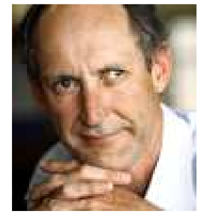
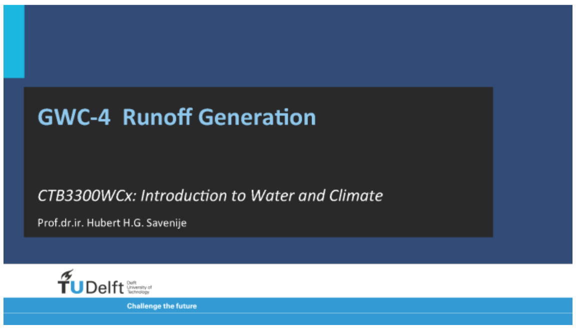
CTB3300WCx – Introduction to Water and Climate

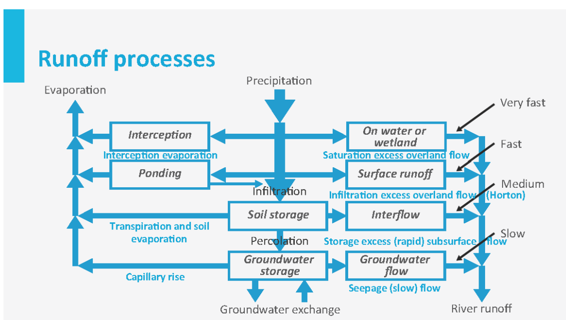
GWC 4 – Runoff Generation



Hubert Savenije



Welcome! My name is Hubert Savenije and I am a hydrologist. The most visible and most intriguing part of the hydrological cycle is the runoff. Every person has at some stage looked in fascination at flowing water, or been inspired by the beauty or violence of a stream Flowing water seems alive. And it is an inseparable part of our life. Water has been essential to create and support our societies and sometime it threatens it with its destructive force. As we saw earlier, it took philosophers and scientists some time before they realized that river runoff is completely dependent on precipitation. At first they thought that there was not enough precipitation to feed the rivers, but in fact there is a lot more than that. Globally, less than 40% of the precipitation leads to runoff.



Globally, less than 40% of the precipitation leads to runoff. As precipitated moisture travels through the terrestrial cycle, it is stepwise partitioned into other fluxes. The first partitioning point is the surface. If rain falls on water or on saturated land, then it runs off directly to the open water. We call this saturation excess overland flow. Above land, rainfall is intercepted by: leaves, the litter on the ground and the ground itself (where it may pond) and from there it evaporates back to the atmosphere. The typical time scale of this process is between an hour and a day. If the ponding is large enough, water may flow overland and find its way to the stream. We call that infiltration excess overland flow, or Hortonian overland flow, after the great American hydrologist Horton. This overland flow is very fast, with a time scale of hours. The remainder infiltrates into the soil, from where it can transpire or percolate into the groundwater. During a rainfall event, the soil can become so saturated that pockets of saturation occur under the ground at relatively shallow depth. If the terrain is sloped, then this sub-surface pocket may connect and generate subsurface runoff through a network of preferential channels. These channels have been created by the water itself, making use of root channels, animal burrows and fissures. In mountainous and hilly area, this is a dominant mechanism, which we call storage excess subsurface flow or shortly ‘interflow’. The water that percolates to the groundwater subsequently feeds the very slow groundwater flow, that sustains the base flow of the river. Finally, groundwater can be exchanged with neighbouring areas or may rise to the unsaturated soil by capillary rise. The many storages and thresholds in this system are the reason why the rainfall-runoff processes is highly non-linear, although the individual processes can often very well be described by linear processes, just like we saw with the groundwater seepage.

Runoff components

Fast surface runoff = *Precipitation* -
- *Interception*
- *Infiltration*

Fast sub-surface runoff = *Infiltration* -
- *Transpiration and soil evaporation*
- *Percolation*

Base flow (seepage to surface water) = *Percolation* -
- *Capillary rise*

So the fast surface runoff is the precipitation minus the interception and the infiltration. The fast sub-surface runoff is the infiltration minus the transpiration, the soil evaporation and the percolation. And the base flow equals the percolation minus the capillary rise.

River runoff

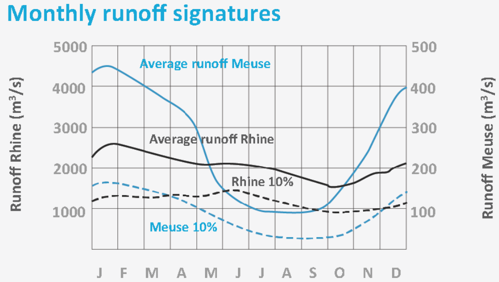
Surface runoff *(fast and turbid)*
- Hortonian (infiltration excess) overland flow
- Saturation excess overland flow

Sub-surface runoff *(fast and mostly clear)*
- Storage excess (rapid) subsurface flow (interflow)

Base flow *(slow and clear)*
- Seepage flow to stream network

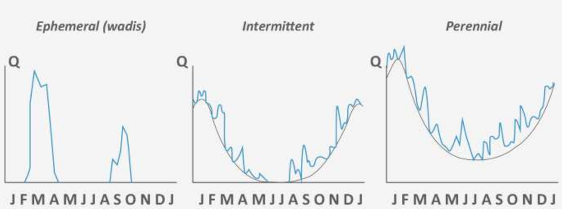
It is hard to distinguish these different runoff components once the water has entered the river. But the water can reveal its origin when we look at its colour and composition. If it is very turbid, and flowing fast, then it stems from surface runoff. If it flows fast and is mostly clear, then it stems from rapid subsurface flow. If the water is clear and the flow is quiet, then it consists of seepage flow from GW. From the chemical elements in the water, the isotope composition and the turbidity we can deduct the origin of the water, but also the time it spent in the catchment before it came to runoff But that goes beyond this introductory course.

Monthly runoff signatures

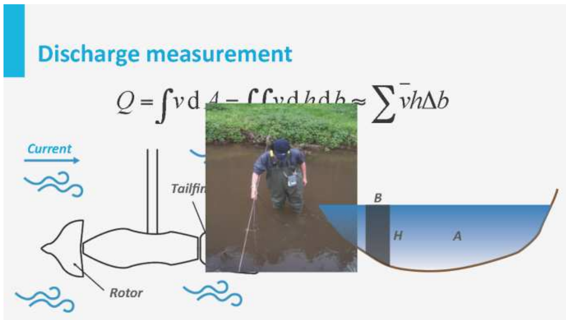


Depending on the climate and the physical properties of the landscapes in the catchment, rivers have different runoff signatures. Here we see clearly different signatures from two neighbouring catchments. On average, the Rhine has about ten times more discharge than the Meuse. Not only is the runoff of the Rhine larger, it is also less variable over the year. What makes these patterns so different? Is it climate? “It’s the landscape, the climate is not so different”. The mountainous part of the Rhine, with its snow cover and glaciers makes that the runoff during the dry summer months is still substantial, whereas the runoff of the Meuse in de dry summer months is very low.

Types of rivers

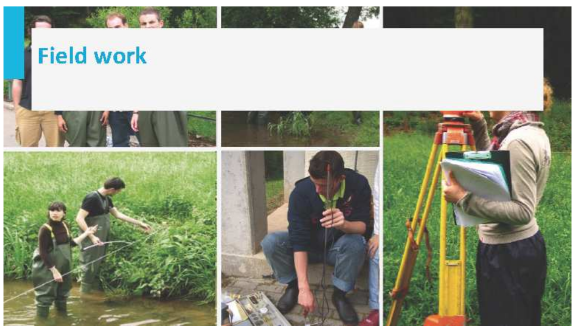


But climate can be very important. Whether a river is ephemeral, intermittent or perennial depends primarily on the climate.

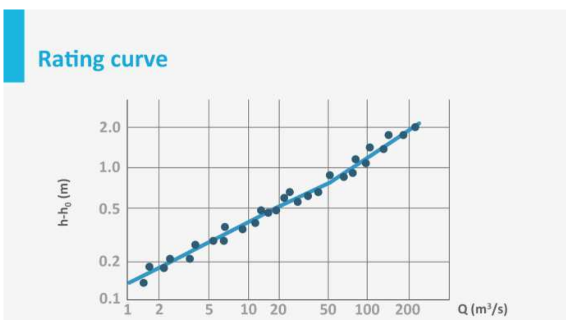


Traditionally we measure discharge by a current meter at a certain position in the cross-section of a river. We find the total discharge by integration of all these points over the cross-section. This is a lot of work, although it is fun.

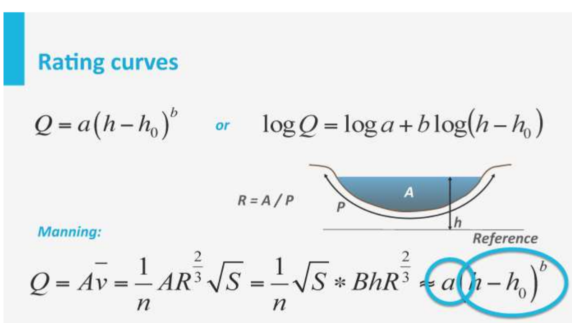
As you can see here.



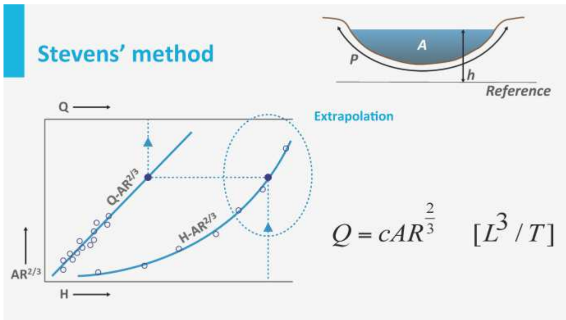
But although its is great fun doing it in this way, it is also a bit old fashioned. Nowadays we use Doppler instruments in the stream that are able to map the entire velocity field or we make use of movies from iPhones to infer the discharge from the flow pattern observed from the top. But this is something for an advanced course.



We use discharge measurements to compose rating curves, linking the water level to the discharge. The relation between depth h and discharge Q is a power function which plots a straight line on double log paper…



…provided we have the zero of the reading right: the so-called h0, or the gauge reading when the discharge is zero. These rating curves are expressions of the Manning formula for 'uniform' flow. The power function of the rating curve completely matches the Manning formula below. The Manning formula consists of two parts: the first part is a constant for the given section and the second part depends on the water level h. The width, the depth and the hydraulic radius R all depend on the depth, whereas the roughness coefficient n and the slope S does not Interestingly, the water level dependent part purely depends on the geometry of the cross-section



Stevens developed a very smart way of combining the two. The first part (the curve), one can derive from a topographical survey of the cross-section. This curve can be extrapolated as far as necessary, as high as the water level may go. The other part, the line, required a couple of discharge measurements, but because it is a straight line, it requires only a limited number of points. And subsequently we can use that line to combine with the curve. Have a look at the example to see how it works.

Exceptional circumstances

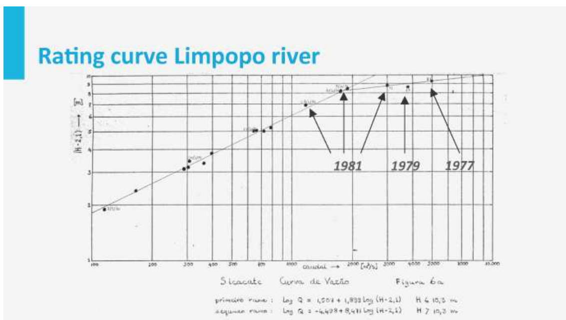
Bangladesh

- Bank overtopping
- Backwater effects

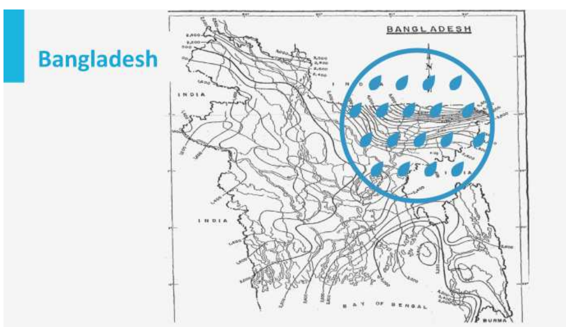
Mozambique

- Bank overtopping

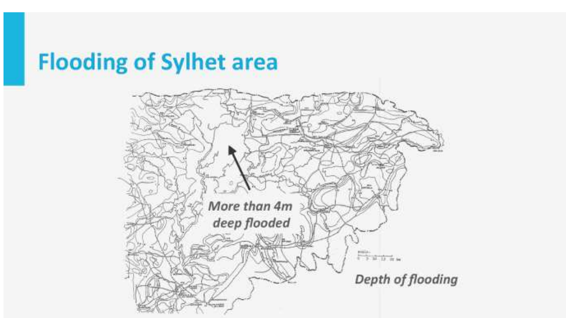
Have a look at the example to see how it works. Rating curves can have peculiarities, On double log paper, they should plot on a straight line, (if you select the right H0) but they can show kinks (inflections) in the curves, which can bend up as well as down.



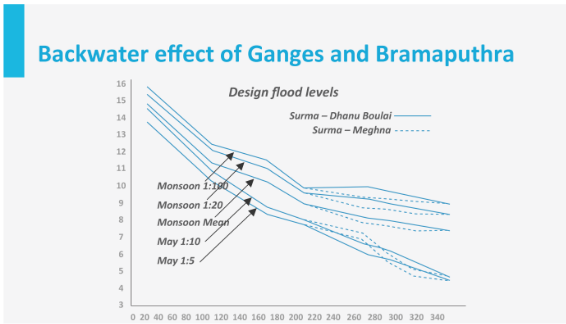
Here you see a hand-drawn rating curve made in the 1980's of the Limpopo river in Mozambique. The dots with the years were observations during big floods, when the whole of the flood plain of the river was covered with water. The inflection point is at the water level where the river starts to fill the floodplain and where the flood plain offers an additional and much wider channel.



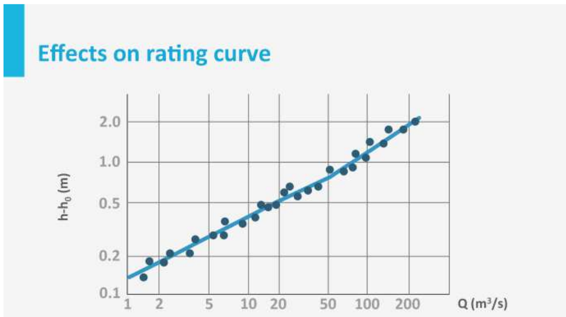
This is Bangladesh, the delta of the Ganges, Bramaputhra and Meghna. Look at the upper Eastern corner, called Sylhet. This is where world record rain is falling.



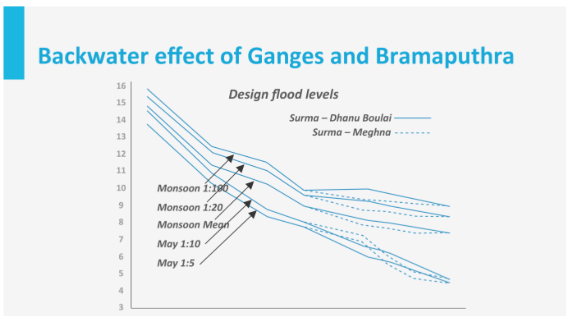
During the monsoon the Sylhet area is deeply flooded, up to more than 4 m deep. You might think this is because of the heavy rainfall in the area, but it is because of the backwater from the Meghna, where it joins the Ganges and the Bramaputhra.



Here you see this backwater effect. During the pre-monsoon, in May, the floods in the Surma, which drains Sylhet, can discharge uninhibited to the Gulf of Bengal. But during the peak of the monsoon, the discharge of the Ganges and Bramaputhra is so high, that it causes a great backwater.



This causes rating curves to tilt up.



We see that these backwater curves are labelled as design floods with a probability of once in a 100 and once in 20 years. How do we determine flood levels with these probabilities?

Extreme discharge

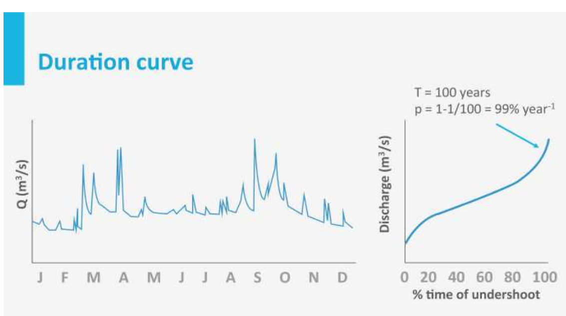
Duration curves → Frequency curves

Extreme value distribution for floods

- Annual maxima

Gumbel extreme values analysis (flood frequency analysis)

In the chapter on precipitation, we prepared duration curves to rank the rainfall events according to their magnitude. In that way we obtained frequency curves. For extreme floods, we shall make use of Gumbel's theory for annual extremes.



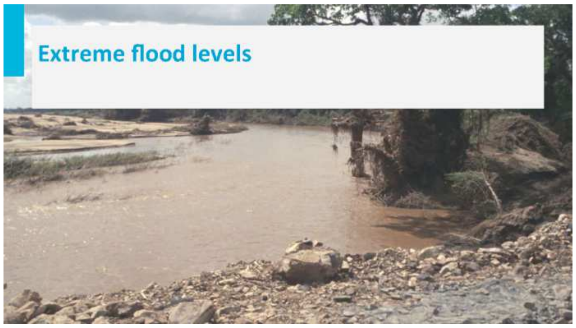
Here you see how a hydrograph can be turned into a duration curve, showing the % of time that a certain discharge is exceeded, or in this case 'not-exceeded'. We call this the probability of non-exceedence. The interesting part of this curve is the upper part, and moreover, we would like to extrapolate the curve to rare probabilities such as once in a 100 years: a probability of non-exceedence of 99%.

Gumbel (1891-1966) extreme values analysis

For the purpose of:

- Design discharge
- Design dike level
- Design of culvert or bridge capacity

Gumbel developed a statistical distribution for such extremes. His statistics are useful for determining design discharges or extreme flood levels.



Such as these.

Gumbel assumption

*"**Assuming** a phenomenon is **normally distributed**, then the **extremes** follow the **Gumbel distribution**"*

BUT

*This **seldom** holds true*

The basic assumption underlying Gumbel's theory is that the underlying phenomenon (in this case river flow, or alternatively water levels or precipitation) are normally distributed. But this is unfortunately seldom true.

Additional Gumbel assumptions

- ***Series is homogeneous***
- ***Series is stationary***
- ***Series is long enough (seldom true)***

Additionally the data series needs to be homogeneous (caused by a single population of events). It should also be stationary (no climatic change or man-induced changes) and long enough (a reasonable part of the return period). But also these things are seldom true. Is Gumbel's theory then still useful?
Well, yes, but you have to use it with good common sense.

Gumbel equation

$$q = P(Q \le x) = 1 - p = \exp(-\exp(-y)) = e^{-e^{-y}}$$

$$p = P(Q > x) = 1 - \exp(-\exp(-y)) = 1 - e^{-e^{-y}}$$

$$y = -\ln(-\ln(q)) = -\ln(-\ln(1-p)) = -\ln\left(-\ln\left(1-\frac{1}{T}\right)\right)$$

Reduced variate of Gumbel: $y = a(x-b)$

These are the equations. I am sure they look difficult and complicated to you, but in fact they are not. They are much easier than the normal distribution, which is very similar Gumbel's equation for q (the probability of non-exceedence) is simpler than Gauss' equation…

Analogy with normal distribution

$$q = P(x < X) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{X} e^{-\frac{1}{2}t^2}\, dt$$

Reduced variate of Gauss: $t = \frac{X-\mu}{\sigma} = \frac{1}{\sigma}(X-\mu)$

Reduced variate of Gumbel: $y = a(x-b) \approx \frac{1}{S}(x - X_m)$

…which we see here.
Unlike the normal distribution, Gumbels's equation can be calculated easily with a pocket calculator or an iPhone. Moreover, the reduced variate looks similar.

How to do Gumbel analysis

- *Determine the anual extreme occurrences*
- *This gives N extreme values for N years*
- *Ranking from large to small with rank number m*
- *Calculate the frequency of occurrence using the "plotting position"*

To carry out a Gumbel analysis, you have to select the extremes of a series. Normally we look at annual extremes. Say you have N years of data, then you take the N highest values of these years. You then rank these extremes in order of magnitude. To determine their frequency, you use the plotting position.

Plotting position

$$p = \frac{m}{N+1} \qquad T = \frac{N+1}{m}$$

p: probability of exceedence (yr^{-1})
T: frequency scale (yr)
N: number of years of observation (yr)
m: rank number (-)

To prevent that the lowest value in the series gets a probability of 1, you add one to the number of years in the denominator. As a result, the highest value in 9 years, has a probability of exceedence of once in 10 years.

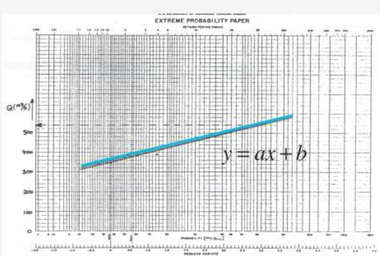
Peak table

datum:	Q in m^3/s	datum:	Q in m^3/s	datum:	Q in m^3/s
01-02-69	340	17-01-72	140	15-04-74	343
17-02-69	57	02-02-72	180	20-04-74	357
24-02-69	324	04-03-72	50	08-05-74	222
26-02-69	110	27-03-72	***345***	16-05-74	120
02-03-69	***343***	23-01-73	214	04-01-75	245
09-03-69	280	14-03-73	***339***	12-01-75	211
12-03-69	50	24-09-73	256	17-01-75	245
29-03-69	342	02-01-74	267	13-03-75	56
15-04-69	112	18-01-74	53	24-03-75	68
30-04-69	[illegible]	21-01-74	48	03-04-75	95
06-01-70	***387***	14-02-74	80	14-04-75	102
23-02-71	***376***	15-03-74	281	21-05-75	269
03-01-72	211	20-03-74	***383***	14-11-75	***431***
08-01-72	299	24-03-74	163	15-12-75	319

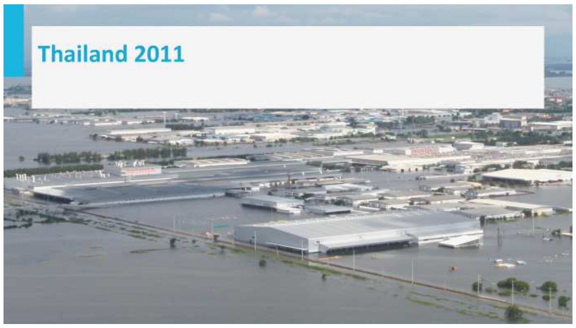
Here is a Table with highest peaks over a period of 7 years. A short series, merely as an example. We select the 7 highest values and rank them.

Gumbel paper

i	*Q* in m^3/s	*T*
1	431	8
2	387	4
3	383	2.67
4	376	2
5	345	1.6
6	343	1.33
7	339	1.14

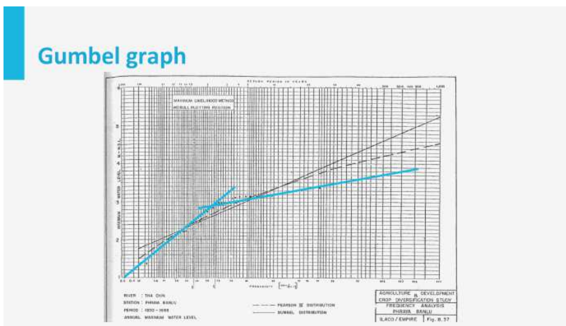


The highest value then has the probability of exceedence of once in 8 years. Gumbel paper is prepared in a way that the horizontal axis for the reduced variate y is linear.
The Gumbel equation then plots as a straight line against the vertical ordinate. The probability of non-exceedence belonging to these y values are calculated with the Gumbel formula resulting in the typical probability pattern of the graph. The vertical ordinate is the x, which has a linear relationship with y. I'll show you an example of a Gumbel line for Thailand.

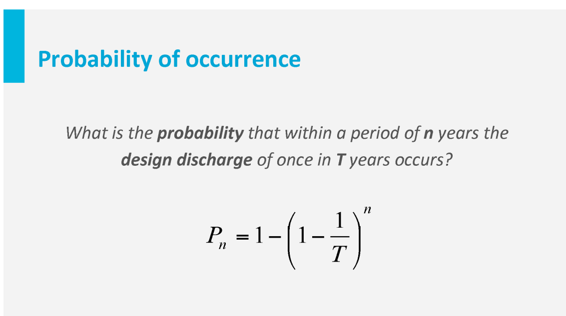


Where as you can see severe floods can take place such as in 2011, when all the bank were overtopped.

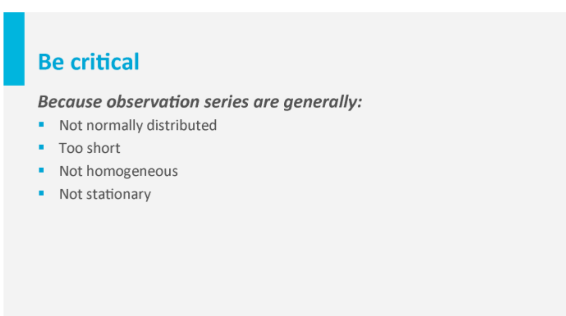
I'll show you the Gumbel graph of Phraya Banlu. It clearly shows that the highest values bend of when the banks overtop.



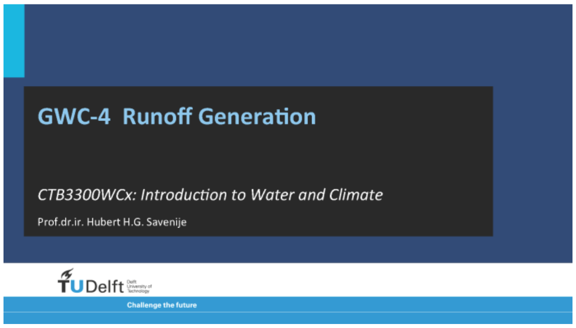
Just like we saw happening with the rating curve. Of course the kink disappears when you build a dike on both sides of the river.



But what is the probability that a flood with a return period of T actually occurs within a period of n years? It's this !
Try it yourself in the exercise.



In applying Gumbel's theory, you should always remain critical Series are seldom normally distributed. You cannot extrapolate the theory much beyond the length of the series and you must always be aware that series are not homogeneous. Moreover, people are always tampering with the hydrological system and as a result, its characteristics change over time.



This was maybe not an easy part of the course, but if you study it closely, and if you practice, then it is simpler than it seems. In the next module we'll discuss the runoff generation mechanisms.