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Quantitative Impact of Monthly Precipitation on Urban Vegetation, Surface Water and Potential Evapotranspiration in Baghdad Under Wet and Dry Conditions

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ABSTRACT

Precipitation is a fundamental variable that is widely used in the organization of water resources and has a great influence on hydrological processes and ecological assessment. This study investigated the quantitative effect of monthly precipitation on surface water area (denoted by the Modified Normalized Difference Water Index, MNDWI), vegetation area (denoted by Normalized Difference Vegetation Index, NDVI), and potential evapotranspiration (PET) during two years (2018 and 2021) in the city of Baghdad, Iraq. Using the Thornthwaite aridity index, the annual aridity was first assessed to quantify the climate category of these years. The result shows that they were semi-arid and very arid, respectively. The empirical relationships between precipitation and areas of MNDWI and NDVI, and between rainfall and PET, were also examined. Due to less precipitation in 2021, no relationship was found in arid climates, while in 2018 for semi-arid climates, precipitation had a positive non-linear correlation with MNDWI and NDVI areas and a negative correlation with PET.

INTRODUCTION

Baghdad, the federal administrative capital of Iraq, is one of the world's megacities characterized by high rainfall variability during only eight months of the year (from October to May) (Muter et al. 2024) and sparse natural surface water bodies, including the Tigris River and small ponds (Mahdi et al. 2024). It is therefore highly sensitive to anthropogenic activities, including high continuous population, urbanization, and land use change. However, climate change could affect the intensity and frequency of precipitation in any region, especially in continental regions such as Baghdad. Therefore, the city was subjected to severe warming effects (Al-Jiboori et al. 2020, Wahab et al. 2022) and the continuous increase in air temperature exacerbates the drought event, so the aridity (or dryness) index is used to quantify the degree of dryness of a climate at a given space and time.

Precipitation is the fall of water in any form (rain, fog, snow, etc.) to the earth's surface in all weather conditions. Precipitation is the main source of soil and surface water, and is a major hydrological factor and an important meteorological metric for determining vegetation growth, maintaining surface flows and groundwater resources, and linking atmospheric and land surface processes (Zeppel et al. 2014, Shi et al. 2016, Naqi et al. 2021). Precipitation also plays a key role in water resources, soil moisture, and potential evapotranspiration (PET). Most aridity index (AI) calculation methods rely mainly on precipitation as an active driver. Highly variable precipitation may not only have direct effects on vegetation growth and water body size but also on local climate conditions (Fay et al. 2011, Halos et al. 2017). Consequently, precipitation may also affect PET, which represents water lost to the atmosphere from different surfaces composed of water and vegetation through evaporation and transpiration (Zhang & Wang 2021). Reductions in vegetation and water areas often lead to increased rates of PET, especially in months with clear skies. This leads to complex relationships between vegetation, surface water, and PET (Adams et al. 2011). However, few researchers have investigated monthly variations across the year, and even fewer have considered the effect of precipitation on vegetation, water, and PET in the same months. This study provides detailed knowledge on these issues for ecosystem resilience to precipitation variability in arid and semi-arid environments.

Water scarcity and vegetation degradation are likely to threaten natural ecosystems and have caused adverse problems for agriculture and industry (Ingrao et al. 2023). Therefore, it is essential to study the quantitative relationships between precipitation, vegetation cover, surface water, and PET, especially their correlation with precipitation variability. Many researchers have investigated these issues for some water bodies. For example, Yan et al. (2017) investigated the response of vegetation growth to precipitation patterns in the Huang-Huai-Hai River basin, in China. They showed that vegetation cover and precipitation have a similar spatial distribution in arid and semi-arid areas, which are characterized by sparse vegetation. When there is less precipitation, surface water areas and vegetation cover are limited. Therefore, the expansion of surface water and vegetation growth can be considered an important reflection of changes in precipitation. Seasonal changes in accumulative precipitation during the year: winter, spring, summer, and autumn were investigated by Zeppel et al. (2014) who found that precipitation had a more dramatic effect on plants in summer than in winter. However, these changes in warm or dry seasons may have greater effects than changes in cool or wet seasons. Based on the Landsat satellite imagery, the seasonal effects of precipitation on the spectral values of the vegetation pixel were investigated by Jaber et al. (2020) for four seasons of 2019 for the same site. Finally, Salwa et al. (2020) also investigated this effect on vegetated areas, but only for two seasons (winter and summer) of three years: 2008, 2013 and 2019. Overall, the last two studies showed that vegetation growth was highly correlated with their monitoring during the current seasons. More recently, Olivares et al. (2021) studied the relationship between normalized difference vegetation index (NDVI), rainfall, and PET in banana plantations in Venezuela for the period January/2016 to December/2017. They showed that there was a delay of 1 month in plant growth response to changes in rainfall and drought conditions, but the low spatial resolution (i.e. 250 m) NDVI derived from MODIS Terra product is not sufficient to identify plant activity. Here, we describe the quantitative impact of highly variable monthly precipitation on surface water and NDVI derived from high resolution (i.e. 10 m) satellite Sentienl-2 and PET under quite different weather conditions, addressing a key research gap in this paper of deeper understanding to derive their empirical relationships. The main objectives of this study were to 1) classify the type of the two years 2018 and 2021 as dry or wet according to AI, 2) analyze the monthly values of vegetation cover area, surface water area and PET in these years, and finally 3) investigate the statistical relationships describing the effects of precipitation on vegetation, surface water and PET under wet and dry conditions.

STUDY SITE AND DATA

Baghdad is located in the center of Iraq, on the Tigris River at the confluence with the Euphrates River, 40 km away. It

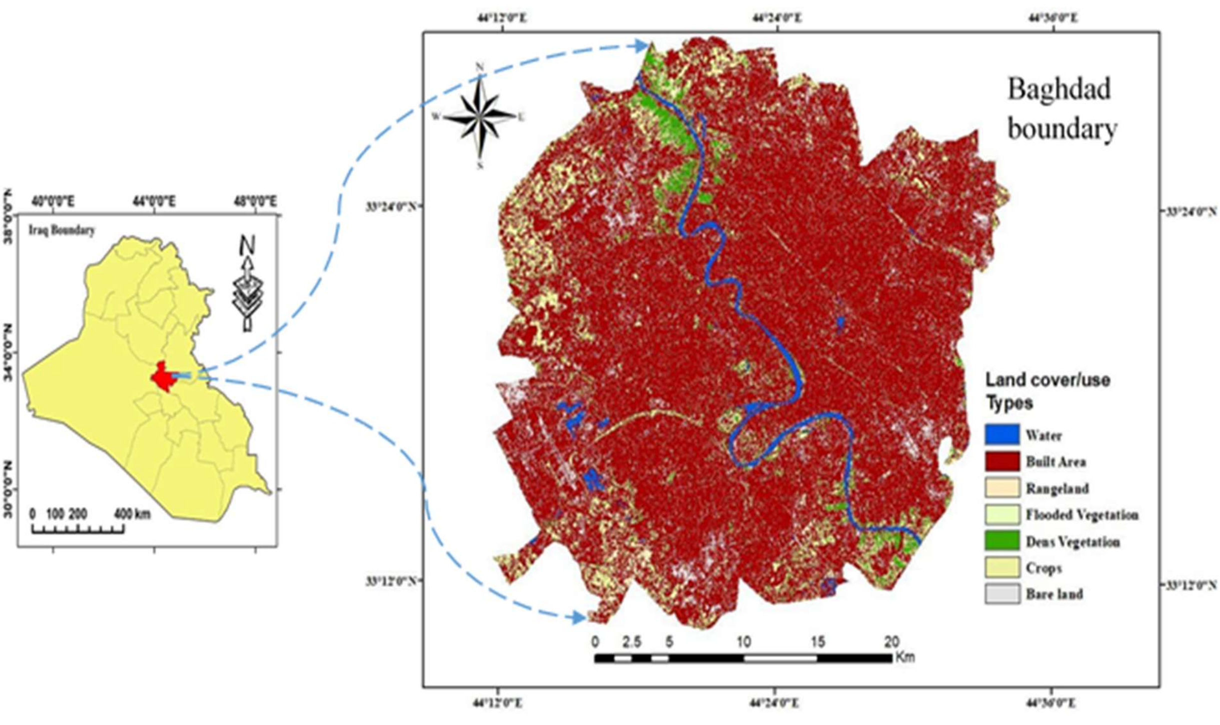

Fig. 1: Map of Iraq (left) and the study area of this study (right).

covers an area of 894.3 km^2, which is 0.2% of the total area of Iraq (see Fig. 1). It extends from 33°12' to 33°29' N and from 44°1' to 44°36' E, with an average elevation of 34 m above sea level. The city stretches along two banks of the Tigris River with a length of about 60 km. The eastern side (called Rusafa) has a high population density but with small and low (1-2 stores) residential buildings, while the western side (called Karkh) has a low population and high buildings. There are also seven bridges connecting the two sides. Due to Baghdad's land being flat with low-lying plains, groundwater with an average depth of 5 m and some small surface water are found within the city as shown in Fig. 1, where urban vegetation is composed of forest of tall trees (like palm) in the north and green areas such as parks, household gardens, sparse shading trees (like eucalyptus, buckthorn, etc.). The city's climate is hot and dry in summer and cool and wet in winter. The spring and autumn seasons are short but pleasant. The average annual temperature, relative humidity, and wind speed reach 27°C, 40%, and 3.5 m/s respectively. Rainfall is scarce with an average of 140 mm per year and falls mainly between December and April, with no summer rainfall.

Precipitation data obtained through direct measurement from weather stations is the most accurate and widely used data. Monthly meteorological data of both air temperature and accumulated precipitation from the Iraqi Meteorological Organization and Seismological (IMOS) for two years, 2018 and 2021, were used. In addition, based on Sentinel-2 images for the same location and period, results of PET, surface water bodies, and vegetation cover from the references (Mahdi et al. 2024, Ahmed et al. 2024) were used to achieve the objectives of this study.

MATERIALS AND METHODS

Aridity Index

To distinguish the type of climate, whether dry or wet, for the two years 2018 and 2021, the aridity index was calculated using the Thornthwaite aridity index, which is based on the monthly temperature and precipitation during each year, defined by the following expression (Mendez 2006, Mustafa et al. 2018).

$$\mathrm{AI} = \sum_{i}^{n} 1.65 * \left(\frac{\mathrm{P}}{\mathrm{Ta} - 10}\right)^{10/9} \quad \ldots(1)$$

where P and Ta are precipitation and air temperature, respectively. n is the number of months. Table 1 shows the classifications of AI used to quantify aridity degree.

Surface Water, Vegetation and Potential Evapotranspiration

The spectral indices for spatial monitoring of urban surface water and vegetation are modified normalized difference water index (MNDWI) and normalized difference vegetation index (NDVI), which are expressed by

$$\mathrm{MNDWI} = \frac{\mathrm{Green\ (band\ 3)} - \mathrm{SWIR\ (band\ 11)}}{\mathrm{Green\ (band\ 3)} + \mathrm{SWIR\ (band\ 11)}} \quad \ldots(3)$$

$$\mathrm{NDVI} = \frac{\mathrm{NIR\ (band\ 8)} - \mathrm{Red\ (band\ 4)}}{\mathrm{NIR\ (band\ 8)} + \mathrm{Red\ (band\ 4)}} \quad \ldots(4)$$

Both indices have values between -1 and +1. The spatial areas of water and vegetation were calculated using a raster calculator in the OGIS program after classifying the results of MNDWI and NDVI. For more details, we could refer to the references of Mahdi et al. (2024) and Ahemd et al. (2024) for the extraction of MNDWI and NDVI, respectively.

Finally, the potential evapotranspiration results reported by Ahemd et al. (2024) were also used in the present paper, which was calculated using the Truc method based on solar radiation (RS), air temperature (Ta), and relative humidity (RH) data.

$$\mathrm{PET} = 0.01333\big((239000 * \mathrm{RS}) + 50\big)\left(\frac{\mathrm{Ta}}{\mathrm{Ta}+15}\right)$$

$$\text{for RH} > 50\% \quad \ldots(5)$$

$$.01333\big((239000 * \mathrm{RS}) + 50\big)\left(\frac{\mathrm{Ta}}{\mathrm{Ta}+15}\right)\left(1 + \left(\frac{50-\mathrm{RH}}{70}\right)\right)$$

$$\text{for RH} < 50\% \quad \ldots(6)$$

where RS, Ta, and RH are expressed in $MJ.m^{-2}.day^{-1}$, °C, and % respectively.

RESULTS AND DISCUSSION

Aridity Index

Using monthly cumulative precipitation and mean temperatures, the aridity index was calculated separately by Eq. 1 for each of the years 2018 and 2021. Table 2 shows the values of the annual means for P, Ta, AI and climate type. According to the standard classifications given in Table 1, the AI values are 16.9 in 2018 with semi-arid climate type due to high annual precipitation and 1.3 in 2021 with severe arid (or hyperarid) climate due to very limiting precipitation, as shown in Table 2. The inter-annual distribution of precipitation for both years is shown in the histogram bars in

Table 1: Climate classifications of Thornthwaite aridity index.

AI	<16	16-31	32-63	64-127	>127
Climate type	Arid	Semi-arid	Sub-humid	Humid	Wet

Table 2: Annual means of (mean, minimum, and highest temperature), precipitation, and aridity Index.

Year	Lowest Ta (°C)	Highest Ta (°C)	Range (°C)	Mean Ta (°C)	P (mm)	Aridity Index	Climate type
2018	12.1	35.4	23.3	24.3±8.8	284.2	16.9	Semi-arid
2021	11.5	37.8	26.3	24.5±9.9	25	1.3	Arid

Fig. 2, where the difference between monthly precipitation amounts is visible. The annual precipitation amounts reached 284.2 mm in 2018 and 25 mm in 2021.

The interesting point can be explained by discussing the inter-annual variations. Although the annual mean temperatures of both years are approximately the same, the standard deviation (SD), denoted by the symbol (±), is quite different. In the dry year (2021) the inter-annual variations of the monthly mean temperature were larger (SD=9.9°C) than in the wet year 2018 (SD=8.8°C). Also, the annual heat range, defined as the difference between maximum and minimum mean temperature, was larger in the dry year than in the wet year.

Owing to a sharp deficit in the amounts of precipitation in 2021, several environmental impacts were produced such as human discomfort (Al Rukabie et al. 2024), fed-rain plants, high evaporation rates (Trenberth 2011), and changes in hydrodynamic and water environment (Limones 2021). The dry year (2021) recorded the highest monthly temperature (37.8°C), while the wet year (2018) recorded the lowest values of the highest temperature (35.4°C).

Inter-Annual Variations of Urban Water, Vegetation and Evapotranspiration

Fig. 3 shows monthly variations of quantitative areas for both surface water and vegetation represented by the calculation of MNDWI and NDVI respectively. Monthly PET results for these years are also added at the bottom of the figure. The green dotted lines are for these quantitative areas in semi-arid conditions (2018), while the red dotted lines are for arid conditions (2021). In general, the surface water areas in 2018 are relatively larger than those in 2021, especially in the six months (i.e. February, March, April, May, June and November). In summer (i.e. July, August and September) the areas are about the same with an average value of 18 km^2. The only exception is January and December, where more water areas were recorded, especially in January. This distribution of water areas was mostly reflected in the growth of vegetation in Baghdad, where the total area of pixels for vegetation (NDVI) in January, March, April, June, October, and December of 2018 was larger than those of 2021. The remaining months have almost the same NDVI areas, especially in May.

Due to large amounts of solar radiation falling on the surface of Baghdad for six months from May to September, a lot of water is lost through evaporation and transpiration, so high PET values were also associated with these months, as shown in Fig. 3. Furthermore, in these months, PET values in the arid year (2021) were expected to be higher than those in the semi-arid year (2018). In the winter months (i.e. December and January) no difference was observed.

Relation Between Precipitation and Water, Vegetation and Potential Evapotranspiration

Here we try to study the effect of monthly precipitation

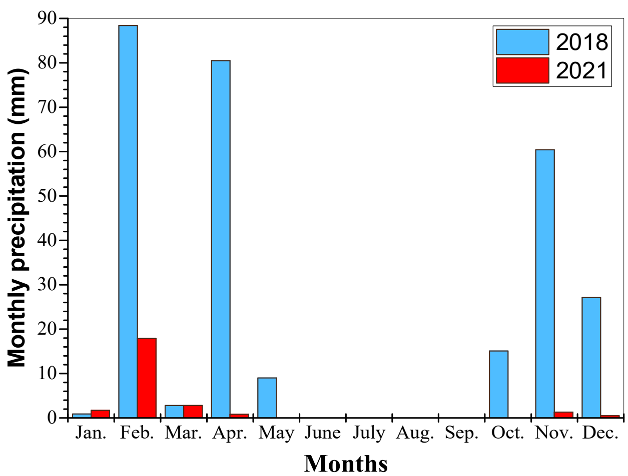

Fig. 2: Histogram bars of monthly precipitation recorded in weather Baghdad station in two years 2018 and 2021.

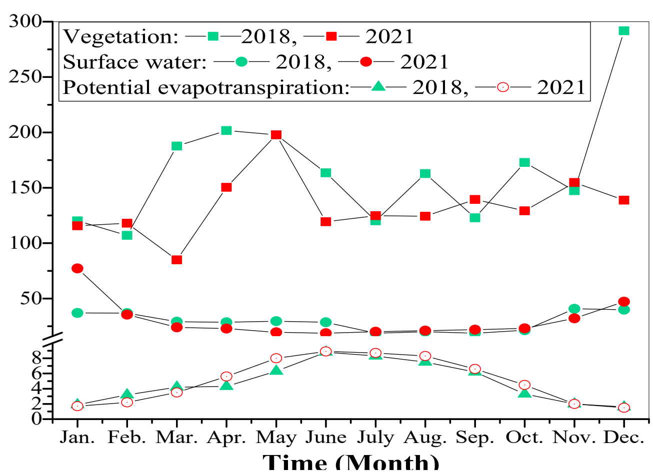

Fig. 3: Monthly variation of areas of surface water and vegetation, and of PET within Baghdad.

on the derived environmental quantities: surface water, vegetation cover, and potential evapotranspiration in an urban environment. For comparison purposes and because precipitation is a spatial distribution phenomenon, the precipitation observed by IMOS can represent a spatial distribution of the city of Baghdad because it is almost produced by extratropical low-pressure systems, mostly from the Mediterranean, Arabian and Red Sea regions (Babu et al. 2011). For a deeper understanding, investigate the relationships between the above parameters, Figs. 4a, 4b, and 4c show the scatter plots between precipitation versus surface water (or MNDWI) area, precipitation versus vegetated (or NDVI) area, and precipitation versus PET, respectively, with precipitation on the x-axis and other quantities on the y-axis. If there was a good relationship, the best-fitting line was drawn through the data points, and the statistical parameter

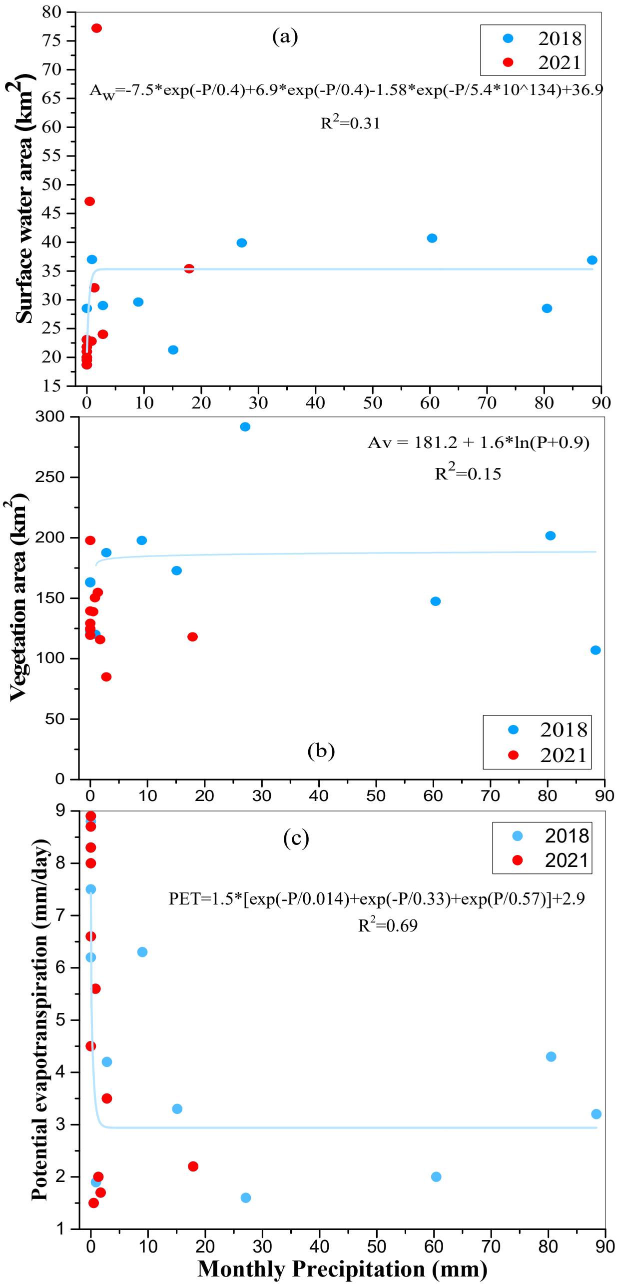

Fig. 4: Relationship of monthly precipitation with (a) surface water area (A_w), (b) vegetation area (Av), and (c) potential evapotranspiration.

of goodness of fit (R^2) was also determined. In addition, due to a sharp lack of precipitation in the dry year (2021), these relationships could not be concluded as shown in Fig. 4 for red points, so during the semi-arid year of 2018, the relationships were discussed below.

Fig. 4a shows monthly precipitation and urban surface water areas over arid and semi-arid periods. In 2018, water areas increased sharply only when there was precipitation of 2 mm, and then increased slowly with high precipitation, resulting in a positive correlation. The best line drawn through the data points obeys the exponential expression written on the panel of the figure with R^2=0.36. The relationship between precipitation and urban vegetation cover is clear in the semi-arid year, which shows a positive non-linear correlation as shown in Fig. 4b. The fitted line could pass through the data points that obeyed the logarithmic equation reported in the panel of the figure with R^2=0.15. This weak correlation is not suppressing, because the high fluctuation of precipitation, as well as NDVI areas in each month, responds slowly to the moisture activities of the previous month produced by precipitation irrigation. Monthly PET results estimated by the Truc method (Eqs. 5 and 6) were plotted against precipitation as shown in Fig. 4c. In the semi-arid period of 2018, when precipitation increased during the winter and spring rainy seasons, PET values decreased dramatically. These quantities are negatively correlated and the best-fitting line could pass through the data points followed by the decay exponential function written in the panel of the figure with moderate strength (R^2=0.69).

CONCLUSIONS

Precipitation is a very important factor in natural ecosystems and plays a key role in the hydrological cycle. By combining precipitation data with surface water bodies, vegetation, and potential evapotranspiration, we have explored the impact of precipitation on these quantities, which can improve better tools and strategies for water resources management and drought risk mitigation. This study presents monthly precipitation and air temperature observations from the Baghdad Ground Meteorological Station for two years, 2018 and 2021. We chose these years for a detailed analysis of the effects of precipitation under different climatic conditions. Using the Thornthwaite aridity index, the year 2018 was found to be in the semi-arid climate class with a value of 16.9, which is between 16 and 31, while the year 2021 was in the very arid class with a very small value of 1.3, which was far from the limit (16). Based on the published results of surface water areas, vegetation cover areas, and PET (Ahmed et al. 2024) for the same years and site, the quantitative effect of precipitation on these quantities in terms of MNDWI for water and NDVI for vegetation, has been examined. In most of the rainy months of 2018, MNDWI areas were larger than in 2021, except for January. The annual mean NDVI area was 166.3 km^2 in 2018, which is larger than the area of 133.1 km^2 monitored in 2021. Also, vegetation degradation with the lowest value of 85 km^2 was found with the lowest precipitation in March 2021. In the warm months (March to October) of 2021, PET estimates were larger than those of 2018. Through quantitative analyses discussed in this paper, the non-linear increased relationship between precipitation and water area was shown, it was also non-linear with vegetation area, and finally, precipitation was inversely correlated with PET values. These results would be valuable for researchers to better understand the changing characteristics of precipitation and for managers to make better decisions in the future.

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