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# COMPUTATION OF MONTHLY RUNOFF COEFFICIENTS FOR ISTANBUL (TURKEY)

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*Water demand for Istanbul is supplied both by impounded reservoirs located within its provincial boundaries and by water transfer from Western and Eastern regions in peripheral areas, located in South-West Black Sea region. The runoff coefficient defined as the ratio of the streamflow to the precipitation, plays a key role in the calculation of the surface water yield of water catchment areas. In this paper, we present the computation of monthly runoff coefficients for an accurate estimation of the yield of the catchment areas. We obtain statistical parameters for monthly temperatures and precipitation, based on 105-year data recorded at Istanbul Kandilli Observatory, modeled as Gaussian and Rayleigh distributed random variables, respectively. We run simulations to predict temperatures and precipitation over a horizon extending to 2100. We apply Turc's formula and Thornthwaite method to obtain monthly runoff coefficients based on long-term data. The results are compared and discussed with the findings of previous researches.*

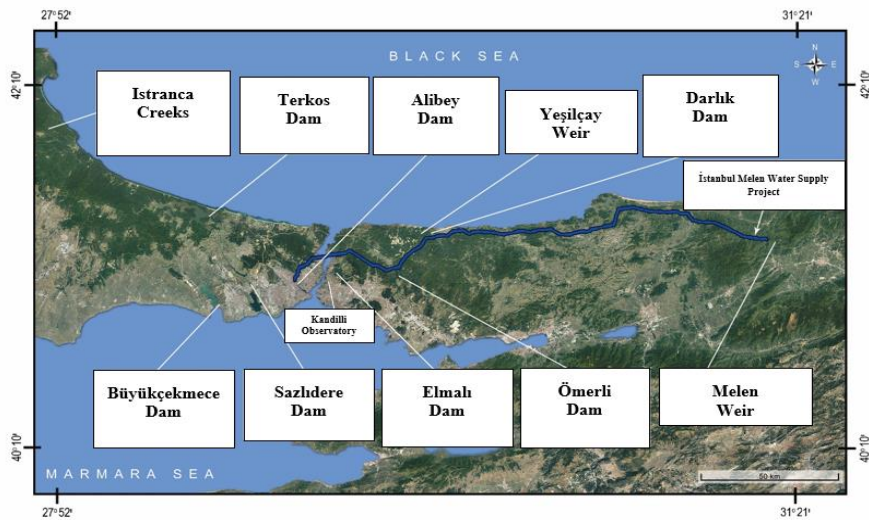
*Keywords: Istanbul, precipitation, runoff coefficient, temperature, water catchment areas*

## 1. Introduction

Absence of precipitation over long periods in wet seasons may have environmental and societal impacts with increasing pressure on water resources. Assessment of water inflow to reservoirs is crucial for the planning and management of sustainable water supply schemes for urban water use.

Istanbul Metropolitan Area which has expanded to cover a surface area of 5400 km<sup>2</sup> is shelter to 15 million people at present. The city is located at 41.01°N, 28.58°E. The southern parts of provincial Istanbul, where urban areas mostly lie, show the general characteristics of the Mediterranean climate. However, to the northward direction, the Mediterranean type climate is modified by the cooler Black Sea and northerly colder air masses of maritime and continental origins. This weather type is locally called 'the Black Sea Climate' and described as having cooler temperatures in both winter and summer, and usually with more rains from mid-Autumn to mid-Spring [1]. The city which has no perennial rivers

relies on stored water in impounded reservoirs as shown in fig. 1. After the 1990s, following a severe drought in Istanbul, water supply systems were re-considered in terms of yield and capacity and water transfer from adjacent basins was planned in order to meet the demand of the growing population [2]. The Istanbul region has experienced a rise of 0.94 °C in average yearly temperature between 1912 and 2016 due to anthropogenic climate change impacts [3]. This rise is slightly higher than the global average temperature increase over the period of 1800-2012 indicated as 0.85 °C in the 5<sup>th</sup> Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) [4]. Also, it is likely that this trend related to global warming will further increase during the 21<sup>st</sup> century under all representative pathways scenarios [4]. In the light of both natural and anthropogenic adverse impacts, (i.e. climate change, urbanization) on the hydrological regime, the yield of water catchment areas may change, resulting in decrease in water inflow to the reservoirs. For instance, reduction of rainfall in wet seasons with lower-than-usual rainfall may cause winter drought resulting in decrease in runoff [5]. Loss in pervious surfaces caused by urbanization reduces infiltration into soils and groundwater [6]. Changes in the features of Istanbul's precipitation and temperature data were analyzed by a number of scientists [3,7]. Absence of rain over prolonged period especially in wet season may have strong environmental and societal adverse impacts [8]. These adverse impacts are likely to be more severe in heavily urbanized cities with congested population like Istanbul.



**Figure 1. Water resources in Istanbul**

The objective of the study is to compute monthly runoff, which is crucial for the optimum management of water works in large cities like Istanbul where water supply is mainly provided from surface water. Knowledge of monthly runoff is important because yearly averages hide monthly fluctuations in hydrological processes that are more important for the operational management of water works. For instance, when winter drought occurs, the reservoirs are very likely to short fall in meeting the demand of the city. We based our work on 105-year data, the longest available period of data provided from the national administration, the Kandilli Observatory, located in Istanbul (fig. 1). The monthly runoff coefficients for Istanbul computed from 105 years' past data will provide statistically meaningful estimates for the future. Nevertheless, it should be noted that increased urbanization is expected to worsen the relationship between runoff and inflow to reservoirs. Our results should be thought of best-case scenarios related to precipitation versus runoff under the initial (baseline) conditions of the catchment areas that are protected by relevant regulations.

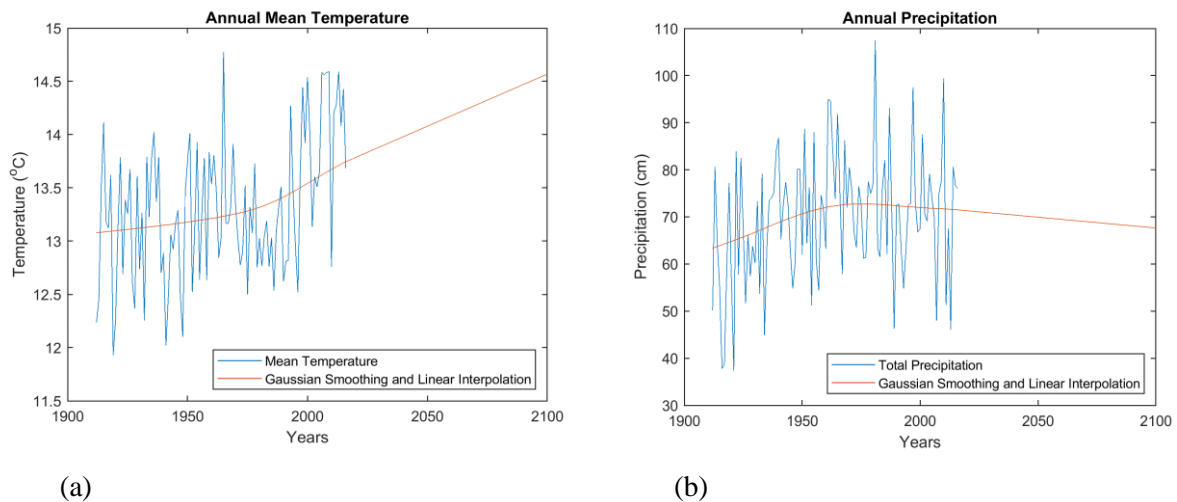
In the present work, we model the temperature and precipitation as Gaussian and Gamma distributed random variables, respectively, and obtain their parameters. We base our model for monthly precipitation to the records for the period between 1912 and 2016 [9]. The estimation of the monthly runoff coefficients is discussed in Section 2, where runoff coefficients are computed by Turc's formula [10] and Thornthwaite's method [11], using long-term temperature and precipitation values and the results are compared with in-situ measurements given by Kadioğlu and Şen [12]. The overall results and discussion are given in section 3 followed by the conclusion remarks in Section 4.

## 2. Methodology

### 2.1. Statistical Models for Monthly Temperature and Precipitation

Daily temperature and precipitation data have been recorded by the Kandilli Observatory, Istanbul, since 1912. The observatory is located at the East shore of the Bosphorus, over a hill, relatively far from urban settlements, hence data collected at this location is representative of the South-East Black Sea region over the whole data collection period. We use the data over the period 1912-2016 obtained from the Kandilli Observatory, as described above.

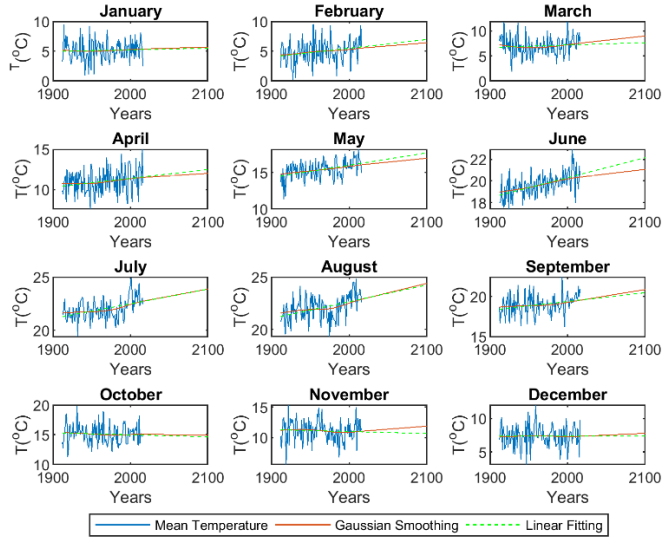
The graphs of annual mean temperature and annual precipitation are given on fig. 2. Gaussian smoothing was applied to the 105 years of temperature and precipitation data, as described by Jones [13] and prediction by linear interpolation up to the year 2100 is implemented (using MATLAB with N=100 parameters). These graphs indicate a clear increase from in annual temperatures by  $0.82^{\circ}\text{C}$  degrees (fig.2(a)) and a slight decrease in precipitation by 4.14 cm (fig.2(b)) between the period 2016 and 2100. These values are in agreement with global trends considering the geographical location of Istanbul under the influence of Mediterranean and Western Black Sea climate [14,15].



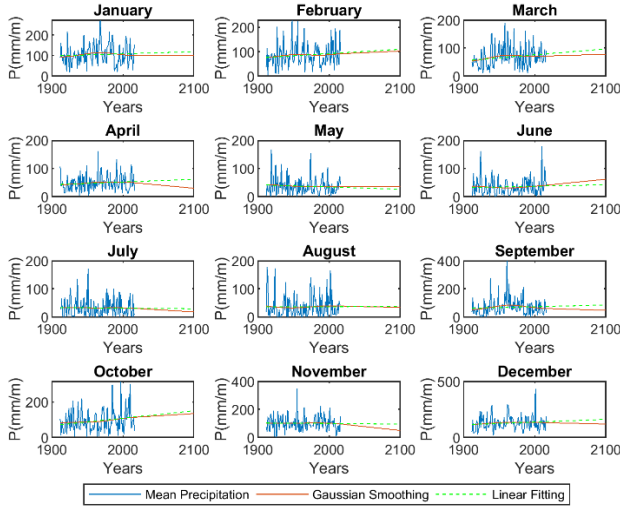
**Figure 2. Prediction of annual mean temperature (a) and annual precipitation (b) with Gaussian smoothing and linear interpolation for Istanbul**

On fig. 3 and fig. 4, we present the graphs of temperature and precipitation for each month, together with linear fitting and Gaussian smoothing and interpolation up to 2100. From fig. 3, we can see that temperatures have a trend of increase in summer months, but no significant change is predicted in winter months, at least within the scope of the models we use. The linear projections for the precipitation, as shown on fig. 4, do not indicate strong trends; nevertheless, we can state that

precipitations are likely to increase in winter and spring and stay unchanged or decrease in summer and fall.

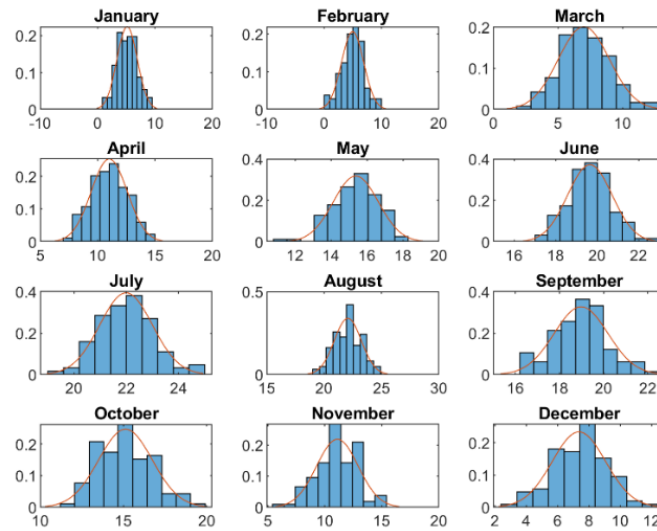


**Figure 3. Monthly temperature over the period 1912-2016 and projections to 2100 via linear fitting and Gaussian smoothing and interpolation**

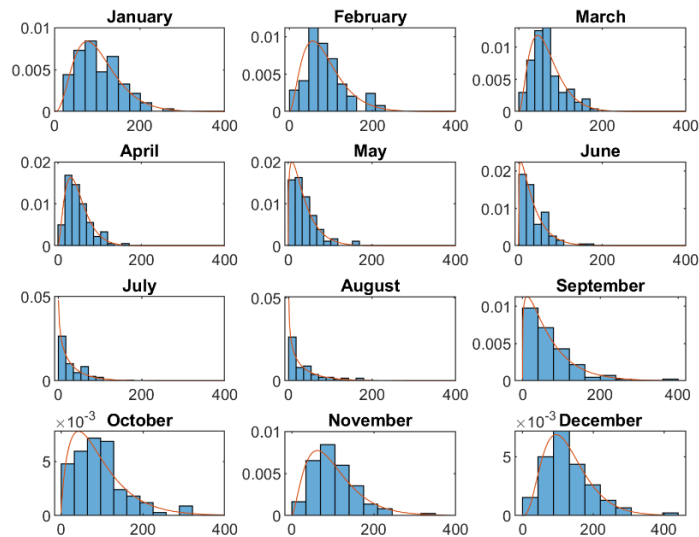


**Figure 4. Monthly precipitation (mm) over the period 1912-2016 and projections to 2100 via linear fitting and Gaussian smoothing and interpolation**

The histograms of daily mean temperatures recorded at Istanbul Kandilli Observatory over the period 1912-2016 are shown on fig. 5, for each month, together with a fitted Gaussian. The Gamma probability distribution is a generally accepted model for monthly precipitation data [16]. We compute the parameters of the best fitting Gamma distribution for each month, using the statistical toolbox of MATLAB and on fig. 6, we present histograms together with the corresponding fitted distribution.



**Figure 5. Histograms of daily mean temperatures over the period 1912-2016. Horizontal axis units are in degree °C.**



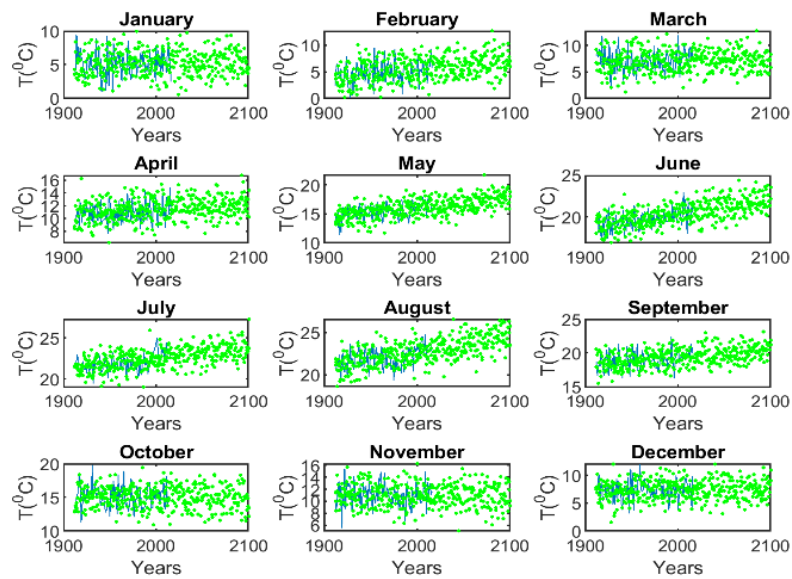
**Figure 6. Histograms of monthly precipitation in Istanbul, 1912-2016 together with Gamma distribution fit**

The Gamma distribution is characterized by its “shape” and “scale” parameters; the parameters of the Gamma distributions fitting to precipitation data for each month are presented in the first 2 columns of tab. 1. The mean and the standard deviation of the temperature distributions are given in the 3<sup>rd</sup> and 4<sup>th</sup> columns of the same table. In this table, in the last column, we also present the runoff coefficient, as explained in section 3.

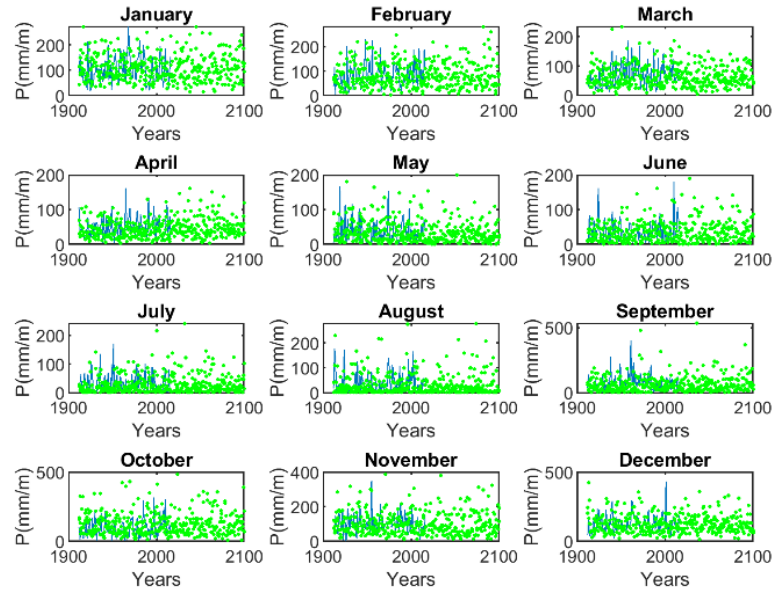
**Table 1. Monthly parameters of the Gamma distribution (as computed with MATLAB)**

Months	A: Shape Parameter (P)	B: Scale Parameter (P)	Mean (T)	Standard Deviation (T)	Runoff coefficient
1	3.7553	27.8695	5.1436	1.7808	0.6325
2	2.9136	29.3994	4.9654	1.9340	0.5821
3	2.9700	23.0044	7.0052	1.9844	0.4636
4	2.7320	17.7674	11.0114	1.5745	0.2576
5	1.3302	27.9445	15.3777	1.2550	0.1530
6	1.1293	31.0962	19.6467	1.0719	0.0969
7	0.6984	45.7084	21.9906	1.0114	0.0732
8	0.5921	61.0171	22.0644	1.1764	0.1204
9	1.1590	58.9881	18.9749	1.2188	0.2715
10	1.8426	50.7605	15.1173	1.6129	0.4090
11	2.6023	38.8352	11.0951	1.8245	0.4980
12	3.8384	33.4749	7.3596	1.7079	0.6500

Based on these statistical models we generate simulations for the temperature and precipitation as shown below on fig. 7 and fig. 8.

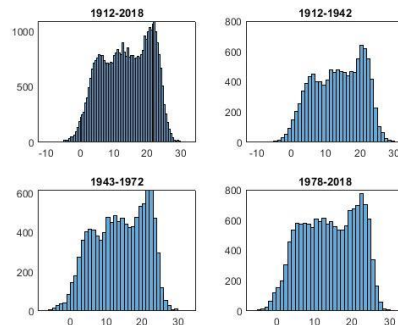


**Figure 7. Simulations for monthly mean temperature in Istanbul**



**Figure 8. Simulations for monthly mean precipitation in Istanbul.**

From linear regression, Gaussian smoothing and interpolation curves, we have seen that there is no appreciable change in precipitation but there is an increase in temperatures with the exception of the ones for winter months.as given in fig. 7 and fig. 8. For a further evidence of this fact, we present the histograms of temperatures for different decades on fig. 9.



**Figure 9. Histograms of monthly temperatures over different decades**

## 2.2. Computation of Runoff Coefficients

The runoff coefficient is defined as the ratio of the surface runoff to the precipitation and it is dimensionless. In this section we present the computation of the runoff coefficient using two different methods. The first one is the Turc's formula that uses temperature and precipitation information only. The second one is the Thornthwaite method, which is an algorithmic computation based on certain tabulated parameters.

**Evaluation of runoff with Turc's formula [10]:** This method is based on the assumption that the precipitation ( $P$ ) is the sum of real evapotranspiration ( $E$ ) and the runoff ( $R$ ), hence  $E \leq P$ . The real evapotranspiration  $E$  is given by the formula in eq. (1)



$$E = \frac{P}{\sqrt{0.9 + \frac{P^2}{[L(T)]^2}}}, \text{ if } \frac{P^2}{[L(T)]^2} > 0.1 \quad \text{and} \quad E=P, \text{ if } \frac{P^2}{[L(T)]^2} = 0.1 \quad (1)$$

where P is the mean monthly precipitation in mm/month, T is the mean annual temperature in degrees Celsius and  $L(T) = 300 + 25T + 0.05T^3$ . Runoff is defined as the difference between precipitation and evapotranspiration,  $R=P-E$ .

We apply the Turc's formula to the monthly precipitation data recorded at Kandilli Observatory, for each month, in order to obtain a monthly time series for E, hence for the runoff, over the period 1912-2016. Then, we compute average precipitation and average runoff for each month, to obtain the runoff coefficients for each month, as their ratio. Note that, in summer months, as precipitation is usually low, it can often happen that  $[P/L(T)]^2=0.1$ , hence  $E=P$ , i.e,  $R=0$ . But as we take average over a 105-year period, the runoff coefficient turns out to be nonzero even in summer.

**Evaluation of runoff with Thornthwaite method as applied by Gudulas *et al.* [17]:** In this scheme, monthly potential evapotranspiration,  $PE_m$ , is computed in terms of monthly mean temperature  $T_m$ , by the formula in eq. (2).

$$PE_m = 16 \left[ \frac{T_m}{I} \right]^a \quad (2)$$

where  $I = \sum_{m=1}^{12} (T_m/5)^{1.514}$  and  $a=0.018 I + 0.49$ . These monthly potential evapotranspiration values are multiplied by the latitude correction coefficient  $\lambda_m=(h_m/12) (d_m/30)$ , where  $h_m$  is the average sunlight hours at month m and  $d_m$  is the number of days in that month. Then, lacking amount of water  $U_m$ , and excess water for vegetation  $V_m$ , are computed in terms of the precipitation  $P_m$  and  $PE_m$  by eq. (3).

$$U_m = \max\{ \lambda_m PE_m - P_m, 0\} \quad \text{and} \quad V_m = \max\{ P_m - \lambda_m PE_m, 0\}. \quad (3)$$

The ground water storage due to soil moisture is estimated to be equivalent to  $S_{\max}=125$  mm. The amount of water lost from ground due to moisture reduction is given in eq. (4).

$$A_{w,m} = \begin{cases} 0 & \text{if } P_m > \lambda_m E_{p,m} \\ A_{w,m-1} + P_m - \lambda_m E_{p,m} & \text{if } P_m < \lambda_m E_{p,m} \end{cases} \quad (4)$$

The soil moisture is then  $S_m = S_{\max} - |A_{w,m}|$  and real evapotranspiration is found as in eq. (5).

$$E = \lambda_m E_{p,m} - U_{w,m} - (S_m - S_{m-1}) \quad (5)$$

Finally, the runoff is defined as eq. (6)

$$R_m = \begin{cases} 0 & \text{if } V_m = 0 \\ V_m - (S_m - S_{m-1}) & \text{if } V_m > 0 \end{cases} \quad (6)$$

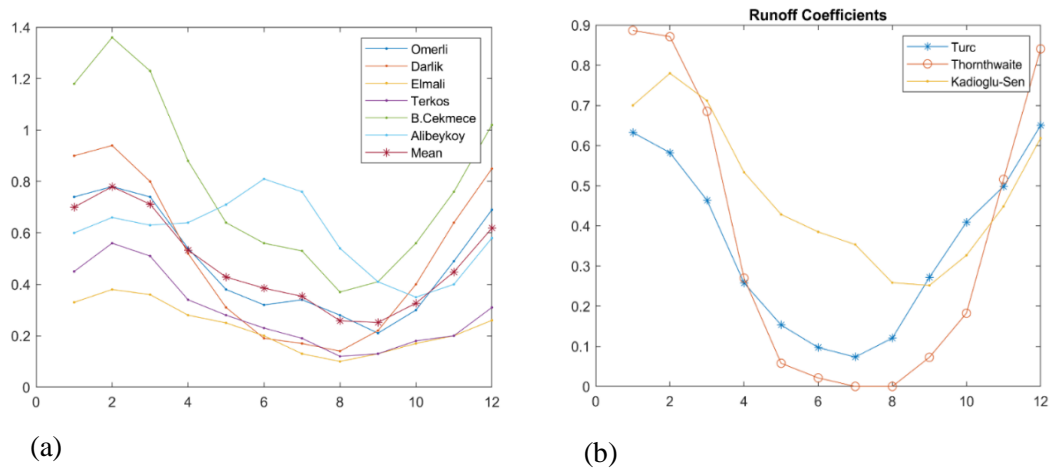
We present the runoff coefficients computed by Turc's formula, by the Thornthwaite method and the average of the measured values on fig. 10(b).

The mean of these monthly runoff coefficients for Istanbul is 0.33. We note that the mean runoff coefficient for Turkey has been computed as 0.37 [18–20]. Also, the runoff coefficients for each single catchment basin within Istanbul range from 0.35 to 0.59 [2] and the variability of the runoff coefficients among various basins is explained by the differences in basin feeding, geological formation, size, as well as form of precipitation.

### 3. Results and Discussion

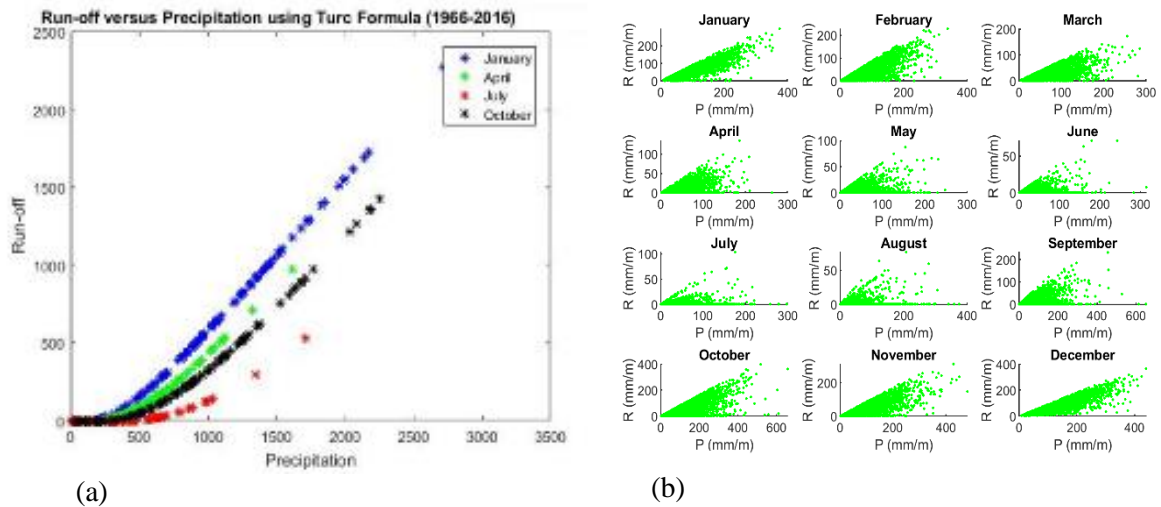
Accuracy of the estimation of the yield of catchment areas is the basis for the design of water structures. Estimating the value of runoff coefficients is a key input in this respect. But the value of these coefficients depends on the features of the catchment areas (e.g. geography, topography, vegetation, land cover) and may change over time due to mainly anthropogenic impacts like urbanization. Therefore, uncertainty related to the runoff coefficient is a major concern in the prediction of the yield of catchment areas that are close to the urbanized areas, in particular. In fact, runoff can be observed and measured directly. Although runoff measurements for various basins in Istanbul area are given in [12], the time span of the available data is not suitable for developing a statistical model. The runoff coefficients calculated from their data are shown on fig. 10(a).

As seen from fig. 10(b), different methods applied to the same data may predict somewhat different runoff coefficients. In addition, the variabilities in precipitation and temperature make it difficult to represent the runoff coefficients by a single graph.



**Figure 10. Runoff coefficients based on precipitation and runoff measurements generated from Kadioglu and Sen [12] (a) and Runoff coefficients computed by Turc’s formula, by the Thornthwaite method and the average of the measured values given by Kadioglu and Sen 2001 [12] (b)**

The variability of the runoff coefficients in time is tied to the variability of the precipitation and temperature. In addition to the runoff coefficients computed from time averages temperatures and precipitation, we computed runoff coefficients for each month, with Turc’s formula, using temperature and precipitation data for 1966-2016, which are considered to be more representative of the current temperature and precipitation levels as given in fig.9. Scatter plots of runoff versus precipitation for representative months are shown on fig. 11(a) whilst simulation results for each month are given on fig. 11(b). These graphs indicate that in summer, runoff is practically zero for moderate levels of precipitation while most of the precipitation is converted to runoff in winter.



**Figure 11. Runoff versus precipitation for Istanbul, in representative months, as computed using Turc's formula (a) and runoff versus precipitation for simulated values of the precipitation based on the model (b)**

As shown by the graphs in fig. 11(b), the higher the precipitation, the higher the runoff in winter. On the one hand, runoff is quantitatively interrelated to various natural factors such as intensity of rainfall, seasonal distribution and type of rainfall, whether it is orographic, convective or frontal. On the other hand, anthropogenic activities such as urbanization, irrigation, inter-basin transfer, aquifer recharge have impact on runoff because these interventions modify the hydrological regime in catchment areas [21].

The distinguishing feature of our approach for computing runoff coefficients is their replication using long-term past data. In fact, a single application of Turc's formula or Thornthwaite method gives practically zero inflow in summer when no precipitation occurs, while non-zero runoff in summer is likely to be encountered as seen on fig. 11. Nevertheless, in summer, precipitation is converted to runoff only after a certain threshold, thus the increase of summer droughts is not reflected to decreases in the runoff. On the other hand, winter droughts affect runoff directly; hence, they are more critical for the performance of the water supply system.

The occurrence of precipitation in rainy season, which extends from mid-Autumn to mid-Spring (October to May), is crucial for the Istanbul region because the water supply scheme of the city relies on impounded reservoirs which are filled up during the rainy period. As a consequence, drought in winter months may generate shortages in water supply during the following summer months [22]. Recent studies support the evidence of worsening drought conditions in neighbouring countries, namely in Bulgaria [23], in Romania [24] in addition to the IPCC report where the Mediterranean Basin is identified as a major hot-spot subject to increasing drought occurrences [25].

#### 4. Conclusion

This work highlights that: (1) increase in annual temperature by 0.82°C and decrease in precipitation by 41,4mm from 2016 to 2100 are predicted; (2) Monthly runoff coefficients put forward the fact that winter drought affects runoff directly; (3) Estimation of monthly runoff is crucial for the management of water supply system because yearly averages hide monthly fluctuations in hydrological regime.

The results of our study highlight that accurate estimation of monthly runoff can help water managers to predict the yield of water catchment basins and the inflow to the impounded reservoirs. In line with this statement, it must be highlighted that land-use changes (e.g. urbanization, loss of forestry areas) in catchment areas must be strictly avoided for controlling the yield of the catchment areas. This is important for the operation of water supply schemes in case supply has to be supplemented by external and/or alternative resources in the case of Istanbul; since the decision of how to and when to supplement timely the lacking water quantity and at which percentage depends on reliable predictions of water resources. Increased urbanization has adverse impact on the hydrological regime by decreasing the yield of catchment areas. In Istanbul where most of the water supply scheme is based on surface water like impounded and lake reservoirs, the protection of the water catchment areas is of the utmost importance. Although there are relevant regulations for the protection of water catchment areas, enforcement in daily practices is crucial in this respect. These practices must go hand-in-hand with public awareness and administrative support by both local and central administrations in order to prevent uncontrolled urbanization and ill-adapted management issues in catchment areas.

Conflict of interest: No

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#### Nomenclature

a	-cubic function of I	$S_{max}$	- max soil moisture (mm)
$A_{w,m}$	-amount of water lost from ground	T	- temperature [Celsius]
$d_m$	-number of days in that month (day)	$T_m$	- mean temperature [Celsius]
E	-real evapotranspiration [mm/month]	$U_m$	- lacking amount of water
$h_m$	-average sunlight hours at month (hr)	$V_m$	- excess water for vegetation
I	-heat index	Greek symbols	
$PE_m$	-potential evapotranspiration	$\lambda_m$	- latitude correction coefficient
R	-runoff [mm/month]		

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