



Disaggregating SDG-6 water stress indicator at different spatial and temporal scales in Tunisia



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HIGHLIGHTS

- A data-driven method is presented to assess the UN SDG-6 water stress indicator.
- The method allows the spatial and temporal disaggregation of the indicator.
- Remotely sensed irrigation data was used as surrogate to governmental data.
- The Medjerda basin reached an increasingly severe water scarcity in recent years.

GRAPHICAL ABSTRACT



$$\text{Level of water stress} = \frac{\text{Water use}}{\text{Water resources} - \text{EFR}}$$

The disaggregation of indicator 6.4.2 at higher spatial and temporal scales is highly recommended

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ABSTRACT

The recently adopted UN Sustainable Development Goals (SDGs) encompasses a specific goal for water (SDG-6). The target 6.4 deals with water scarcity and refers to two main indicators: water use efficiency and water stress (WS), monitored by the UN statistical services yearly at the country level. Yet, for more efficient development planning, indicators should also be provided with higher spatial and temporal resolutions. This study presents a data-driven method allowing to disaggregate the WS indicator at higher spatial and temporal resolution. We applied the method for the Medjerda catchment in Tunisia, known as being severely water-stressed. We disaggregated the WS indicator from the overall catchment to the administrative regional level at yearly and monthly scales. In order to overcome poorly documented irrigation water withdrawals, two approaches were adopted: 1) we used yearly governmental data at both catchment and regions scales; 2) we replaced governmental irrigation data by remote sensing-based irrigation estimation. First Order Uncertainty Analysis (FOUA) was performed to characterize the uncertainty associated with the assessment of WS. Results reveal that the WS at the scale of the catchment increases considerably in recent years, exceeding 50% from 2005 and surpassing the 100% threshold in 2015 and 2016 (102%, 108% respectively). The two adopted approaches result in similar WS trends. However, the second approach yields higher WS values compared to the first approach (144% versus 108% in 2016). The monthly-disaggregated WS at catchment scale exhibits a similar increasing trend. The highest WS values are at the end of the fall and during the summer season, which is mainly due to the increasing demand for irrigation and drinking water. Siliana region is the most affected by WS, while Beja is the least affected. The FOUA shows that the integration of remote sensing-based irrigation data reduces the WS uncertainty.

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1. Introduction

In the past 50 years, water has become a limited resource in many nations all over the world. Nowadays, about 4 billion people face severe water stress at least one month per year, in particular in arid and semi-arid regions like in North Africa (Mekonnen and Hoekstra, 2016). According to FAO (2018), North African countries face severe water scarcity, which exerts a significant burden on the overall development of these countries.

Given the global water crisis, a specific goal dedicated to water (SDG-6) has been integrated in the recently adopted UN 2030 Agenda for Sustainable Development. The different targets and indicators of SDG-6 are linked to all water functions and services and considered to be important for sustaining life on Earth. Indicator 6.4.2 of target 6.4 measures the level of water stress (WS). It is a blue water WS indicator. It is defined as the ratio of total yearly national freshwater withdrawn by all sectors to the total of fresh blue water resources minus the Environmental Flow Requirements (EFR) (Vanham et al., 2018). The quality of the assessment of this indicator depends primarily on the quality of available water data. Governments generally use traditional hydrometric data to assess the WS indicator. Yet, traditional hydrometric data archives suffer from data gaps, incomplete time series, poor spatial resolution, often leading to poor quality databases. Alternatively, Remote Sensing (RS) offers hydrometric attributes with a high space-time resolution that may complete the poorly monitored national data such as precipitation, land cover and irrigation consumption. Yang et al. (2018) showed for instance that RS data could be used to estimate water consumption of ecosystems including arable lands using different evapotranspiration (ET) products such as MODIS. RS data can, therefore, be used to reduce the uncertainty in assessing the WS indicator of SDG-6. In addition, with the availability of new RS products and RS processing platforms such as the Google Earth Engine, a capacity exists to downscale SDG-6 indicators at higher spatial and temporal resolutions. This offers an opportunity to address the recommendation of Vanham et al. (2018) stating that more advanced monitoring levels of the WS indicator are needed. It offers also perspectives to support more efficiently regional water management design and planning. Yet the processing streams of RS based methods for assessing SDG-6 indicators have not been tested, and the final quality of the disaggregated indicators is not yet known.

The objective of this study is to present a data-driven method allowing to evaluate and disaggregate the SDG-6 indicator using traditional and RS based data products. We evaluate the method for the case study of the Medjerda catchment in Tunisia. Tunisia is considered as one of the most arid countries in the Mediterranean region, suffering from extreme water scarcity in recent years (FAO, 2018). Tunisia's Medjerda catchment represents the most important river basin in the country, however, it is highly affected by climate change and the pressure on its water resources is high. We assess the WS indicator at the scale of the entire Tunisian catchment and at the scale of four administrative regions (the "governorates") within the catchment (Jendouba, Beja, El kef and Siliana), both at the yearly and monthly time scales. Annual assessment of the WS indicator might not be sufficient enough to obtain insights into its intra-annual variations. Therefore, the disaggregation of the indicator at a monthly time scale is useful. The monthly assessment provides more knowledge about WS seasonality and its intra-annual variability which are not revealed by assessment at an annual temporal resolution (Degefu et al., 2018; Gain and Wada, 2014). We propose two data-driven approaches: (1) measurement using nationally produced data; and (2) measurement based on ET-derived irrigation water consumption as a substitute for governmental irrigation data. We include First Order Uncertainty Analysis (FUOA) to characterize in each approach the uncertainty in the measurement of WS resulting from uncertainties in the input data.

2. Materials and methods

2.1. Study area

Tunisia lies between the hot desert in the south and the Mediterranean in the north. It is dominated by arid and semi-arid climates and affected by limited water supplies. Most of the country's water resources are concentrated in the Medjerda river basin, which represents the most important catchment in the country. The upstream is located in the semi-arid Atlas Mountains of eastern Algeria and it runs over a distance of 312 km in the North of Tunisia. The study area lies in the sub-humid to the Mediterranean humid bio-climatic zone where the average annual rainfall is about 600 mm. It covers a total area of 23,700 km², of which 7870 km² (33%) are located in Algeria. The Medjerda river meets with "Mellegue River" coming from Algeria and its confluence is located in Jendouba Governorate in Tunisia, just before Sidi Salem Dam. This latter dam is one of the largest dams in the country (Fig. 1). The population within the Medjerda river basin was estimated to be 2 million in 2014 (14% of country's population, (INS, 2014)), while the basin occupies 9.8% of the land area of Tunisia. Agriculture represents the basin's major economic activity. In fact, most of the water resources are used for agricultural purposes (84%) and only about 10% is used for services and industries (Bouraoui et al., 2005). According to the Ministry of Agriculture (2005), the area of irrigated lands in the Medjerda is rapidly increasing over the years. It increased from 49,000 ha in 1987 to 260,000 ha in 2005. Irrigated lands are estimated to represent 9.4% of the total basin area putting considerable pressure on the available water resource very often leading to water scarcity. In addition to water shortage, water quality issues exert an additional burden on the water resource. The salinity of both surface and ground water, reduce the water quality in particular in the downstream coastal part of the catchment. Soil erosion further affects the long-term storage, capacity and water quality of dams. Additional pollution originates from urban areas, industries and agriculture practices that intensively use fertilizers and pesticides (Bouraoui et al., 2005). The Medjerda basin has a major economic importance in the country, it encompasses six Governorates: Ariana, Mannouba, Beja, Siliana, Jendouba and El Kef. The latter four Governorates are considered as the most "economically" and "hydrologically" sensitive regions of the Medjerda. The basin's contribution to the Tunisian economy is significant. According to the INS (2014), 51% of total national wheat production is cultivated in the basin, and around 60% of the population is provided with drinking water from the Sidi Salem reservoir.

2.2. Data sources

Data on river flow, available groundwater, and withdrawals for the irrigation, domestic and industrial sector are needed to assess the WS indicator for the Medjerda catchment.

Monthly and yearly data including averaged river flow of 9 hydrological stations (Fig. 1), groundwater recharge, irrigation, and industrial water withdrawal for all 6 Governorate of the Medjerda basin for the period of 2000–2016 were collected from the bulletins of the General Direction of Water Resources (DGRE) and the compilations made by the Regional Commissary for Agricultural Development (CRDA). Withdrawals for domestic and industrial consumption for the same period and at the same temporal and spatial scales were collected from the Water Exploitation and Distribution National Company (WEDNC, SONEDE).

Land cover (CCI_Landcover) and MODIS-ET data (Fig. S1) where combined to estimate monthly and yearly water consumption in the irrigation sector. Yearly Land Cover (LC) data at a spatial resolution of 300 m were provided by the ESA Climate Change Initiative (ESA-CCI, CCI-LC) (available at <http://maps.elie.ucl.ac.be/CCI/viewer/>) for the period of 1992 to 2015. The dataset is based on the MERIS FR and Reduced Resolution (RR) archive, and uses Advanced Very High-Resolution

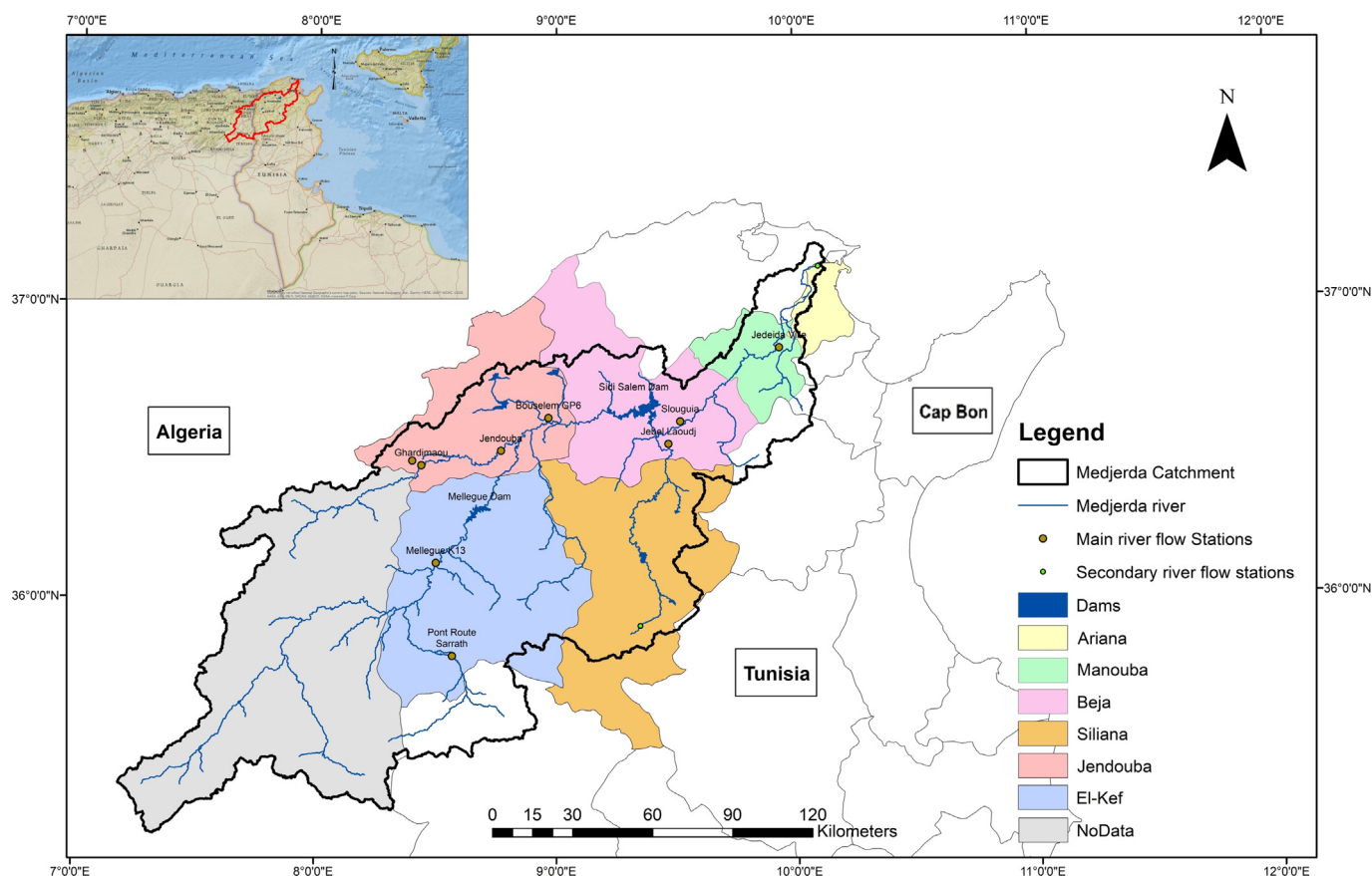


Fig. 1. The study area. The right down figure is the situation of the study area, while the inset yields the location of the study area in North Africa.

Radiometer (AVHRR), SPOT-Vegetation (SPOT-VGT) and Project for On-Board Autonomy (PROBA-V, with the V standing for Vegetation) for LC change detection (Bontemps et al., 2013) sensor data. The MODIS-ET is a product of the National Aeronautics and Space Administration (NASA) under a project to estimate global terrestrial ET from remote sensing data. It is based on the improved ET algorithm by Mu et al. (2011) which uses the Penman-Monteith equation (Monteith, 1965). Data were extracted using the Google Earth Engine (GEE) at 500 m spatial resolution and at 8-day time step for the entire Medjerda catchment. Data were aggregated at monthly and yearly scales in order to match the time scale of the WS indicator.

2.3. Estimation of irrigated lands' water consumption

At the scale of the Medjerda catchment, the information about the monthly irrigation water withdrawal is not consistent and limited as it doesn't cover all the Medjerda regions, only yearly data were delivered by the DGRE for all the Medjerda regions. Yang et al. (2018) used different ET products to estimate water consumption of different ecosystems at a basin scale, considering ET as a substitute for water consumption. We, therefore, adopted ET in irrigated land as a surrogate for irrigation water consumption. This will improve the calculation of WS indicator at different temporal and spatial scales, in particular at monthly scale for the whole catchment and its subregions. Irrigated land was estimated from the land cover map (CCI-LC 300 m). Land cover was considered to be constant within a year, and we adopted the land cover of 2016 as the same land cover for 2015 due to the unavailability of the 2016 CCI-LC product at the time of processing. ArcGIS software was used to assess yearly and monthly mean ET over irrigated lands. The LC-300 m and ET-500 m images (Table S1) were resampled in a

100 m frame in advance in order to avoid processing errors. Yearly and monthly water consumption of irrigated lands in the entire basin and the regions within was determined from the product of the average water consumption per pixel and the number of pixels (Yang et al., 2018).

$$U_{Irrig,RS} = V_{pp} \times N_p \quad (1)$$

with $U_{Irrig,RS}$, estimated water consumption of irrigated lands; V_{pp} , average water consumption per pixel, and N_p , number of pixels.

Irrigation efficiency in the Medjerda region was taken into account in this assessment, irrigation water which have been lost through drainage systems, infiltration and through leakage in the irrigation networks should be added to the volume of evapotranspiration from irrigation lands in order to have a realistic estimation of irrigation water consumption in the Medjerda region. According to Dhahbi (2018), irrigation efficiency at the perimeter level in the Medjerda catchment ranged from 60% to 45% during the 2000–2016 period, which means 40% to 55% of irrigation water was lost in the system. The irrigation network in the basin performed well in the early 2000s with an efficiency of 60% as it was newly operational following the launch of new irrigated lands. However, in recent years, the efficiency decreased to reach 45% due to the lack of maintenance of the irrigation network and the absence of operational systems of irrigation water management (Dhahbi, 2018). Hence, this irrigation efficiency range (60% to 45%) was added to the estimated volume of evapotranspiration at the scale of the irrigated lands of the Medjerda catchment and its subregions with a decrease of 1% each year of the 2000–2016 period. Although there is no available official assessment of monthly irrigation efficiency in the Medjerda, we adopted for the monthly scale the same efficiency as each year of the study period (2000–2016).

2.4. SDG-6 water stress indicator

The WS indicator measures the level of water stress and is defined as the freshwater withdrawal as a proportion of available freshwater resources (WHO, UNISEF, and JMP, 2016). It is computed as follows:

$$WS (\%) = \frac{TFWW}{TRWR - EFR} \times 100 \quad (2)$$

with TFWW, the total freshwater withdrawn ($m^3/year$); TRWR, the total renewable water resources ($m^3/year$); and EFR, the environmental flow requirements ($m^3/year$). The TFWW represents the sum of the water withdrawal of the three main sectors in the Medjerda catchment, i.e. the agricultural, the services (drinking water distribution) and industrial sector. In this research, we focus on the agricultural sector as the irrigation water consumption, it represents the major water consumer in the basin. The domestic and industrial sectors exert pressure on the water resources of the catchment as well. Domestic water demand increases significantly at the end of the spring and during the summer season as the available water resources in dams and easily accessible groundwater decrease. Similarly, the industrial water use in the catchment is significant during the same period of the year as most of the existing industries are agri-food industries. They reach the peak of water consumption during the summer season. The TRWR refers to the maximum theoretical yearly amount of renewable freshwater available for the basin and the regions within. It is expressed as the sum of Internal (IRWR) and External Renewable Water Resources (ERWR) (FAO, 2017):

$$TRWR = IRWR + ERWR \quad (3)$$

IRWR is defined as the sum of the Surface Water Produced Internally, SW_p , and the groundwater recharge, GW_R . The exchange between surface water and groundwater ($Q_{Overlap}$) is subtracted to avoid overestimation of TRWR (FAO, 2017). SW_p represents the sum of average annual of monthly exploited water of dams and the flow of rivers generated internally in the basin measured by official stations in each governorate located in the basin. GW_R is delivered by the "Direction Générale des Ressources en Eau (DGRE)" at yearly and monthly scales. GW_R is estimated by the DGRE based on their piezometric archive for each aquifer in the basin. In the case of the Medjerda basin, $Q_{Overlap}$ is set to 30% of the groundwater recharge according to the hydrogeological archives of the DGRE. IRWR is computed then as:

$$IRWR = SW_p + GW_R - (Q_{Overlap}) \quad (4)$$

ERWR represent the part of average annual or monthly renewable water resources that are not generated in the basin (FAO, 2017). The equation is then:

$$ERWR = SW_{IN} - SW_{OUT} \quad (5)$$

with SW_{IN} , the volume of surface water entering the basin or a region per time step ($m^3/year$); and SW_{OUT} , the volume of surface water leaving the basin or a region per time step ($m^3/year$).

At the scale of the entire basin, SW_{IN} encompasses the average annual or monthly flow entering the basin from Ghardimaou station right at the border with Algeria and from the Mellegue station (30 km away from the border), which measures the flow of Mellegue river entering the basin before connecting with the Medjerda. We did not perform a specific modeling to estimate the discharge of Mellegue river right at the border with Algeria given the significantly low flow ($0.10 m^3/s$ average annual) coming from the tributaries before the Mellegue station (Sarrath river and two small streams).

The Environmental Flow Requirements (EFR) is defined as the quantity, quality and timing of water flows needed to maintain the components, functions, processes, and resilience of aquatic ecosystems that

provide goods and services to people, where flows are regulated (Hirji and Davis, 2009). The explicit inclusion of EFR in the equation of SDG-6 WS indicator increases the reliability of the indicator and its usefulness as a tool to enhance informed water management decisions (FAO, 2017) and it is a key requirement for maintaining freshwater populations and habitats (Vanham et al., 2018). The quantification of EFR can be achieved through different methods grouped in literature into three categories: hydrological, hydraulic-habitat and holistic methods (Tharme, 2003; European Commission, 2015; Sood et al., 2017; Pastor et al., 2014). According to Vanham et al. (2018), hydrological methods are considered to be highly recommended at the planning level of water resource management. In our case, we adopted the hydrological method to quantify the EFR in the Medjerda basin. Pastor et al. (2014) proposed that, globally, EFR for "fair" ecological conditions ranges between 25% and 46% of the mean annual flow. For the annual assessment of the WS, we propose EFR as 45% of the mean annual flow according to the hydrological bulletins of the DGRE. For the monthly assessments, we adopted the "Variable Monthly Flow (VMF)" method (Pastor et al., 2014; Fasel et al., 2016), which considers the classification of months into three groups: the low, intermediate and high-flow seasons. These groups are based on the monthly flow variability compared to the mean annual flow. During low-flow months (Jun, July, August, and September), we fixed EFR as 65% of the mean monthly flow. For the intermediate period (October, November, December, and January) we adopted 45% and for the high-flow season (February, March, April, and Mai) EFR was fixed as 30%. These definitions of EFR represent a default environmental protection policy implying the lowest level of recommended protection from a water management perspective (Smakhtin et al., 2004).

Substituting Eqs. (3), (4) and (5) in Eq. (2) yields:

$$WS (\%) = \frac{U_{irrig} + U_{Indus} + U_{Serv}}{(SW_p + GW_R - (Q_{Overlap})) + (SW_{IN} - SW_{OUT})} - EFR \times 100 \quad (6)$$

with U_{irrig} , the irrigation water use ($m^3/year$); U_{Indus} , the industries water use ($m^3/year$); and U_{Serv} , the water use for other services ($m^3/year$).

In order to improve the calculation method of WS indicator at different temporal and spatial scales compared to the existing approaches (UN-Water, 2015), two methods were adopted based on two different data sources: a method using only governmental data and a method based on the estimated water consumption of irrigated lands ($U_{irrig,RS}$) as a surrogate for governmental irrigation data. Therefore, Eq. (6) yields:

$$WS_{Gov} (\%) = \frac{U_{irrig, Gov} + U_{Indus} + U_{Serv}}{(SW_p + GW_R - (Q_{Overlap})) + (SW_{IN} - SW_{OUT})} - EFR \times 100 \quad (7)$$

with $U_{irrig, Gov}$, governmental irrigation data.
And,

$$WS_{RS} (\%) = \frac{U_{irrig, RS} + U_{Indus} + U_{Serv}}{(SW_p + GW_R - (Q_{Overlap})) + (SW_{IN} - SW_{OUT})} - EFR \times 100 \quad (8)$$

Eqs. (7) and (8) of WS were used to compute the indicator at yearly scale for the whole catchment and its subregions. For the temporal disaggregation, we used Eq. (8) to measure monthly WS at the same spatial scales.

2.5. First-order uncertainty analysis

First-order uncertainty analysis (FOUA) is a widely used technique for estimating the uncertainty in a deterministic model generated by the uncertainty in the parameters (Loague et al., 1989). The theoretical

basis and limitations of FOUA are detailed and described by Cornell (1972). In order to determine the total uncertainty in the WS indicator at yearly scale through FOUA, uncertainty measurement for each parameter is required. In this study, the uncertainties in U_{irrig} , U_{Indus} , U_{Serv} , SW_P , GW_R , SW_{IN} , and SW_{OUT} are included in the FOUA of WS indicator, hence, this application yields:

$$\overline{WS(\%)} = \frac{1}{\left(\frac{\overline{U_{irrig}} + \overline{U_{Indus}} + \overline{U_{Serv}}}{\overline{SW_P} + \overline{GW_R} - \overline{Q_{Overlap}}} \right) + \left(\overline{SW_{IN}} - \overline{SW_{OUT}} \right)} - \overline{EFR} \times 100 \tag{9}$$

where the overbars designate mean values and $\underline{\quad}$ signify equal in the first order sense. The uncertainty contributed by the i_{th} parameter is given by:

$$C_i = \left| \frac{\partial WS}{\partial P_i} \right| S_{P_i} \tag{10}$$

where S_{P_i} represents the standard deviation of the parameter P_i . For this study, we used available monthly and yearly data of U_{irrig} , U_{Indus} , U_{Serv} , SW_P , GW_R , SW_{IN} , and SW_{OUT} from our reference database to compute the mean and variance. S_{P_i} was determined for each parameter at the yearly scale. Although S_{P_i} does not include all the uncertainty sources that might interfere directly in the measurement of the parameters such as errors related to gauging equipment and the observations, it represents the interannual variability of each dataset, which contains a part of uncertainty sources.

The total uncertainty in WS indicator is:

$$S_{WS} = \left(\sum_{i=1}^n C_i^2 \right)^{1/2} \tag{11}$$

We adopted both of the governmental irrigation data ($U_{irrig, Gov}$) and the estimated irrigation consumption ($U_{irrig, RS}$) to yield the total uncertainty in the WS indicator for both approaches ($S_{WS (Gov)}$ and $S_{WS (RS)}$). Therefore, comparison can be made to assess the added value of the estimated irrigation data in the calculation of the WS indicator (Section 3.4).

3. Results and discussion

3.1. WS estimates at basin and administrative region scale using governmental data

Fig. 2 shows the yearly WS at the scale of the Medjerda catchment for the period 2000–2016. It follows a significant increasing trend (Mann-Kendall trend test, $P_{value} < 0.05$). Lowest values of WS were in the early 2000s with only 30% of WS in 2000 and 36%, 41% and 42% of WS in 2001, 2002 and 2003 respectively. This low level of WS is a result

of the low demand for irrigation (only 117.44 Mm³ in 2000), the presence of important hydrological events (especially between 2002 and 2003), and the low population in the Medjerda in that period (around 950,000 thousand in 2004 according to the (INS, 2014)) which implies lower water demand for drinking water provision. For the period from 2004 to 2012, the WS increased and ranged between 50% and 64%. This increase is consistent with a population increase during that period, as well as the increase of demand for irrigation and the rapid expansion of irrigated lands. Since the year 2011, the WS increased further to reach 72% in 2013 and to exceed 100% in 2015 and 2016 (102% and 108% respectively). This fast increase of WS is a result of a high increase of irrigation demand (319 Mm³ and 291 Mm³ in 2016 and 2015 respectively versus 117 Mm³ in 2000) in the basin and from neighboring regions such as Cap Bon connected to the Medjerda hydrosystem since 1982 through the Medjerda-Cap Bon channel. In this study, the volume of water withdrawn by the Cap Bon region was not included due to the non-availability of public data. In addition, an increase of the domestic demand influences the level of WS as the population grew significantly in the basin (around 2 million in 2014). The industrial withdrawal in the basin wasn't significantly affected during the 2000–2016 period and remained stable between 4.5 Mm³ and 6 Mm³ per year. The increasing demand, mainly from the irrigation and domestic sectors, results in excessive exploitation of the available water resources. About 90% of the groundwater resource of the Medjerda aquifers were overexploited in 2015 and 2016 (DGRE, 2016). FAO (2017) and Vanham et al. (2018), consider "serious water scarcity" when the WS exceeds 70%. Hence, the Medjerda catchment suffers from serious water scarcity since 2013.

Different WS patterns are obtained when disaggregating the indicator at the level of four regions within the basin (Fig. 3).

The yearly spatial distribution of WS followed a significant increasing trend ($P_{value} < 0.05$) in Jendouba, Beja and El Kef (Fig. 3a, b, c). However, in Siliana (Fig. 3d) the time course of the WS was very irregular marked with peaks, illustrating the dependence of the WS on the hydrologic regime of the Siliana river which flows into the Medjerda at Laouedj Station in Beja. The WS reached 70% (severe water scarcity) only in El Kef in 2016 and in Siliana in the majority of the period 2000–2016 with an increasing trend since 2013 (Fig. 3d). Jendouba and Beja regions didn't reach the severe water scarcity situation over the entire period of 2000–2016. The critical situation in the Siliana region is related to the overexploitation of aquifers (100% of which are over exploited) as well as the decrease in the capacity of dams (the Lakhmes, Rmil and Siliana Dams). The dams in the Siliana region are exclusively dedicated to irrigation. They collect particle laden surface waters, drained from basins that are subjected to poor erosion management. Hence, these dams are prone to sedimentation and reduction of freshwater storage capacity. Many factors may contribute to these different spatial patterns of WS in the Medjerda subregions. First, the water resources of each region vary greatly, in terms of the number of dams and the average annual discharge of rivers. For instance, Jendouba region contains 3 main dams (Bouhertma, Kesseb, and Bni Mtir) dedicated to domestic water supply and irrigation. The average annual discharge of the Medjerda river in Jendouba is 10 m³/s in the period 2000–2016. In contrast, El Kef region contains only one dam (Mellegue dam) and depends on Mellegue river and the Sarrath stream, with an average annual discharge of 6 m³/s and 0.8 m³/s respectively for the period 2000–2016. Second, the irrigation demand varies between the regions depending on the available irrigated lands. The highest irrigation demand is in Beja region with 150 Mm³ in 2016 compared to Jendouba, El Kef, and Siliana with 15 Mm³, 42 Mm³, and 43 Mm³ respectively. Another important factor of the high variation of WS between regions is the different domestic water demand, which depends on the population of each region. The demand in Jendouba region is the highest of the 4 regions with 12 Mm³ in 2016 compared to Beja, El Kef and Siliana with 11 Mm³, 8 Mm³ and 7 Mm³ respectively.

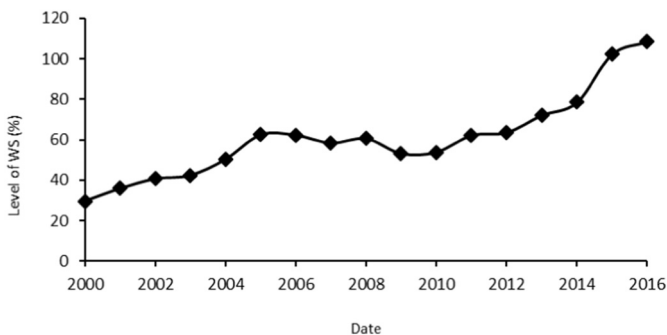


Fig. 2. Yearly WS at the scale of the Medjerda catchment.

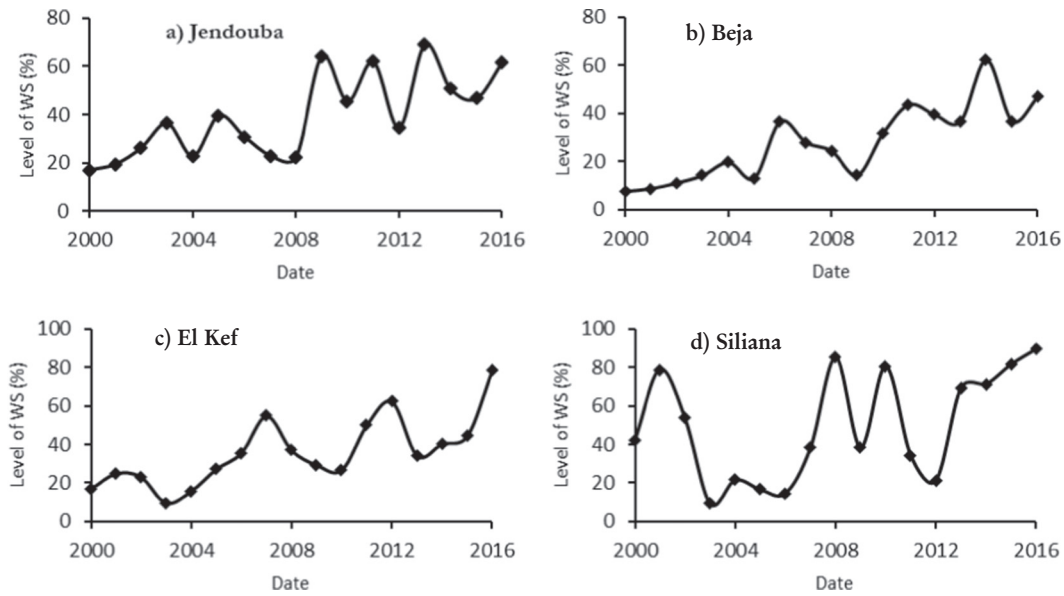


Fig. 3. Yearly WS at the scale of the administrative regions.

3.2. Governmental data vs. RS data-based irrigation water consumption and WS estimates

Fig. 4 compares the yearly estimated irrigation water consumption to the data provided by governmental at the scale of the entire Medjerda basin. We mark the presence of significant differences between the values coming from both data streams. The differences decrease with time. This may lead to the assumption that the remote sensing method tends to overestimate irrigation water consumption. The differences in estimated water consumption data with both methods can be due to many reasons. First, governmental data don't provide highly accurate measurements of irrigation withdrawal in the basin. According to the DGRE hydrological bulletins, the provided data don't account the illegal water withdrawn from surface and groundwater. Such illegal withdraws have been regularly reported in the basin, in particular since the early 2000s. Second, our estimation of irrigation water withdrawal take into account the irrigation efficiency which ranges from 60% to 45% for the period 2000–2016 (Dhahbi, 2018) which adds 40% to 55% (water lost through the irrigation systems) to the volume of evapotranspiration from the irrigated lands in basin (Section 3.3).

Estimated irrigation withdrawals were integrated into the assessment of the WS indicator at both yearly and monthly temporal resolutions for the entire Medjerda catchment and Jendouba, Beja, El kef and Siliana regions. Fig. 5, compares the estimated yearly WS values based

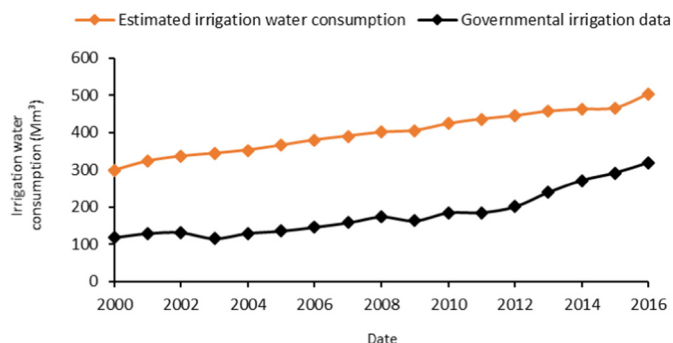


Fig. 4. Comparison of yearly irrigation water consumption.

on remote sensing and governmental data. At the scale of the whole catchment, both approaches lead to an increasing WS trend ($P_{\text{value}} < 0.05$), with higher WS values when remote sensing data are used. The WS level reached 71.8% (sever water scarcity) in 2004 and exceeded 100% in 2011 (102.31%).

At the regions' scale (Fig. 6), similar observations can be made. Both methods follow the same pattern and trend ($P_{\text{value}} < 0.05$) for the entire period with higher WS values using remote sensing data.

This increasing trend of yearly WS is mainly due to the increasing demand for irrigation, domestic and industrial water consumption in the period 2000–2016, which is directly related to the expansion of irrigated lands and the important population growth at the scale of the catchment and its subregions.

3.3. Disaggregating yearly WS estimates

The monthly disaggregation of the WS indicator at the scale of the entire basin is shown in Fig. 7. There is a significant trend ($P_{\text{value}} < 0.05$) of increasing WS with a clear seasonal pattern for the whole period. We observed higher levels at the end of the spring season (May) and the entire summer season (Jun, July, and August). Severe water stress ($WS > 70\%$) is reached mainly in summer (dry season) due to the increase of irrigation withdrawals, domestic and industrial water consumption and the decrease of precipitation.

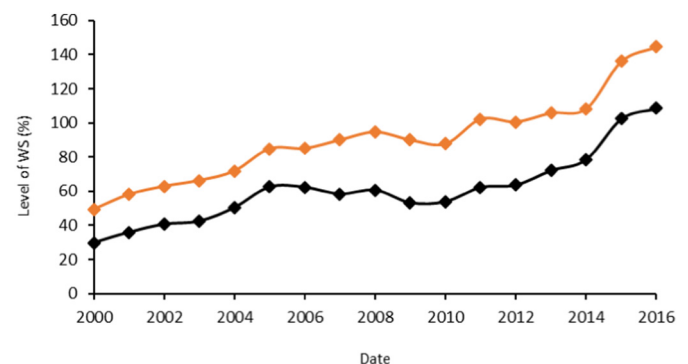


Fig. 5. Level of WS at the scale of the Medjerda (black color refers to WS using only governmental data and the orange refers to WS that includes estimated irrigation).

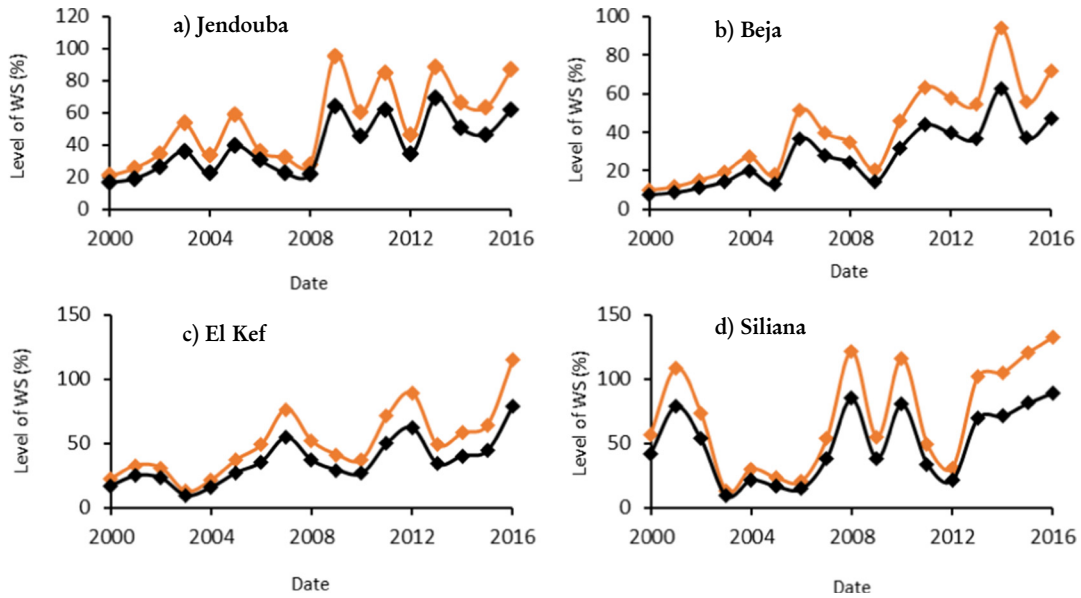


Fig. 6. Comparison of Level of WS at the scale of Medjerda subregions.

Monthly-disaggregated WS data for the smaller Medjerda regions (Fig. 8) showed a slightly less seasonal behavior with more significant irregularities in Siliana region (Fig. 8d) which confirms the dependence of the WS on the hydrologic regime of the Siliana river. Yet, the higher values of WS at the end of the spring season and the entire summer season are consistent with the assessment at the scale of the entire Medjerda basin.

The seasonal behavior of WS at the scale of the Medjerda catchment and the regions within is mainly due to the seasonality in the irrigation water consumption. In addition, the domestic and industrial water withdrawals are marked by a similar pattern with a rise at the end of spring and during the summer season, which contributed to the specific dynamic behavior of WS.

3.4. Uncertainty analysis (UA)

The contribution of each input parameter to the uncertainty in yearly WS at the scale of the Medjerda is summarized in Table 1.

The greatest uncertainty in WS assessment is contributed by the mean annual flow parameters (SW_{in} , SW_{out} , and SW_P), which is due to

the high seasonal variability of discharge measurements in the study area. GW_R , U_{indus} , and U_{serv} contributed less to the uncertainty in the WS assessment. Indeed, these parameters exhibit low seasonal variability. Irrigation water withdrawal provided by governmental data ($U_{irrig, GOV}$) contributed also to less uncertainty. However, since 2012, the uncertainty in this parameter increased significantly. This is mainly due to the higher seasonal variability of $U_{irrig, GOV}$ in that period marked by high irrigation demands in Jendouba and Siliana regions.

The estimated irrigation water consumption ($U_{irrig, RS}$) was included in the UA as well, Table 1 and Fig. S2, show that the remote sensing method contributed slightly more uncertainty than the governmental data until the year 2012, and significantly less uncertainty in the last four years.

The total calculated WS uncertainty (S_{WS}), both for assessments based on remote sensing ($S_{WS (RS)}$) and governmental data ($S_{WS (GOV)}$) is shown in Table 1 and Fig. S3. The WS uncertainty for both approaches follows the same pattern and trend with slightly higher values of uncertainty when governmental irrigation withdrawal data are used. Therefore, the inclusion of remote sensing based irrigation water consumption data does not only allow to downscale WS assessments

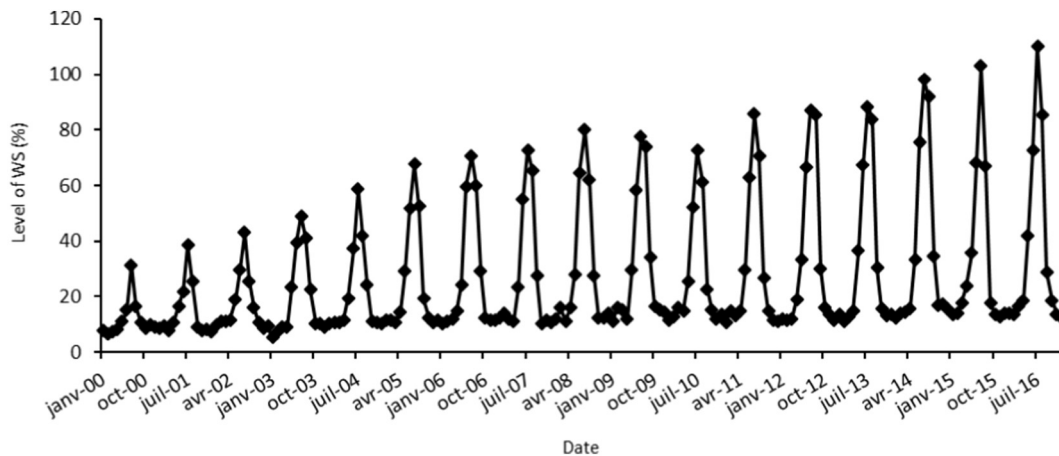


Fig. 7. Monthly distribution of WS at the scale of Medjerda catchment.

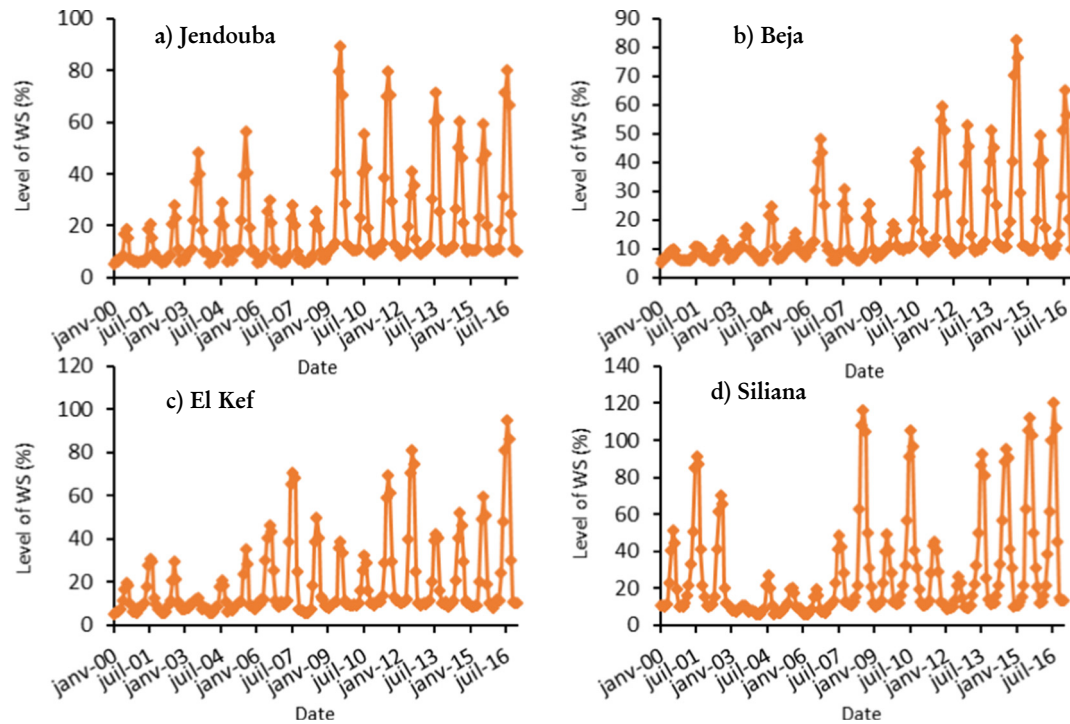


Fig. 8. Monthly distribution of WS at the scale of Medjerda subregions.

to the regional and monthly scale but also reduces the total uncertainty in the WS assessments.

4. Conclusion

We disaggregated in this study the SDG-6 WS indicator for the Tunisian case study of the Medjerda catchment at different spatial and temporal scales. The disaggregation was conducted by the means of two approaches to assess irrigation water withdrawals. The major conclusions are as follows:

- (1) Yearly WS in the Medjerda basin showed an increasing trend for the period 2000–2016. The level of WS remained acceptable for the first four years with 42% in 2003. However, from 2004 to 2012, WS ranged between 50% and 64%. In the last four years of the period, WS reached 70% (72% in 2013) and exceeded 100% in 2015 and 2016 (102% and 108% respectively), which considers the Medjerda catchment to be in a

situation of severe water scarcity.

- (2) The pattern of yearly WS at a finer spatial scale of the regions Jendouba, Beja, EL Kef, and Siliana followed, in general, the same increasing trend as the entire Medjerda. The level of WS reached 70% only in El Kef (79% in 2016) and Siliana. The Silianan subregion showed a different response in WS than the other subregions.
- (3) Irrigation water consumption was estimated using MODIS-ET and CCI Land Cover (CCI-LC) products at the scale of the entire catchment and the subregions. The irrigation water consumption assessment method based on remote sensing provided slightly higher yearly values of irrigation water than the governmental data.
- (4) Yearly WS assessments based on governmental and remote sensing approaches were compared. As well at the catchment and at the subregion scale, both assessments showed the same increasing pattern for the entire period. The monthly assessment of WS at the scale of the entire basin exhibited a seasonal

Table 1

Parameter contribution to the uncertainty in WS assessment at the scale of the Medjerda catchment.

Pi	C1 (SW _{IN})	C2 (SW _{OUT})	C3 (GW _R)	C4 (U _{Irrig, gov})	C5 (U _{Irrig, RS})	C5 (U _{Indus})	C6 (U _{Serv})	C7 (SW _P)	S _{ws} (GOV)	S _{ws} (RS)
2016	30.31%	20.18%	3.14%	7.83%	3.23%	0.18%	0.48%	22.51%	43.64%	41.76%
2015	28.23%	20.02%	3.00%	6.35%	3.10%	0.17%	0.46%	30.57%	46.71%	44.22%
2014	21.89%	21.72%	1.79%	4.20%	3.12%	0.13%	0.42%	20.19%	37.14%	35.12%
2013	28.46%	14.44%	1.63%	3.11%	2.05%	0.14%	0.48%	16.81%	36.24%	34.85%
2012	29.92%	19.02%	1.43%	2.03%	2.92%	0.12%	0.51%	23.00%	42.34%	40.90%
2011	24.58%	25.84%	1.56%	1.96%	3.15%	0.13%	0.44%	19.91%	40.92%	39.80%
2010	18.32%	3.79%	1.22%	1.64%	2.37%	0.11%	0.35%	15.60%	24.45%	21.34%
2009	23.37%	23.61%	1.27%	1.56%	3.10%	0.11%	0.40%	20.29%	38.98%	37.51%
2008	19.90%	2.03%	1.64%	1.75%	1.94%	0.13%	0.44%	16.97%	26.34%	23.05%
2007	10.30%	15.92%	1.60%	1.72%	3.27%	0.13%	0.37%	21.94%	29.10%	24.12%
2006	21.33%	23.26%	1.91%	1.72%	2.40%	0.14%	0.44%	26.22%	41.12%	38.59%
2005	23.23%	21.54%	1.98%	1.61%	1.70%	0.14%	0.54%	28.44%	42.66%	39.89%
2004	26.60%	26.21%	1.35%	1.25%	2.17%	0.11%	0.41%	18.86%	41.88%	40.99%
2003	25.36%	20.25%	1.01%	0.93%	2.57%	0.10%	0.37%	20.97%	38.67%	36.97%
2002	18.69%	17.48%	0.86%	1.03%	2.49%	0.11%	0.25%	13.02%	28.75%	27.43%
2001	14.96%	5.50%	0.67%	0.89%	2.23%	0.09%	0.23%	11.14%	19.48%	17.35%
2000	23.11%	3.40%	0.48%	0.64%	2.23%	0.08%	0.19%	9.68%	25.30%	24.41%

pattern and an increasing trend over time. At the spatial scale of the subregions, the seasonal pattern of WS was less pronounced. The highest values of WS were at the end of the fall and during the summer.

- (5) FOUA was utilized to characterize the uncertainty contribution of each parameter in the WS indicator. Results showed that river flow data contributed the most to the total uncertainty (S_{WS}) due to its high seasonal variability in the period 2000–2016. The uncertainty on WS assessed using governmental ($S_{WS (GOV)}$) and RS data ($S_{WS (RS)}$) were compared. The comparison showed that the uncertainty of WS using RS data was smaller as compared to the uncertainty of WS using governmental data. Therefore, the inclusion of the estimated irrigation water consumption based on RS data reduced the total uncertainty in the indicator.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2019.133766>.

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