used to compute flow direction and drainage network. Precipitation and evaporation data were interpolated using the Inverse Distance Weighted (IDW) method. For precipitation calculations, the Thiessen polygons (areal precipitation) method was chosen to compute mean areal precipitation for each sub-basin based on rain gauging station observations. Calculations were based on precipitation data from 13 stations during 1980–2020 (Fig. 4 [Figure 4: see original paper] and Table 1). Each station has an influence area determined after polygon construction. The precipitation value measured by a rain gauging station is assigned to the area by multiplying the precipitation by its representative area, as shown in the following equation:

$$P = \frac{\sum (A_i \times P_i)}{A}$$

where P is the total precipitation in the basin (mm); A is the total area of the basin (km^2); A_i is the Thiessen polygon area (km^2); and P_i is the amount of precipitation over each Thiessen polygon (mm). Point data from stations surrounding the study area were interpolated to a raster surface using the surface interpolation method IDW. Subsequently, the interpolated surface was used to derive the contour map of mean annual precipitation of YRB (ESRI, 2021).

Furthermore, six climatic stations (Table 2) located in YRB were considered for analysis. Each station measures daily temperature, relative humidity, hourly sunshine, wind velocity and direction, monthly average precipitation, and potential evaporation. Among these parameters, daily temperature and monthly average precipitation measurements were validated during 1980–2020 for evaporation calculations. Preliminary evaporation estimation was calculated using the Turc formula (Eq. 2) (Turc, 1951). The Turc formula is used for evaporation calculation in Mediterranean climatic conditions with limited data and is mainly applied for large areas (Adamovic et al., 2015). This equation is written as follows:

$$E = \frac{P}{\sqrt{0.9 + (P/f(t))^2}}$$

where E is the actual evaporation (mm); P is the mean annual precipitation (mm); and $f(t)^2$ is the atmospheric capacity to evaporate water, expressed by:

$$f(t) = 300 + 25T + 0.05T^3$$

where T is the annual mean temperature (°C). The mean temperature used in the Turc formula was taken for wet months between October and May. Evaporation for the entire record period (1980–2020) was calculated for the basic climate stations.

Moreover, abstraction well locations were identified. Abstraction amounts from these wells were measured monthly by MWI and varied according to well yield and reservoir storage capacity. Monitoring wells are used only to measure static water level by recording water depth from the well top. Measurements were taken monthly and stored in the Water Information System (WIS) as an oracle database. Data were imported to ArcGIS for validation and analysis. Streamflow data represent wastewater treatment plant effluent, springs, flood flow, baseflow, and water stored in the Wehdah Dam. These data were collected by MWI during 1980–2020, with flow amounts measured as charts using installed gauging stations and stored in WIS for value extraction. Annual streamflow values for two representative gauging stations were calculated and displayed in charts.

2.4 Building Thematic Maps and Recommending Management Scenarios

Hydrogeological and climatic data were processed to produce exemplified maps or compute climatic parameter values as discrete values delineated as maps. Thematic maps were generated as visual representations of on-site changes to assess the current water resources situation in YRB. These maps help researchers answer different questions concerning studied on-site changes, enabling decision makers to improve water resources management effectiveness and anticipate water conservation projects.

3 Results and Discussion

Many significant changes were analyzed either visually through geospatial mapping techniques using GIS or arithmetically. The footprint of these changes on water resources in the study area is presented and discussed in the following subsections.

3.1 Watershed Delineation

YRB consists of several sub-basins as shown in Figure 3 [Figure 3: see original paper]. A DEM layer was integrated using GIS to delineate existing sub-basins in the study area as well as new hydrological features. Flow direction is obvious from southwestern highlands of 1148 m a.s.l. toward northwestern plains of -133 m a.s.l., extending through the Jordanian border toward Syria.

3.2 Precipitation

The spatial distribution of mean annual precipitation over YRB was carried out using the Thiessen Polygons technique during the record period as shown in Figure 4 [Figure 4: see original paper]. The highest monthly precipitation was recorded at Ras Muneef station and the minimum at Jaber Mughayyir station, while En Nueiyime and Turra stations represented average basin values.

Table 1 describes mean annual precipitation at these stations from 1980 to 2020 on the Jordanian side of YRB using the Thiessen Polygons method. The hydrological year in Jordan is divided into a rainy season from October to May and a dry season for the remainder. Mean annual precipitation is shown in the isohyetal map in Figure 5 [Figure 5: see original paper]. Precipitation decreases dramatically from 520 mm in southwestern highlands at Ras Muneef station to less than 150 mm in the eastern plateau at Mafraq Airport station, reflecting the rain shadow effect of the western highlands. Using the Thiessen Polygons method, weighted mean precipitation for YRB was estimated as 277 mm during 1980–2020, similar to prevalent semi-arid Mediterranean conditions with highly variable climate in Jordan (Obeidat et al., 2020). Since precipitation is a main climatic factor affecting watershed water resources (Duan et al., 2020), it is crucial to develop practices to manage scarce water resources and increase water use efficiencies to conserve and sustain already fragile resources.

3.3 Evaporation

Evaporation for climate stations was calculated with results summarized in Table 2 . Calculated long-term evaporation rates ranged from 92% at Ras Muneef station to approximately 100% at Mafraq Airport station and surrounding regions. The spatial distribution of long-term evaporation rate shown in Figure 6 [Figure 6: see original paper] increases dramatically when shifting from west to east, reflecting variation in climate patterns from semi-arid to arid across YRB.

3.4 Streamflow

The majority of the basin' s water comes from streams, including intermittent spring-fed ponds or ground depressions that fill after rain events. Runoff in the Yarmouk River consists of two main parts: direct runoff from precipitation (flood flow) to drainage channels, which is extremely variable and effective from October to May; and baseflow originating from groundwater that flows in wadis throughout the year (perennial flow) without storage. Baseflow in semi-arid regions is considered the component of total streamflow predominantly due to groundwater discharge into rivers under low-flow conditions during dry seasons, as is the case in YRB (Courcier et al., 2005). Two main streamflow gauging stations exist in YRB on the Jordanian side since the late 1960s: Maqaren and Adasiya. Maqaren station is situated at 32°44 N and 35°51 E with an elevation of 12 m a.s.l., covering Al Wehdah catchment. Adasiya station is located at 32°41 N and 35°37 E with an elevation of -210 m a.s.l., representing the outlet of the entire YRB where both Jordanian and Syrian parts drain. The majority of baseflow or groundwater contribution recorded at these stations flows from aquifers and springs on the Syrian side. Figures 7 [Figure 7: see original paper] and 8 [Figure 8: see original paper] show annual streamflow at Maqaren and Adasiya stations during 1980–2020.

A clear declining trend in streamflow is evident since 1992, interpreted as a warning sign that warming can significantly influence rainfall patterns and dramatically impact runoff and groundwater recharge. These findings align with Kunstman et al. (2007). Two other streamflow gauging stations (Shallala and Esh Shaumar) exist in YRB as secondary stations but were not considered because they have sporadic datasets—unavailable for 30 years during 1990-2020 for Shallala station and for 25 years during 1995-2020 for Esh Shaumar station —representing a source of uncertainty. Despite this, the two main gauging stations adequately cover streamflow measurement at the outlet of Yarmouk River' s main tributaries.

3.5 Abstraction

Despite water scarcity in Jordan (Awawdeh et al., 2020; UNICEF Jordan, 2021), water supply coverage in the basin is fairly high at 94% of the population (MWI, 2016). However, distribution system performance remains below optimal level with low efficiencies. Households in YRB receive water once weekly for limited hours and use roof-top tanks to store weekly needs. This intermittent supply creates additional risks such as water quality deterioration during storage. Total groundwater delivered to YRB for domestic purposes is approximately 59\$×10^{6}\$ m^{3}. Since total domestic use of the basin' s water is 12\$×10^{6}\$ m^{3}, which does not fulfill local needs, the difference is complemented from other basins. Groundwater pumping of 50\$×10^{6}\$ m^{3} from the basin surpasses the safe yield of 40\$×10^{6}\$ m^{3}, creating a water deficit of 10\$×10^{6}\$ m^{3} (MWI, 2019). Within the basin boundary, there are about 69 state-owned wells for domestic purposes and 126 private wells, of which 11 illegal wells are used for agriculture, compared to only 98 wells in the 1980s (WAJ, 2019). Abstraction rates from pumping wells are shown in Figure 9 [Figure 9: see original paper], where symbol size indicates water quantity abstracted per year. Pumping rates range from 550$\times10^{\{3\}-300\times10}\{3\},300\times10^{\{3\}-200\times10}\{3\},200\times10^{\{3\}-150\times10}\{3\},150\times10^{\{3\}-75\times10}\{3\},to75\times10^{\{3\}-2\times10}\{3\}$\$ m^{3}/a as shown in Figure 9 for 2019. The numbers of state-owned and private wells for each class are 33 and 12, 4 and 25, 6 and 33, 8 and 29, and 10 and 26, respectively. Total water abstraction reached 50\$×10^{6}\$ m^{3} to cover local demand, exceeding the basin' s safe yield of 40\$×10^{6}\$ m^{3}.

3.6 Groundwater Monitoring

Monitoring wells assess abstraction impacts on groundwater levels, with most equipped with automatic recorders. Drawdown rates during 1980-2020 are shown in Figure 10 [Figure 10: see original paper], varying from -3.2 to -0.9 m/a. This can be attributed to low precipitation, over-abstraction in the aquifer body, increased private wells, drastic population growth, and sudden refugee influx. However, lack of hydrological information sharing between partner countries makes it difficult to distinguish between natural and man-made factors affecting the water body.

3.7 On-Site Changes on Water Resources in YRB

This study highlights a newly integrated approach to "on-site changes on water resources" that can cause degradation. Changes were selected based on hydrological properties and water resources in the study area. Various parameters discussed showed significant changes, illustrated either visually by mapping or arithmetically. The imposed changes of different parameters are interpreted in detail, with impacts summarized in Table 3 . It is plausible that a limitation may have influenced results regarding the data period length (1980–2020) for assessing water resource changes in YRB. Further data for a longer period may provide more accurate and reliable assessment results.

4 Conclusions and Recommendations

On-site changes on water resources in YRB during 1980–2020 can be summarized as follows: precipitation amount significantly declined since 1992, subsequently causing a declining trend in annual streamflow. Groundwater pumping rates surpassed the safe yield. This situation was aggravated by climatic conditions leading to high evaporation rates, rapid population growth, and refugee influx. Decision makers and concerned parties are encouraged to implement more stringent strategies to comply with extensive abstraction. A legislative framework is suggested to handle illegal wells, and more attention should be paid to water-saving awareness among the public and farmers. Additionally, further studies are recommended to establish a full monitoring system for continuous and accurate measurements for more effective basin management and to evaluate on-site changes on water resources in YRB in collaboration with riparian countries.

Table 3. Extent of Imposed On-Site Changes on Water Resources in YRB

On-Site Change	Extent of Change
Change in surface water availability (streamflow amount including baseflow and flood flow) using data from relevant gauging stations	During 1980–2020, the highest mean annual precipitation occurred at the southwestern boundary (520 mm) and the lowest at the eastern boundary (142 mm) due to weather system interactions with basin relief. Using the weighted average method, mean precipitation for the entire basin is 277 mm, reflecting semi-arid Mediterranean to arid climate conditions in YRB. Annual streamflow values clearly show an obvious declining trend, especially after 1992 (440\$×10^{6}\$ m^3) compared to 2020 (50\$×10^{6}\$ m^3) at Maqaren gauging station, confirming warming influences on precipitation and dramatic impacts on runoff and groundwater recharge.
Change in evaporation rate from bare ground and open watershed	Calculated long-term evaporation rates for climate stations ranged from 92% to 100% at southwestern highlands and eastern regions, respectively. This influence increases dramatically from west to east, reflecting climatic pattern effects from semi-arid to arid regions in YRB.
Change in groundwater availability (abstraction, monitoring wells, and depth to water table)	Pumping rate ranges with maximum values of 550\$×10$^{\{3\}-300\times10}${3}\$ m^3/a are relatively high, causing excess over the basin’ s safe yield. Drawdown rates vary from -3.2 to -0.9 m/a due to low precipitation, natural conditions, sudden population increases, and agribusiness requirements.
Expansion in water extraction from growing numbers of private or unlawful wells	Numbers of state-owned and private wells are 33 and 12, 4 and 25, 6 and 33, 8 and 29, and 10 and 26, respectively, for pumping rate ranges from 550\$×10$^{\{3\}-300\times10}${3}, 300×10$^{\{3\}-200\times10}${3}, 200×10$^{\{3\}-150\times10}${3}, 150× m^3/a.

References

Abdulla F, Al-Shurafat A. 2020. Rainfall-runoff modelling for semi-arid and trans-boundary Yarmouk river basin. Procedia Manufacturing, 44: 180–188.

Adamovic M, Braud I, Branger F, et al. 2015. Assessing the simple dynamical systems approach in a Mediterranean context: application to the Ardèche catchment (France). Hydrology and Earth System Sciences, 19(5): 2427–2449.

Avisse N, Tilmant A, Rosenberg D, et al. 2020. Quantitative assessment of contested water uses and management in the conflict-torn Yarmouk River Basin. Journal of Water Resources Planning and Management, 146(7): 1–41.

Awawdeh M, Jaradat R, Al Qudah K, et al. 2019. GIS-based analysis of potential water infiltration in the upper Yarmouk River basin, north Jordan. The Jordan Journal of Earth and Environmental Sciences, 10(3): 136–144.

Awawdeh M, Al-Kharbsheh N, Obeidat M, et al. 2020. Groundwater vulnerability assessment using modified SINTACS model in WadiShueib, Jordan. Annals of GIS, 26(4): 377–394.

Bunning S, McDonagh J, Rioux J. 2016. Manual for local level assessment of land degradation and sustainable land management: Water resources assessment-LADA project, 139–153. [2021-07-30]. http://www.fao.org/3/a-i6362e.pdf.

Courcier R, Venot J, Molle F. 2005. Historical transformations of the Lower Jordan River Basin (in Jordan): Changes in water use and projections (1950–2025), Comprehensive assessment of water management in agriculture research report 9, 32–60. [2021-08-03]. https://horizon.documentation.ird.fr/exl-doc/pleins_{textes}/divers15-08/010039160.pdf.

Duan W, Zou S, Chen Y, et al. 2020. Sustainable water management for cross-border resources: The Balkhash Lake Basin of Central Asia, 1931–2015. Journal of Cleaner Production, 263(2020): 121614, doi: 10.1016/j.jclepro.2020.121614.

Duan W, Maskey S, Chaffe P, et al. 2021. Recent advancement in remote sensing technology for hydrology analysis and water resources management. Remote Sensing, 13(6): 1097, doi: 10.3390/rs13061097.

ESRI (Environmental Systems Research Institute). 2021. How to: Create contour lines based on values other than elevation points. [2021-07-31]. https://support.esri.com/en/technical-article/00001427.

Hoff H, Bonzi C, Joyce B, et al. 2011. A water resources planning tool for the Jordan River Basin. Water, 3: 718–736.

Kunstmann H, Suppan P, Heckl A, et al. 2007. Regional climate change in the Middle East and impact in hydrology in the upper Jordan catchment. In: Quantification and Reduction of Predictive Uncertainty for Sustainable Water Resources Management, Symposium HS2004 at IUGG2007. Perugia: IAHS Publication, 313: 141–148.

Meran G, Siehlow M, von Hirschhausen C. 2021. Integrated water resource management: Principles and applications. In: Andrey G K. Springer Water. Switzerland: Springer International Publishing, 23–121.

MWI (Ministry of Water and Irrigation). 2016a. Water Reallocation Policy. Amman: MWI, 1-17.

MWI (Ministry of Water and Irrigation). 2016b. National Water Strategy 2016-2025. Amman: MWI, 7-61.

MWI (Ministry of Water and Irrigation). 2016c. Surface Water Policy 2015-2025. Amman: MWI, 1-6.

MWI (Ministry of Water and Irrigation). 2019. Water Budget. Amman: MWI, 1-12.

Obeidat M, Awawdeh M, Lababneh A. 2019. Assessment of land use/land cover change and its environmental impacts using remote sensing and GIS techniques, Yarmouk River Basin, north Jordan. Arabian Journal of Geosciences, 12: 685.

Obeidat M, Awawdeh M, Al-Kharabsheh N, et al. 2020. Source identification of nitrate in the upper aquifer system of the Wadi Shueib catchment area in Jordan based on stable isotope composition. Journal of Arid Land, 13(4): 350-374.

Salameh E. 2004. Using environmental isotopes in the study of the recharge-discharge mechanisms of the Yarmouk catchment area in Jordan. Hydrogeology Journal, 12(4): 451-463.

Turc L. 1951. New formulas for the water balance according to the average annual values of precipitation and temperature. The Academy of Science (Paris), 233: 633-635.

UNICEF (The United Nations International Children’ s Emergency Fund). 2021. Water, sanitation and hygiene. UNICEF, Amman, Jordan. [2021-05-20]. https://www.unicef.org/jordan/water-sanitation-and-hygiene.

US Geological Survey. 2021. Earth explorer, data sets. [2021-04-15]. http://earthexplorer.usgs.gov.

WAJ (Water Authority of Jordan). 2019. Open Files of WAJ. Amman: WAJ, 1-6.

Note: Figure translations are in progress. See original paper for figures.