Final project - 203200068 - flash droughts

introduction
For my final project, I will try to focus on one hydrological phenomenon and the topic I chose is a term called flash drought. After working on the first three assignments on precipitation, evapotranspiration and streamflow we will now try to use the knowledge we acquired and use these tools to understand better what a flash drought is. I will try to focus on the important factors that contribute to the understanding of this specific drought while comparing it to a normal drought with the hope that at the end of the road will have the results and conclusions of how it actually looks like. To understand better this hydrological event I used an article and other resources to build my hypothesis and to have more information on what are the variables we are focusing on when processing the data.

So let's start by trying to define what is a drought?
Drought is a prolonged dry period in the natural climate cycle that can occur anywhere in the world. It is a slow-onset disaster characterized by the lack of precipitation, resulting in a water shortage. Drought can have a severe impact on health, agriculture, economies, energy and the environment. (WHO - world health organization)
The definition of when a drought begins and when it ends is quite hard and the fact a drought can last between several weeks to decades makes it hard to create an exact definition.
There are five types of droughts: meteorological, agricultural, hydrological, socioeconomic (Wilhite and Glantz 1985) and ecological (Jason A et al 2018).
meteorological drought refers to a deficit in normal precipitation.
hydrological drought refers to the stream flows, reservoir and lake levels and groundwater and is not always affected by a lack of precipitation in a specific period of time.
agriculture drought refers to a lack of precipitation, high ET rates, soil water deficit and reduced groundwater level.
socioeconomic drought refers to a shortage of economic goods such as water, forage, food grains, fish, and hydroelectric power.
ecological drought refers to a deficit of naturally available water that creates multiple stresses across ecosystems.
(NDMC - national drought mitigation center)

<u>so what makes a normal drought to be a flash drought?</u>

Flash drought is quite a new term for a drought and it is combined with the basic requirement of precipitation deficit and other environmental anomalies such as high temperature, high evapotransipiration, low humidity, strong winds and sunny skies. A combination of a few of the above will usually affect most of the droughts types we mentioned and will lead to a flash drought.

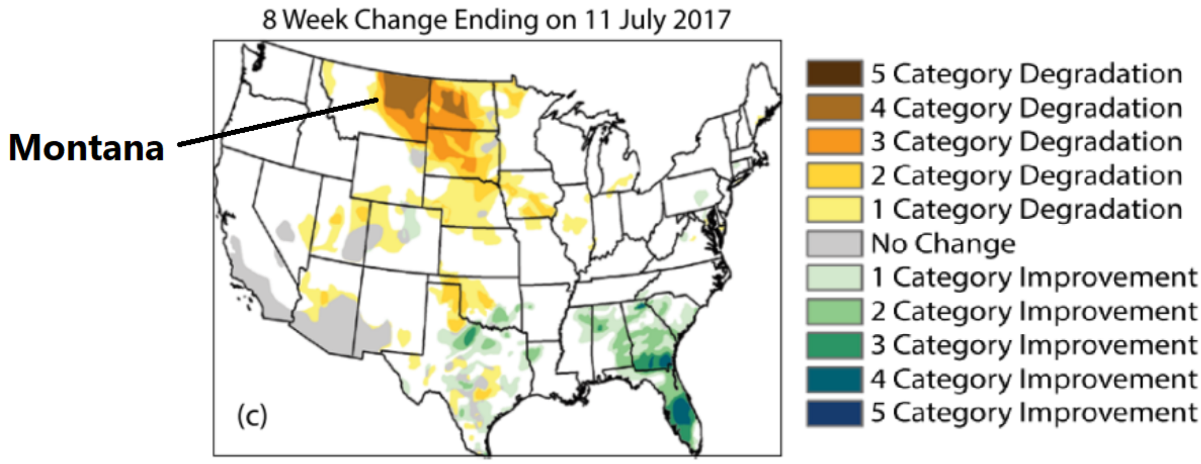
Another important factor for a flash drought is the speed of intensification- a rapid change of a few of the factors above in a manner of weeks while a normal drought takes usually months or years to reach its full intensity.

In this work, we will try to focus on these two - anomalies in different parameters and the speed of intensification.

<u>Choosing location</u>

A good example we can see in the article of a recorded flash drought is in the northern high plains in 2017 after exceptional dry weather and a precipitation deficit led to a four-category type increase in 8 weeks which led to severe damage to wheat yields across the region (Jason A et al 2018).

<u>Map number 1 - US drought map by number of category degradation</u>

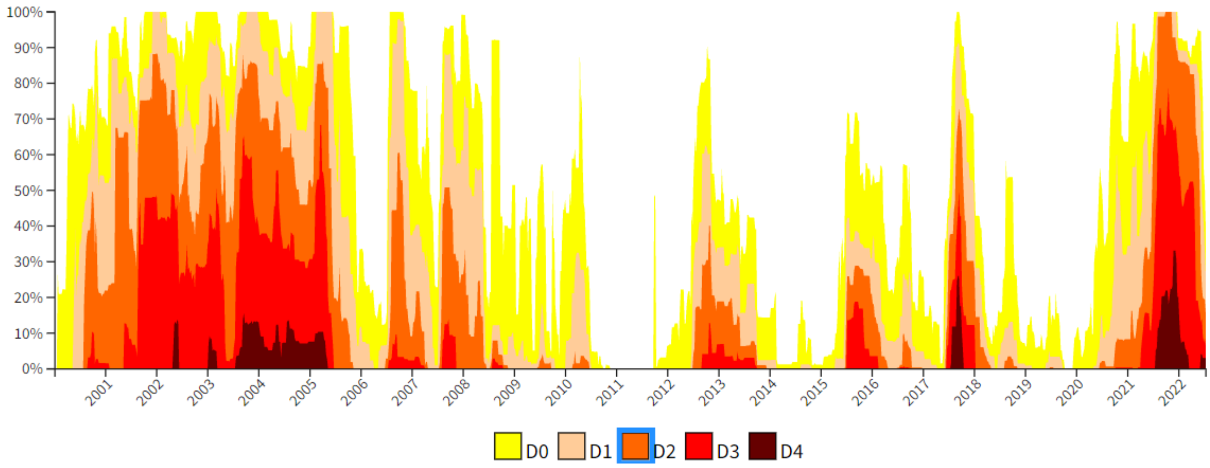


(Jason et al 2018)

When looking at the map we can see the severe four categories degradation while in the southeast we can see an improvement in four categories which reflect the difference between areas in the US.

The state with the most severe drought seeing in the map is Montana and it is known for droughts over the years and since the U.S drought monitor started in 2000 the longest drought seen was for 307 weeks (!) between 2000-2006 (NIDIS - national integrated drought information system). in the next graph also taken from the NIDIS website, we can see the level of droughts from 2000 until today.

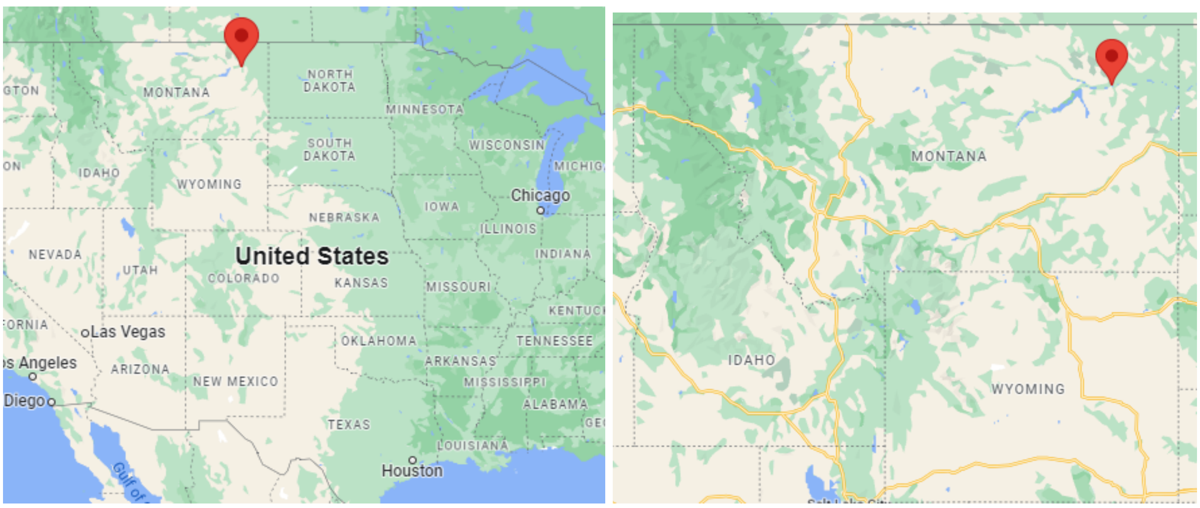
Graph number 1 - droughts severeness 2000-2022



We can see again the long drought at the beginning of the century and also the severe drought that is reviewed in the article in 2017 followed by a couple of quite calm years drought-wise. Also, we can see that at the moment it seems like the situation is very bad Montana is having one of the worst droughts in the last couple of decades.

With that said I will choose my location in Montana and going back to the map above we can see that if to be even more precise the flash drought on the map is located in the northeast of Montana. I found a station in that area in a small city called Wolf point.

Map number 2 - Wolf point, Montana location



Wolf point has a population of around 2000 people it is 2.27 square km big. the climate is semi-arid and typically cold and dry winters (November to March) and hot and wet summers with commonly thunderstorms (April to October). A fun fact about wolf point is that its the home of the annual wild horse stampede, the oldest rodeo in Montana, and is called the grandaddy of Montana rodeos

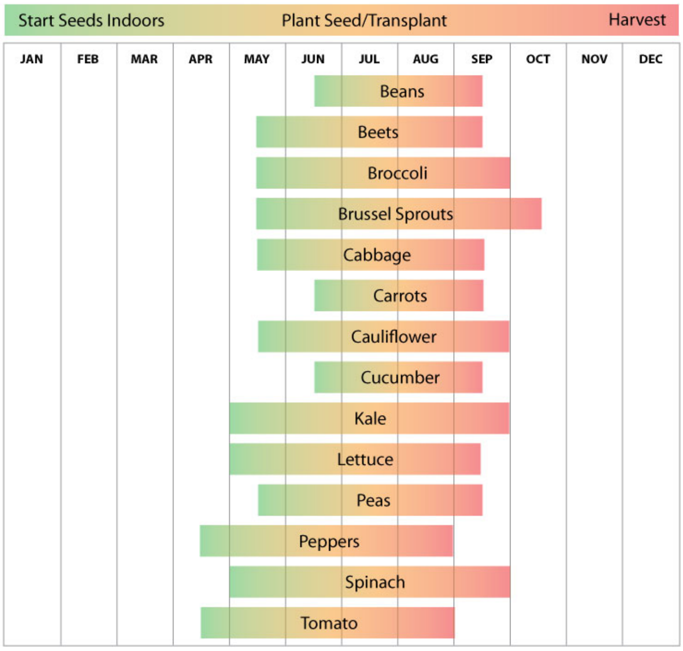
Referring to the discharge part the station near Wolf point is located on the Missouri river which is the ninth largest river in the US talking about discharge and because it drains a semi-arid regiom its discharge is much lower and more variable than other rivers it compared to.

<u>choosing time range</u>
For choosing the right time to explore our flash drought phenomenon I will try to choose a year that a flash drought has occurred and another that has not for the comparison. when looking again on graph number 1 and using the article we can easily choose 2017 as our flash drought event year. I want to have a consecutive year so I will choose 2018 and 2019 for my two other years. 2018 still has some droughtnes when looking at the graph but not as severe as 2017 while 2019 should give us a good comparison to a droughtless year.
In this PDF we will look mostly on 2017 and 2019 while in the jupyter notebook we have more graphs for 2018.

<u>Hypothesis and expectations</u>
After explaining widely about the term flash drought and understanding what are the factors that determine if a drought is extremely severe or not we will now try to use our data and explore it. The question I would like to answer is how the differences between a flash drought to a normal drought look and I will mainly do it with the focus of the comparison between the years 2017 and 2019. I'm expecting to have differences mainly in precipitation but also in other aspects like temperature, relative humidity, evapotranspiration and wind.

Another thing we expect to see is that the flash drought scenario is most likely to occur during the growing season when evaporative demand is climatologically highest, which exacerbates the impact of flash droughts on agriculture (Otkin et al. 2013).
In the next graph we can see the plating schedule in Montana:

<u>Graph number 2 - Planting schedule in Montana</u>



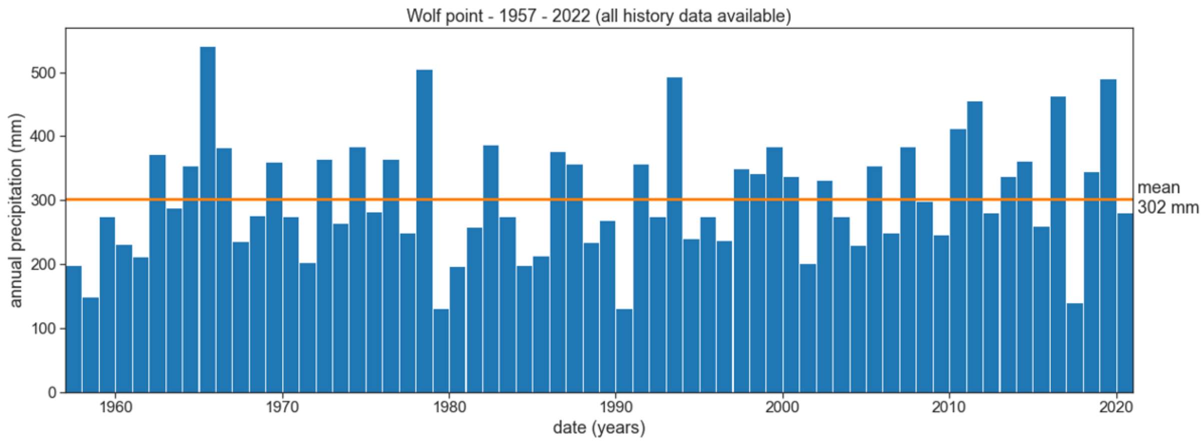
urban farmer - ufseeds

Looking at the graph we can easily see that the growing season is between May to September which is not a surprise for us since we know it is the rainy season and also summer in Montana.

Results
Moving on to the interesting part of the results, finally. I will present the results while discussing each one of them right after to have easy reference and to be able to see the result while discussing them.

We will start with the most important factor of a drought, **Precipitation**.

graph number 3 - Precipitation in Wolf point 1957 - 2022

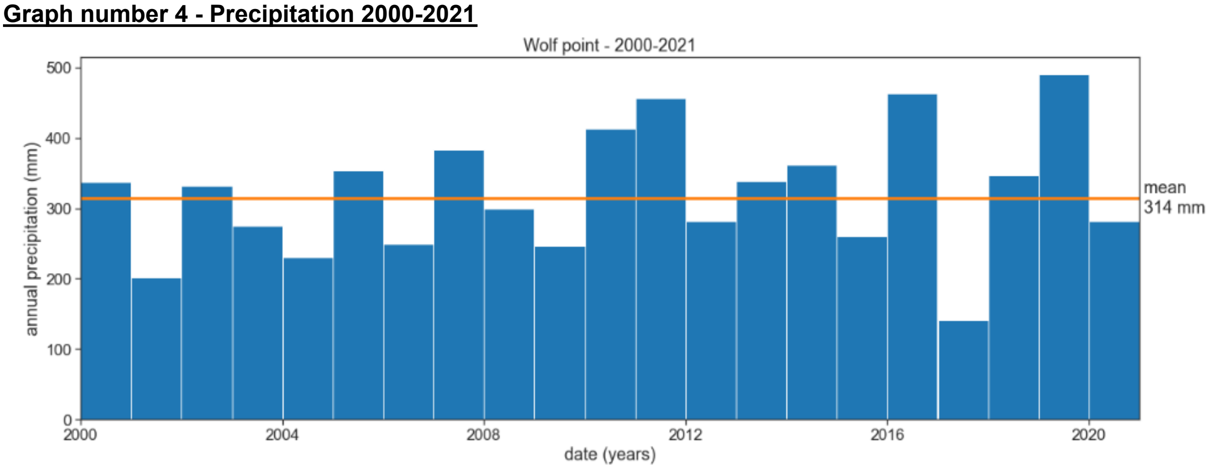


In the bar plot graph above we can see the annual precipitation in Wolf point between the years 1957 - 2022 which is all the years with data recorded and available on the NOAA website.
Looking at the graph we can see that we have mean annual precipitation of 302 mm.

It doesn't seem that there is a change in precipitation over the years and most years are around the yearly average.
We can also see a few years with very high precipitation of around 500 mm per year and others with very low precipitation of around 150 mm per year.

Let's zoom in on the last two decades we talked about in the introduction.

Graph number 4 - Precipitation 2000-2021



We can see in the bar plot graph the precipitation between 2000 - 2021. The annual mean for those years of 314 mm per year is higher but quite similar to the yearly average of 302 mm per year for all the recorded data we have.

We mention that between 2000-2006 Montana suffered a long drought and we can see that three out of those six years had quite low annual precipitation while the other three years have a bit higher than average. For the total six years, we can say that there is lower precipitation in total.

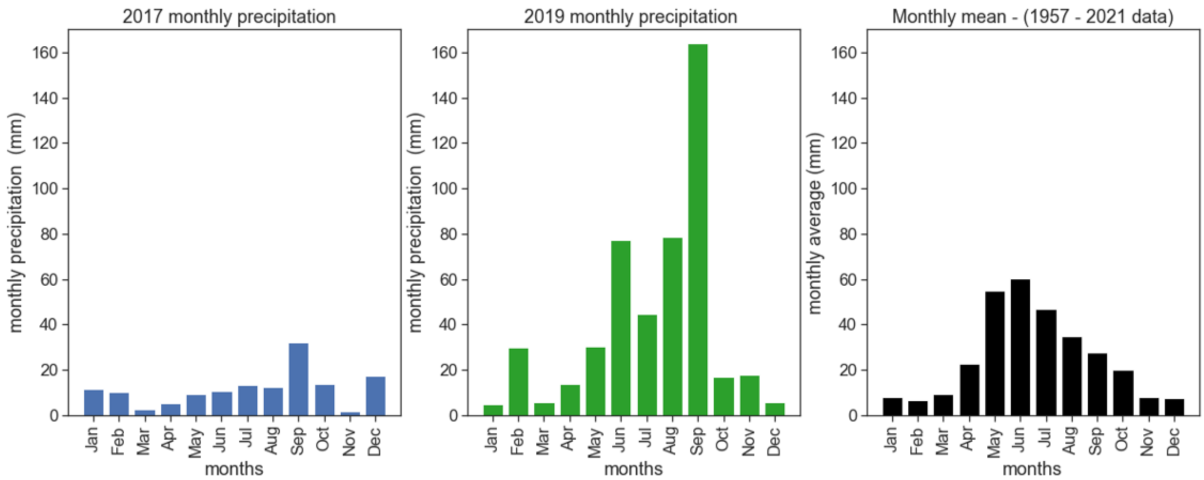
When focusing on our two chosen years for comparison we can see that 2017 is a dramatically low precipitation year with only 141.1 mm per year which is actually the third lowest year in the last 64 years after 1990 and 1979 with 132.2 mm per year while 2019 is extremely high precipitation year located as the fourth rainiest year in the last 64 years.

Table number 1 - highest and lowest precipitation years 1957 - 2021

	rain (mm)
DATE	
1965-01-01	541.8
1978-01-01	504.9
1993-01-01	492.9
2019-01-01	490.2
2016-01-01	463.4
...	...
2021-01-01	156.9
1958-01-01	148.8
2017-01-01	141.1
1990-01-01	132.2
1979-01-01	132.2

After talking about the annual precipitation we will now move on to talk about monthly precipitation and also talking about the hydrological year.

Graph number 5 - comparison between monthly precipitation

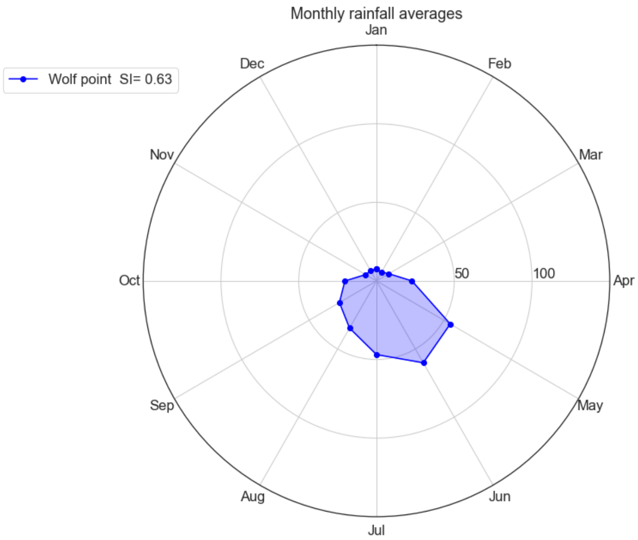


focusing on what happened during the year we are now looking at graphs showing the monthly precipitation of 2017 and 2019 and also comparing it to the monthly mean of 1957 - 2021. Talking about 2017 we can easily see that it was a very dry year not only comparing it to 2019 which was a very rainy year but also to the average when almost all months are lower than average especially when talking about the growing season between May and September which gives us a first indication on how intense was the drought. We already said

that the precipitation is the basic and most important factor of a drought and we can see the intensification of 2017 when May and June had almost no rain at all and compared to the monthly mean Montana usually gets.
It's interesting to see how amazing was 2019 precipitation wise with a few months above average and especially September which is usually around 25 mm on average but in 2019 had 160 mm (!!) which is 20 mm more than all of 2017 precipitation.

To choose the hydrological year for Wolf point we will use the monthly mean graph and the month probably will suit the most for the beginning of the hydrological year will march since after that we can see the rise in the monthly precipitation. As we mention in the introduction those are the summer rainy months so we are not surprised with the results.

Radar chart - monthly rainfall averages and seasonally index



In the radar chart above we can see the seasonality of Wolf point and it is very clear to see how a few months have lots of rain while others have much less. If talking about numbers we received a seasonality index of 0.63. Using the table below from the lecture of Yair:

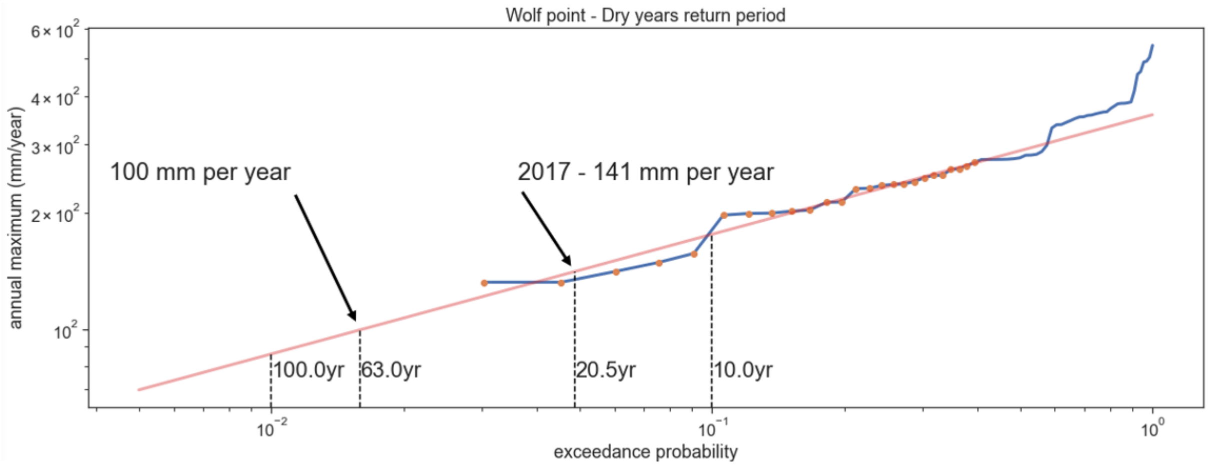
SI	Precipitation Regime
<0.19	Precipitation spread throughout the year
0.20-0.39	Precipitation spread throughout the year, but with a definite wetter season
0.40-0.59	Rather seasonal with a short dry season
0.60-0.79	Seasonal
0.80-0.99	Marked seasonal with a long dry season
1.00-1.19	Most precipitation in < 3 months

We can see that our assumption was good and Wolf point is actually a seasonal place.

Extreme events and return period

Remembering our first assignment and the extreme events and return periods we calculated the chances of having some very rainy days. In my topic talking about droughts it is less relevant of finding very rainy events and also less important to talk about specific days (though they still appear in the Jupyter notebook file). That is why I chose to show the opposite first talking about a scale time of years which are more relevant to us but also making a graph showing the chances to receive very dry years.

graph number 6 - return period for dry years



In the graph above we can see a curve with the recorded annual precipitation for the last 64 years. Using this graph we can calculate the chances of having a certain event of a dry year. It is obvious when looking at the right side of the curve why the chance of having a year that is drier than a very rainy season is very high and close to 100% but when going left on the curve the chances of having a dryer year is smaller. Remembering our talked year of 2017 with 141 mm we can see that the chances of having a year like that are every 20.5 years which is not extremely rare while for comparison the chance of having a year dry as 100 mm per year is every 63 years.

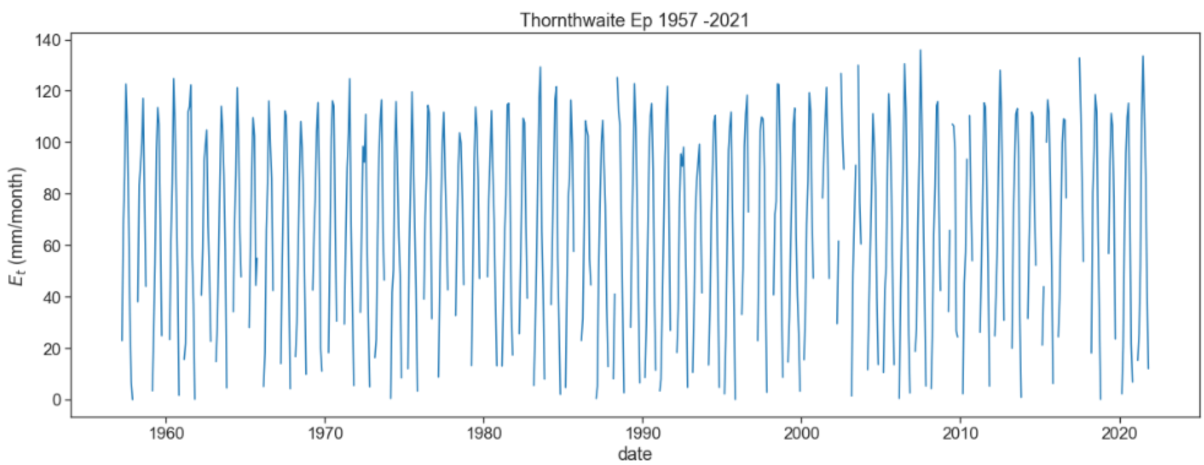
After widely talking about the most important factor of droughtiness - precipitation - we will now talk about the other factors starting with ET and moving on to temperature, RH (relative humidity), VPD and wind speed.

evapotranspiration using the Thornthwaite equation

calculating evapotranspiration using the Thornthwaite equation is based on one factor only and its temperature.

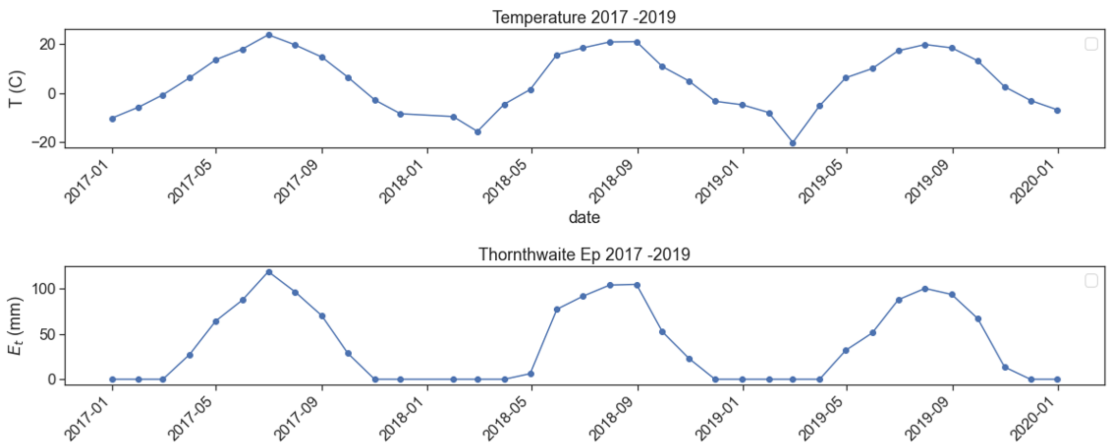
We will start with a graph showing Thorntwaite for all the recorded data between 1957-2021.

Graph number 7 - Thorthwaite results for 1957-2021



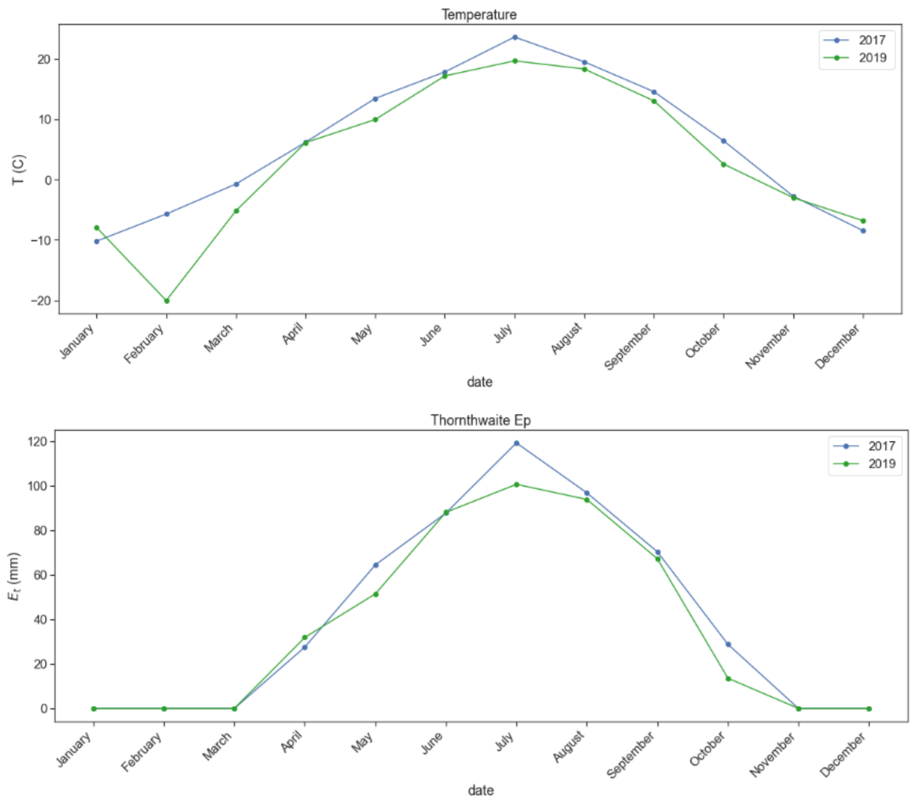
Looking at this graph it is hard to see actual changes in Thornthwaite results, besides the fact that maybe it is possible to see some more high picks in our discussed range time between 2000 -2021.
To have a closer look we will see a graph for the temperature followed by a graph of Et for our specific years 2017-2019.

Graph number 8 - Temperature and Thornthwaite 2017 - 2019



In the graph, we have three consecutive years for temperature and Thornthwaite between 2017 - 2019. We can already see that looking at these three years there is some level of higher temperatures and higher ET, especially looking at the picks.
If we want to have an even better look between these parameters going back to our two chosen years we can use a graph of those two years on top of each other.

Graph number 9 - Temperature and Thornthwaite 2017 VS 2019



Looking at the two graphs above first of all we can see that Wolf point is quite cold during the winter and the temperatures go below zero on a monthly average all winter long. During the summer the temperatures go high at 25 degrees Celcius.
it is reflected in the Et which is zero for the winter months while during the summer the average Et can go higher than 100 mm per month using the Thornthwaite equation.

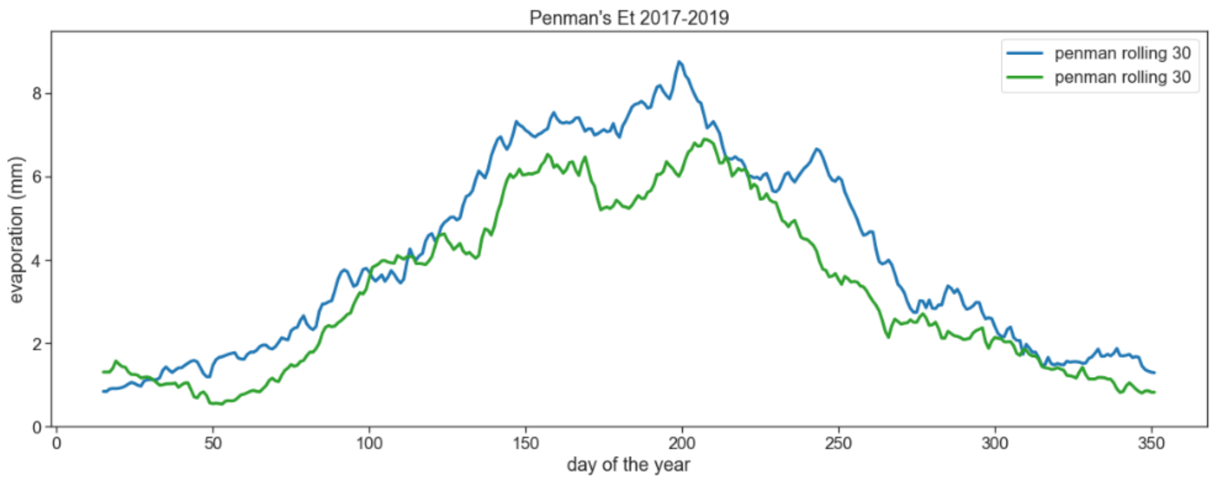
we can also see that 2017 was higher in temperature for almost all months which again is reflected in higher Ep for the same months. Once again we can see the drought factors which are higher for our year supposed to call flash drought events. Talking about the intensification of the 2017 drought which was supposed to be a change in 8 weeks we can see the curve is quite similar for both years apart from the fact that 2017 reach higher eventually. The change actually happens gradually for more than two months between March and July which is 4 months period. We will talk more about that in the final conclusions.

*<u>A comment about the Thornthwaite equation</u>

An important comment about the Thornthwaite method is that we know that the actual Et is affected by many more parameters and that is why we should be a bit skeptical with the results that we have. Even Thornthwaite himself doubted his equation by saying "The mathematical development is far from satisfactory. It is empirical… The chief obstacle at present to the development of a rational equation is the lack of understanding of why potential ET corresponding to a given temperature is not the same everywhere" It would be reasonable to say that the method is not that far from real life for the area that the empirical tests were taken and if we could collect data for different kinds of climate and areas we could have different equations that based only on temperature which will give better results and still a very easy method to estimate the Et. We will now move on to penman's equation which is based on much more parameters (In this work I will not focus again like in the second assignment on the comparison between Thorthwaite and Penman results).

Penman Et and other factors

Graph number 10- Temperature and Thornthwaite 2017 VS 2019



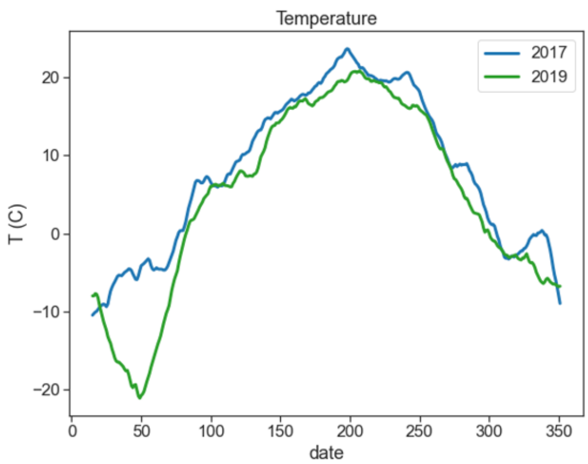
Comparing again the level of Et now with Penman's equation we can see the results for both years. The graphs are a result of daily data and using rolling averages to smoother them and clear noise. The fact that we are using daily data and much more parameters to calculate the Et with penman's equation we can believe that these results are more precise.

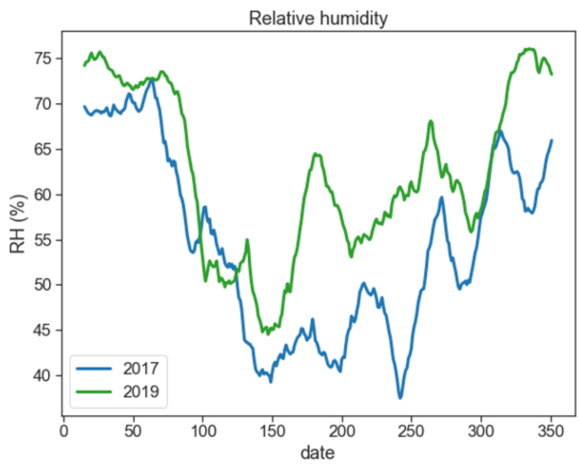
In this graph, we can see again that the Et for 2017 was higher for almost every day of the year in more than 1-2 mm per day. It is quite a dramatic difference first when thinking about the fact that it is for each day of the year and second when talking about 1 or 2 mm of Et per day which is around 20% higher evaporation and will result in a huge amount of water loss that probably will be needed to come back with irrigation and anyway will result in less yield eventually.

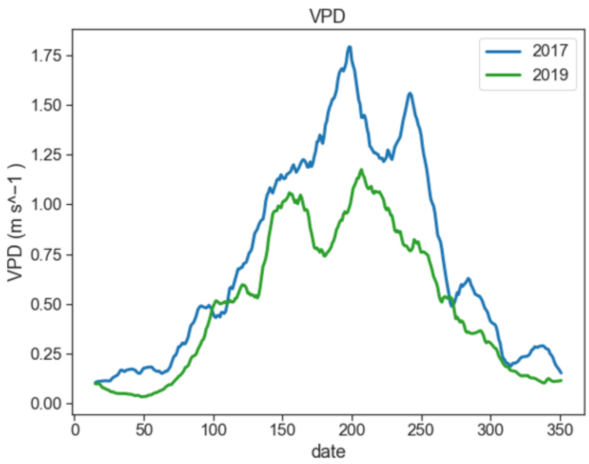
We can see again in this graph as we spoke about Thornthwaite Et that again it is hard to see the effect of intensification since both graphs are starting to climb around the same point when the only difference is the height they reach.

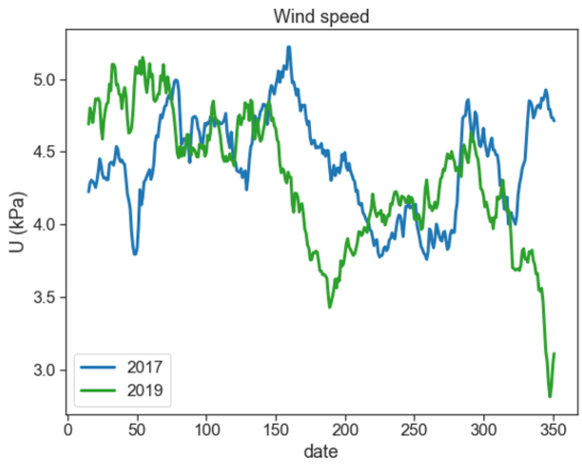
As we said Penman's equation is based on many other parameters and if the result in 2017 is higher we can expect that also the other parameters such as temperature, RH, VPD, and wind speed will be higher in 2017 than in 2019.
We already have all of this data in our hands and we can separate each one of them into a graph to look closer at each one of them.

Graph number 11 - RH, T, VPD and wind speed









the first graph on the upper left side is the temperature again and it is shown again first because it is now with daily data and we can see again the same trend of higher temperature in 2017 than in 2019.
The second reason that it is shown is that together with the RH graph on the upper right side they are used to calculate the VPD which is a very important factor for the degree of evaporation since the vapor pressure deficit is the requirement of the air for water and the higher it will be the higher the evaporation will be. First, when looking at the RH we can see that the relative humidity for most of the year is lower for 2017 which will result in a higher VPD level. The same for temperature when the high temperature will result in high VPD. And not surprisingly the bottom left graph of VPD for 2017 is higher than 2019 and especially when looking at the middle of the year which is the growing time. We can see a dramatic difference from around May to September which will affect a lot on the evaporation level.

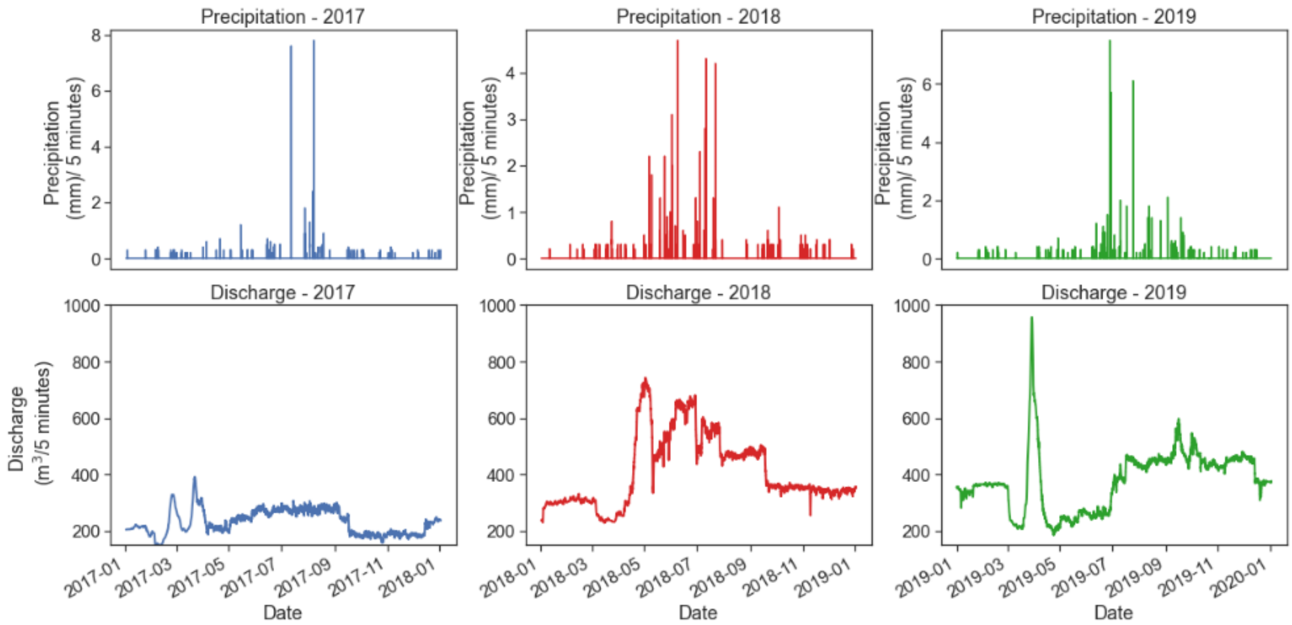
The last graph on the bottom right side is the wind speed. We can focus again on the growing season and see that most of the time the wind speed is higher for 2017. it is interesting to see that there was a high pick at the beginning of the year for 2019 which probably will not affect much on the Et or its effect first because the temperatures are very low but also because it is not the growing season. It is also interesting to see that after that there was a big drop in the wind speed for 2019 and the opposite for 2017. I wonder if it is related to the precipitation factor we discussed earlier even though I expect to have more wind when it is raining and more stormy weather we see that in our case it might affect the other way around for both years.

It's important to notice again as we mentioned before regarding the intensification that we can't say it is clear to see the 8 weeks rapid change the article talked about. All graphs for both years have gradual changes throughout the year for all the parameters we looked at and we can't say looking at our result that there is a quick change in anomalies of climate.

Discharge

we will now discuss the discharge even though I think it is quite less of a factor that will contribute to our subject since the drainage area for the station is huge (80000 square miles) and the discharge is very big as we are about to see. We also mention in the introduction the fact that it is one of the biggest rivers in the US talking about discharge and probably most of the water that reaches this river is linked to other precipitation in the region and not to our specific area so it is hard to say it is some kind of reflection to the status in Wolf point.

graph number 12- Precipitation and discharge 2017-2019



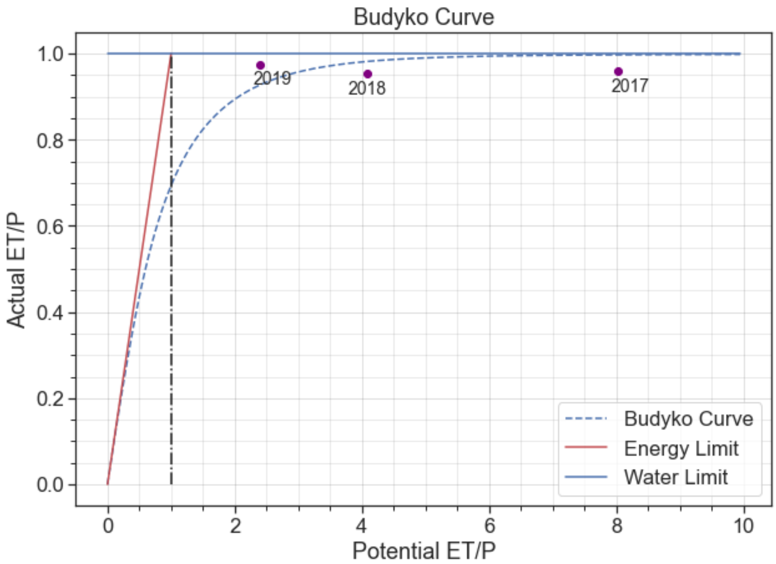
We can see above 3 graphs for precipitation for the years 2017-2019 in the upper part and 3 graphs for discharge at the bottom side. Just a few sentences ago I said that the precipitation in Wolf point station probably doesn't have a main effect on the discharge and I think the graphs above can show that the correlation between the two is not as good. First, the amount of precipitation during the time is not as big as the changes seen in the discharge and second, the picks don't match that well.

Still, we can see that we have the same trend when looking at all three years of discharge having very low discharge in 2017 compared to the following two years and we can link that to a reasonable option that as we saw in the flash droughts map (map number 1) that all the surrounding area had a drought that year and probably in those surrounding areas had much less precipitation resulting in lower discharge.

A very interesting thing I noticed in all three graphs is that a very big pick (in comparison to the same year) is seen around March to May. I found it strange since it is springtime just before the rainy season starts and after a few months of the less rainy period. After exploring a bit more this anomalies I found that in the Missouri River there is a thing called the “April rise” or the “spring fresh” which is the melting of snow plains of the watershed and might be the big pick we see in all three graphs.

Budyko

Graph number 13 - Budyko framework based on 2017-2019



When looking at our Budyko framework and the Actual Et/P results we first need to mention the fact that we neglect changes in watershed stored water and it is hard to say that all water goes to evapotranspiration or to discharge but probably some ends up in other ways.
With that said and relating to the results we have we can have a look at Yairs table from the Budyko framework lecture:

Dryness Index	Classification
$D_I < 1.54$	Humid
$1.54 < D_I < 2$	Dry Subhumid
$2 < D_I < 5$	Semi-arid
$5 < D_I < 20$	Arid
$20 < D_I$	Hyper-arid

The result of the potential ET/P can be classified using the dryness index. in our case, we can remember in the introduction that we mention that Wolf point is a semi-arid area in normal times. The results we have show that for 2018 and 2019 we received a dryness index between 2-5 that suit semi-arid areas according to the table. When looking at the 2017 dryness index we can see the reflection of a very arid year with a high dryness index of 8 which suit more for an arid area showing us again the level of the severe drought we had that year.

Final discussion and conclusions

After reviewing the subject in the introduction and looking closer at our data, analyzing each part and discussing all the results we now have a better look on how a flash drought suppose to look.

In the article, we used about flash droughts they clearly said that in 2017 there was a flash drought in Montana with the intensification and the climate anomalies happened in 8 weeks while we found in our data a year to compare to (2019) which surely didn't suffer a flash drought and had a very rainy year. We can easily say that we found a higher level of drought severity in all the factors we looked at (precipitation, temperature, Et, RH, VPD, wind speed and even discharge).
With that said I believe that I managed to find all the factors needed to call a drought a flash drought since we have found that all 5 categories for a drought (meteorological - lack of precipitation, hydrological - effect on stream flow, agriculture - precipitation and high Et, socioeconomic - lack of water, and ecological - a deficit of naturally available water that will create multiple stresses across ecosystems) accrued and as we mention we need 4-5 of them to call a drought a flash drought.

Talking about the intensification of a drought according to the article and our hypothesis, we assumed that we will see in the data a rapid change and for 2017 the change was supposed to be seen in 8 weeks. After reviewing the results it is hard to say that it is clear to see when the changes they referred to are starting or ending and in all graphs we saw a gradual climb without clear borders or lines. Also, the changes happened in the expected time when the summer rainy season has started and we expect to have for example higher temperatures or high VPD. The only difference we can say is clear to see is the degree of the anomalies which was again more severe in all parameters for 2017 than for 2019.

To sum up I believe I chose a good location to observe because of the fact it is a location that has suffered big droughts and has variability during the years. The location has shown good results for our question and enabled us to have a first good look at a flash drought. Talking about the time I chose to explore we can say that 2017 obviously reflected a severe drought but on the other hand 2019 was far from being a drought year after looking at the results. It might have been better to choose a year that reflects more of the normal drought or maybe to compare 2017 to an average of a few years as we saw in the comparison of the monthly mean precipitation to 2017 and 2019 which was easy to see that 2017 was lower than average while 2019 was higher.
Also, we explore only one flash drought and it would obviously have been better to look at a few more flash droughts and maybe in other places to have a better understanding.
I think the flash droughts subject is still very new and even in the article they only suggest how to define this new term and still needed much more understanding on how to set borders and clear principles of how a flash drought is seen especially when talking on so many parameters.

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https://www.ufseeds.com/montana-vegetable-planting-calendar.html#:~:text=Montana%20on%20average%20has%20approximately,tomatoes%2C%20peppers%20and%20other%20vegetables

Precipitation data -
https://www.ncei.noaa.gov/maps/monthly/

Et data -
https://www.ncei.noaa.gov/access/crn/qcdatasets.html

Discharge data -
https://maps.waterdata.usgs.gov/mapper/index.html