PROJECT WORK REPORT

Climate Sensitivity of Evapotranspiration based on Observations of a small catchment (Wernersbach) and several EC flux towers (especially DE-Tha)

GROUP-11
Shayan Kamali
Aditya Anand

Supervisor
Prof. Christian Bernhofer
Thomas Plunkte

September 13, 2022
Hydro Science & Engineering

Table of Contents

Table of Figures

List of Tables

List of Abbreviation

°C	Degree of Celsius
3D	three-dimensional
ADF-test	Augmented Dickey-Fuller test
Avg	Average
DegC	Degree of Celsius
DSP	Difference-Stationary Process
EC	Eddy Covariance
ed	Vapour Pressure
Eq	Equation
ET	Evapotranspitration
ET-hargreaves	Potential evapotranspiration Calculated by the Hargreaves method
ET-penman	Potential evapotranspiration Calculated by the Penman-Monteith method
ET-thorn	Potential evapotranspiration Calculated by the Thornthwaite method
FAO	Food and Agriculture Organization
Fig	Figure
ha	Hectare
Hzd	Hetzdorf
IPCC	Intergovernmental Panel on Climate Change
km	Kilometer
kPa	Kilopascal
KPSS	Kwiatkowski–Phillips–Schmidt–Shin
l	Liter
lat	Latitude
m	Meter
Max	Maximum
Min	Minimum
mm	Millimeter
P	Atmospheric Pressure at the Catchment Surface
P0	Atmospheric Pressure at Sea Level
PAR	photosynthetically Active Radiation
PET	Potential Evapotranspiration
Pre	Precipitation
R_s	Solar Radiation
s	Second
Tha	Tharandt
Tmax	Maximum Temperature
Tmin	Minimum Temperature
U2	Wind Speed
VPD	Vapour Pressure Deficit
W	Watt
z	Catchment Elevation
"R"	R programming language
GDR	German Democratic Republic

Introduction

Water and food security for the ever-growing population while maintaining the already stressed environment is one of the most crucial issues raised by climate change. The availability of enough water and the reduction of water loss are essential for agricultural yield. The amount and distribution of evapotranspiration (ET), streamflow, and plant-available soil water are likely to change due to global climate change. Since ET is a key part of the hydrological cycle, it significantly impacts agricultural productivity.

Considering that 15% of the water vapor in the atmosphere is produced by evapotranspiration, it is a crucial mechanism in the water cycle. Cloud formation and precipitation wouldn't be possible without this input of water vapor. The terms evaporation and transpiration are combined under a single term known as evapotranspiration. Water evaporated over land and water surfaces is referred to as evaporation. This comprises water stagnant on surfaces like roofs and puddles as well as evaporation from the soil, wetlands, and other sources. It can also describe the direct water evaporation from a plant's surface. Plants release water vapor through microscopic openings in their leaves, known as stomata, during the process of transpiration. This results from the plant's photosynthesis, which turns carbon dioxide into oxygen, as well as other chemical and biological changes. Plants use transpiration to cool down their leaves, serving the same purpose as human sweating. There are many factors affecting evapotranspiration: - (i) Temperature, (ii) Humidity, (iii) Wind speed, (iv) Water availability, (v) Soil type, (vi) Plant type ("Evapotranspiration | North Carolina Climate Office ", o. J.).

ET is heavily dependent on climate variability because these variables always keep changing with the environment. Increases in temperature, radiation, water vapour deficit, and wind speed all lead to an increase in evapotranspiration. The FAO Penman-Monteith approach, Thornthwaite method, and Hargreaves method can all be used to estimate ET. Each approach uses a standard equation for estimating ET based on specific meteorological variables. When accurate wind speed, solar radiation, and vapor pressure data are available, FAO Penman-Monteith is found to produce more accurate results, but when climate data are deficient, the ET estimating method based on temperature and radiation shows better performance (TYAGI u. a., 2019).

Additionally, ET has been a crucial measure in calculating agricultural drought, a state of water stress in which there is insufficient water for crop development. It significantly affects crop productivity. So regular drought monitoring is essential for minimizing effects and ensuring food security. Given the foregoing, the following objectives of the current study are set forth: (1) to assess the long-term trend of ET for the Wernersbach Catchment over the period of

(1968-2019) (2) Evaluation of observed ET using various techniques and (3) calculating the ET's response to environmental changes over the given period that affect climate variables including temperature, solar radiation, wind speed, and relative humidity.

Wernersbach Catchment

The Wernersbach catchment may be found 20 kilometers south-west of Dresden in the lower Eastern Ore Mountains of Saxony, Germany, in the northern section of Tharandt Forest (Fig. 1). It has a drainage area of 4.6 km2 and a mean elevation of about 370 m asl. Since 1966, the University has been collecting data on numerous hydrological, meteorological, canopy, and soil characteristics. The watershed has an average slope of 0.25% and is oval. The Wernersbach Creek, its left tributary - Triebenbach, and a few other small creeks and ditches make up the majority of the channel network. The old coniferous forest dominates the landscape, with over 70% Norway spruce (VOROBEVSKII u. a., 2022).

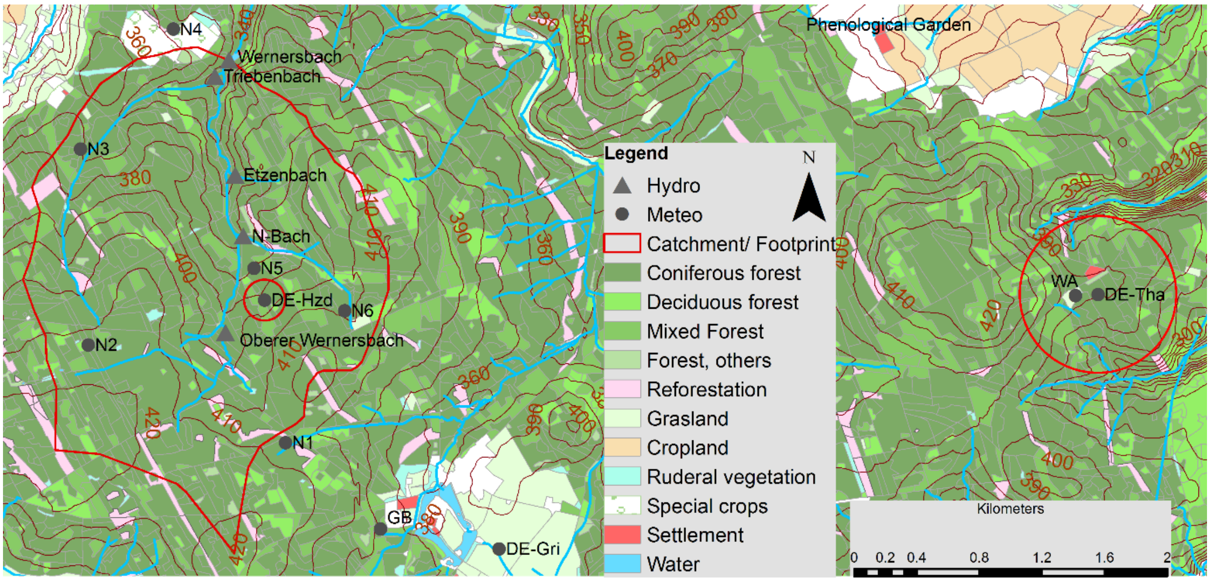

Fig 1: - Vegetation characteristics at Wernersbach catchment and the two EC Towers – EC-Tower Tha & EC-Tower Hzd (PLUNKTE T u. a., 2022)

The soil comprises loamy silt, sandy loam, and loamy sand that range in depth and have some backwater-affected areas. There are 3-gauge stations (Wernersbach, Triebenbach, Oberer Wernersbach) and five precipitation measuring points located inside the catchment. There are also 26 discharge measuring points for recording the spring discharge. The climatological data from the Grillenburg climate station, 30-year series (1961-90) suggests that the annual mean air temperature of the catchment is 7.2 °C while the average annual precipitation is 853 mm. The Largest flow rate measured in this catchment up to the flood of August 2002 was 6533 l/s on 22nd august 1980 („Wernersbach catchment aera“, o. J.).

Fig 2: - Outlet of Wernersbach catchment where all the data of the catchment is measured (PLUNKTE T u. a., 2022)

EC Tower DE-Hzd

This eddy covariance tower is located inside the Wernerbach catchment in the middle of the re-growing oak forest. Before this EC tower was constructed, the area was occupied by spruce forests. In 2007 there was a major wind break event in this part of the catchment where a large amount of shallow-rooted spruce trees were uprooted. In 2008, oak trees were planted in the same place where the event occurred. In 2010, to monitor the carbon, water, and energy flux of the re-growing oak trees, the Eddy Covariance tower (DE-Hzd) was constructed.

Fig 3: -First Eddy Covariance Tower - EC Tower DE-Hzd located inside the Wernersbach catchment (Picture taken during a site visit of the catchment in June, 2022)

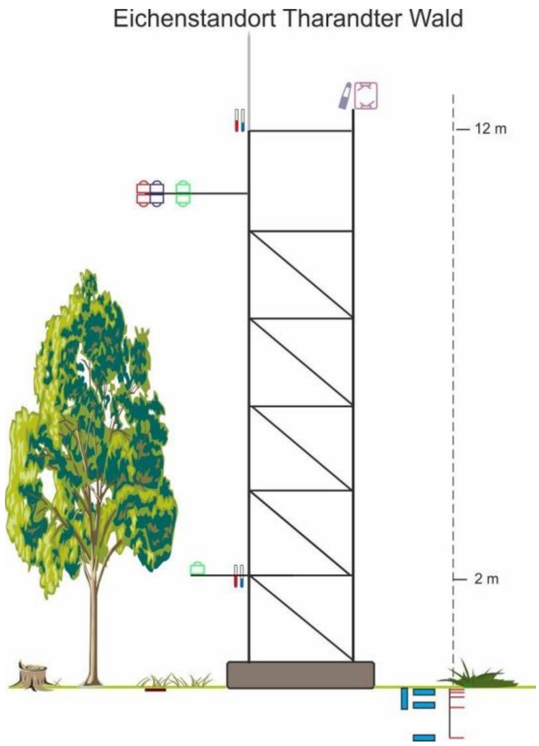

Fig 4: - A schematic diagram of EC Tower DE-Hzd showing different fluxes which it can measure (PLUNKTE T u. a., 2022)

This EC tower can measure: -

1. air temperature, relative humidity
2. soil moisture
3. soil temperature
4. ground heat flux
5. photosynthetically active radiation
6. short- and long-wave radiation
7. 3D-Wind
8. H_2O and CO_2 fluxes

In the first ten years, it was found that the area of re-growing oak trees acted as a source of carbon, but now they have also become sink.

Fig 5: - The picture was taken from the top of EC Tower DE-Hzd, which shows the re-growing oak trees in light green color surrounded by spruce forest in the far distance in grey (Site visit, 2022)

EC Tower DE-Tha: -

The Anchor Station Tharandt (DE-Tha) is situated in the eastern portion of a huge forested region (60 km2) close to the city of Tharandt, about 25 km south-west of Dresden (50°57'49'' N, 13°34'01''E, 380m a.s.l.). Meteorological and hydrological measurements have been taken in this forest over a long time, including climate data from the 1950s. The site is situated in a subcontinental/suboceanic climate. The mean yearly air temperature is 7.8°C, with the highest and minimum values of 9.4°C in 2000 and 6.0°C in 1996, respectively, in the long-term records of the nearby weather station (1959–2005). The mean annual precipitation is 823 mm, with maximum and minimum values of 1287 mm and 501 mm, respectively. (GRÜNWALD & BERNHOFER, 2007)

In 1887, a spruce stand was planted at the Anchor Station Tharandt. In addition to the dominant spruce trees, other tree species are also present. Near the measurement tower, the main canopy is made up of 87% coniferous evergreen and 13% deciduous forest species. There are two small, non-forested regions next to the tower. A small opening of about 1 ha, mostly covered in grass, may be found in the western direction. Various forestry department laboratories are located to the north (about 0.5 ha) (GRÜNWALD & BERNHOFER, 2007).

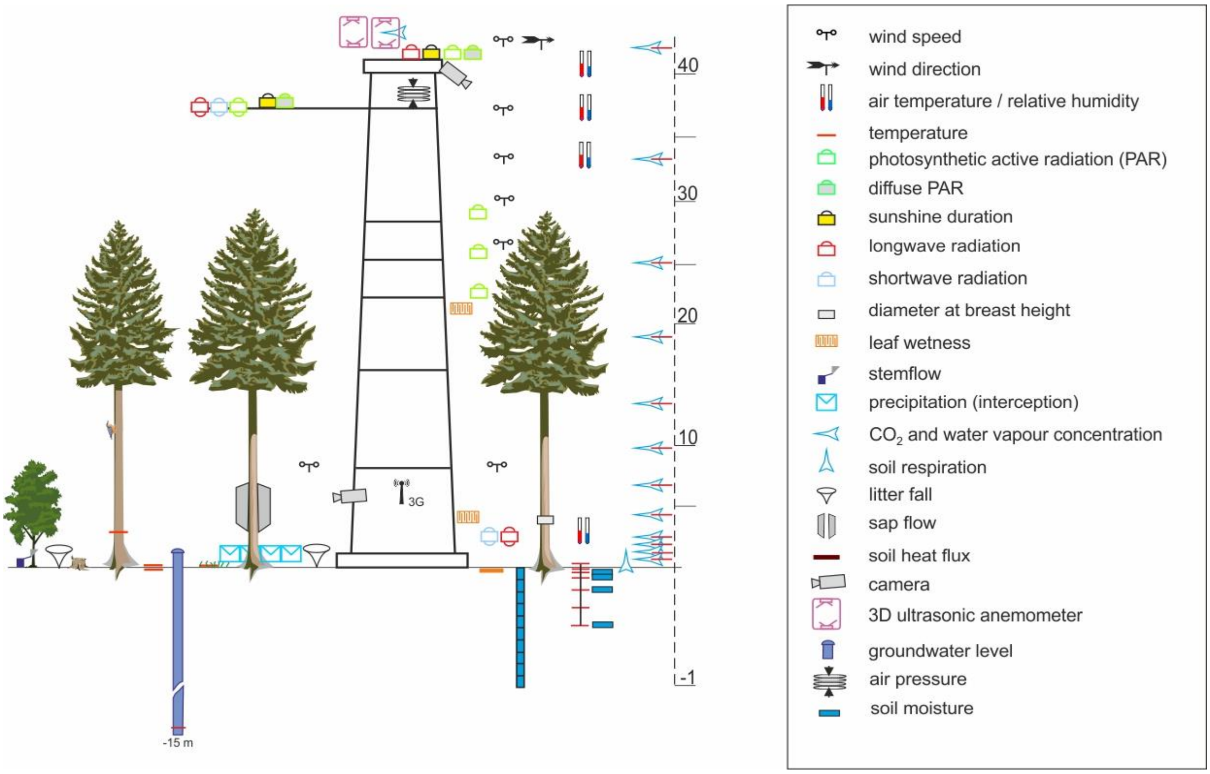

Fig 6: - A schematic diagram of EC Tower DE-Tha showing different measurement techniques located on the tower (PLUNKTE T u. a., 2022)

Methodology

The following observational information was given for the Wernersbach study catchment in Saxony, Germany: -

1. Temperature (Min, Max, Mean)
2. Precipitation (uncorrected and corrected)
3. Windspeed
4. Vapour pressure (based on relative humidity)
5. Global Radiation
6. Runoff of the catchment
7. Grass reference evapotranspiration

Monthly data was provided for the years 1968 to 2019, as well as daily data for the year 2017. Data uniformity and gap filling were already verified. Additionally, ET estimates derived from Eddy Covariance data collected at two towers were also included. The Wernersbach catchment (1997–2019, spruce forest) is where the EC tower DE-Tha is located, and the catchment is where the tower DE-Hzd is located (2010-2019, young oak forest) ("Hydrometeorological observations for the catchment Wernersbach (Germany) and Eddy Covariance observations of two nearby EC towers. | CUAHSI HydroShare ", o. J.).

Data were provided on the monthly values of various parameters from 1968-2019, as recorded in the Wernersbach catchment. The first task at hand was to analyze the given data and see how it changes with time and also are there any outliers. For this, an initial trend analysis was run in “R,” and every parameter was visualized on a line graph. In figure (Fig. 7), we can see the variation of precipitation which shows a decrease in precipitation till 1990, then an increase till 2008, and again a decrease till 2019. A decrease in precipitation might be explained by the high concentration of pollution in the area during those times. As the situation improved, the precipitation also increased. The recent decrease can be explained by frequent droughts experienced in the area. The runoff shown in figure (Fig. 8) changes according to the trend in precipitation, as we know that amount of runoff generated is directly proportional to the precipitation received. Also, there might be some influence on the surface flow of groundwater in the changes in runoff in the catchment.

The wind speed in figure (Fig. 9) peaked in 2000, after which it has been decreasing in the area. The annual average temperature shown in figure (Fig. 10) has an overall increasing trend from 1968 to 2019. As we all know, global warming is increasing day by day, which is also increasing the temperature around us; that is why it has been increasing since 1968.

For comparison and better understanding, the trend in maximum and minimum temperature in the given time period have been represented in figures (Fig. 11) and (Fig. 12), respectively.

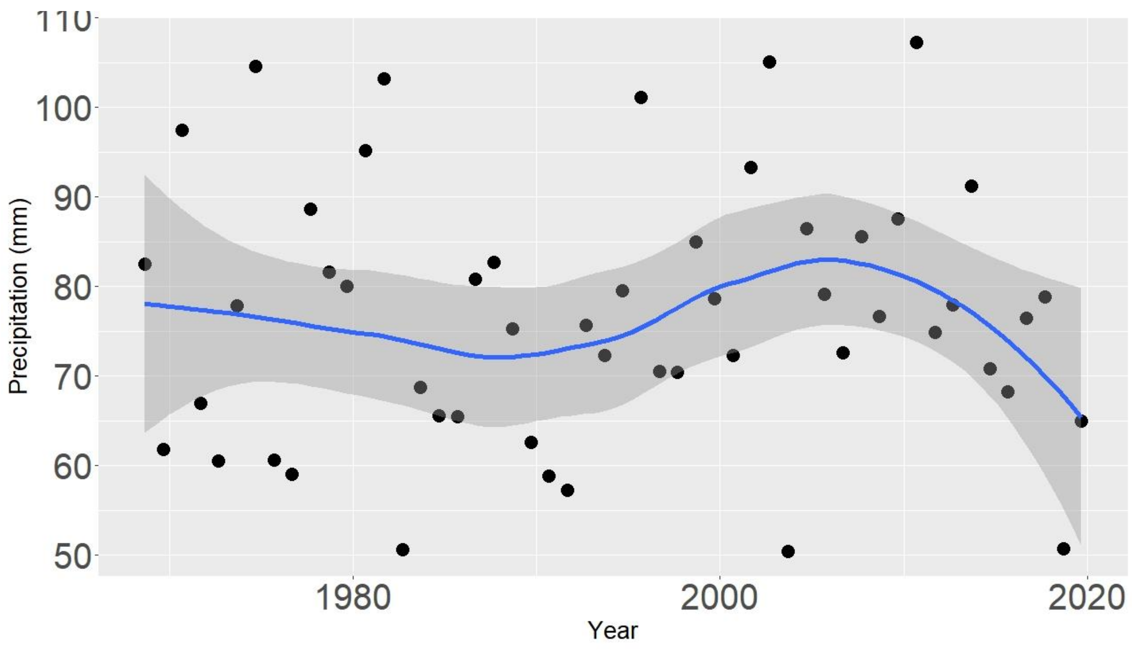

Fig 7:- Average Annual Variations of Precipitation obtained from received data (1968-2019) (“R,” 2022)

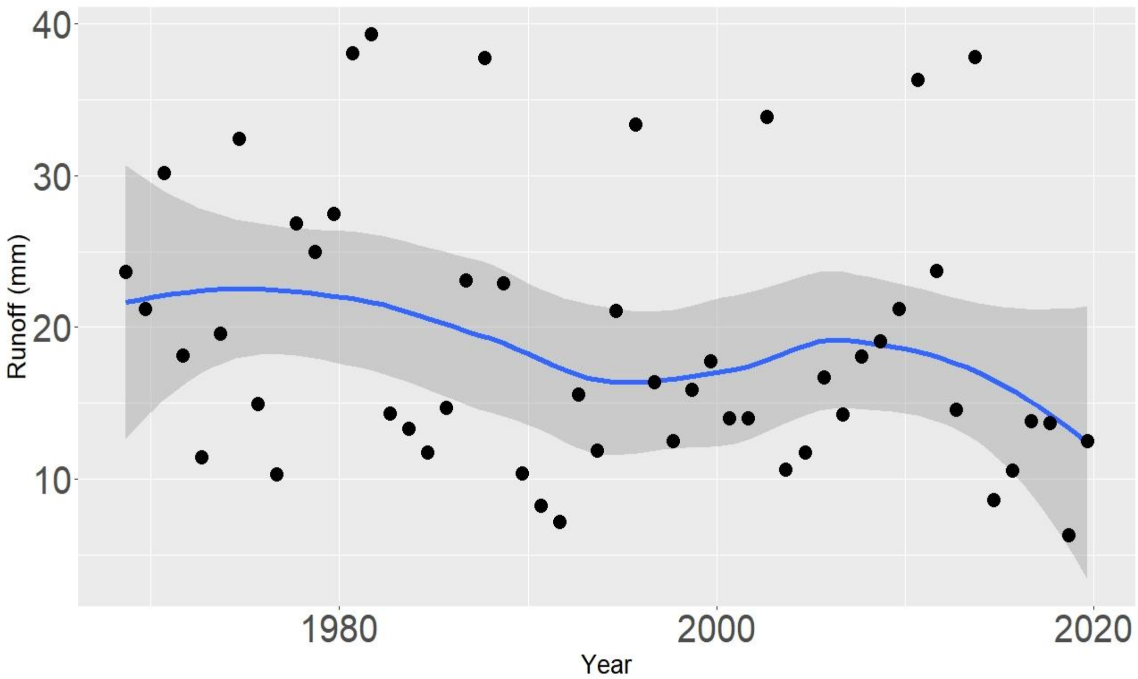

Fig 8:- Average Annual Variations of Runoff obtained from received data (1968-2019) ("R," 2022)

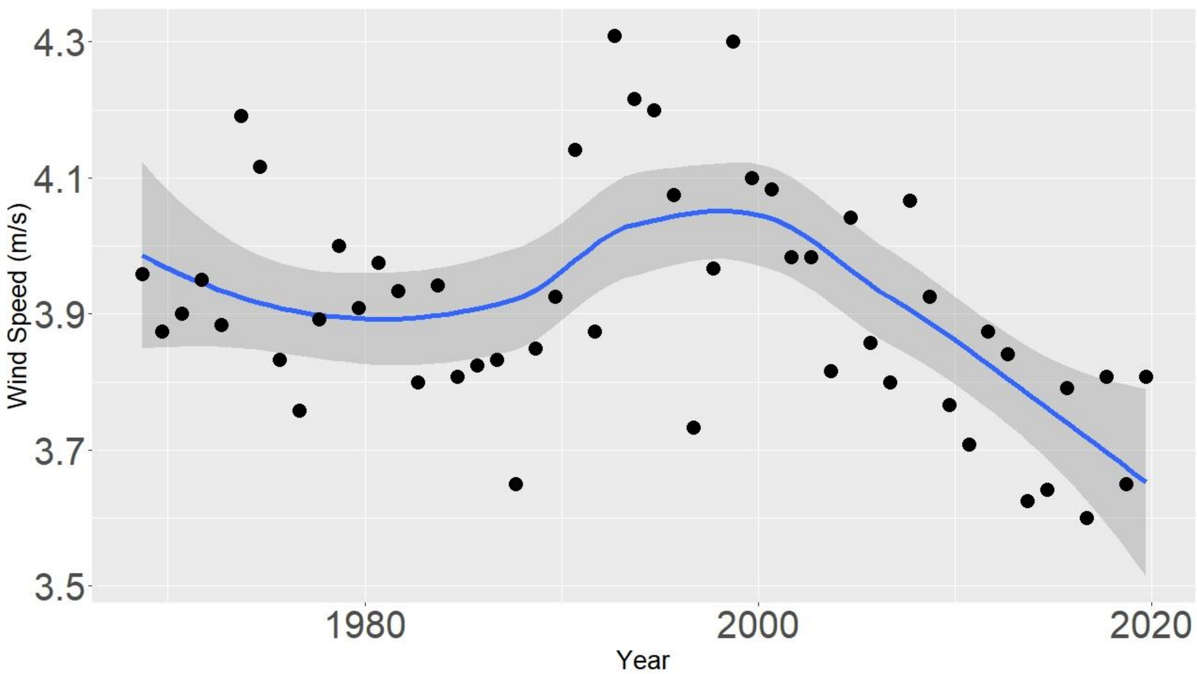

Fig 9:- Average Annual Variations of Windspeed obtained from received data (1968-2019) ("R," 2022)

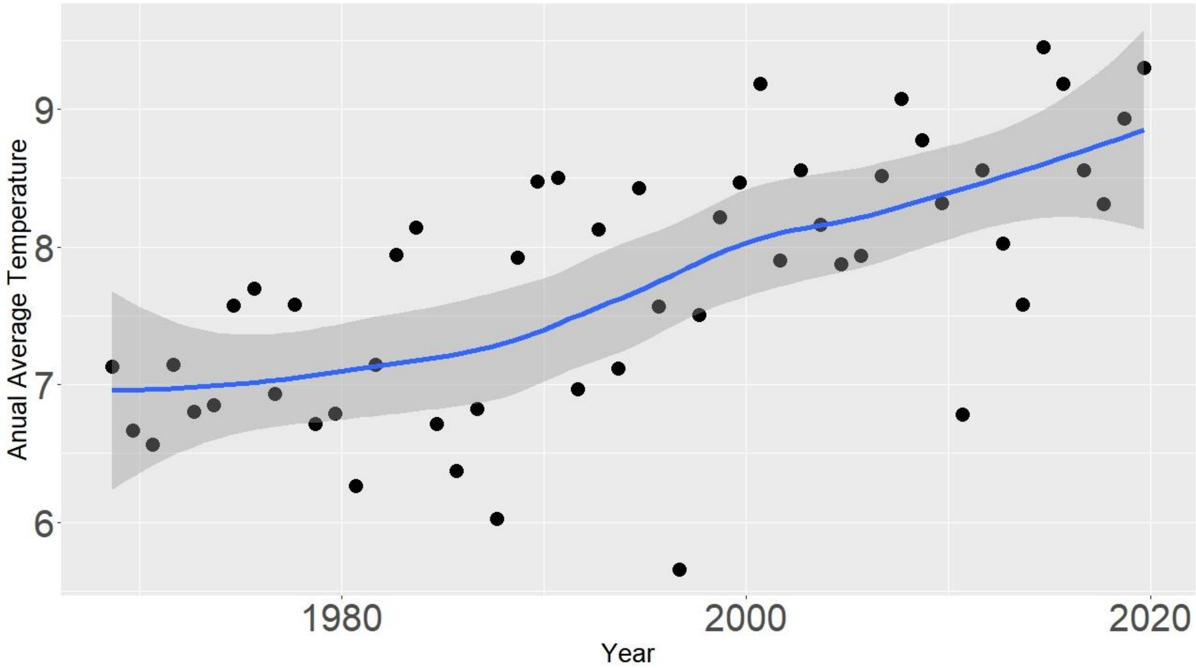

Fig 10:- Average Annual Temperature Trend obtained from received data (1968-2019) (“R,” 2022)

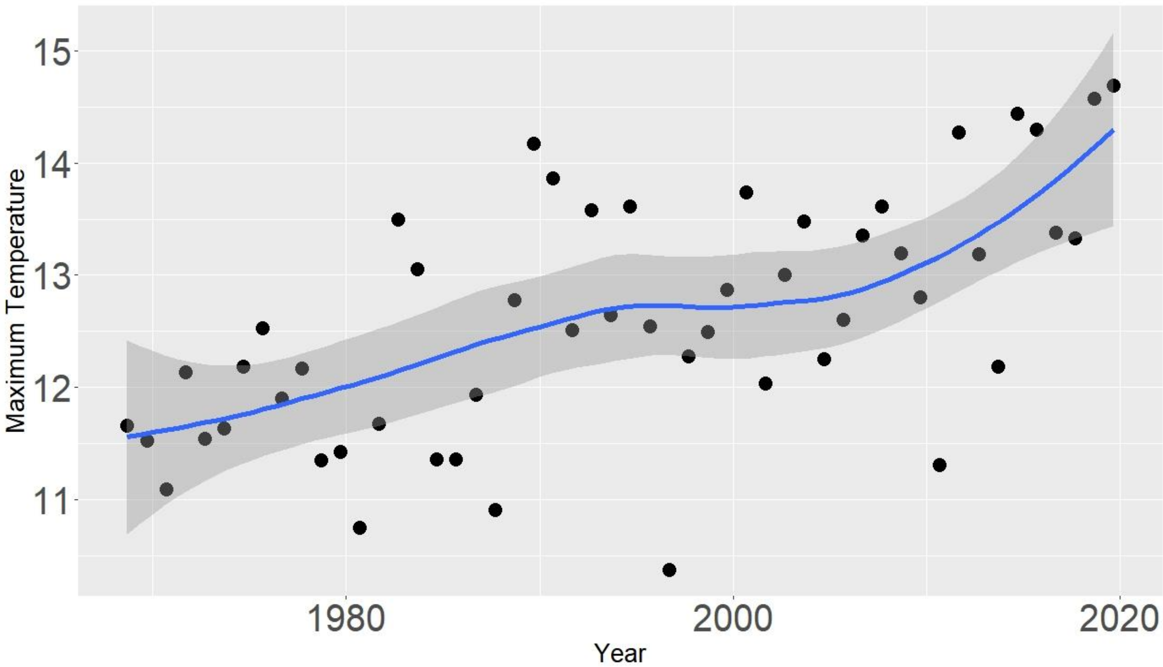

Fig 11:- Average Maximum Temperature Trend obtained from received data (1968-2019) (“R,” 2022)

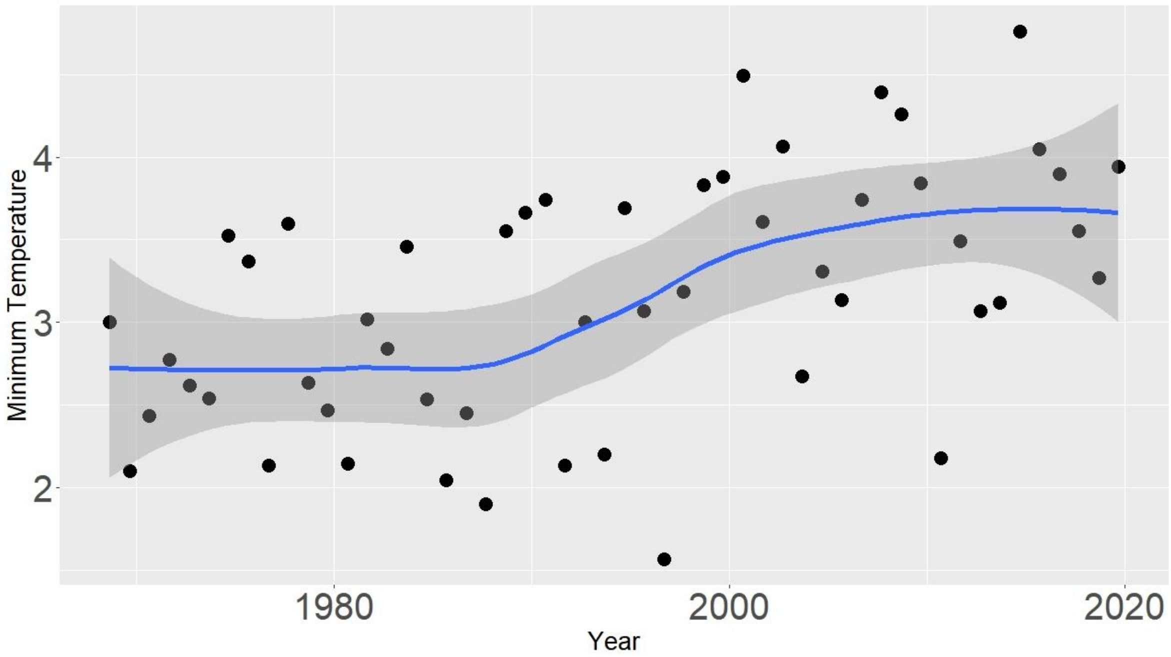

Fig 12:- Average Minimum Temperature Trend obtained from received data (1968-2019) (“R,” 2022)

After sorting the received data and importing them to R, we visualized the general pattern of the mentioned data with package ggplot2. Next, we installed the package "SPEI," with which we calculated the PET from Thornthwaite, Hargreaves, and Penman-Monteith equations. We are going to check the sensitivity of potential evapotranspiration to climate change with these three methods. The results of these methods, in some cases, differ in terms of their sensitivity to temperature and other climate inputs due to the factors they consider (Table-1). Simulating the impact of the climate on potential ET and the impact of precipitation changes on soil moisture availability has generally been used to account for climate change.

In this report, we concentrate on how potential ET, which is the ET when soil moisture conditions are not a constraint, may be impacted by climate change. Many methods with different data demands can be used to compute the PET. Some of them are simpler and require only monthly average information, like Thornthwaite. In contrast, others are more complex and need daily values for maximum and minimum temperature, humidity, radiation, wind speed, and vegetation characteristics. Besides requiring different inputs related to the climate, these methods also have quite different computational structures. Simplified formulas for each approach are shown in (Table-2), which highlights variations in input specifications and computational formulas. The premise that temperature is a good predictor of the atmosphere's ability to evaporate water underlies temperature-based approaches.

While temperature-based approaches are helpful when other meteorological data are lacking, the results are typically less accurate than those obtained using other climatic considerations (Table-2).

Table 1 - Data requirements of selected formulae for computing potential evapotranspiration (McKenney & Rosenberg, 1993)

Method	T	R_s	e	u	Latitude/day-length	Plant parameters	The temporal resolution of input data
Thornthwaite	✔				✔		monthly
Hargreaves	✔		✔		✔		monthly
Penman-Monteith	✔	✔	✔	✔		✔	daily

Table 2: - Formulas for three different potential ET computation techniques, stated in a way that highlights differences in data needs and computational structure. (McKenney & Rosenberg, 1993)

Method	Formula
Thornthwaite	$PET = C * f(LAT, JD)_m * [T_m/f(T_m)]^{f[f1(Tm)]}$
Hargreaves	$PET = f(LAT, JD)_m * T_m * f(T_m, e_m)$
Penman-Monteith	$PET = [f_1(T) * R_n + f_1(T) * f_2(T) * [f_3(T) - f(T,e)]/(u,HT)] \div [f_1(T) + f_4(T)*[1 + r_c/f_1(u,HT)]]$

Where: -

C-constant term; **T-**temperature; **f (variable)-**term computed as a function of (variable); **R_s-**solar radiation; **R_n-**net radiation; **e-**humidity (actual vapor pressure); **u-**windspeed; **r_c,-**canopy resistance; **LAT-**latitude; **HT-**vegetation height; **JD-**Julian day.

Subscripts: the **m-**monthly value of a variable; **(no subscript)-**assumes a daily value of the variable; **etc.-** used to denote different functions of the same variable(s) within an equation or different constants; **max or min-**daily maximum or minimum value of the variable.

We can see that each of the three methods requires knowledge of the latitude and season in order to accurately reflect the latitudinal and seasonal variation in solar radiation. The Hargreaves (1974) approach utilizes an empirical "monthly factor," whereas the Thornthwaite (1948) methods use the information on day length; both are functions of latitude and season. Penman-Monteith combines the impacts of both radiation and mass transfer on PET, including both climatic and vegetation characteristics. Penman-Monteith is the approach we are considering here with the most solid physical foundation. It also requires the greatest data, including data on temperature, radiation, humidity, wind speed, and many vegetation-related parameters like vegetation height to calculate the vapor flux's aerial resistance (Fig. 13) (MCKENNEY & ROSENBERG, 1993).

```r
install.packages("SPEI")
library(SPEI)
library(dplyr)
library(tidyr)
library(ggplot2)

wernersbach_data_daily = read.table("Wernersbach_2_EC.Towers_daily_2017.csv", sep = ",", dec = ".", header = T)
wernersbach_data = read.table("Wernersbach_2_EC.Towers_monthly_1968-2019.csv", sep = ",", dec = ".", header = T)

wernersbach_data$ET_thorn = thornthwaite(Tave = wernersbach_data$Temperature.Mean_Avg_DegC,
                                         lat = 50.966)

wernersbach_data$ET_har = hargreaves(Tmin = wernersbach_data$Temperature.Min_Avg_DegC,
                                     Tmax = wernersbach_data$Temperature.Max_Avg_DegC,
                                     Pre = wernersbach_data$Precipitation_Corrected_mm,
                                     lat = 50.966)

AtmosphericPressure = 101.325*exp(-(9.80665*0.02896968*330)/(288.16*8.314462618))

wernersbach_data$ET_pen = penman(Tmin = wernersbach_data$Temperature.Min_Avg_DegC,
                                 Tmax = wernersbach_data$Temperature.Max_Avg_DegC,
                                 U2 = wernersbach_data$Windspeed42m_Avg_ms.1,
                                 Rs = wernersbach_data$GlobalRadiation_Avg_Wm.2*(0.0864),
                                 P0 = 101.325,
                                 P = AtmosphericPressure,
                                 ed = wernersbach_data$VapourPressure_Avg_kPa,
                                 z = 330,
                                 crop = "tall",
                                 lat = 50.966)
```

Fig 13: Codes in R Script for calculation of PET (Taken from the codes used for running the analysis in “R” programming language, 2022)

Sensitivity analysis

Now that we have our empirical model, we are interested to see which variable, potential evapotranspiration (PET), has the most dependency. In other words, which parameter in the model is the most influential? For that, we have downloaded the sensitivity analysis pre-written codes from (ARTICLES u. a., 2018) and entered our data as input to the built functions. Considering the principle of Parsimony, we chose an interactive linear model for our data instead of a simple linear model or a complex polynomial one. In this model, all the parameters in an equation are considered interactively. However, the impact of changing only one variable is measured while keeping other parameters constant at their starting value, which is their average value.

Time series analysis

For trend and time series, we need the package "tseries." Unit root tests can assess if a time series is of type difference-stationary process (DSP). It is impossible to discuss the mathematical theory upon which they are built. However, the ADF-test (augmented Dickey-Fuller test) is commonly applied in real life. It is included in the R package "tseries." Also, The Kwatkowski-Phillips-Schmidt-Shin test (KPSS test) evaluates stationarity or trend stationarity directly. Since in trend stationary data, the residuals are autocorrelated, we can use common trend tests like the Mann-Kendall test using the library("Kendall").

By fitting curves or employing so-called smoothers, a tendency can be found or eliminated. A linear regression against time, for instance, can be used to find a linear trend. Then, the residuals match the time series that have been trend-corrected.

This is applicable to both difference-stationery and trend-stationary time series in principle. However, as was already indicated, the autocorrelation of the residuals makes it likely that the significance tests often employed for linear regression models may produce false findings. In conclusion, while using linear regression to eliminate trends is acceptable, the accompanying tests may not succeed depending on the specific time series characteristics. As an alternative, moving averages (linear filters), exponential smoothing, or so-called "kernel smoothers" can be used to detect trends. Another option is also provided for comparison, the LOWESS-Filter (CLEVELAND, 1981), which is highly common in contemporary data analysis (PETZOLDT, o. J.).

Results

The boxplots (Fig. 14) show Potential Evapotranspiration (PET) with Hargreaves, Penman-Monteith, and Thornthwaite. We can observe that Penman-Monteith gives the greatest monthly values with more statistical dispersion, while Thornthwaite gives the lowest. Hargreaves method also gives less PET compared to Penman-Monteith. Compared to the other approaches, Thornthwaite, a very empirical method, tends to significantly underestimate PET. This under-prediction tendency has been observed before (ROSENBERG u. a., 1983), and it is most likely caused by the method's initial calibration in humid settings. However, since the Penman and Penman-Monteith approaches are founded on physical principles and take into account all of the climatic elements that have an impact on PET, we will assume it as the most reliable method and continue the rest of the analysis with it.

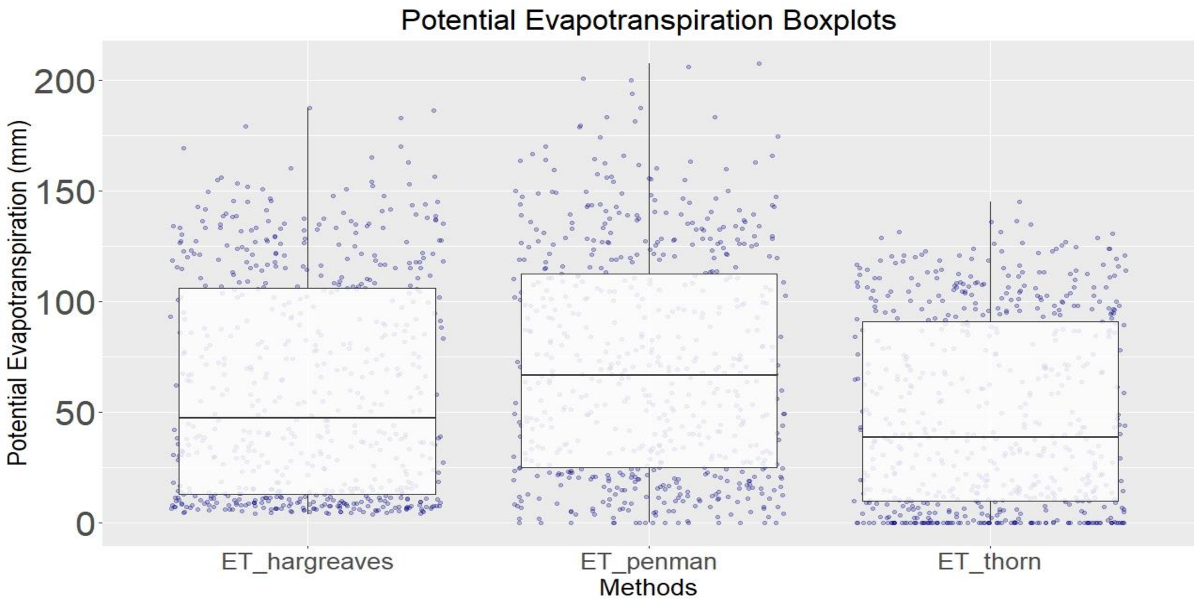

Fig 14: -Comparison of PET from Penman-Monteith, Hargreaves, and Thornthwaite (Obtained from "R" with ggplot2 package, 2022)

The sensitivity of PET has been analyzed for Penman-Monteith (Fig. 15) and actual evapotranspiration from the water budget equation (Fig. 16). As we can see in the graph, the PET is highly dependent on first relative humidity, second max temperature, followed by global radiation, min temperature, and wind speed. Figure 15 shows that in humid conditions like our catchment, the PET mostly depends on vapor pressure with an inverse relation. Vapor pressure is an indication of humidity, which directly correlates with Vapour pressure deficit (VPD) (Eq. 1).

Eq. 1: - Vapor Pressure Deficit = Saturated Vapour Pressure - Actual Vapour

Vapour Pressure Deficit is the difference between the quantity of moisture in the air and the maximum amount the air can retain before becoming saturated. VPD is directly proportional to PET. The more the deficit, the higher the PET. In the package "SPEI" in the "R" program, the Penman-Monteith equation asks for input as the vapor pressure, atmospheric pressure at the surface, and atmospheric pressure at sea level. Then it calculates the vapor pressure deficit in itself.

The second place is taken by maximum temperature, directly related to PET. An increase in Tmax would lead to an increase in PET which is plausible. For instance, if there is an increase in Tmax by 2.5°C, the PET will rise by nearly 1.5 times its starting value. If cloudiness changes, incoming solar radiation might vary. An increase in solar radiation elevates the PET but at a lower rate than Tmax, and it never exceeds a 50% change in PET, in a 40% change.

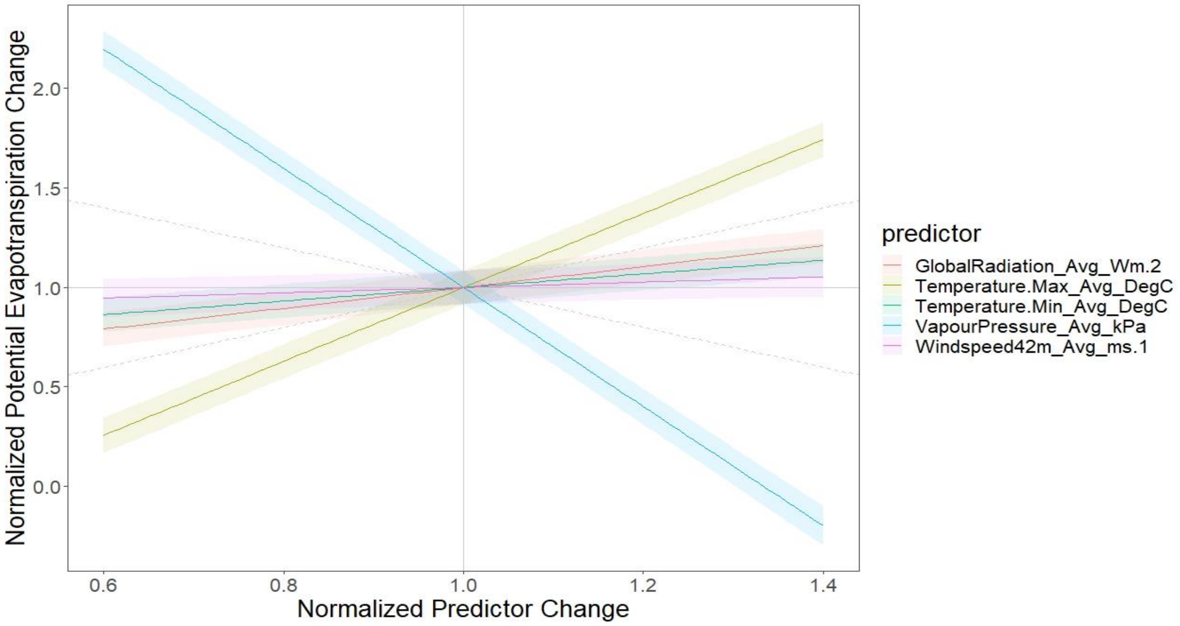

Fig 15: - Sensitivity Analysis of PET obtained from Penman-Monteith ("R," 2022)

Since in cold weather, we only have limited evaporation, the dependency of PET on minimum temperature is low.

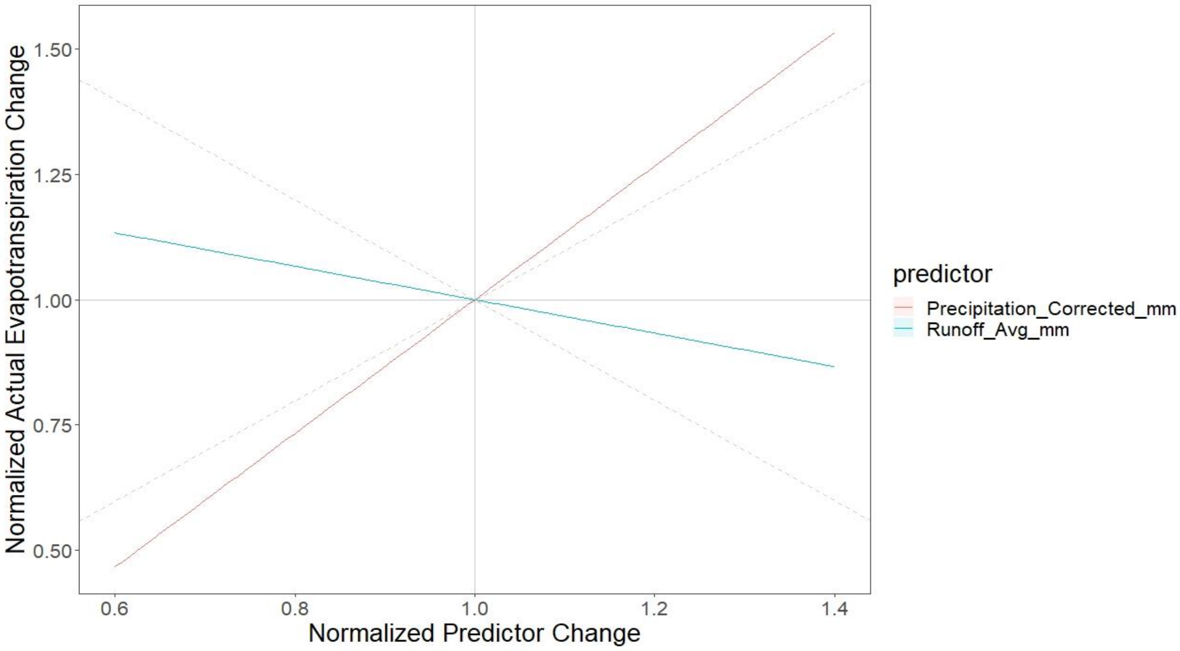

Fig 16: - Sensitivity Analysis of Actual ET from Water Budget Equation ("R," 2022)

In the second graph, the actual evapotranspiration of the catchment calculated by the water budget equation has been shown (Fig. 16). As expected, actual ET increases with precipitation rise and also decreases with an increase in runoff.

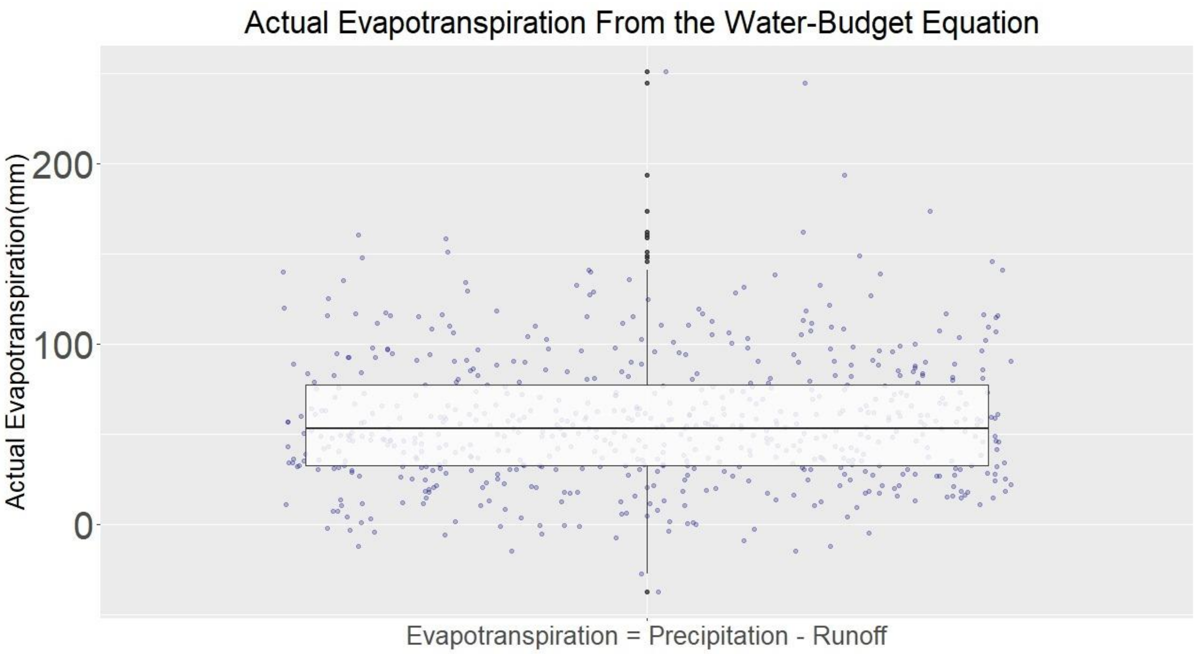

Fig 17: - Boxplot for Actual Evapotranspiration from Water Budget Equation (“R,” 2022)

The boxplot mentioned above in (Fig. 17) represents the values of actual evapotranspiration obtained from the water budget equation over 51 years from 1968 to 2019. There are some outliers in the given plot since, during some periods in the catchment, runoff has exceeded the precipitation values, resulting in negative evapotranspiration. This can be explained by the fact that storage was not considered during the analysis as no data was available. Also, upon further investigation of the given catchment, it was also found that there were many underground sources of water to the surface in the form of an aquifer which can explain the larger values of runoff in comparison to precipitation; hence, the outliers in the plot.

Time Series:

In the first step of the Time Series Analysis, different tests were performed on the given climatic variables to check whether there is a significant trend or not (the trend is significant according to the p-value = 0.05). The results from this trend analysis are mentioned in (Table 3) as it can be seen that a significant trend is present in all the mentioned climatic variables.

Table 3: P-values resulted from different trend tests for the four most important climate variables

P-values					
Climate variables	ADF	KPSS(Level)	KPSS(Trend)	Mann-Kendall	Trend presence
Maximum Temperature	0.011360	0.010000	0.100000	0.000006	Yes
Solar Radiation	0.077850	0.010000	0.044260	0.000100	Yes
Vapour Pressure	0.323600	0.031960	0.048210	0.004808	Yes
Potential Evapotranspiration	0.312200	0.010000	0.040850	0.000001	Yes

In the following, the time series of maximum temperature and solar radiation have been brought to see how they changed in the catchment during the 50 years. The graph (Fig. 18) generally shows an increasing trend in Tmax. We can observe that during the flood years 1985, 2002, and 2013, the Tmax rose to a great degree compared to its neighboring values, which caused more capacity for the air to hold more water and more evapotranspiration, which subsequently led to more precipitation in the catchment.

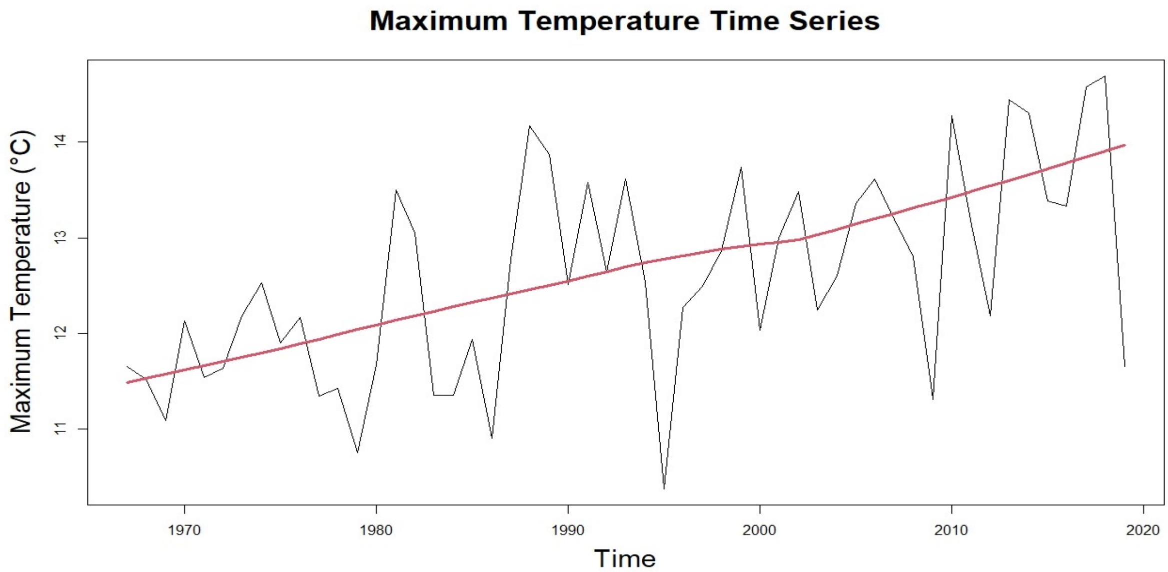

Fig 18: - Maximum Temperature Trend in the Catchment from 1968-2019 (“R”,2022)

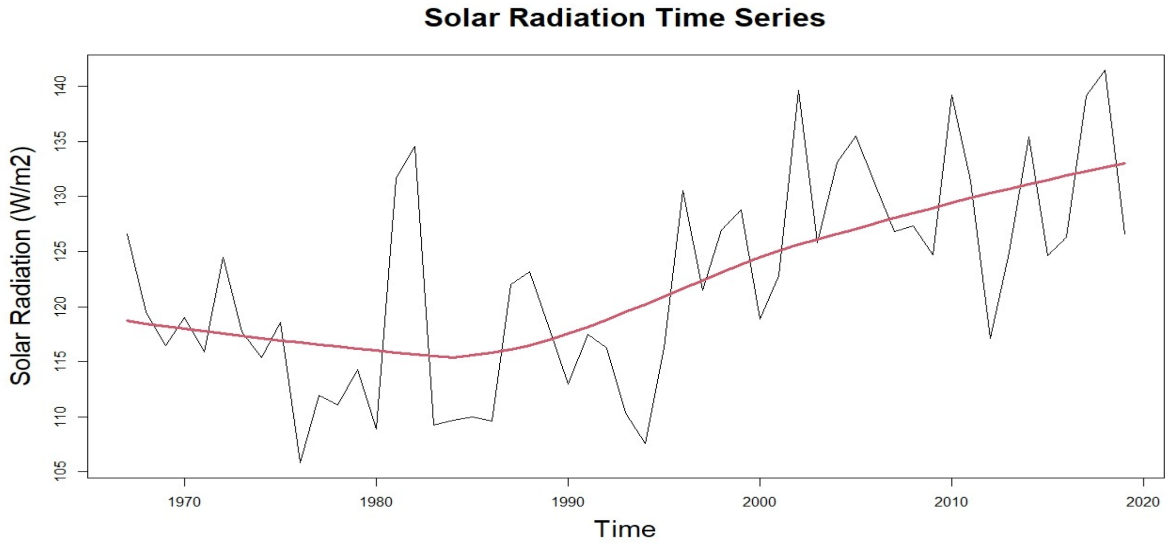

Fig 19: - Variation in Solar Radiation in the given interval of time from 1968-2019 (“R,” 2022)

Graph (Fig. 19) illustrates solar radiation, which has decreasing trend till 1990 due to the fact that before 1990 many power plants in the area emitted lots of pollution and aerosol into the atmosphere. These aerosols remain suspended in the atmosphere and cause scattering of the incoming solar radiation, which reduces the intensity of radiation received by the earth's surface. This can ultimately lead to a cooling effect and decrease the ET in the given area. In 1990, Germany was unified, where east Germany was reunited with the west, and a new government was formed. The new government enacted regulations to shut down most of these power plants and started transitioning towards more sustainable energy sources. This change can be seen in the upward trend in solar radiation in the graph (Fig. 19) since 1990.

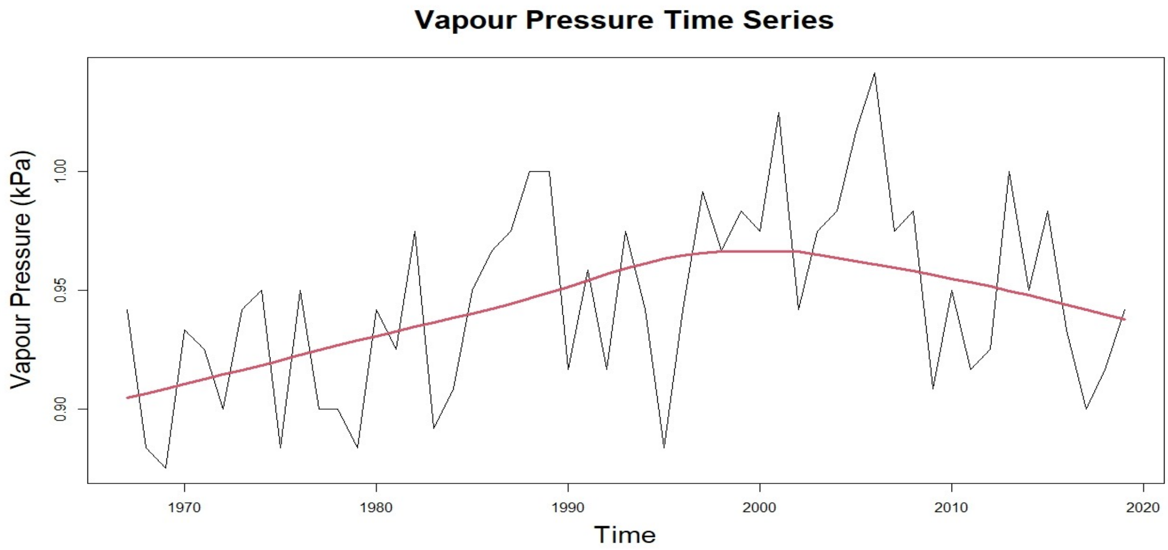

Fig 20: - Changes in Vapour Pressure in the catchment from 1968-2019 (“R,” 2022)

In the graph (Fig. 20), you can see the vapour pressure trend in the catchment, which is related to vapour pressure deficit (Eq. 1).

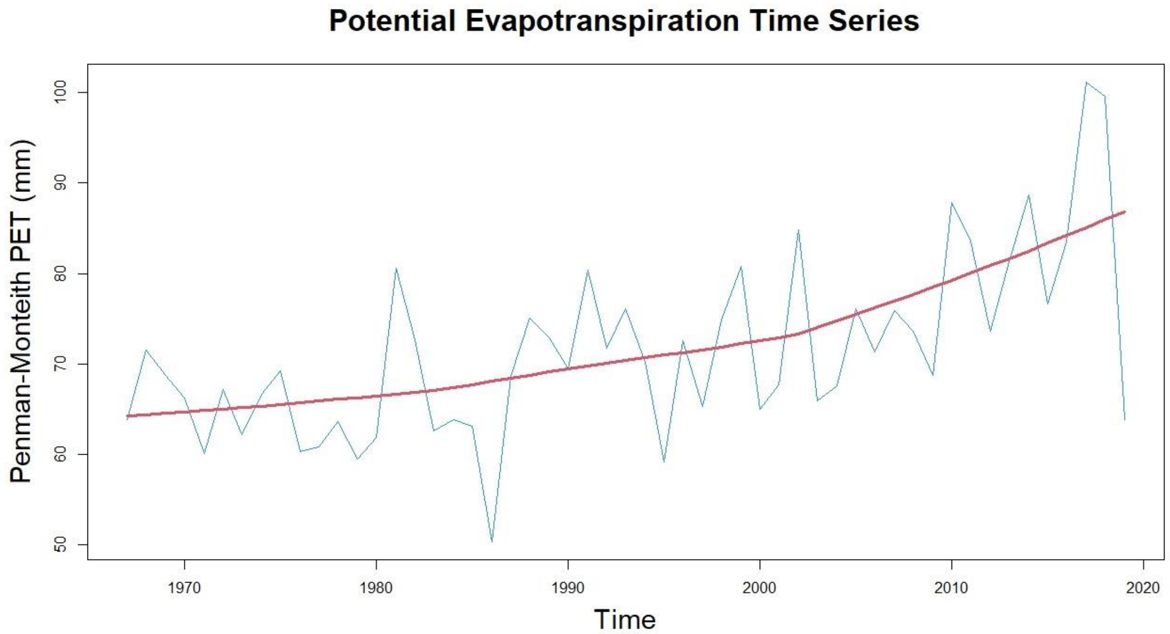

Fig 21: -Changes in PET of the catchment during the 51 years 1968-2019 (“R,” 2022)

The graph (Fig. 21) illustrates the calculated PET from Penman-Monteith in the Wernersbach catchment during the 50 years. As we can see, from 1968 to 1990, it more or less increases. In this period, the Tmax increases, but vapor pressure deficit and solar radiation decrease, which reduce the effect of rising temperature on the increase in PET. In the 1990s, after removing mentioned power plants, solar radiation started to increase, which made the slope of rising PET steeper. From 2000 to 2019, Vapour Pressure Deficit is also rising, which causes a significant increase in potential evapotranspiration in the catchment. However, actual evapotranspiration measured by flux towers inside the catchment has a down warding slope in recent years.

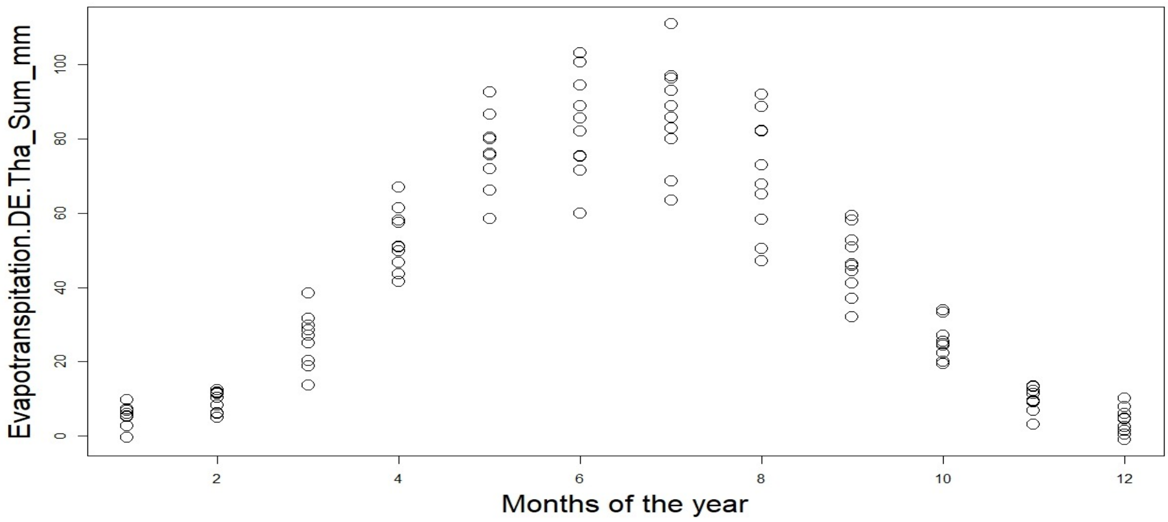

Fig 22: - Monthly Variations of ET obtained from EC Tower-Tha (2010-2019) ("R," 2022)

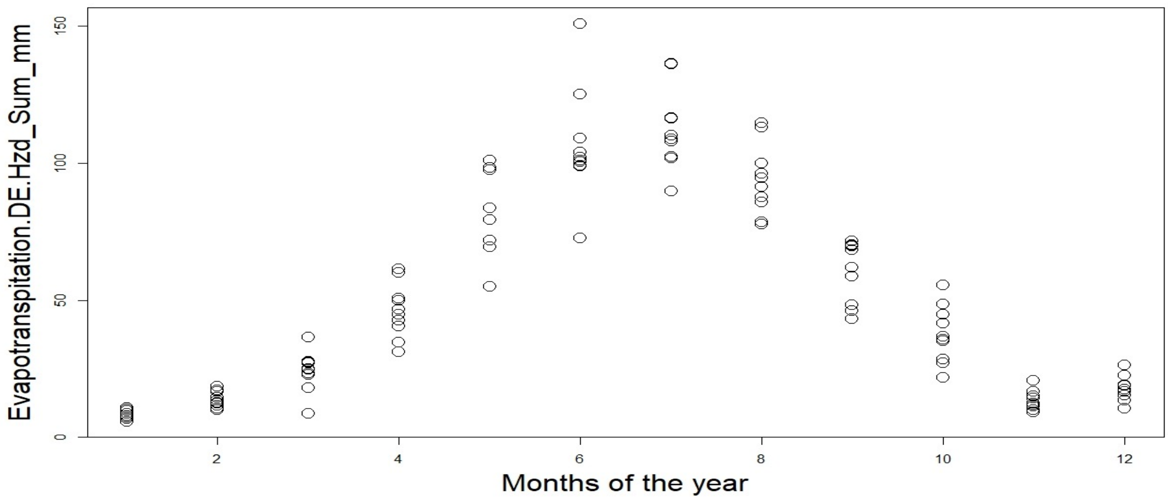

Fig 23: - Monthly Variations of ET obtained from EC Tower-Hzd (2010-2019) ("R," 2022)

In (Fig. 22, 23), the monthly values of evapotranspiration (ET) recorded by EC Tower Tha and EC Tower Hzd have been represented from 2010 to 2019. The most recognizable trend, which is common in both, is that ET starts increasing from January and goes to a maximum in the months of June-July and then again decreases till December. This is because the given area has peak temperature in the summer months of June & July, while the lowest temperature in winter is January & December. As we all know, ET is directly influenced by the temperature, which is why it more or less follows the change in temperature trend across the whole year. While the most interesting thing to notice is that in EC Tower-Tha, the transition of decrease in ET from June to December is smooth, while in EC Tower-Hzd, this decrease has an abrupt end in the months of October-November.

Since EC Tower Tha is surrounded by coniferous trees (spruce trees) which don't shed their leaves in winter, that's why the smooth transition. At the same time, the second tower EC Tower Hzd is located in a Deciduous forest (oak trees) that sheds their leaves in winter, and that's why there is an abrupt decrease in ET.

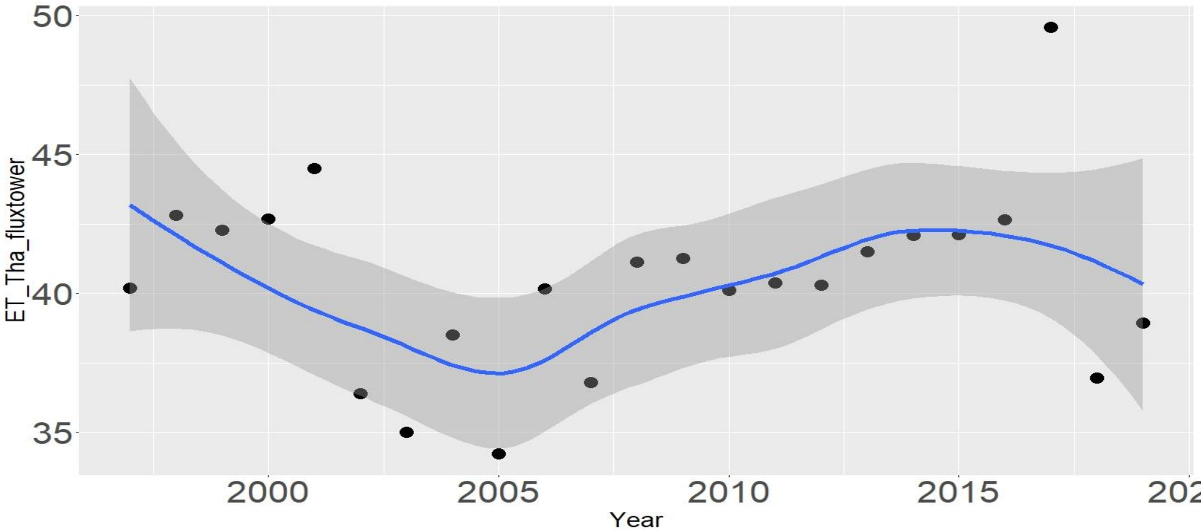

Fig 24: - Annual Variations of ET obtained from EC Tower-Tha (1997-2019) ("R",2022)

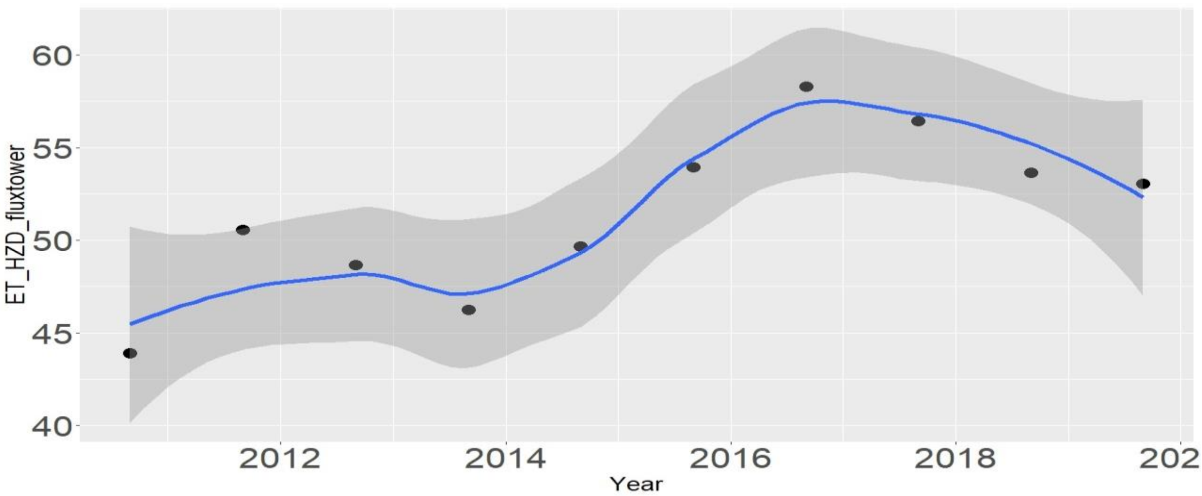

Fig 25: - Annual Variations of ET obtained from EC Tower-Hzd (2010-2019) ("R," 2022)

In (Fig. 25), actual evapotranspiration recorded by Eddy Covariance (EC) Tower – EC Tower Hzd is shown from its year of establishment, 2010 to 2019. This tower, as already explained, is surrounded by a re-growing oak forest planted in 2008 after a windbreak event uprooted a part of the initial spruce forest. As a result, we can see an overall upward trend of increase in ET over the years, indicating the growth of the oak trees along with it. There was a small dip in ET in 2014, which might be explained by the drought that occurred during the same time.

Also, after 2018 the same decreasing trend can again be seen in the graph, which was due to "beetle infestation" and the second break event experienced by the forest in the given catchment in 2018-2019. If the trees infected by beetles are not removed immediately, these beetles can quickly spread and consume a lot of trees in a very small interval (Fig. 26).

Fig 26: - Beetle Infestation in Wernersbach catchment (Picture taken during a site visit of the catchment in June, 2022)

While in the second figure (Fig. 24), actual evapotranspiration recorded by Eddy Covariance (EC) Tower – EC Tower Tha is shown from its year of establishment 1997 to 2019. It is located inside the spruce forest, which is located 5km away from the Wernersbach catchment. The evapotranspiration has a decreasing trend till 2005, then it increases till 2018, and then again there is a small dip till 2019. The initial decrease in ET can be explained by the drought experienced by the catchment in 2003. As regards ET, it was most affected by the droughts (ZINK u. a., 2016), which can explain the initial decrease in ET till 2005.

Discussion

These simulations have demonstrated that significantly different conclusions can be drawn on the effects of climatic changes depending on the method employed to compute PET. The findings can be affected by both the data requirements and the structural form of the equation; approaches with comparable inputs can produce radically different estimations of PET. Most variables' sensitivities are affected by the values of the climatic variables. Therefore, it is important to use caution when projecting the findings of a sensitivity analysis from one place or season to another.

Which approach is best for modeling the impact of climate change on PET? The response is somewhat influenced by our current understanding of the direction and scale of the climate changes brought on by global warming, as well as whether or not the intention is to make forecasts or investigate the implications of alternative scenarios. Some temperature-based techniques seem to provide accurate PET values, both in the absolute sense and in reaction to simulated changes in the environment. As was previously said, temperature-based approaches were created with the presumption that there is some relationship between other climate variables and temperature. If we can assume that these correlations will hold when temperatures rise due to greenhouse warming, then the more dependable temperature-based methodologies may be sufficient for making broad-scale, if rough, forecasts of the effects of climate change when that is the only factor taken into account.

Temperature is not the only climatic factor that will likely be impacted by greenhouse warming, as these methods have demonstrated that other climatic variables can either offset or amplify the impacts of rising temperature on PET. Also, we have already seen that PET was most sensitive to annual fluctuations in humidity at the given study site, but solar radiation and wind speed also had an impact.

Potential Evapotranspiration (PET) has been the sole focus of our investigation. However, Evapotranspiration (ET) rarely happens consistently at the pace it could, particularly in non-humid areas. The availability of soil water and the state of the vegetation can both help to keep ET below potential values. Runoff may be significantly impacted by variations in real evapotranspiration rates. The scope of this study does not allow for a thorough examination of the effects on runoff. But some conclusions can be drawn.

If we assume that changes in soil moisture storage and deep seepage are negligible over the long term, runoff is the net result of precipitation minus actual evapotranspiration. The sensitivity analysis described here could be used in conjunction with precipitation data to offer a first approximation of the effects of climate change on runoff in regions where ET occurs at the potential rate. If soil moisture content stays high and does not restrict ET, runoff behavior would be closely related to changes in potential ET. The sensitivity analysis done in this study on the water budget equation shows that ET is most sensitive to the amount of precipitation followed by runoff.

The impacts of a limited supply of soil moisture would need to be considered in drier environments. The field capacity of the soil, vegetation parameters (height, leaf area, stomatal control), and precipitation information would all need to be known. Actual ET is typically assumed to decrease linearly as a function of soil moisture content in water balance models. Actual ET would be less sensitive to changes in temperature, solar radiation, humidity, and wind speed than potential ET when soil moisture goes below field capacity. Therefore, it follows that runoff would be less sensitive to changes in potential ET when soil moisture is limiting than when it is not. However, in areas where water is scarce, even a slight change in actual ET could have a big impact. Of course, this is a highly basic explanation of how actual ET and runoff may be impacted by climatic changes. In actuality, variations in the depth of the water table, the amount of precipitation, the speed at which the snow melts, and other variables may impact the runoff response in ways that are challenging to anticipate without additional research.

The sensitivity of runoff is more to precipitation than temperature variations, at least on an annual basis, according to some earlier studies of the effects of climatic change on runoff (NĚMEC & SCHAAKE, 1982) (KARL & RIEBSAME, 1989). This viewpoint is also supported by a 1990 report from the IPCC Working Group on Climate Impacts.

Summary

The recording of data for Wernersbach Catchment started in 1968. During that time, entire Germany was divided into East and West Germany and was ruled by different governments. Dresden, under east Germany, was ruled by the Soviet government and was known as German Democratic Republic (GDR). Due to rapid industrialization, the air quality in East Germany was deteriorating day by day. The GDR's most persistent issue at the turn of the century was air pollution. This was due to the fact that lignite (brown coal) was used as the main source to generate power. Burning lignite produced significant emissions of sulfur dioxide (SO2) and particulate matter (PM) due to its high sulfur and ash content. The GDR is thought to have had Europe's greatest total SO2 emissions, totaling 5.8 million tons (HEINECKE, 2021). Also, the laws and regulations on pollution were not perfectly established as well as not closely monitored. Due to this, there was a lot of pollution in the areas where the catchment is located. Acid rains, along with a high concentration of aerosols in the air, were common during these times. These aerosols reduced the concentration of sunlight reduced by the earth's surface, as already shown in (Fig.13). In 1990, the soviet government fell, leading to the unification of east and west Germany (EDITORS, o. J.). A new central government was formed, which made numerous laws and regulations to reduce the level of pollution, including the closing of many power plants. As a result, the aerosol concentration decreased, increasing the solar radiation on the surface.

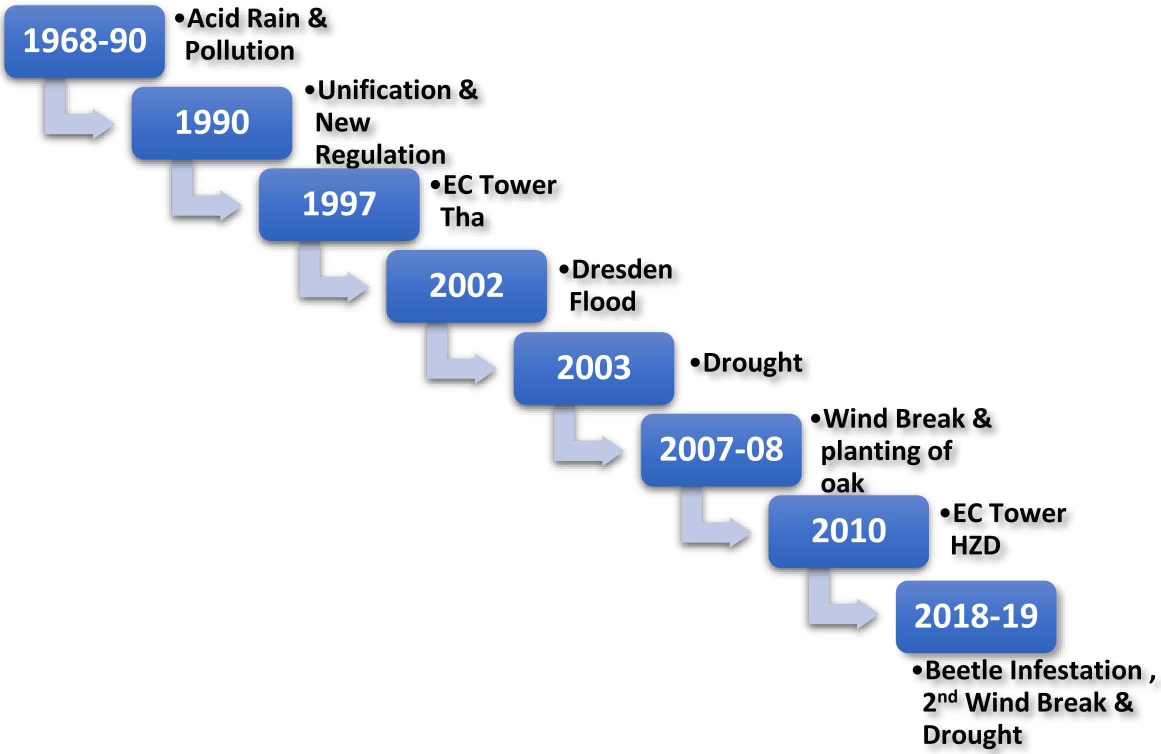

Fig 27: - Timeline of Events in Wernersbach catchment

In 1997, the first Eddy covariance tower, EC Tower-Tha, was constructed in Tharandt forest (Fig. 6), 5km away from Wernersbach Catchment, to monitor the carbon and water vapor fluxes in the area. In 2002, there was a huge flood in the area, the largest flood ever in the catchment. A discharge of 6533 l/s was recorded at the outlet of the catchment in August 2002 ("Wernersbach catchment aera ", o. J.). Also, the following year 2003, there was a drought in Germany and the given area. While flood did not affect the ET of the catchment, the drought in 2003 led to a decrease in Actual Evapotranspiration, which can be seen from the ET recorded by EC-Tower Tha in figure (Fig. 24).

In 2007, there was a wind break event in the Wernersbach Catchment where an entire section of forest was uprooted which was later plated by oak trees in 2008 (Fig. 5). To monitor the growth and carbon emission of these re-growing oak forests, the second Eddy covariance tower- EC Tower-Hzd was established (Fig. 3). There was the second flood in the given interval in 2013 which was not as devastation as 2002 flood but still affected the area. Finally, there was a beetle infestation and second windbreak event in 2018, which also caused a small decrease in ET which can be seen in (Fig. 26). All these major events in the catchment have been summarized in (fig. 27), where it can be easily seen which event happened when and in what sequence.

Conclusion

Evapotranspiration (ET) is increasing globally due to the rise of temperature, and looking at future predictions of climate change, it is not going to decrease anytime soon; rather, chances are it will keep increasing due to the accelerated anthropogenic emissions by humans. With the increase in ET, more and more water will be evaporated from the surface to the atmosphere. If there is no change in the current conditions, with time, all the trees and vegetation with a higher water requirement will die or become extinct. The irregularities in precipitation will also increase, leading to heavy and less duration of rainfall in summer while more precipitation in winter. As the water requirement by plants in summer is more than in winter, it will also lead to the destruction of the ecosystem. The only solution is to either take a step back and try to do things differently so that climate change can be reduced in the future or try to adapt to the coming changes so that the negative effects can be minimized. One such adaptation measure that can be taken is planting more beech trees as they can survive in semi-arid conditions and are a very good carbon sink. This can help reduce future climatic change and restore overall balance in the environment (REHSCHUH u. a., 2021).

After analyzing all the methods, it is pretty clear that the best way to find Actual ET is through an Eddy Covariance tower as they directly measure the fluxes in the air, reducing the personal and calculation error. Forest ET can be easily measured using this EC-based method with hardly any interference. These systems often include equipment that enables accurate high-frequency measurements of CO2 and H2O fluxes. These systems offer valuable long-term flux observations. As the EC approach can accurately quantify the gas and energy exchange between ecosystems and the atmosphere throughout forest regions, its use in the future will steadily increase (SRINET u. a., 2022).

Climate change will negatively impact sustainable agricultural production in the future, which will ultimately result in less food being produced to feed an expanding population. Water availability in arid and semi-arid parts around the world is already expected to decline due to a lack of precipitation and rising temperatures, which will cause a rise in dry areas. At the same time, crop production will likely decrease due to a shorter crop growth cycle as a result of rising temperatures, lack of precipitation, and unavailability of soil water. Therefore, it is crucial to comprehend how sensitive evapotranspiration is to climate change in order to lessen its negative effects in the face of future climate change. We have to find enhanced management techniques, drought-tolerant crop varieties, and soils with high water-holding capacities, which will all help farmers better deal with the effects of drought.

Reference

ARTICLES, Mladen Jovanovic on 13/09/2018 in Must-Read, CONTENT, Non-Membership, STATISTICS, ANALYSIS, Data (2018, 13. September): Simple Sensitivity Analysis with R. Complementary Training. Online verfügbar unter URL: https://complementarytraining.net/simple-sensitivity-analysis-with-r/ [04.09.2022]

EDITORS, History com (o. J.): East and West Germany reunite after 45 years. Online verfügbar unter URL: https://www.history.com/this-day-in-history/east-and-west-germany-reunite-after-45-years [07.09.2022]

Evapotranspiration | North Carolina Climate Office (o. J.). Online verfügbar unter URL: https://legacy.climate.ncsu.edu/edu/Evap [04.09.2022]

GRÜNWALD, Thomas, BERNHOFER, Christian (2007): A decade of carbon, water and energy flux measurements of an old spruce forest at the Anchor Station Tharandt. Tellus B: Chemical and Physical Meteorology, 59 (3): S. 387–396. Online verfügbar unter DOI: https://doi.org/10.1111/j.1600-0889.2007.00259.x

HEINECKE, Robert (2021, 27. August): How has air quality in Germany changed in the last 40 years? Breeze Technologies. Online verfügbar unter URL: https://www.breeze-technologies.de/blog/how-has-air-quality-in-germany-changed-in-the-last-40-years/ [07.09.2022]

Hydrometeorological observations for the catchment Wernersbach (Germany) and Eddy Covariance observations of two nearby EC towers. | CUAHSI HydroShare (o. J.). Online verfügbar unter URL: https://www.hydroshare.org/resource/ca36686775a14c75bfe4ada5c51a98c5/ [04.09.2022]

KARL, Thomas R., RIEBSAME, William E. (1989): The impact of decadal fluctuations in mean precipitation and temperature on runoff: A sensitivity study over the United States. Climatic Change, 15 (3): S. 423–447. Online verfügbar unter DOI: https://doi.org/10.1007/BF00240466

MCKENNEY, Mary S., ROSENBERG, Norman J. (1993): Sensitivity of some potential evapotranspiration estimation methods to climate change. Agricultural and Forest Meteorology, 64 (1): S. 81–110. Online verfügbar unter DOI: https://doi.org/10.1016/0168-1923(93)90095-Y

NĚMEC, J., SCHAAKE, J. (1982): Sensitivity of water resource systems to climate variation. Hydrological Sciences Journal, 27 (3): S. 327–343. Online verfügbar unter DOI: https://doi.org/10.1080/02626668209491113

PETZOLDT, Thomas (o. J.): Data Analysis with R Selected Topics and Examples., S. 141

PLUNKTE T, BERNHOFER C, GRNWALD T, RENNER M, PRASSE H (2022): Long-term climatological and ecohydrological analysis of a paired catchment – flux tower observatory near Dresden (Germany) Is there evidence of climate change in local evapotranspiration? J Hydrol

REHSCHUH, Stephanie, JONARD, Mathieu, WIESMEIER, Martin, RENNENBERG, Heinz, DANNENMANN, Michael (2021): Impact of European Beech Forest Diversification on Soil Organic Carbon and Total Nitrogen Stocks–A Meta-Analysis. Frontiers in Forests and Global Change, 4. Online verfügbar unter URL: https://www.frontiersin.org/articles/10.3389/ffgc.2021.606669 [04.09.2022]

ROSENBERG, Norman J., BLAD, Blaine L., VERMA, Shashi B. (1983): Microclimate: The Biological Environment. John Wiley & Sons, 538 S.

SRINET, Ritika, NANDY, Subrata, WATHAM, Taibanganba, PADALIA, Hitendra, PATEL, N. R., CHAUHAN, Prakash (2022): Measuring evapotranspiration by eddy covariance method and understanding its biophysical controls in moist deciduous forest of northwest Himalayan foothills of India. Tropical Ecology, 63 (3): S. 387–397. Online verfügbar unter DOI: https://doi.org/10.1007/s42965-021-00216-8

Stud<Project_Wernersbach (o. J.). Online verfügbar unter URL: https://cloudstore.zih.tu-dresden.de/index.php/s/xToes4ZzfaAZT8N [04.09.2022]

TYAGI, Shoobhangi, SINGH, Nidhi, SONKAR, Geetika, MALL, R. K. (2019): Sensitivity of evapotranspiration to climate change using DSSAT model in sub humid climate region of Eastern Uttar Pradesh. Modeling Earth Systems and Environment, 5 (1): S. 1–11. Online verfügbar unter DOI: https://doi.org/10.1007/s40808-018-0513-2

VOROBEVSKII, Ivan, KRONENBERG, Rico, BERNHOFER, Christian (2022): Linking different drought types in a small catchment from a statistical perspective – Case study of the Wernersbach catchment, Germany. Journal of Hydrology X, 15: S. 100122. Online verfügbar unter DOI: https://doi.org/10.1016/j.hydroa.2022.100122

Wernersbach catchment aera (o. J.). Document. Online verfügbar unter URL: https://tu-dresden.de/bu/umwelt/hydro/ihm/meteorologie/forschung/mess-und-versuchsstationen/wernersbach-einzugsgebiet?set_language=en [29.06.2022]

ZINK, Matthias, SAMANIEGO, Luis, KUMAR, Rohini, THOBER, Stephan, MAI, Juliane, SCHÄFER, David, MARX, Andreas (2016): The German drought monitor. Environmental Research Letters, 11 (7): S. 074002. Online verfügbar unter DOI: https://doi.org/10.1088/1748-9326/11/7/074002