Runoff signatures from runoff timeseries - an Austrian example

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1 Introduction

Following Jothityangkoon et al. (2001) and Eder et al. (2003), the temporal patterns of the observed runoff response of catchments, when viewed at different time scales, are termed runoff 'signatures', and deemed emergent patterns. We term them 'signatures' because they are considered as reflections of the overall functioning of the catchments, including the co-evolutionary features of the catchments' surface and subsurface architecture.

Runoff variability at any location is a temporal continuum covering a wide range of time scales, but the characteristics one sees depend on the temporal scale one chooses to look at. This is because catchments exhibit the characteristics of complex systems, so different patterns emerge at different time scales. At time scales of seconds one may recognise the effects of turbulence and wave action in the runoff. At time scales of millennia, if such data were available as in the case of Jefferson et al. (2010), one would recognise long-term climate and landscape evolution trends. There may be several emergent patterns in the time domain and they are all inter-connected because they are all the result of the same complex system and co-evolutionary processes.

Depending on the collective behaviour of the catchment processes and the underlying drivers, the runoff signatures may differ. Therefore they can be seen as windows that enable us to look into the catchment dynamics at different time scales. They help us to understand the system holistically. Signatures provide insights into catchment processes, and are thus outward manifestations of the internal dynamics of the catchment.

As in Blöschl et al. (2013) and Viglione et al. (2013), we consider six signatures, each of them meaningful of a certain class of applications of societal relevance: annual runoff, seasonal runoff, flow duration curves, low flows, high flows and runoff hydrographs. Annual runoff is a reflection of the catchment dynamics at relatively long time scales, which is particularly evident in its between year variability. It is related to the hydrological problem of how much water is available (see e.g. McMahon et al., 2011), which is fundamental for water management purposes such as water allocation, long-term planning, groundwater recharge etc. Seasonal runoff reflects the within-year variability. It addresses the question of when water is available throughout the year (see e.g. Sauquet et al., 2008; Hannah et al., 2011) and is necessary to plan water supply, hydropower production and river restoration measures. The flow duration curve represents the full spectrum of variability in terms of their magnitudes. It measures for how many days in a year water is available (Vogel and Fennessey, 1994, 1995) and is the basis of studies on river ecology, hydropower potential, industrial, domestic and irrigation water supply. Low flows focus on the low end of that spectrum, and so provide a window into catchment dynamics when there is little water in the system, and high flows are at the opposite end, when there is much water in the system. Low flow statistics (Smakhtin, 2001) are needed to estimate environmental flows for ecological stream health, for drought management, river restoration, dilution of effluents etc. High flow (flood) statistics (Merz and Blöschl, 2008a,b), instead, are required for the design of spillways, culverts, dams and levees, for reservoir management, river restoration and risk management. Hydrographs are a complex combination of all other signatures. They are the most detailed signatures of how catchments respond to water and energy inputs (Parajka et al., 2013). They can be used for all the applications listed above and are specifically needed when the dynamics of runoff have to be taken into account, such as for water quality studies.

The objective of this document is to illustrate how to calculate runoff signatures (but also precipitation and potential evaporation signatures) using R.

First of all load the library:

```
library(PUBexamples)
```

We consider data from 8 catchments in Austria, which are those that we will use also when illustrating runoff modelling in ungauged basins (see Chapter 10 in Blöschl et al., 2013).

```
help(data4chapter10)
```

```
data(data4chapter10)
str(ObsDischarges)
```

```
List of 8
 $ 200287:'data.frame':        4383 obs. of  4 variables:
  ..$ day : int [1:4383] 1 2 3 4 5 6 7 8 9 10 ...
  ..$ mon : int [1:4383] 1 1 1 1 1 1 1 1 1 1 ...
  ..$ yr  : int [1:4383] 1999 1999 1999 1999 1999 1999 1999 1999 1999 1999 ...
  ..$ disc: num [1:4383] 0.563 0.54 0.572 0.909 1.21 0.934 0.895 1.19 1.11 0.685 ...
 $ 204768:'data.frame':        4383 obs. of  4 variables:
  ..$ day : int [1:4383] 1 2 3 4 5 6 7 8 9 10 ...
  ..$ mon : int [1:4383] 1 1 1 1 1 1 1 1 1 1 ...
  ..$ yr  : int [1:4383] 1999 1999 1999 1999 1999 1999 1999 1999 1999 1999 ...
  ..$ disc: num [1:4383] 0.502 0.502 0.49 0.593 0.839 0.755 0.642 6.21 2.79 1.56 ...
 $ 204925:'data.frame':        4383 obs. of  4 variables:
  ..$ day : int [1:4383] 1 2 3 4 5 6 7 8 9 10 ...
  ..$ mon : int [1:4383] 1 1 1 1 1 1 1 1 1 1 ...
  ..$ yr  : int [1:4383] 1999 1999 1999 1999 1999 1999 1999 1999 1999 1999 ...
  ..$ disc: num [1:4383] 1.75 1.68 1.67 1.86 2.41 2.36 2.14 3.99 4.21 3.07 ...
 $ 205799:'data.frame':        4383 obs. of  4 variables:
  ..$ day : int [1:4383] 1 2 3 4 5 6 7 8 9 10 ...
  ..$ mon : int [1:4383] 1 1 1 1 1 1 1 1 1 1 ...
  ..$ yr  : int [1:4383] 1999 1999 1999 1999 1999 1999 1999 1999 1999 1999 ...
  ..$ disc: num [1:4383] 3.95 3.84 3.82 4.65 9.31 7.94 7.08 9.75 8.96 6.54 ...
 $ 208579:'data.frame':        4383 obs. of  4 variables:
  ..$ day : int [1:4383] 1 2 3 4 5 6 7 8 9 10 ...
  ..$ mon : int [1:4383] 1 1 1 1 1 1 1 1 1 1 ...
  ..$ yr  : int [1:4383] 1999 1999 1999 1999 1999 1999 1999 1999 1999 1999 ...
  ..$ disc: num [1:4383] 1.44 1.4 1.36 1.28 1.31 1.47 1.45 1.88 2.35 2.18 ...
 $ 208835:'data.frame':        4383 obs. of  4 variables:
  ..$ day : int [1:4383] 1 2 3 4 5 6 7 8 9 10 ...
  ..$ mon : int [1:4383] 1 1 1 1 1 1 1 1 1 1 ...
  ..$ yr  : int [1:4383] 1999 1999 1999 1999 1999 1999 1999 1999 1999 1999 ...
  ..$ disc: num [1:4383] 1.97 1.94 1.93 1.95 2 2.01 2 1.99 2 1.94 ...
 $ 212076:'data.frame':        4383 obs. of  4 variables:
  ..$ day : int [1:4383] 1 2 3 4 5 6 7 8 9 10 ...
  ..$ mon : int [1:4383] 1 1 1 1 1 1 1 1 1 1 ...
  ..$ yr  : int [1:4383] 1999 1999 1999 1999 1999 1999 1999 1999 1999 1999 ...
  ..$ disc: num [1:4383] 0.23 0.22 0.213 0.208 0.203 0.2 0.197 0.195 0.192 0.189 ...
 $ 212647:'data.frame':        4383 obs. of  4 variables:
  ..$ day : int [1:4383] 1 2 3 4 5 6 7 8 9 10 ...
  ..$ mon : int [1:4383] 1 1 1 1 1 1 1 1 1 1 ...
  ..$ yr  : int [1:4383] 1999 1999 1999 1999 1999 1999 1999 1999 1999 1999 ...
  ..$ disc: num [1:4383] 4.56 4.47 4.39 4.33 3.83 3.6 3.73 3.63 3.65 3.76 ...
```

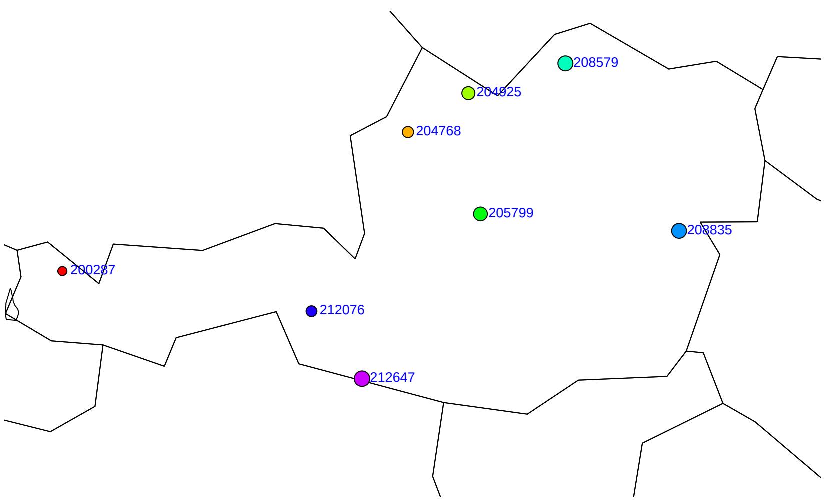
```
valCatChar <- CatChar[CatChar$idnr %in% names(ObsDischarges),]
 valCatChar
```

	idnr	station	river	lat	lon	xcor	ycor	area	elev	slope	forest	xcen	ycen	map	aridity
10	200287	Schoenenbach_(Hengstig)	Subersach	47.3864	10.0411	151606.5	392637.5	31.1	1460	0.328	0.383	152577.7	390048.9	1954	0.232
56	204768	Osternach	Osternach	48.3136	13.4539	408938.6	490432.8	68.6	431	0.096	0.173	413971.8	485148.3	964	0.689
66	204925	Hartmannsdorf	Steinerne_Muehl	48.5731	14.0506	452911.5	519510.8	137.8	751	0.101	0.574	460207.6	518379.4	898	0.666
97	205799	Kniewas	Steyr	47.7678	14.1700	462686.7	430096.1	184.9	1176	0.399	0.718	460291.4	421944.6	1513	0.383
147	208579	Hoheneich	Braunaubach	48.7719	15.0089	523125.8	542706.1	291.5	574	0.044	0.430	529472.0	550207.9	628	0.959
153	208835	Warth	Pitten	47.6547	16.1314	610053.4	420977.1	277.0	830	0.200	0.707	602316.4	412489.4	962	0.664
183	212076	Matreier_Tauernhaus	Tauernbach	47.1186	12.5017	336915.9	357954.7	59.9	2485	0.426	0.050	331012.2	358505.3	1143	0.255
195	212647	Mauthen	Gail	46.6686	13.0003	374522.2	307665.4	348.6	1628	0.478	0.548	355967.8	309782.2	1200	0.378

Plot stations on a map:

```
library(rworldmap)
newMap <- getMap(resolution="coarse")  # you may use resolution="low"
```

```
colori <- rainbow(length(valCatChar$idnr), start=0, end=.8)
 names(colori) <- valCatChar$idnr
plot(newMap, xlim=c(11.5, 15.5), ylim=c(46, 49))
 points(valCatChar$lon, valCatChar$lat, pch=21,
        bg=colori,
        cex=log10(valCatChar$area))
 text(valCatChar$lon, valCatChar$lat, valCatChar$idnr,
      pos=4, col=4)
```



You may want to search them on GoogleMaps, for example:

- 200287, Subersach at Schoenenbac (Hengstig) `www.google.at/maps/place/47.3864,10.0411`;
- 204768, Osternach at Osternach `www.google.at/maps/place/48.3136,13.4539`;
- ...

Now select one station, display the data and calculate the runoff signatures.

2 Timeseries

I select, for example, the first catchment: 200287, Subersach at Schoenenbac (Hengstig).

```
#idnr='200287'
idnr='212647'
```

Read the observed discharges and put it into a `zoo` object:

```
library(zoo)
data <- ObsDischarges[[idnr]]
 head(data, 20)
```

```
   day mon   yr disc
1    1   1 1999 4.56
2    2   1 1999 4.47
3    3   1 1999 4.39
4    4   1 1999 4.33
5    5   1 1999 3.83
6    6   1 1999 3.60
7    7   1 1999 3.73
8    8   1 1999 3.63
9    9   1 1999 3.65
10  10   1 1999 3.76
11  11   1 1999 3.83
12  12   1 1999 3.80
13  13   1 1999 3.63
14  14   1 1999 3.81
15  15   1 1999 3.91
16  16   1 1999 3.86
17  17   1 1999 3.68
18  18   1 1999 3.71
19  19   1 1999 3.67
20  20   1 1999 3.64
```

```
days <- as.Date(strptime(paste(data[,1], data[,2], data[,3]), format="%d %m %Y"))
Q <- zoo(data[,4], order.by=days)    # daily discharge (m3/s)
```

which can be plotted with the following code:

```
# all timeseries
plot(Q)
# zoom
plot(Q, xlim=as.Date(c("2001-09-01","2003-08-31")))
# alternatively, window of a timeseries
plot(window(Q, start=as.Date("2001-09-01"), end=as.Date("2003-08-31")))
```

Since we have also the catchment inputs for rainfall runoff modelling, let's use them too:

```
data <- ModelInput[[idnr]]
 head(data, 20)
```

```
   day mon   yr     prec     temp     pet    snowd
1    1   1 1999  0.04763 -2.48391 0.00009 21.73572
2    2   1 1999  0.94459 -3.11109 0.00000 21.60294
3    3   1 1999  0.78459 -2.70237 0.00000 26.73503
4    4   1 1999  0.00025 -1.56583 0.00087 29.99337
5    5   1 1999  0.00000  0.15496 0.03194 27.93798
6    6   1 1999  0.00000  1.94619 0.11581 26.44494
7    7   1 1999  0.00000  1.17386 0.07081 25.75872
8    8   1 1999  0.71750 -1.19378 0.00390 23.79028
9    9   1 1999  0.00182 -4.01630 0.00023 25.44898
10  10   1 1999 17.10046 -6.54997 0.00000 24.80868
11  11   1 1999 33.43050 -4.09053 0.00049 42.12260
12  12   1 1999  2.29278 -5.22904 0.00003 63.56495
13  13   1 1999  0.32928 -6.86169 0.00000 62.58823
14  14   1 1999  0.04194 -7.91414 0.00000 60.67310
15  15   1 1999  0.00000 -6.92316 0.00000 61.10793
16  16   1 1999  0.00157 -3.17174 0.00035 53.73684
17  17   1 1999  0.00000 -2.33058 0.00306 55.34182
18  18   1 1999  0.00000 -1.54667 0.01277 51.39588
19  19   1 1999  0.01327 -3.30166 0.00182 49.39432
20  20   1 1999  0.00000 -1.93486 0.01705 48.56589
```

```
days <- as.Date(strptime(paste(data[,1], data[,2], data[,3]), format="%d %m %Y"))
P <- zoo(data[,4], order.by=days)     # daily catchment precipitation (mm/d)
T <- zoo(data[,5], order.by=days)     # mean daily catchment temperature (deg C)
EP <- zoo(data[,6], order.by=days)    # mean daily pot.evaporation (mm/d)
```

which can be plotted in the same way as before.

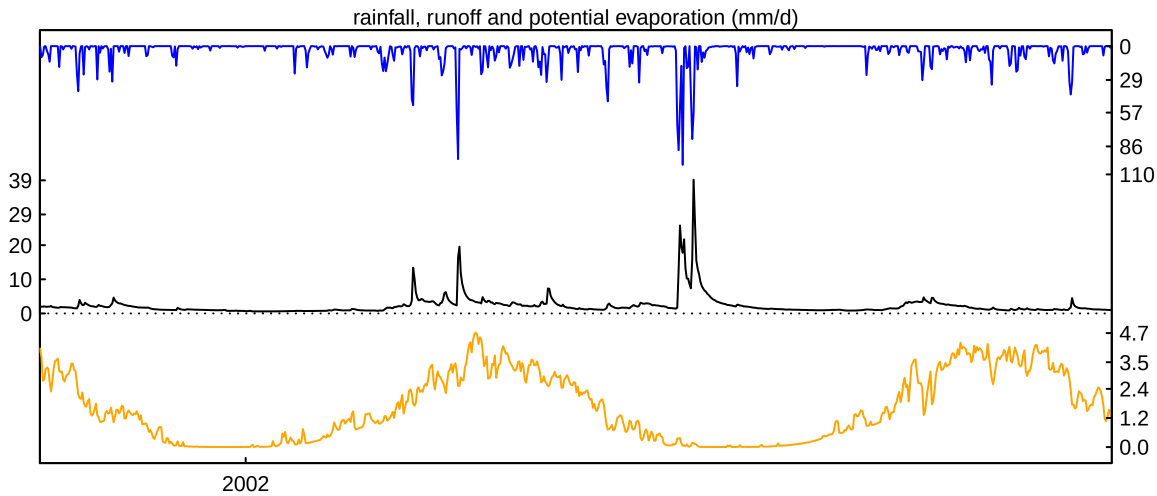
It would be nice to plot, for example, runoff, precipitation and potential evaporation on the same graph. We can do it if we scale the runoff by the area:

```
area <- CatChar[CatChar$idnr == idnr, "area"]
Qmm <- 24*3.6*Q/area  # conversion of discharge from m3/s to mm/d
```

Now create a function which plots everything on the same plot

```
plot_3timeseries <- function (prec, et, dis, ...) {
 # ... can be used to give xlim
 plot(dis, ylim=c(-max(dis), 2*max(dis)), yaxt="n",
      xlab="", ylab="", ...)
  axis(2, at=round(signif(seq(0, max(dis), length=5), 2)))
  abline(h=0, lty=3)
 par(new=TRUE)
 plot(time(prec), as.numeric(prec), col="blue", type="l",
      ylim=rev(c(0, 3*max(prec))),
      xlab="", ylab="", axes=FALSE, ...)
  axis(4, at=round(signif(seq(0, max(prec), length=5), 2)))
 par(new=TRUE)
 deltaet <- max(et) - min(et)
 plot(time(et), as.numeric(et), col="orange", type="l",
      ylim=c(min(et), max(et) + 2.5*deltaet),
      xlab="", ylab="", axes=FALSE, ...)
  axis(4, at=round(signif(seq(min(et), max(et), length=5), 2), 1))
}


plot_3timeseries(prec=P, et=EP, dis=Qmm, xlim=as.Date(c("2001-09-01","2003-08-31")))
title("rainfall, runoff and potential evaporation (mm/d)", cex.main=1, font.main=1)
```



Investigate the series at the yearly time scale

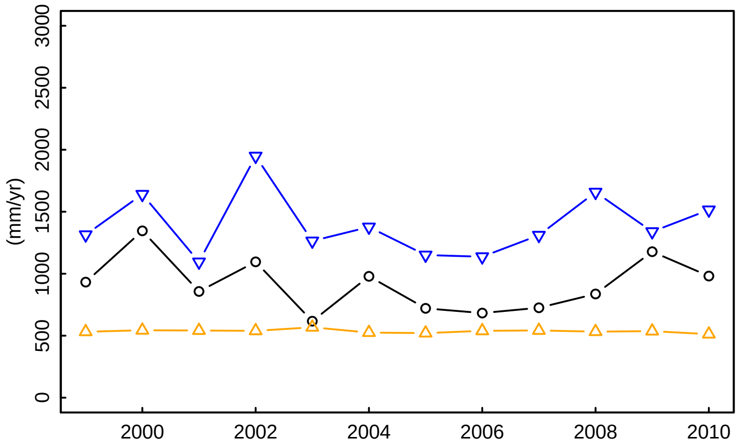
```
t=1
Deltat=365
while (t <= length(P) - Deltat - 1) {
 plot_3timeseries(P[seq(t, t + Deltat)],
                  EP[seq(t, t + Deltat)],
                  Qmm[seq(t, t + Deltat)])
  title(main=paste(as.Date(range(time(P[seq(t, t + Deltat)]))), collapse=" --> "),
        cex.main=1, font.main=1)
 readline()
 t <- t + Deltat
}
```

3 Annual precipitation, potential evaporation and runoff

We define annual runoff as the total volume of water discharging past a point of interest in a river or stream in one year divided by the contributing catchment area. Using this definition, the units of runoff are usually mm/yr. Annual rainfall over the catchment and potential evapotranspiration have the same unit.

```
Qmm_yr <- aggregate(Qmm, format(time(Qmm), "%Y"), FUN=sum)  # mm/yr
P_yr <- aggregate(P, format(time(P), "%Y"), FUN=sum)
EP_yr <- aggregate(EP, format(time(P), "%Y"), FUN=sum)
```

```
plot(Qmm_yr, type="b", ylim=c(0,3000), xlab="", ylab="(mm/yr)")
lines(P_yr, type="b", pch=6, col="blue")
lines(EP_yr, type="b", pch=2, col="orange")
```




```
summary(cbind(Qmm_yr, P_yr, EP_yr))
```

```
    Index       Qmm_yr            P_yr          EP_yr
1999   :1   Min.   : 617.0   Min.   :1095   Min.   :512.2
2000   :1   1st Qu.: 724.0   1st Qu.:1236   1st Qu.:529.9
2001   :1   Median : 894.5   Median :1327   Median :537.9
2002   :1   Mean   : 912.5   Mean   :1396   Mean   :536.1
2003   :1   3rd Qu.:1009.6   3rd Qu.:1546   3rd Qu.:541.9
2004   :1   Max.   :1345.9   Max.   :1948   Max.   :567.8
(Other):6
```

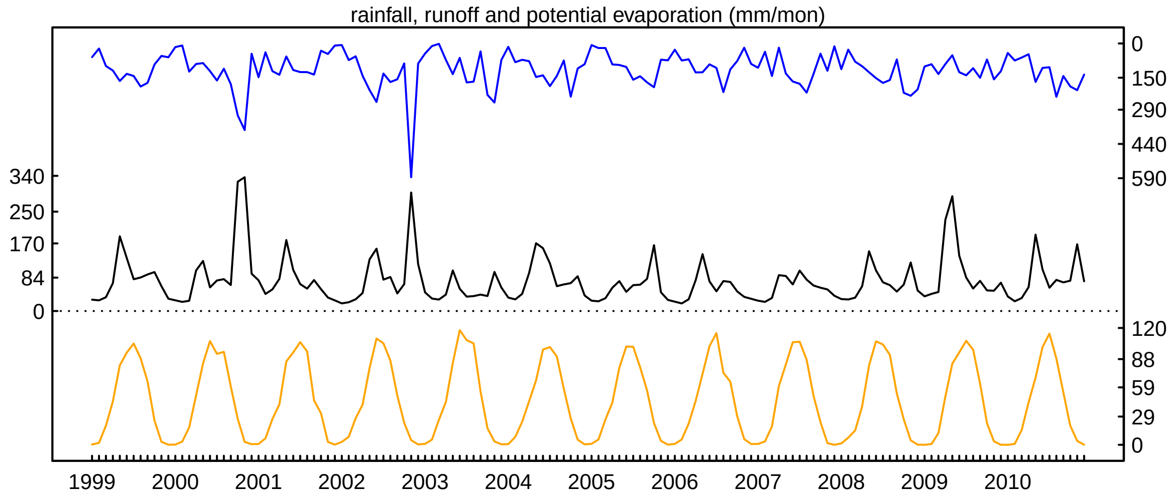
3.1 Seasonal precipitation, potential evaporation and runoff

The focus of this section is on the mean seasonal pattern of runoff variability over the annual cycle (hydrological year), which is termed the ‘seasonal flow regime’, or ‘flow regime’ for short.

First I get the monthly timeseries

```
Qmm_m <- aggregate(Qmm, as.yearmon(time(Qmm)), FUN=function(x){30.43*mean(x)})  # mm/mon
P_m <- aggregate(P, as.yearmon(time(P)), FUN=function(x){30.43*mean(x)})
EP_m <- aggregate(EP, as.yearmon(time(EP)), FUN=function(x){30.43*mean(x)})
```

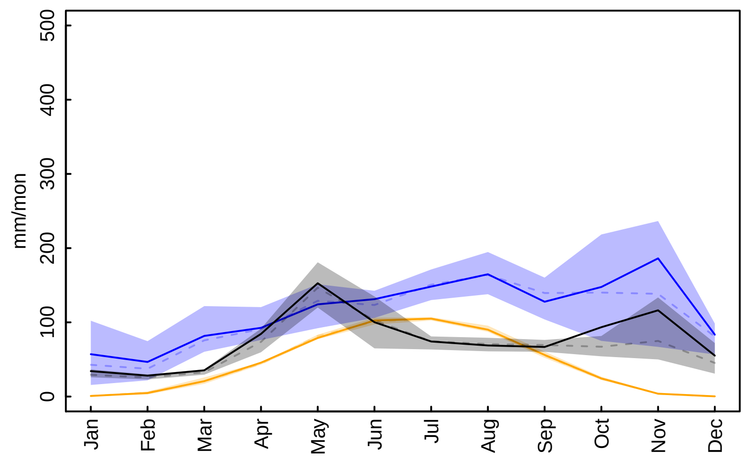
```
plot_3timeseries(prec=P_m, et=EP_m, dis=Qmm_m)
title("rainfall, runoff and potential evaporation (mm/mon)", cex.main=1, font.main=1)
```



Then I calculate statistics for the regimes:

```
mQmm_m <- aggregate(Qmm_m, format(time(Qmm_m), "%m"), mean)  # mm/mon
mP_m <- aggregate(P_m, format(time(P_m), "%m"), mean)
mEP_m <- aggregate(EP_m, format(time(EP_m), "%m"), mean)
qQmm_m <- aggregate(Qmm_m, format(time(Qmm_m), "%m"), quantile)  # mm/mon
qP_m <- aggregate(P_m, format(time(P_m), "%m"), quantile)
qEP_m <- aggregate(EP_m, format(time(EP_m), "%m"), quantile)


plot(c(1,12), c(0,500), type="n", xlab="", ylab="mm/mon",
     xaxt="n")
  axis(1, at=1:12, labels=month.abb, las=2)
 polygon(c(1:12,12:1), c(as.numeric(qP_m$`25%`), rev(as.numeric(qP_m$`75%`))),
         border=NA, col="#0000FF44")
  lines(1:12, as.numeric(qP_m$`50%`), col="#0000FF44", lty=2)
  lines(1:12, as.numeric(mP_m), col="blue")
 polygon(c(1:12,12:1), c(as.numeric(qEP_m$`25%`), rev(as.numeric(qEP_m$`75%`))),
         border=NA, col="#FFA50044")
  lines(1:12, as.numeric(qEP_m$`50%`), col="#FFA50044", lty=2)
  lines(1:12, as.numeric(mEP_m), col="orange")
 polygon(c(1:12,12:1), c(as.numeric(qQmm_m$`25%`), rev(as.numeric(qQmm_m$`75%`))),
         border=NA, col="#00000044")
  lines(1:12, as.numeric(qQmm_m$`50%`), col="#00000044", lty=2)
 lines(1:12, as.numeric(mQmm_m))
```



3.2 Flow duration curves

A feature of runoff variability that has considerable practical relevance is the period of time runoff remains higher than a specified magnitude, otherwise known as ‘flow duration’. The flow duration curve (FDC) is a graphical representation of the frequency, or the fraction of time (hence the word duration) during which a specified magnitude of runoff is equalled or exceeded. Representation of the entire runoff hydrograph time series (typically daily runoff, but it can also be hourly, or even monthly) in the form of the FDC makes the latter a compact signature of runoff variability, and a valuable tool to diagnose rainfall-runoff responses in gauged catchments at a holistic level, and to regionalise them to ungauged catchments. However, by representing runoff variability in the frequency domain as the FDC, information on the timing of the runoff response is lost. The latter is better reflected in the basin's runoff seasonal flow regime and, of course, in the complete runoff hydrograph.

The FDCs (for daily runoff) can be constructed empirically for gauged sites by (i) ranking observed runoff in ascending order and (ii) plotting each ordered observation versus its corresponding duration (e.g., in days), or its fractional duration (which is dimensionless).

```
quantili <- c(1,.999,.995, seq(.99,.01, by=-.01), .005,.001,0)
Q_fdc <- quantile(Q, prob=quantili)
 head(Q_fdc)
```

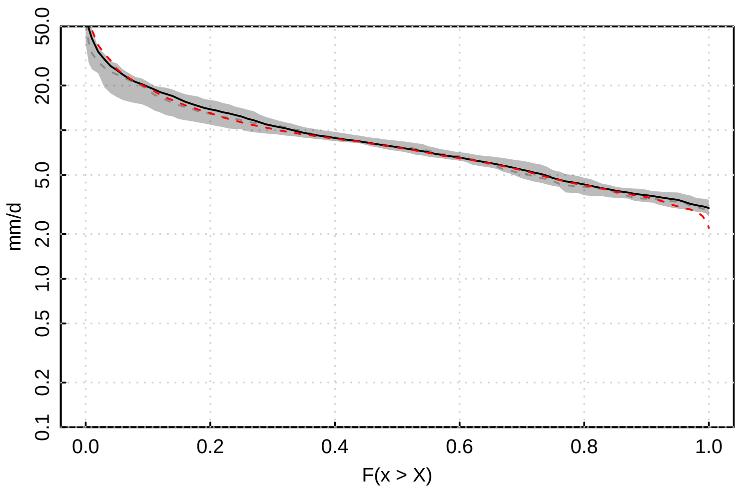
```
  100.0%    99.9%    99.5%    99.0%    98.0%    97.0%
158.0000  99.0722  62.6540  47.4180  37.3720  32.8000
```

The FDC can be constructed for the entire runoff record giving a long-term representation of the runoff regime, or as an ensemble of annual FDCs (AFDCs) estimated for each year of record (Vogel and Fennessey, 1994, 1995; Castellarin et al., 2007). To calculate confidence bounds for AFDCs we do:

```
Q_afdc <- sapply(split(Q, format(time(Q), "%Y")), quantile, prob=quantili)
 head(Q_afdc)
```

```
          1999     2000    2001    2002   2003    2004    2005    2006    2007    2008    2009    2010
100.0% 52.7000 132.0000 31.5000 158.000 43.700 39.6000 63.2000 33.3000 31.6000 57.2000 51.8000 91.1000
99.9%  49.1328 127.6200 30.8812 139.800 38.604 37.5925 62.5084 31.0432 29.4524 53.2215 50.9992 82.9464
99.5%  40.1940  95.1675 28.8160 104.720 26.584 33.4400 58.1840 26.5260 22.2560 37.2250 47.7960 59.6800
99.0%  32.6240  81.1850 26.3360  81.968 19.612 31.3350 46.2520 23.7880 20.9520 33.3850 45.5240 54.0760
98.0%  28.4200  65.7000 25.5000  65.856 18.172 29.3500 26.8360 20.3000 16.9600 31.5100 42.8000 33.7760
97.0%  26.1400  59.0250 25.1080  53.632 15.816 26.6400 19.5320 19.1640 16.0160 29.7450 41.8240 28.1640
```

```
mQ_afdc <- apply(Q_afdc, 1, mean)
qQ_afdc <- apply(Q_afdc, 1, quantile)
plot(c(0,1), c(1e-1,5e1), type="n", xlab="F(x > X)", ylab="mm/d", log="y")
 grid(equilogs=FALSE)
 polygon(c(1-quantili, quantili), c(as.numeric(qQ_afdc["25%",]), rev(as.numeric(qQ_afdc["75%",]))),
         border=NA, col="#00000044")
 lines(1-quantili, as.numeric(qQ_afdc["50%",]), col="#00000044", lty=2)
 lines(1-quantili, as.numeric(mQ_afdc))
lines(1-quantili, as.numeric(Q_fdc), col=2, lty=2)
```



3.3 Low flows

Depending on the application and the science question different low flow characteristics may be of interest (see Smakhtin, 2001): (i) characteristics that represent low flow runoff with a certain probability; (ii) characteristics that represent durations or deficit volumes of low flows; and (iii) characteristics that represent how quickly the low flow runoff decreases with time. Indices that relate to the first group (i.e., representing runoff) include the following:

- Flow quantiles (Q_x): runoff values exceeded x% of the time corresponding to points on the flow duration curve. For perennial streams, 90th or 95th quantiles (i.e., Q_{90} and Q_{95}) are often used, while for intermittent or ephemeral streams, quantiles based on runoff within a typical runoff season, or quantiles with a lower exceedance probability (e.g., 60%) may be more appropriate (Smakhtin, 2001). Flow quantiles are relatively robust to measurement errors and anthropogenic effects, which has made them widely used around the world (Smakhtin, 2001).
- Mean annual minimum flows over d consecutive days (MAM_d): long-term average of runoff during the driest period of each year. A moving average time window of 7 or 10 days is often used to remove fluctuations of the hydrograph due to measurement errors or anthropogenic effects. The choice of the moving window size may also depend on the problem at hand. The magnitudes of mean annual minimum flows over 7 or 10 consecutive days are often similar to Q_{95} (e.g., Smakhtin, 2001).
- Instead of the mean, annual low flows $Q_{d,T}$ of a given return period T can be used, where $Q_{d,T}$ (d-day, T-year runoff) relates to the annual minimum d-day low flow that is expected to occur, on average, once every T years. They are estimated by extreme value statistics from a d-day moving average of the daily hydrograph. The 7-day runoff with a return period of 10 years ($Q_{7,10}$) is often used in the USA and Canada.

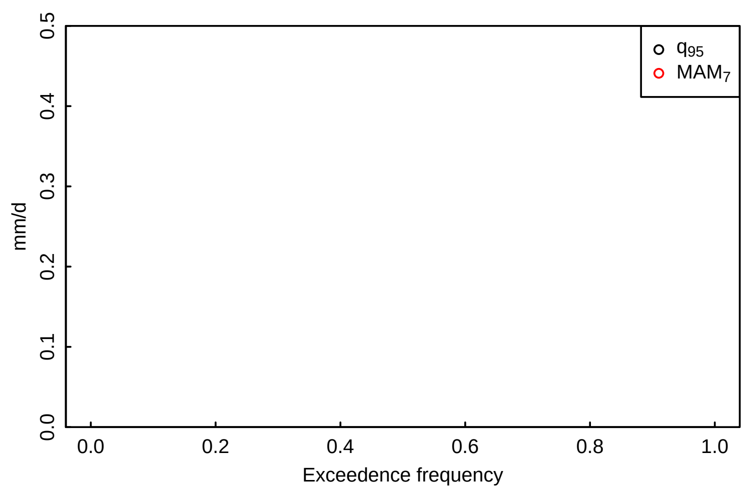
Let's calculate Q_{95} and MAM_7:

```
Q95 <- aggregate(Q, format(time(Q), "%Y"), quantile, prob=.05)
dummy <- zoo(filter(Q, filter=rep(1,7)/7), time(Q))
MAM7 <- aggregate(dummy, format(time(dummy), "%Y"), min, na.rm=TRUE)
```

Let's plot them in a plotting position:

```
points_pp_lows <- function (x, ...) {
 # x = sample
 ordered <- sort(x, decreasing=TRUE)
 n <- length(ordered)
 exceedencefreq <- seq(1,n)/(n+1)  # Weibull
 points(exceedencefreq, ordered, ...)
}
```

```
plot(c(0,1), c(0,.5), type="n", xlab="Exceedence frequency", ylab="mm/d")
 points_pp_lows(as.numeric(Q95), col="black")
 points_pp_lows(as.numeric(MAM7), col="red")
legend("topright", legend=c(expression(q[95]), expression(MAM[7])), pch=1, col=c(1,2))
```



3.4 High flows/floods

In the context of this exercise, flood prediction is defined as the estimation of flood runoff and the associated exceedance probability at an unknown future point in time, as opposed to real-time flood forecasting where forecasts are made for the immediate future. The focus is on river floods induced by heavy rain, sometimes in association with snowmelt, but dam breach floods, ice jam floods, and floods due to other processes are also possible.

One of the ways that humanity has learned to live with floods is to understand the severity of flooding in terms of the frequency or probability of flooding. Hydrology then needs to understand the risk of rare or extreme events, and factor that risk in cost-benefit analyses of engineering decisions. Therefore, the quantity of interest in flood estimation is the magnitude of the flood (normally flood runoff at a particular point at a river, or the corresponding stage or water level) for a specified return period (also called average recurrence interval). An example is the so-called 100-year flood, the magnitude of the annual maximum flood that will be exceeded, on average, once in 100 years; put another way, there is a 1% chance in any year that the largest flood of the year will exceed the 100-year magnitude. The choice of return period in specific circumstances depends on the risk society is prepared to accept, and is usually decided on the basis of consensus or cost-benefit analysis. For example, a lower return period might be accepted for design of a stormwater drain than for design of a dam spillway, since the potential damage is lower in the case of the former. This exercise is particularly concerned with the flood frequency curve.

Let's calculate the maximum annual daily flows:

```
MAF <- aggregate(Q, format(time(Q), "%Y"), max)
```

Let's plot them in a plotting position:

```
points_pp_floods <- function (x, ...) {
 # x = sample
 ordered <- sort(x)
 n <- length(ordered)
 nonexceedencefreq <- seq(1,n)/(n+1)  # Weibull
 RP <- 1/(1 - nonexceedencefreq)
 points(RP, ordered, ...)
}
```

Plot them:

```
plot(c(1,100), c(0,100), type="n", xlab="Return period (yrs)",
     ylab="Maximum annual daily flow (mm/d)", log="x")
 points_pp_floods(as.numeric(MAF), col="black")
```

Let's fit a Gumbel distribution.

The density function of the Gumbel distribution is:

$$f(x) = \frac{1}{d} \exp\left(-\frac{x-c}{d}\right) \cdot \exp\left[-\exp\left(-\frac{x-c}{d}\right)\right]$$

where x is the random variable and c and d the parameters. The cumulative distribution function is:

$$F(x) = \exp\left[-\exp\left(-\frac{x-c}{d}\right)\right]$$

The quantile function is:

$$x_T = c - d \cdot \ln\left[-\ln\left(1 - \frac{1}{T}\right)\right]$$

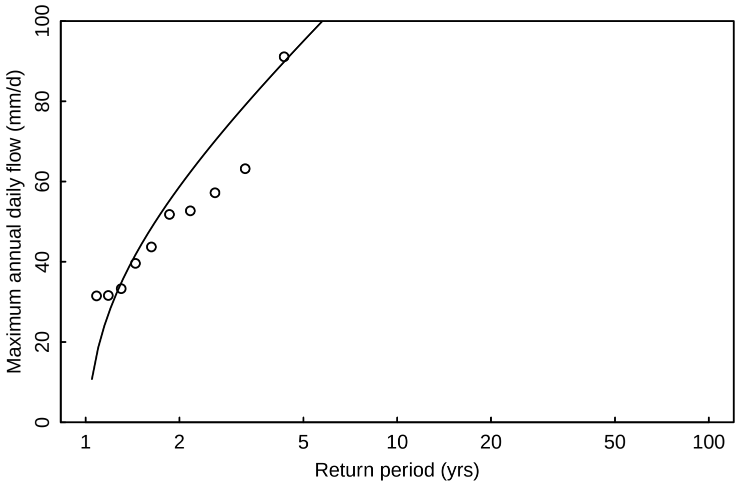
where T is the return period and the parameters estimated with the method of moments are:

$$d = \frac{\sqrt{6}}{\pi} \cdot \sigma \text{ und } c = \mu - 0.5772 \cdot d$$

where μ and σ are the population moments.

```
lines_fitgumbel <- function (x, ...) {
 # x = sample
 m <- mean(x)
 s <- sd(x)
 d <- sqrt(6)/pi * s
 c <- m - 0.5772*d
 curve(c - d*log(-log(1 - 1/x)), add=TRUE, ...)
}
```

```
plot(c(1,100), c(0,100), type="n", xlab="Return period (yrs)",
     ylab="Maximum annual daily flow (mm/d)", log="x")
 points_pp_floods(as.numeric(MAF), col="black")
 lines_fitgumbel(as.numeric(MAF), col="black")
```



From which Q_{100} can be read.

4 Comparison of the different sites

How do the signatures of the different sites differ?

I would propose that we go through the figures we have plotted for each signature, put them on a map and discuss them together.

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