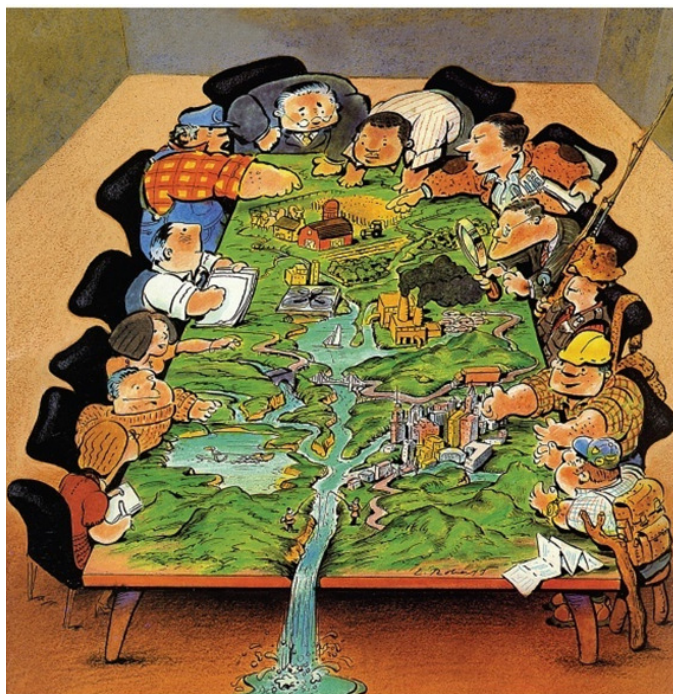




Modelação e planeamento de recursos hídricos (superficiais)

Surface water resources modelling and planning

M.M.Portela (2019/2020) ---- 1

Part 1 – FLOOD ANALYSIS. UNIT HYDROGRAPH MODEL

1. Background reviewing . Fundamental concepts
2. Components of the observed flood hydrograph at a given river section
3. Models to separate between direct runoff and baseflow
4. Excess or net rainfall and rainfall losses
5. Summary of the components of the flood hydrographs and the precipitation hyetographs
6. Determination of the unit hydrograph

PART 2 – FLOOD ANALYSIS. HEC-HMS PROGRAM

PART 3 –STEADY FLOW IN NATURAL CHANNELS. HEC-RAS PROGRAM

PART 5 –ECONOMICAL ANALYSIS CRITERIA

PART 6 – EVALUATION OF THE SURFACE RUNOFF. DESIGN OF ARTIFICIAL RESERVOIRS

PARTE 1 – ANÁLISE DE CHEIAS. MODELO DO HIDROGRAMA UNITÁRIO

1. Revisão da matéria. Conceitos fundamentais
2. Componentes do hidrograma de cheia observado numa secção de um curso de água
3. Modelos de separação do escoamento direto e do escoamento de base
4. Precipitação efetiva e modelos de perdas de precipitação
5. Resumo das componentes do hidrograma a cheia e do hietograma da precipitação
6. Determinação do hidrograma unitário

PARTE 2 – ANÁLISE DE CHEIAS. PROGRAMA HEC-HMS

PARTE 3 – ESCOAMENTOS EM CANAIS NÃO PRISMÁTICOS EM REGIME PERMANENTE. PROGRAMA HEC-RAS

PARTE 5 – CRITÉRIOS DE ANÁLISE ECONÓMICA

PARTE 6 – ESTIMAÇÃO DE ESCOAMENTOS E DIMENSIONAMENTO DE ALBUFEIRAS

M.M.Portela (2019/2020) ---- 2

EVALUATION

- ✓ **Practical task + final exam**
- ✓ **Final grade = (0,5 x average of the grades of the practical tasks) + (0,5 x grade of the final exam)**
(minimum grade in the average of the practical tasks and in the exam of 8.00)

AVALIAÇÃO DE CONHECIMENTOS

- ✓ **Trabalhos práticos + exame final**
- ✓ **Nota Final = (0,5 x média das notas dos trabalhos práticos) + (0,5 x nota do exame final)**
(nota mínima no exame e na média dos trabalhos práticos: 8,00 valores)

BIBLIOGRAFIA NA PÁGINA DA DISCIPLINA

(Apontamentos, livros, artigos e slides)

(most of the references are provided in the webpage of the course)



M.M.Portela (2019/2020) ---- 3

Timetable

Horas/Dias	Segunda	Terça	Quarta	Quinta	Sexta
12:30-13:00					
13:00-13:30	MPRH3T01 T V1.13				
13:30-14:00					
14:00-14:30					
14:30-15:00					
15:00-15:30					
15:30-16:00					
16:00-16:30					
16:30-17:00					MPRH3T01 T V1.20.1
17:00-17:30					
17:30-18:00			MPRH3T01 T V1.20.1		
18:00-18:30					
18:30-19:00					
19:00-19:30					

M.M.Portela (2019/2020) ---- 4

Provisional schedule of the classes - Programação tentativa das aulas

Semana	1	2	3	4	5	6	7	8	–	9	10	11	12	13	14	Semana		
	Fevereiro		Março					Abril				Maio						
2 ^ª f	17	24	2	9	9	16	23	30	6	13	20	27	4	6	11	18	25	2 ^ª f
3 ^ª f	18	25	3	10	17	24	31	7	14	21	28	5	12	19	26	3 ^ª f		
4 ^ª f	19	26	4	11	11	18	25	1	8	15	22	29	6	8	13	20	27	4 ^ª f
5 ^ª f	20	27	5	12	19	26	2	9	16	23	30	7	14	21	28	5 ^ª f		
6 ^ª f	21	2 8	6	13	13	20	27	3	10	17	24	1	8	10	15	22	29	6 ^ª f
Sáb.	22	29	7	14	21	28	4	11	18	25	2	9	16	23	1	Sáb.		
Dom.	23		8	15	22	29	5	12	19	26	3	10	17	24	2	Dom.		

n.º	Scope of the practical tasks - âmbito dos trabalhos práticos
1	Revisão de conceitos. Análise estatística e modelos de regionalização de caudais de ponta de cheia (Concepts revision. Statistical analysis and peak flood discharge regionalization models)
2	Separação dos escoamentos de base e direct. Cálculo da precipitação efectiva. Modelo do hidrograma unitário. Modelo HEC-HMS (Direct runoff and baseflow separation. Excess rainfall computation. Unit hydrograph model. HEC-HMS model)
3	Análise económica aplicada à comparação de projectos alternativos (economical analysis applied to the comparison of alternative projects)
4	Geração de escoamentos e dimensionamento de albufeiras (generation of river discharges and design of artificial reservoirs)

Exercício de aplicação do Modelo HEC-RAS (Example of application of the HEC-RAS program)

Modelação e Planeamento de Recursos Hídricos

+ Info

PT / EN

Últimos anúncios

Corpo Docente



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Responsável

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Métodos de Avaliação

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Sumários

Notas

- ✓ **Objective** – additional knowledge regarding modelling, flood routing, water resources management, with emphasis on flood modelling and routing, economical analysis criteria, and design of artificial reservoirs.
- ✓ The initial part aims at establishing **flood hydrographs** in river sections **under natural conditions** based on the **unit hydrograph model**.
- ✓ **Objetivo** – formação complementar nos âmbitos da modelação e propagação de cheias e do planeamento de recursos hídricos, com ênfase para critérios de análise económica, para a estimação de escoamentos e para o dimensionamento de albufeiras.
- ✓ 1ª parte focada na obtenção de **hidrogramas de cheia** em secções de cursos de água em **condições naturais** mediante aplicação **do modelo do hidrograma unitário**.

Review of concepts / Revisão de conceitos

- **Flood** (cheia)
- **Flood hydrograph** (hidrograma de cheia)
- **Flood hydrograph under natural conditions** (hidrograma de cheia em condições naturais flood hydrograph under natural conditions)

At the scale of the Earth, **floods** are the **natural hazard that disturb more people**. They affect the areas located near the rivers, downstream dams or along lateral dikes and along the shoreline. According to the **World Meteorological Organization**, the **disasters caused by floods have been increasing**, due to urban expansion into floodplains ... climate change

À escala da Terra, as **cheias** são o **perigo natural que maior fracção da população afecta**. Atingem as áreas localizadas nas proximidades da rede hidrográfica, da linha de costa, ou de diques e de barragens. Segundo a **Organização Meteorológica Mundial**, os **desastres provocados por cheias têm vindo a aumentar**, como consequência da expansão urbana em planícies aluviais ... mudança climática

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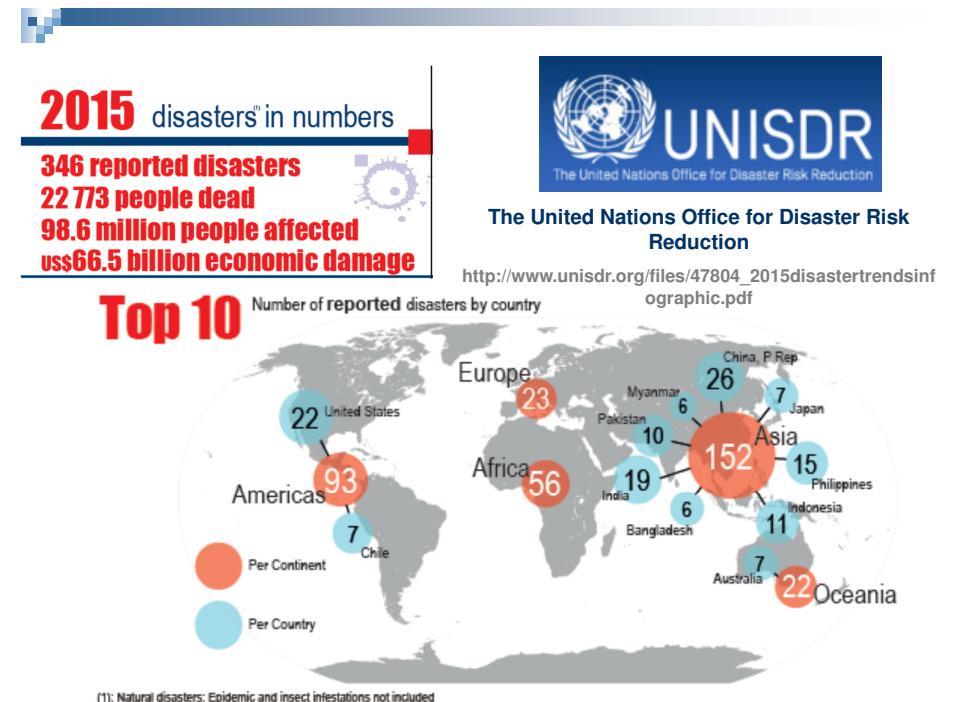
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a flood can be defined as "a general and temporary condition of partial or complete submersion of an area of about ... (8000 m²) of land usually dry ... as a result of the river overtopping or of the tidal raising, or by the rapid and unusual accumulation of water from any source, mud or land collapse along the shoreline "

... uma cheia pode ser definida como "uma condição geral e temporária de submersão completa ou parcial de uma área superior a cerca de ... (8000 m²) de terreno habitualmente seco como resultado do transbordar de águas interiores ou de maré, ou ainda pela acumulação rápida e invulgar de água superficial de qualquer origem, lama ou colapso de terras ao longo da costa, de uma superfície de água, como consequência de erosão ou destruição pelas ondas ou pela corrente cuja intensidade seja superior aos níveis cíclicos"



Figure 4 – Natural disaster subgroup classification



2015 disasters in numbers

346 reported disasters
22 773 people dead
98.6 million people affected
us\$66.5 billion economic damage

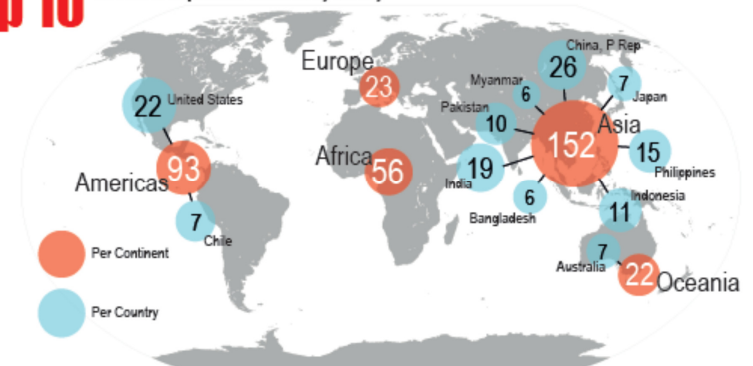


The United Nations Office for Disaster Risk Reduction

http://www.unisdr.org/files/47804_2015disastertrendsinfoographic.pdf

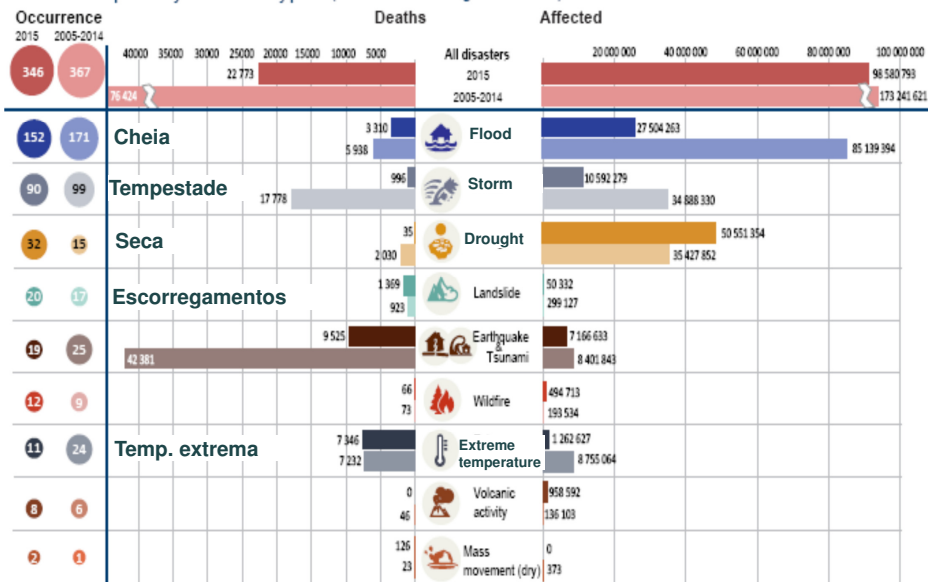
Top 10

Number of reported disasters by country

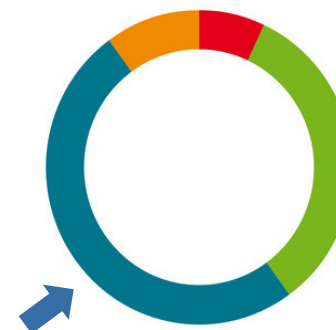


(1): Natural disasters: Epidemic and insect infestations not included

Human impact by disaster types (2015 versus average 2005-2014)

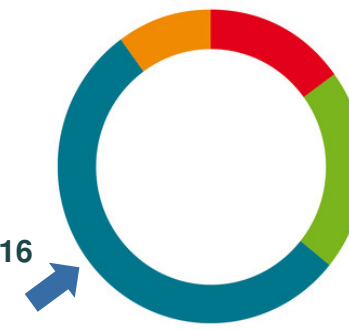


Events: 750
Percentage distribution



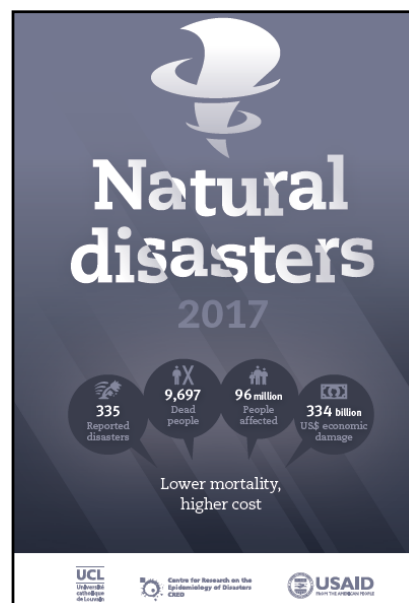
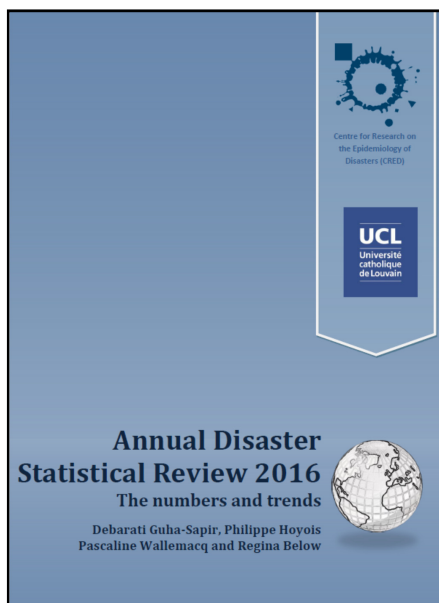
Geophysical events	7%
Meteorological events	33%
Hydrological events	50%
Climatological events	10%

Fatalities*: 9,200
Percentage distribution



Geophysical events	15%
Meteorological events	21%
Hydrological events	54%
Climatological events	10%

* Fatalities do not include famine victims or people missing

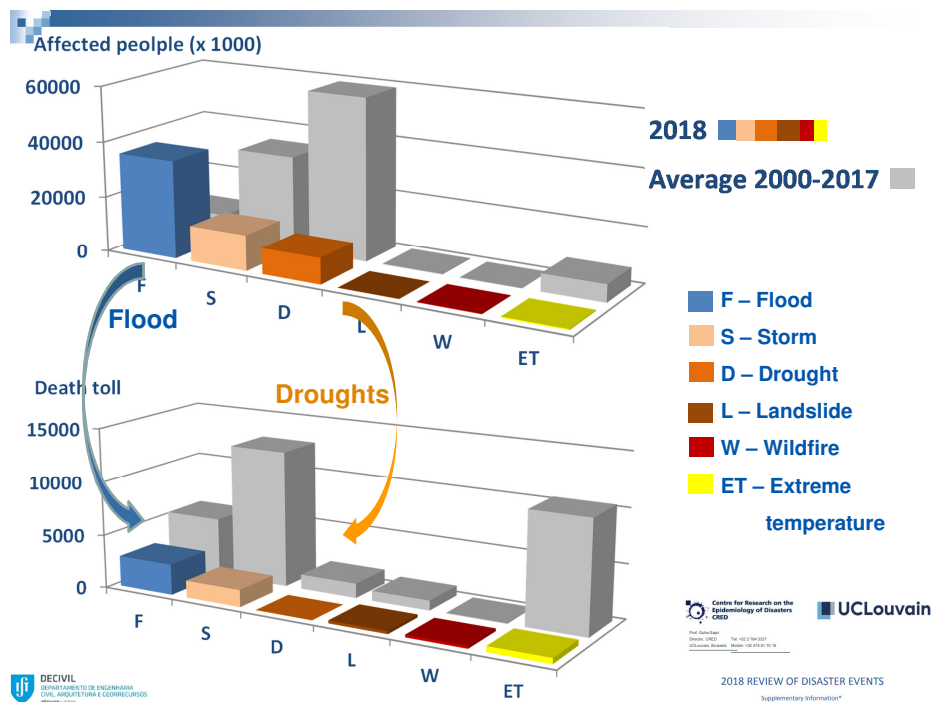
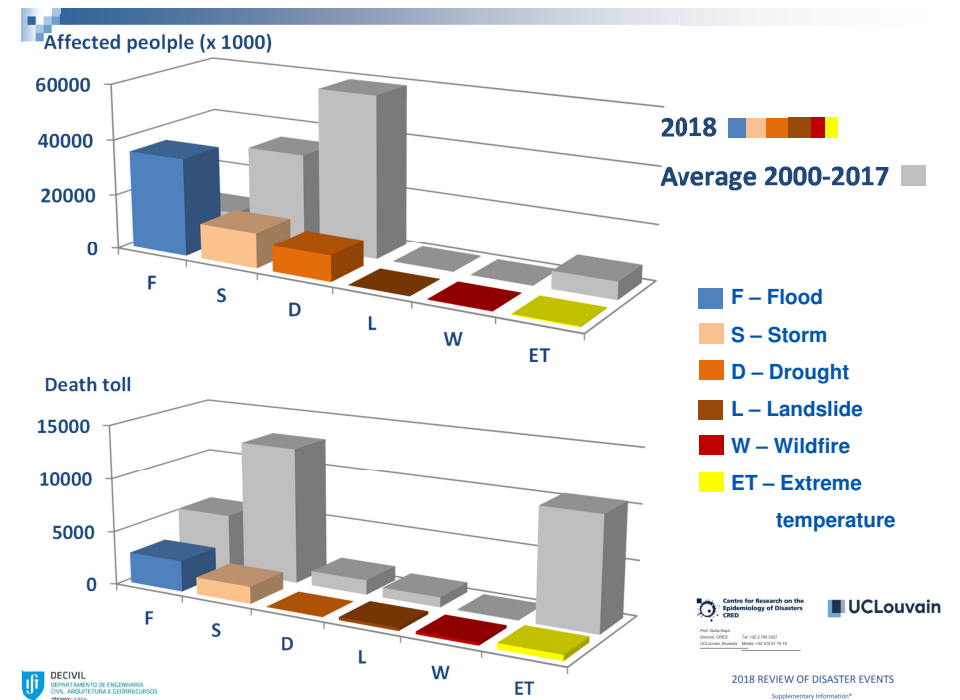
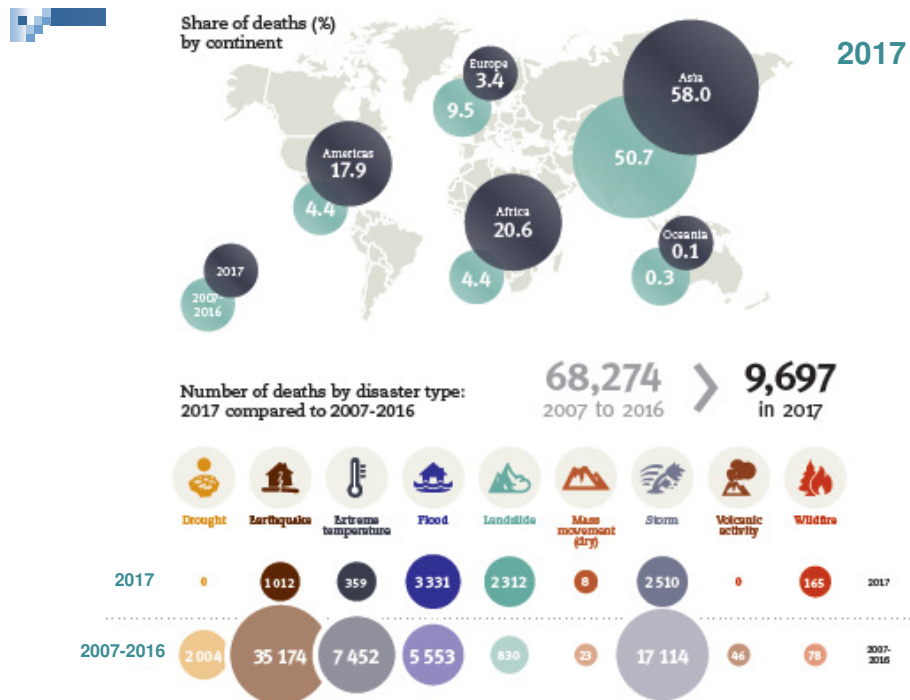


Number of disasters by continent and top 10 countries



Occurrence by disaster type:
2017 compared to 2007-2016





CONCEITOS GERAIS / GENERAL CONCEPTS (cont.)

Podem identificar-se diferentes circunstâncias de formação e ocorrência de cheias: as **cheias fluviais progressivas**, as **cheias repentinas (flash floods)**, incluindo torrentes de lama, as junto da costa associadas a **tempestades (storm surges)**, o **colapso de diques ou barragens**,

There are different types of circumstances that may result in floods ... in terms of river floods, there are the **(1) progressive floods**, like those along some of the large European rivers, like Danube or Seine, and the **(2) flash floods**, inducing mudslide; the floods along the shoreline due to **(3) storm surges**; the floods caused by the **(4) collapse of dams and dikes**, ...



Concept of natural flood ... although widely used does not have a precise definition (perhaps because the floods are mostly recognized by its anthropogenic consequences)

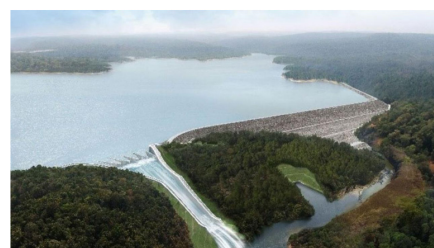
Gradual and progressive raising of the water surface along a river resulting in exceptional maximum heights that propagate downstream. The flood concept is always connected with the occurrence of exceptional water heights in the river and, accordingly, with exceptional river discharges.

Conceito de cheia natural ... embora de utilização generalizada, não tem definição precisa... (talvez porque no essencial seja reconhecido pelas suas interferências com a sociedade)

Intumescência gradual e progressiva da superfície livre do curso de água a que correspondem alturas máximas de escoamento excecionais e que se propagam para jusante. A noção de cheia está associada à ocorrência de elevados níveis de água em rios e, portanto, de elevados caudais.



Infrastructure collapse - OROVILLE (Northern California, 235 m high - the tallest dam in the U.S; start of operation 1968) – Feb/2017



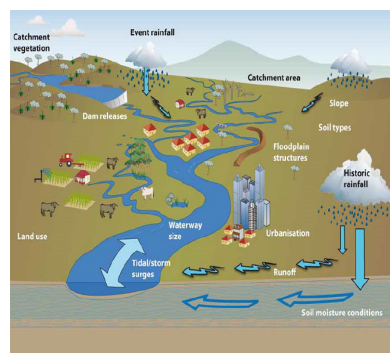
WEATHER July 24, 2018
Hundreds of People Missing after Dam Collapses in Laos

Heavy rainfall events
... heavy rainfall over a period of several days, killing ... Laos, 2018

.... Kenyan dam bursts following weeks of heavy rainfall, killing ..., May/2018

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CONCEITOS GERAIS/GENERAL CONCEPTS (cont.)



From a hydrological point of view, a flood is considered to occur when the watershed is fed by intensive and prolonged rainfall that results in river discharges that exceeds the normal conveyance capacity of the river, causing the overtopping of the margins and the submersion of the lateral fields.

- **Natural causes** (intensive rainfall events)
- **Artificial causes** (dam break; internal and external emergency plans)

Do ponto de vista hidrológico, verifica-se a ocorrência de uma cheia quando a bacia hidrográfica é sujeita a uma alimentação de precipitação de tal forma intensa e prolongada que o caudal que daí advém e que afluí à rede hidrográfica excede a capacidade normal de transporte ao longo desta rede, extravasando-a e alagando os campos marginais.

- Causas naturais (acontecimentos pluviosos excecionais)
- Causas artificiais (segurança hidráulica e operacional; planos de emergência internos e externos)

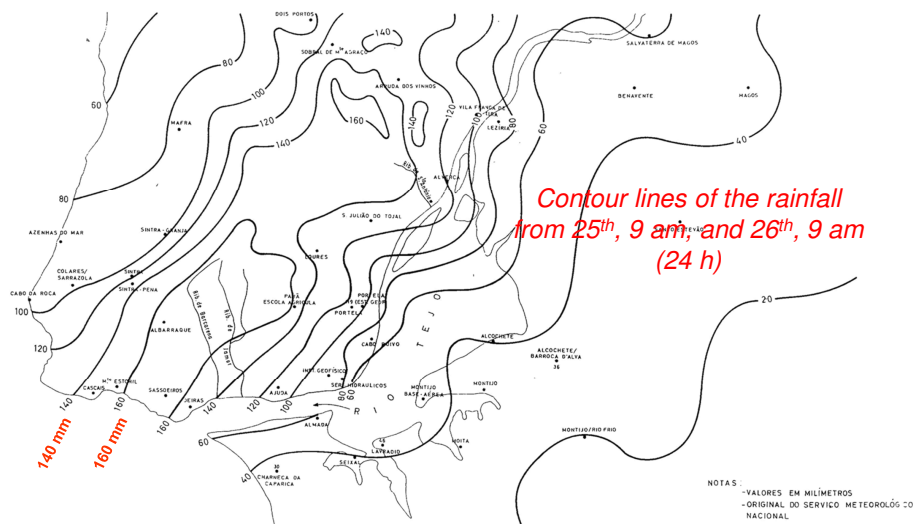
Portugal is particularly prone to flash floods



Lisboa,
1967
(> 750
mortos)

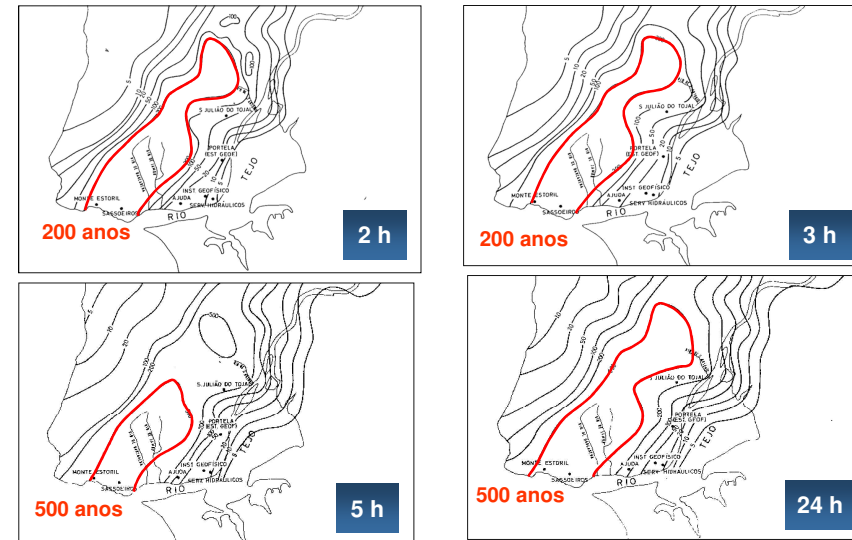


Odivelas,
1983



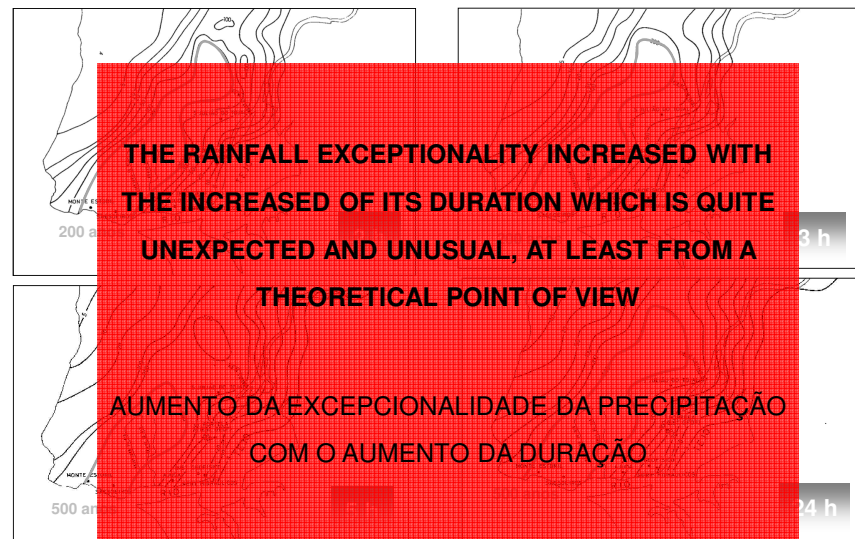
Novembro de 1967. Isolinhas da precipitação (mm) no período entre as 9:00h do dia 25 de novembro e as 9:00 h do dia 26 de novembro.

(HP – Hidrotécnica Portuguesa, Consultores para Estudos e Projectos, 1969).



Novembro de 1967. Isolinhas do período de retorno (anos) para durações da precipitação de a) 2 h; b) 3h; c) 5h; d) 24 h (**contour lines of the return period for different rainfall duration**)

(HP – Hidrotécnica Portuguesa, Consultores para Estudos e Projectos, 1969).



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(HP – Hidrotécnica Portuguesa, Consultores para Estudos e Projectos, 1969).

A catástrofe abate-se sobre os concelhos de Cascais e Oeiras

A vila de Cascais (sobretudo a parte baixa) ficou irreconhecível
Mortes a lamentar
Milhares de contos de prejuízos

COMO OCORREU A TRAGÉDIA

Em 25/26 de Novembro de 1967, sobre a vila de Cascais abateu-se uma catástrofe que a tornou irreconhecível. A vila de Cascais (sobretudo a parte baixa) ficou irreconhecível. Mortes a lamentar. Milhares de contos de prejuízos.

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ASPECTO DA TRAGÉDIA QUE ATINGIU CASCAIS

Rua Visconde de Luz

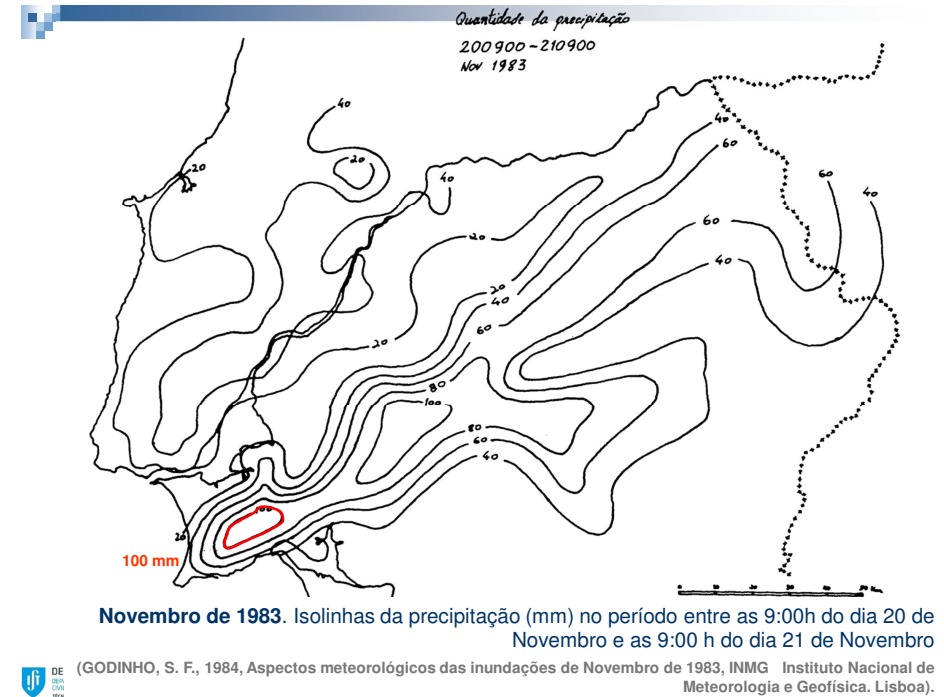
O acesso à nossa redacção ficou vedado, pelo lençol de água que se estendeu da Av. dos Combatentes da Guerra até à H. Alonso Sanchez. Os prejuízos nos estabelecimentos da Trav. Alonso Sanchez foram incalculáveis.



Cheia de 1983

Jornal da Costa do Sol, 12/4/1984

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Madeira, 20 Fevereiro de 2010



Directive 2007/60/EC on the assessment and management of flood risks (FLOOD DIRECTIVE) - in force since 26 November 2007. It requires Member States to assess if all water courses and coast lines are at risk from flooding, to map the flood extent and assets and humans at risk in these areas and to take adequate and coordinated measures to reduce this flood risk. It also reinforces the rights of the public to access this information and to have a say in the planning process – introduced in each country legal framework by specific decree-laws.

DECRETO-LEI 115/2010, DE 22 DE OUTUBRO, que transpõe para a ordem jurídica nacional a Diretiva nº 2007/60/EC, de 23 de Outubro de 2007, do Parlamento Europeu e que estabelece um quadro para a avaliação e gestão dos riscos de inundações.

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De acordo com o anterior DL, os instrumentos de avaliação e de gestão dos riscos de inundações estão divididos nas seguintes fases (... *stages of the evaluation and management of the flood risks*):

- ✓ **AVALIAÇÃO PRELIMINAR DOS RISCOS DE INUNDAÇÕES** (*preliminary evaluation of the flood risk*)
- ✓ **ELABORAÇÃO DE CARTAS DE ZONAS INUNDÁVEIS E CARTAS DE RISCOS DE INUNDAÇÕES** (*mapping of the flooded areas and of the flood risk areas*).
- ✓ **ELABORAÇÃO DOS PLANOS DE GESTÃO DOS RISCOS DE INUNDAÇÕES** (*preparation of flood risk management plans*).

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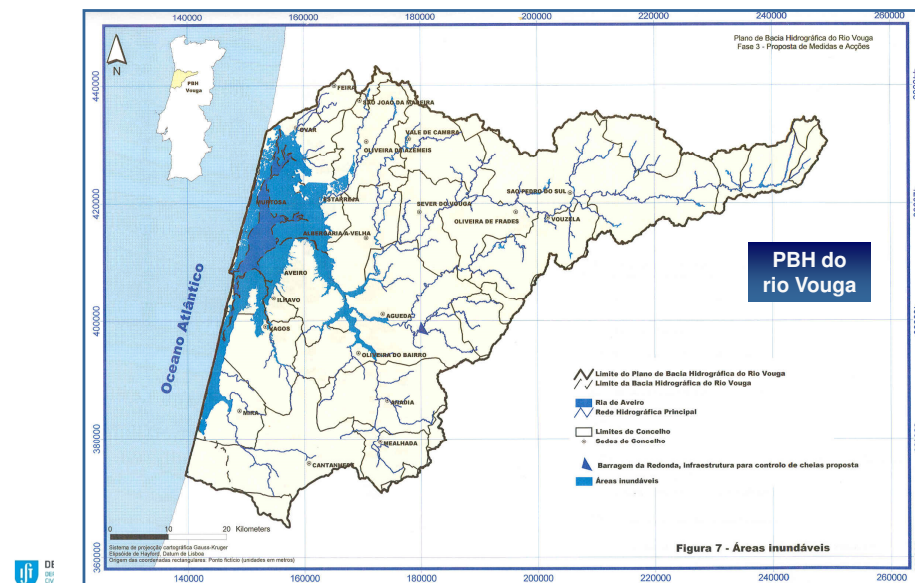
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- ✓ **ELABORAÇÃO DOS PLANOS DE GESTÃO DOS RISCOS DE INUNDAÇÕES** (*preparation of flood risk management plans*).

Each country has its own legal framework (within the EU, always complying with the European flood directive)

DECRETO-LEI 115/2010, DE 22 DE OUTUBRO

- ✓ **Avaliação preliminar dos riscos de inundações** (*preliminary evaluation of the flood risk*), visa fornecer uma avaliação dos riscos potenciais e, com base na mesma, identificar as zonas onde existem riscos potenciais significativos de inundações ou nas quais a concretização de tais riscos se pode considerar provável.
- ✓ **Elaboração das cartas de zonas inundáveis e das cartas de riscos de inundações** (*mapping of the flooded areas and of the flood risk areas*), na sequência da etapa anterior, com a indicação dos caudais de cheia para diversos períodos de retorno, das respetivas profundidades de água em relação ao nível médio da superfície da água e das extensões das inundações. As cartas de riscos de inundações deverão indicar as potenciais consequências prejudiciais associadas às áreas indicadas nas cartas de zonas inundáveis, tais como, um número indicativo de habitantes potencialmente afetados, os edifícios sensíveis (hospitais, infraestruturas de gestão de efluentes, edifícios com importância na gestão de emergência...) e o tipo de atividade económica potencialmente afetada.
- ✓ **Elaboração dos planos de gestão dos riscos de inundações** (*preparation of flood risk management plans*) visando a redução das potenciais consequências prejudiciais das inundações para a saúde humana, o ambiente, o património cultural, as infraestruturas e as atividades económicas nas zonas identificadas com riscos potenciais significativos. Deverão abranger todos os aspetos da gestão dos riscos de cheia e inundações, centrando-se na prevenção, proteção e preparação, incluindo sistemas de previsão e de alerta precoce, tendo em conta as características de cada bacia ou sub bacia hidrográfica. Para tanto, e para além de definirem medidas destinadas a prevenir e reduzir os danos causados por inundações, poderão também incluir a promoção de práticas de utilização sustentável do solo, a melhoria da retenção da água e a inundações controlada de determinadas zonas em caso de cheia.

Zonas sujeitas a inundações (anterior ao DL 115/2010) – flooded area mapping (done before the flood directive)

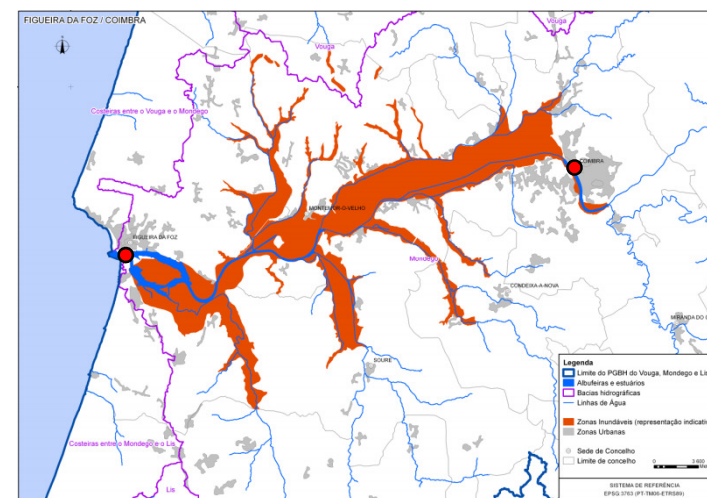


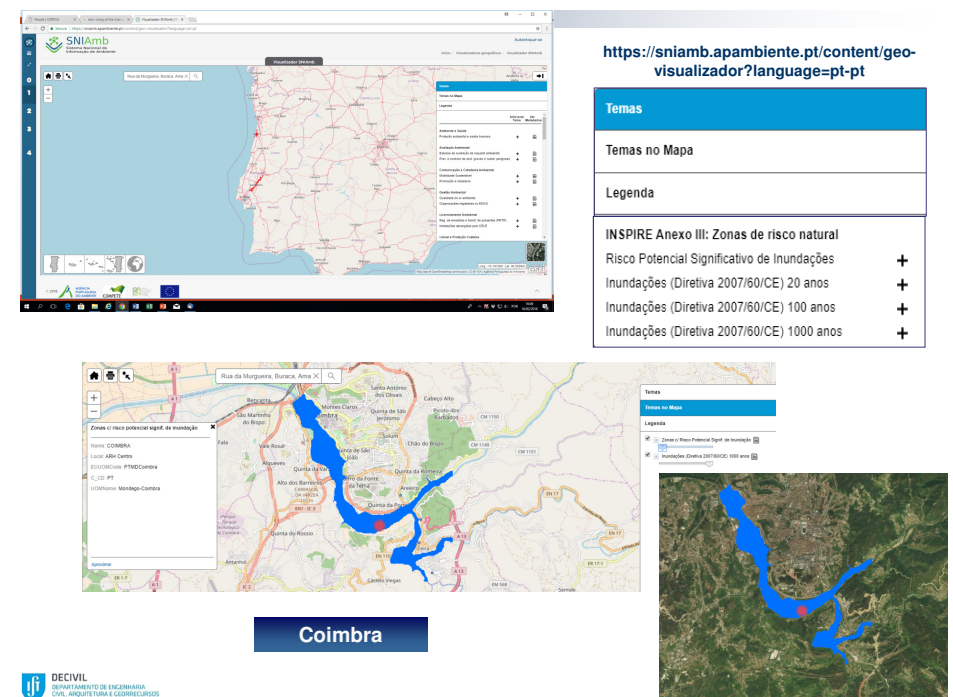
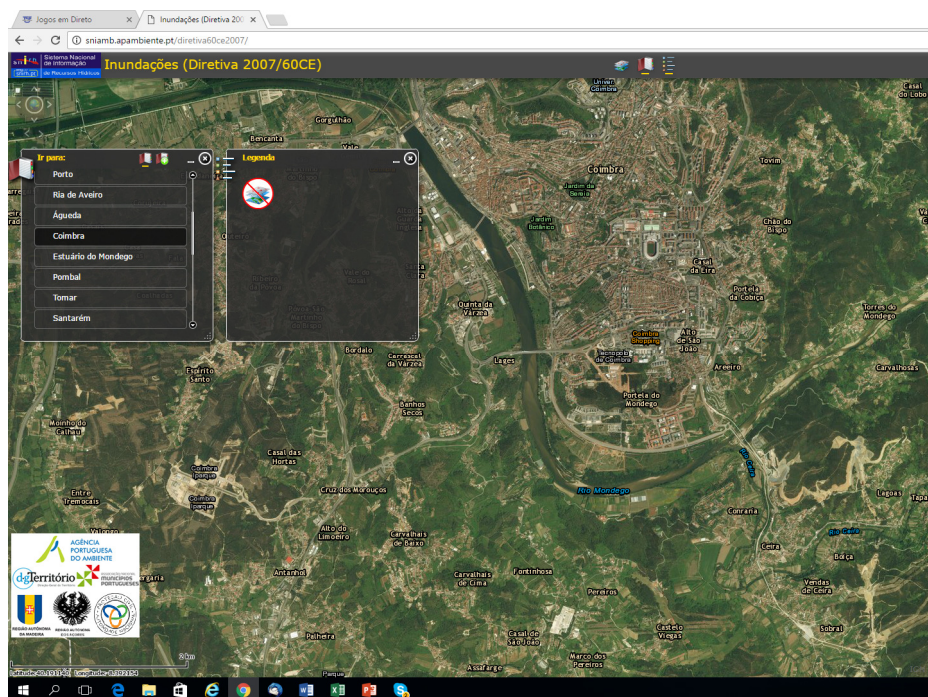
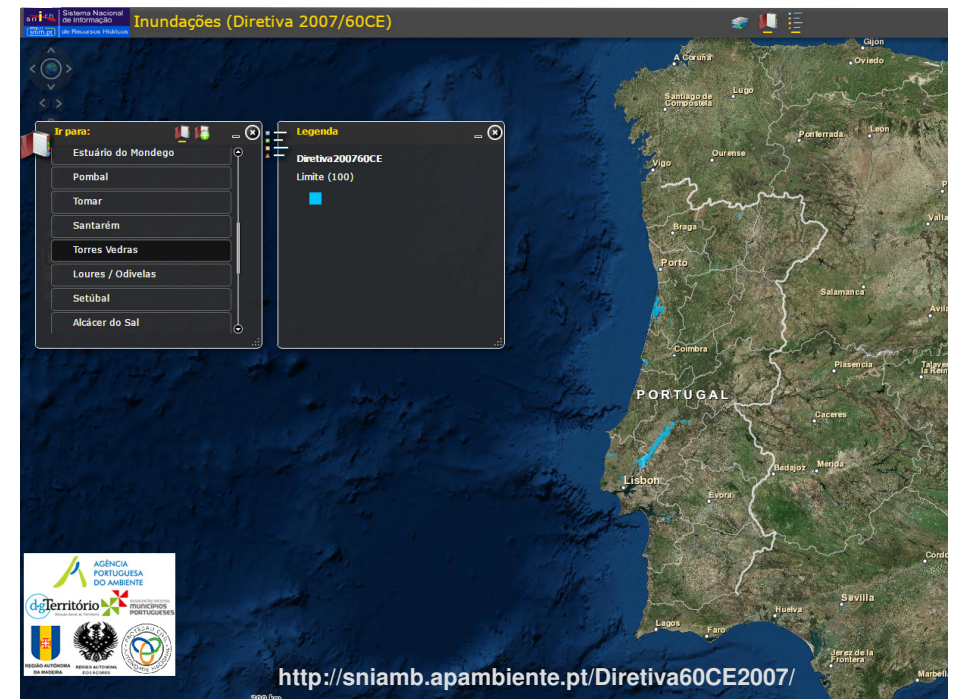
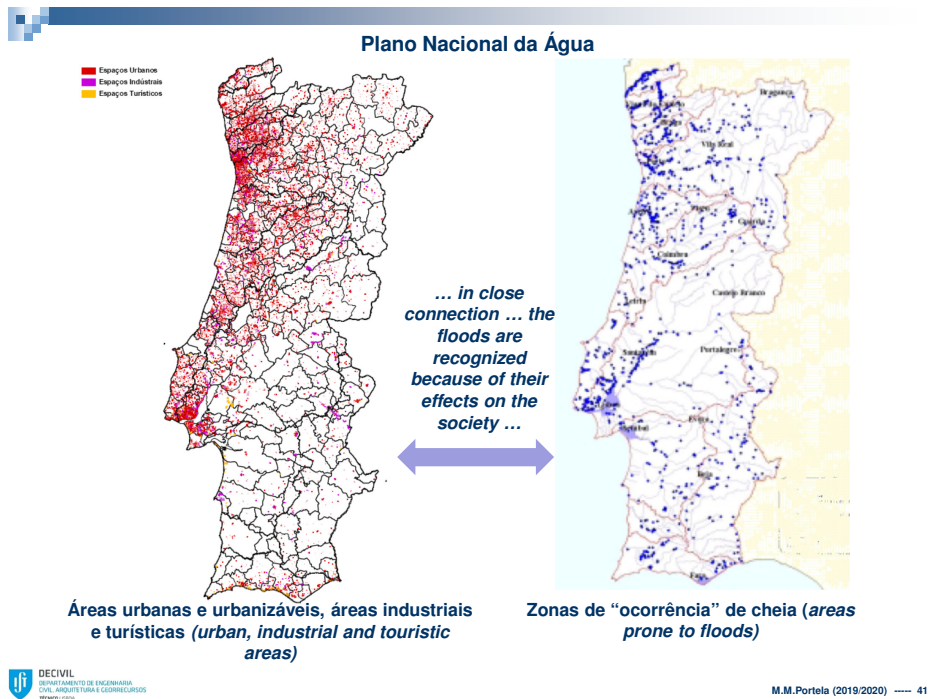
Zonas sujeitas a inundações (anterior ao DL 115/2010) – flooded area mapping (done before the flood directive)

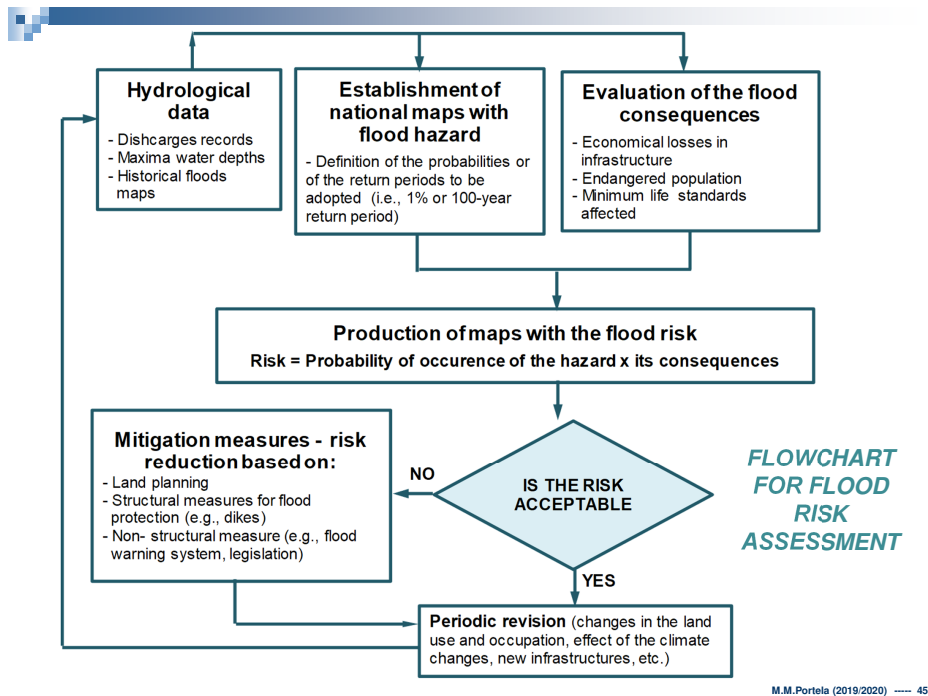


Zonas sujeitas a inundações entre Figueira da Foz e Coimbra (areas prone to flood defined in accordance with the flood directive - Portuguese Decree-Law 115/2010)

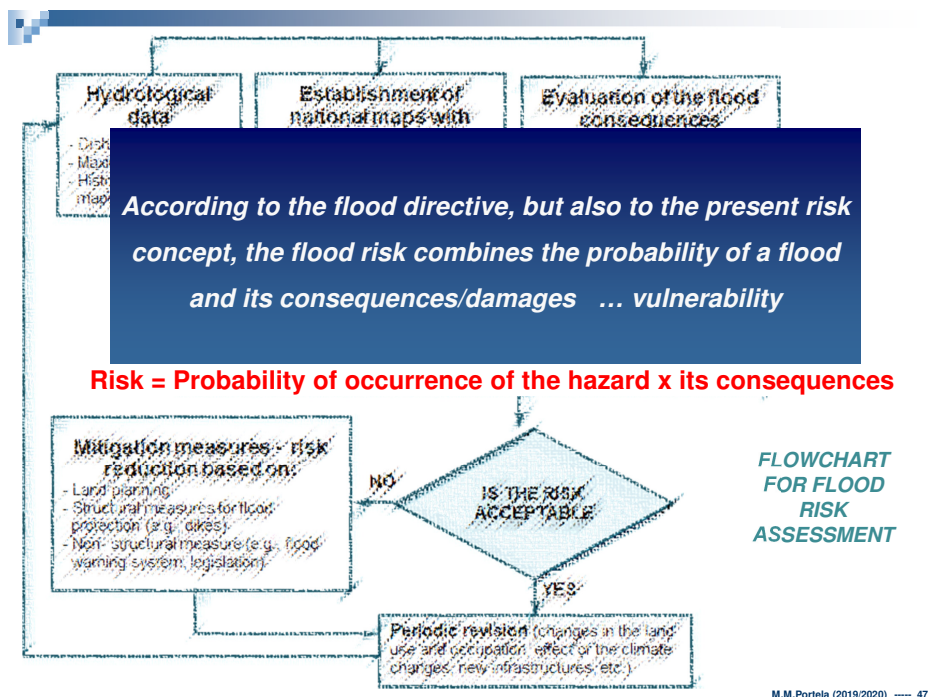
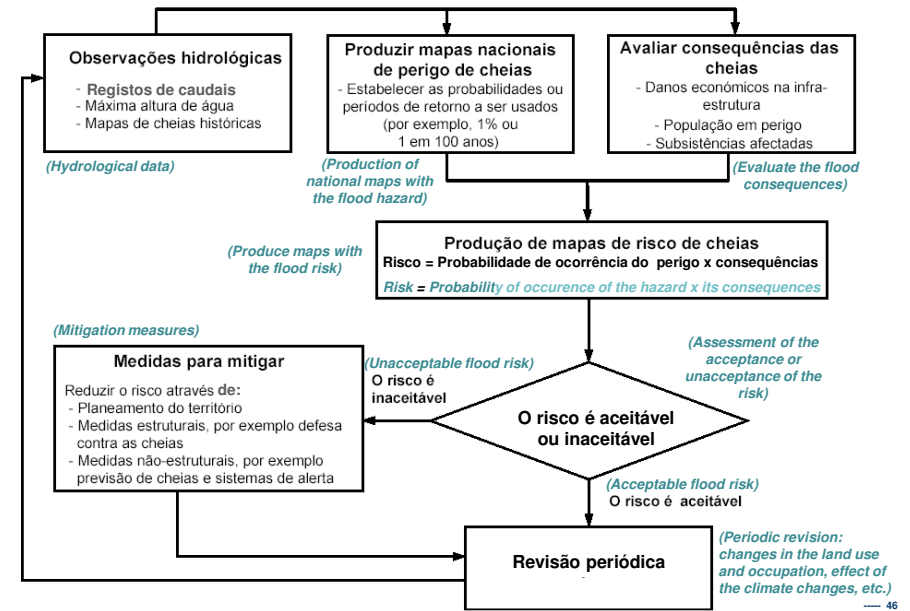
PGRH do rio Mondego





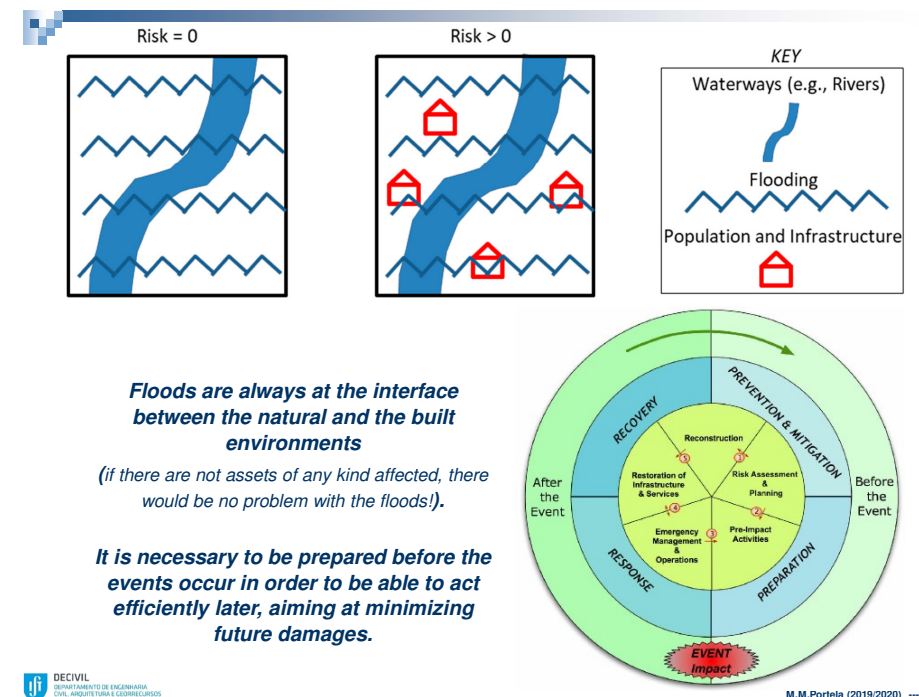


Organograma para avaliação de risco de cheia (Orientação sobre avaliação nacional de risco de cheias, HR Wallingford Limited, s/d) (Approach to flood risk evaluation)



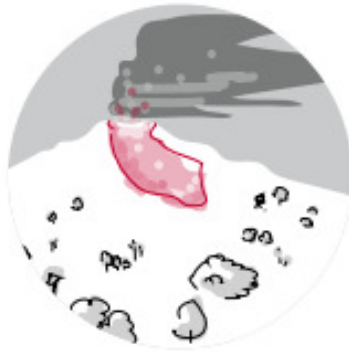
According to the flood directive, but also to the present risk concept, the flood risk combines the probability of a flood and its consequences/damages ... vulnerability

Risk = Probability of occurrence of the hazard x its consequences





Risk and the context of hazard, exposure and vulnerability



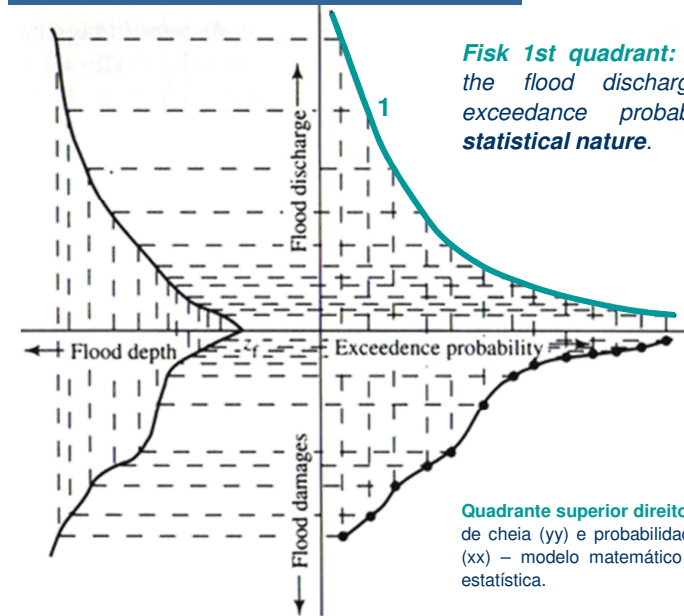
There is no such thing as a **natural disaster**, only **natural hazards**



We make **choices** as to where we inhabit, how we build and what research we do

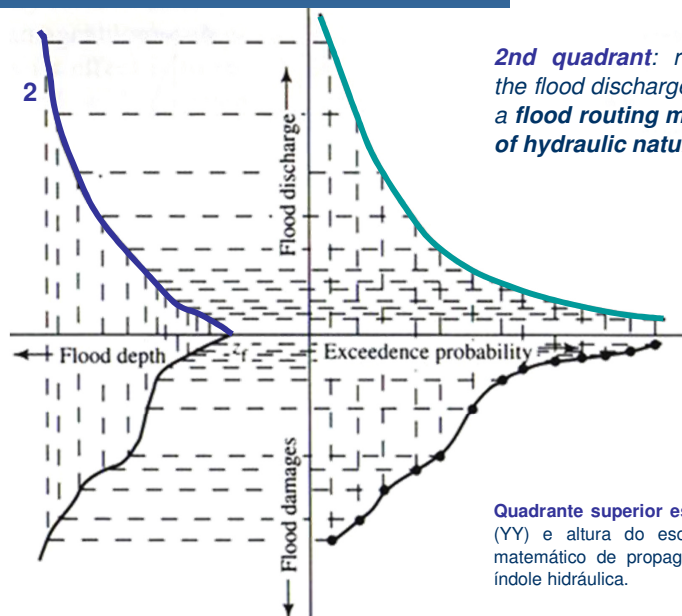
Two D representation of the flood risk assessment

DINGMAN, S. L., *Physical hydrology*, Prentice-Hall, Inc., 1994



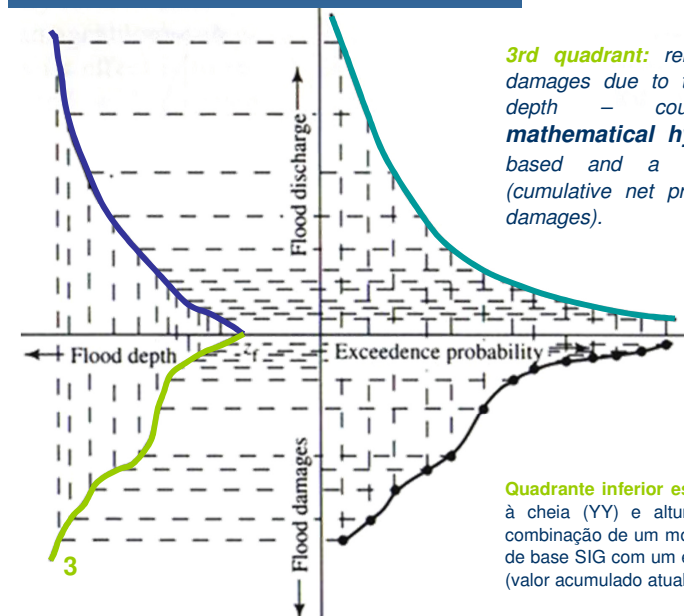
Two D representation of the flood risk assessment

DINGMAN, S. L., *Physical hydrology*, Prentice-Hall, Inc., 1994



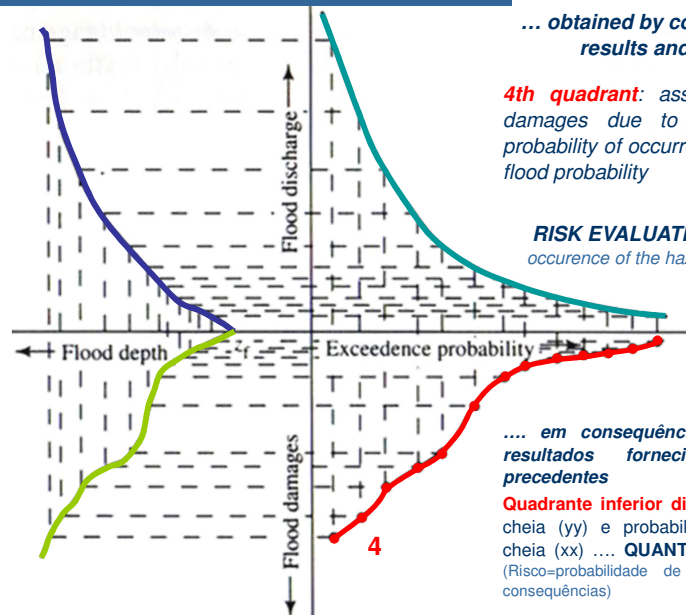
Two D representation of the flood risk assessment

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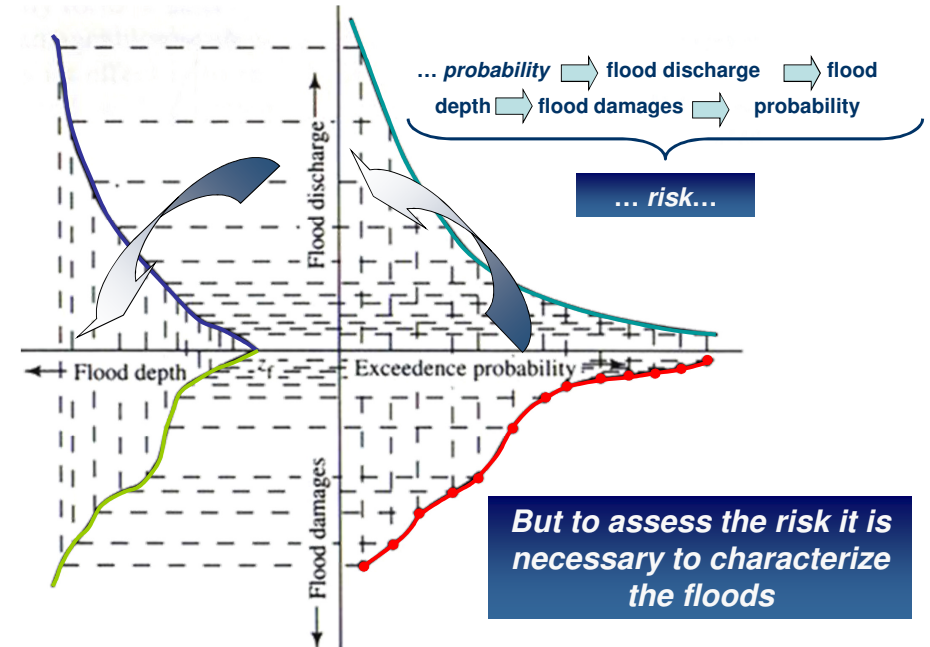
Two D representation of the flood risk assessment

DINGMAN, S. L., *Physical hydrology*, Prentice-Hall, Inc., 1994

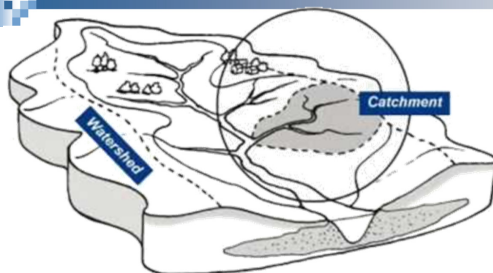


Avaliação do risco

DINGMAN, S. L., *Physical hydrology*, Prentice-Hall, Inc., 1994

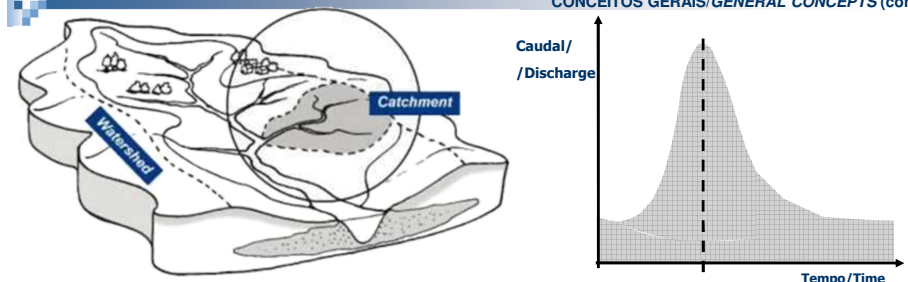


CONCEITOS GERAIS/GENERAL CONCEPTS (cont.)



- ✓ Geographic unit adopted in the characterization: **catchment** all the processes occur at the watershed/catchment level

CONCEITOS GERAIS/GENERAL CONCEPTS (cont.)



- ✓ Geographic unit adopted in the characterization: **catchment** all the processes occur at the watershed/catchment level
- ✓ Flood characterization

Exceptionality/probability

Chronological diagram – **flood hydrograph (Q versus time)**

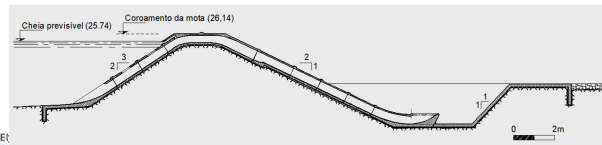
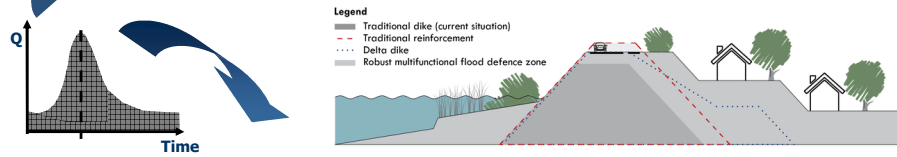
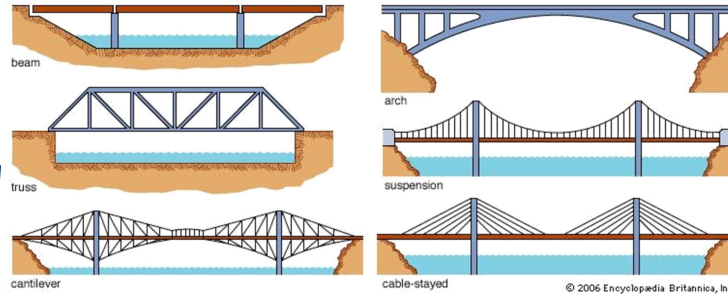
Peak flood discharge
Flood volume

Depending on the target

- ✓ Unidade de caracterização: bacia hidrográfica
- ✓ Caracterização da cheia
Excepcionalidade
Diagrama cronológico
Caudal de ponta de cheia
Volume da cheia

Consoante o objectivo em vista

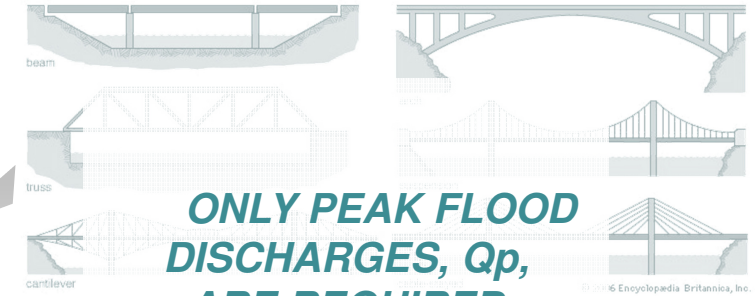
Bridge design



Dikes for lateral protection

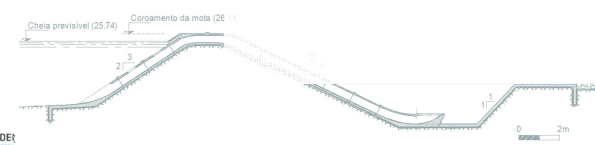
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Bridge design



ONLY PEAK FLOOD DISCHARGES, Q_p , ARE REQUIRED

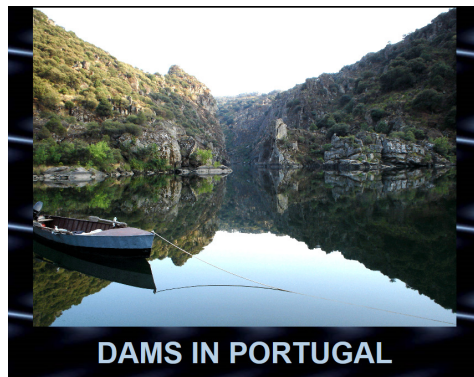
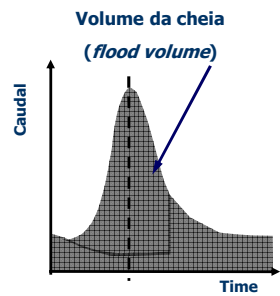
(apenas são necessários caudais de ponta de cheia)



Dikes for lateral protection

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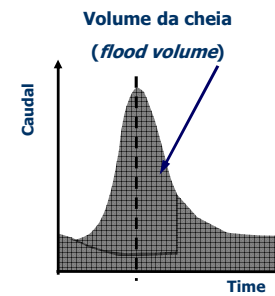
Flood control in artificial reservoirs aiming at reducing the peak flood discharges downstream



http://cnpgeb.apambiente.pt/gr_barragens/gbportugal/index.htm
http://cnpgeb.apambiente.pt/gr_barragens/gbingles/index.htm

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Flood control in artificial reservoirs aiming at reducing the peak flood discharges downstream



BOTH FLOOD VOLUME AND PEAK FLOOD DISCHARGE ARE REQUIRED

DAMS IN PORTUGAL

http://cnpgeb.apambiente.pt/gr_barragens/gbportugal/index.htm
http://cnpgeb.apambiente.pt/gr_barragens/gbingles/index.htm

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Castelo do Bode (1951)
 $4750 \text{ m}^3/\text{s} \rightarrow 4000 \text{ m}^3/\text{s}$



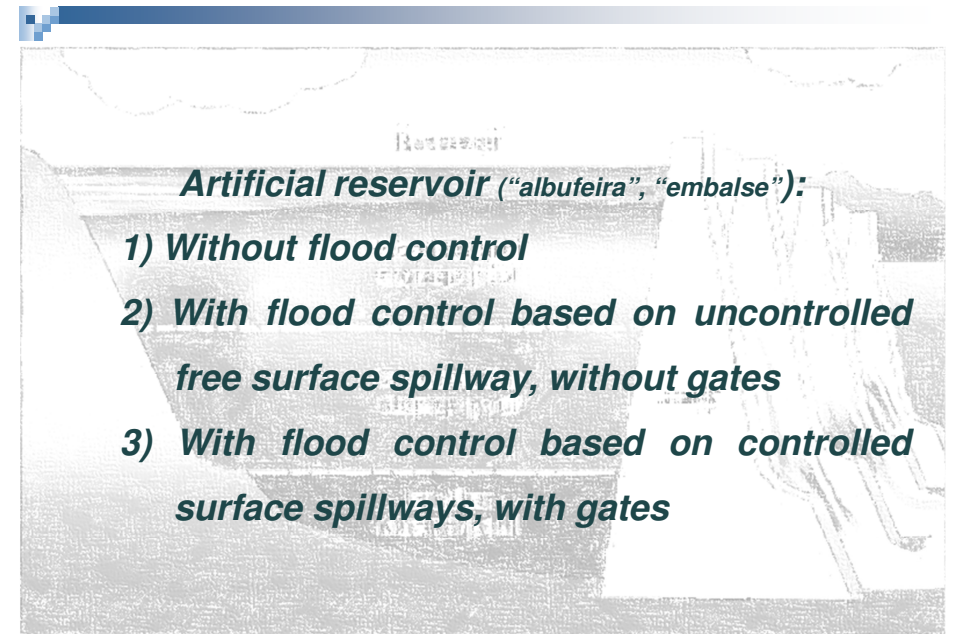
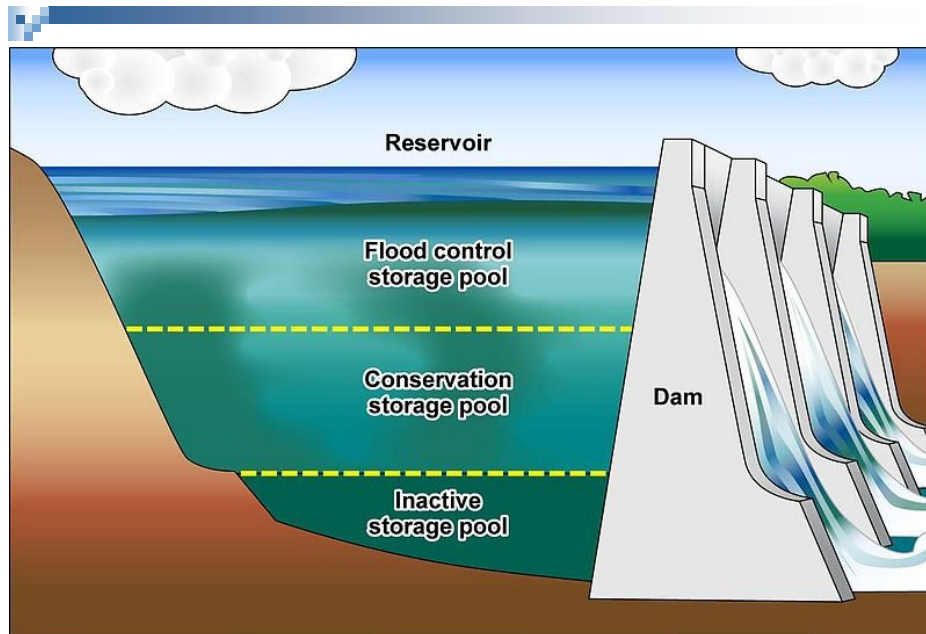
Aguieira (1981)
 $3500 \text{ m}^3/\text{s} \rightarrow (2080 + 180) \text{ m}^3/\text{s} *$



Cabril (1954)
 $4000 \text{ m}^3/\text{s} \rightarrow (2200 + 200) \text{ m}^3/\text{s} *$



Baixo Sabor (2005)
 $6400 \text{ m}^3/\text{s} \rightarrow (5000 + 220) \text{ m}^3/\text{s} *$



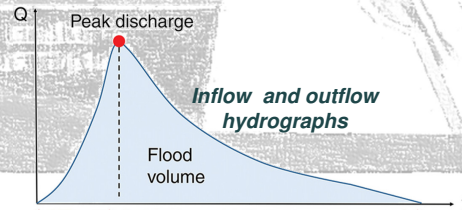
Artificial reservoir (“albufeira”, “embalse”):

- 1) **Without flood control**
- 2) **With flood control based on uncontrolled free surface spillway, without gates**
- 3) **With flood control based on controlled surface spillways, with gates**

Reservoir:

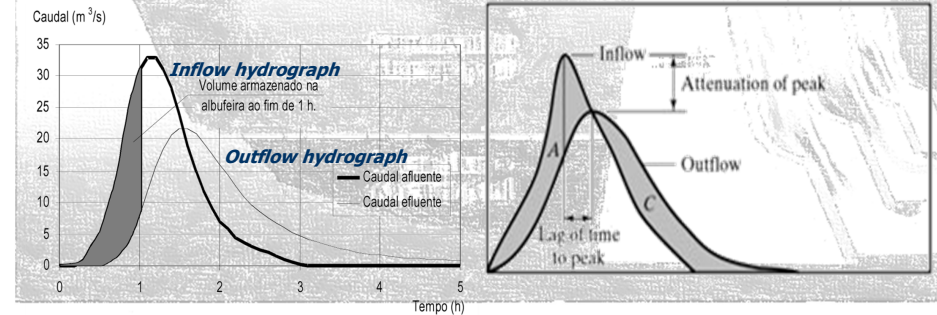
1) Without flood control

If there is not flood control the design of the spillway is done for the highest peak flood discharge with a given return period - design peak flood discharge. Either under design flood conditions or for any other flood, necessarily characterized by a smaller peak flood discharge, the inflow and outflow hydrographs coincide



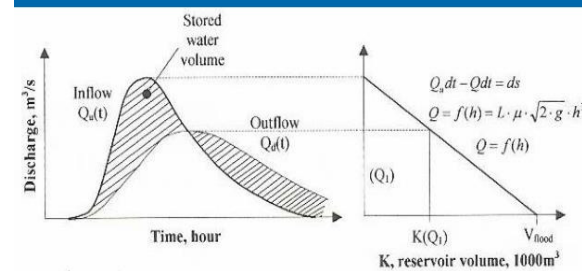
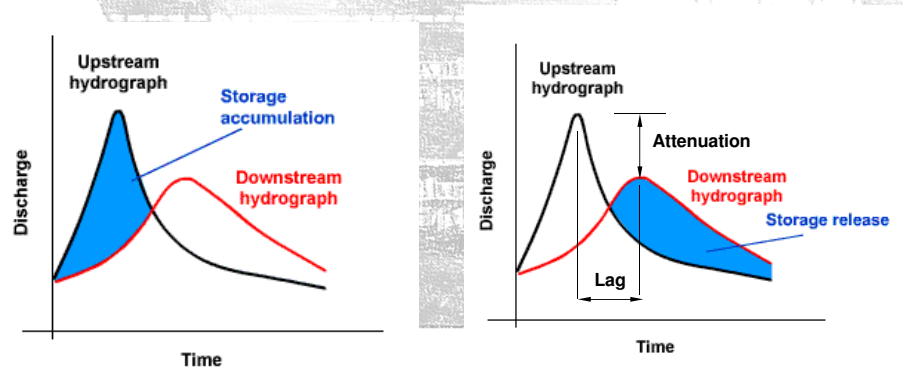
Reservoir:

2) With flood control based on uncontrolled free surface spillway (but without gates)



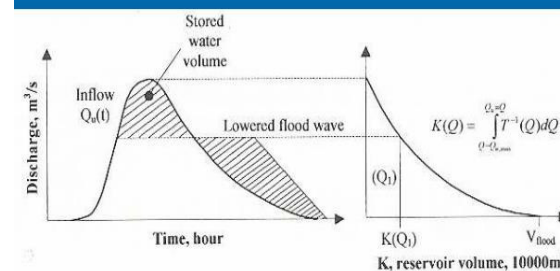
Reservoir:

3) With flood control based on controlled surface spillways (with gates)



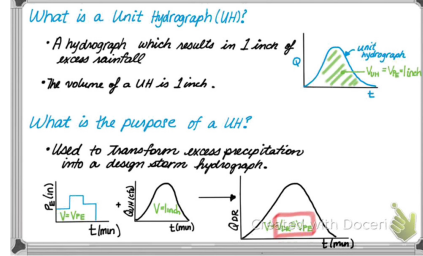
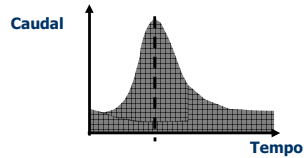
2. Opened sluice

A flood pool with an uncontrolled spillway stores water as it is released according to the weir flow equation. The hydrograph is delayed and attenuated. The outflow hydrograph depends on the area of the reservoir and the length of the spillway.



1. Regulated sluice

A gated structure can more efficiently control the release. Less storage space is needed for the same outflow peak Q . However, the gates add significant cost to the project.



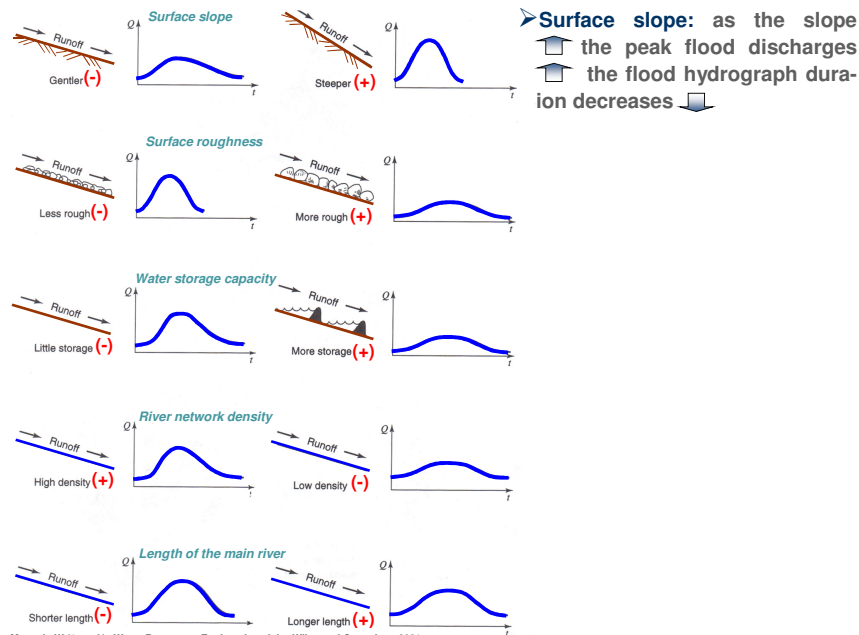
The unit hydrograph model only allows to study floods under natural conditions i.e., floods due to rainfall events in river sections without dams upstream promoting the flood control and without water transfers and water abstractions that may modify the natural behaviour of the watershed under natural conditions regarding the floods.

O modelo do hidrograma unitário apenas permitir obter hidrogramas de cheias em condições naturais, entendendo-se por tal hidrogramas de cheias resultantes de acontecimentos pluviosos, em secções da rede hidrográfica a que correspondam bacias hidrográficas em que não existam intervenções tendo em vista a modelação de cheias, designadamente, aproveitamentos hidráulicos que procedam ao controlo (amortecimento) de ondas de cheia, nem tão pouco transvases significativos que resultem em alterações do comportamento hidrológico das bacias em condições de cheia.

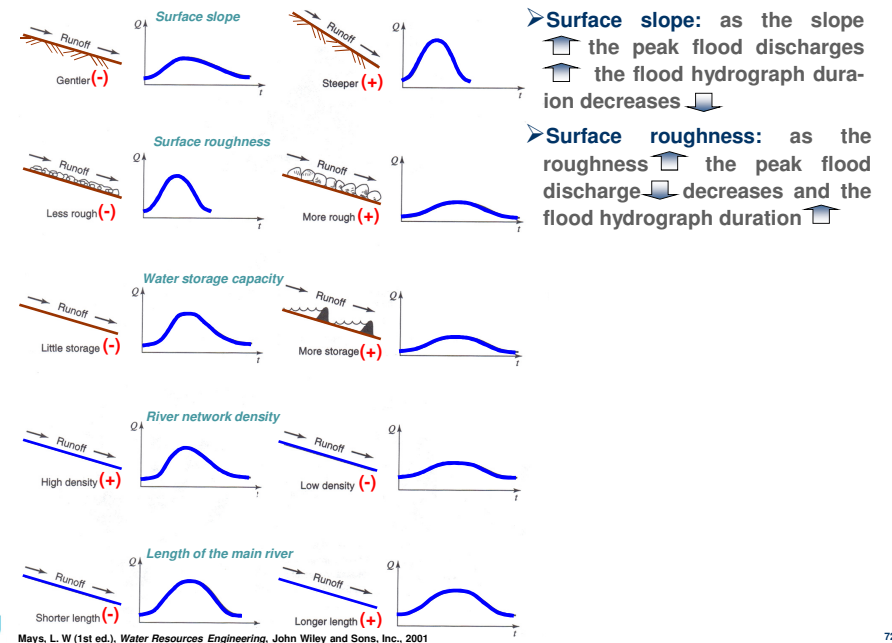
Factors that affect the natural river floods

- Factors related to the time of concentration - watershed area and relief, river networks characteristics (time needed for water to flow from the most remote point in a watershed from a kinematic point of view to the watershed outlet)
- Factors related to the rainfall losses or abstractions – previous water storage and moister conditions in the watershed, vegetal cover, land use.
- Factors directly affecting the shape of the flood hydrograph - temporal and spatial distribution of the rainfall.

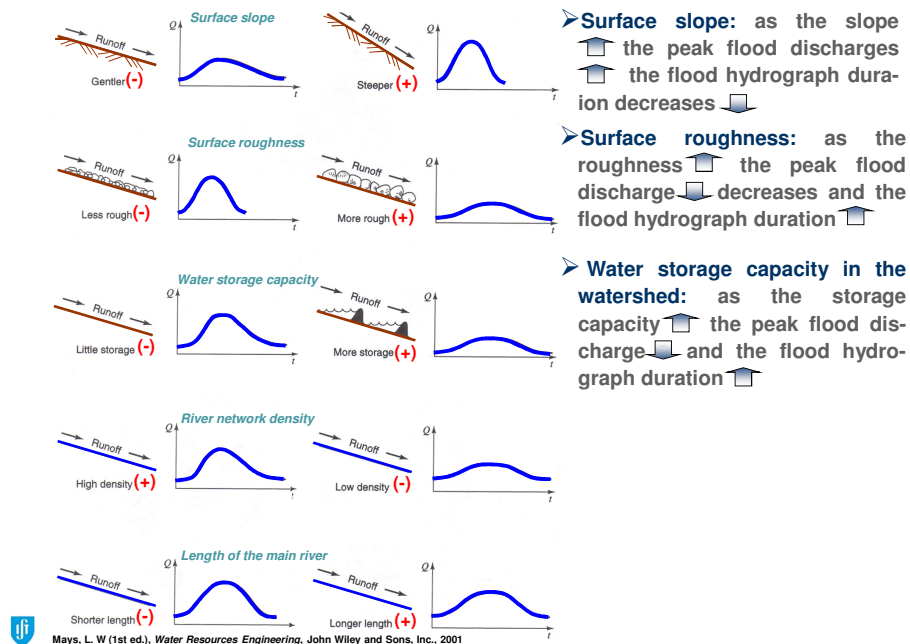
Factors related to the time of concentration .. with all other conditions remaining unchanged



Factors related to the time of concentration .. with all other conditions remaining unchanged

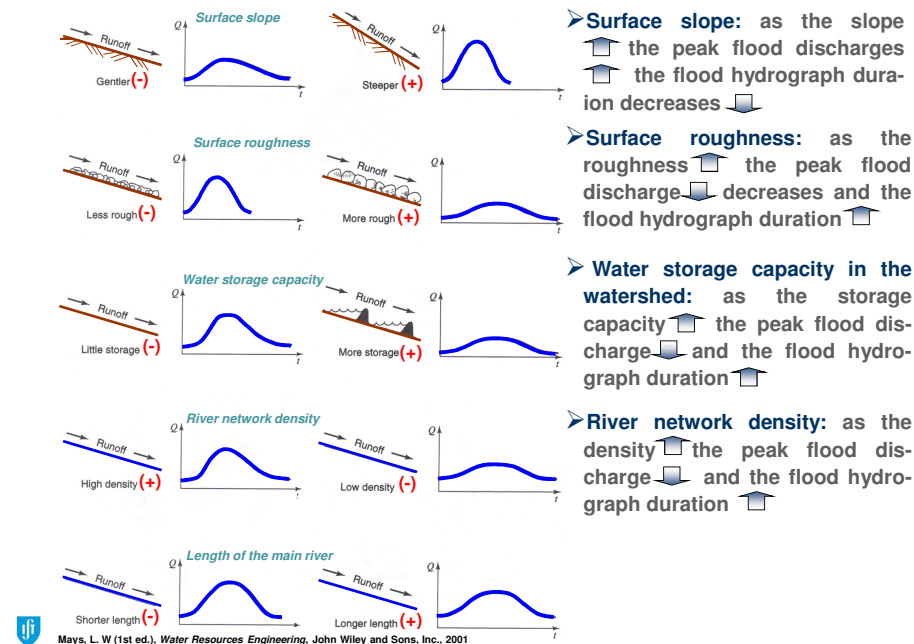


Factors related to the time of concentration .. with all other conditions remaining unchanged



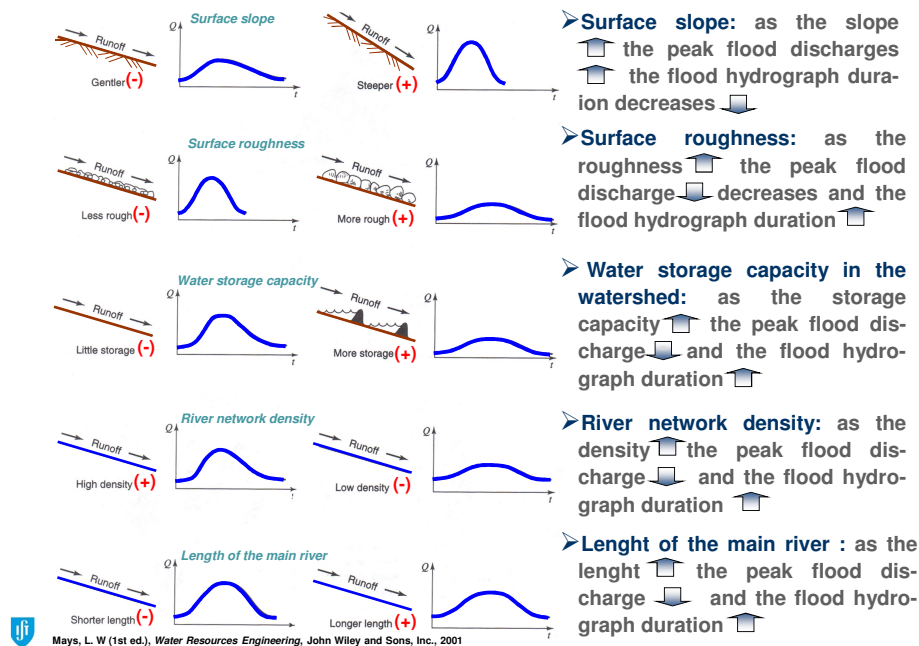
73

Factors related to the time of concentration .. with all other conditions remaining unchanged



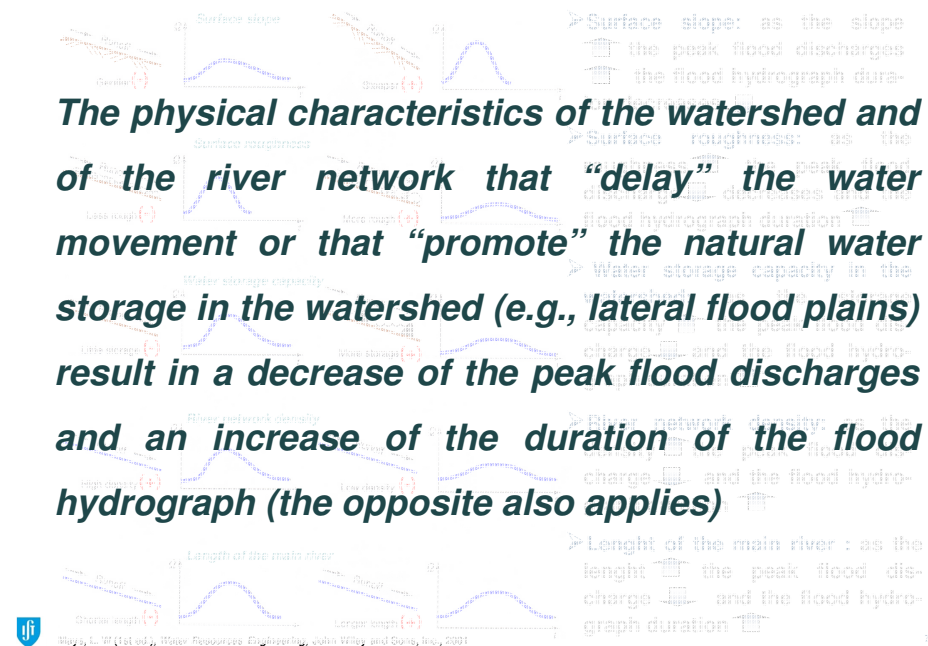
74

Factors related to the time of concentration .. with all other conditions remaining unchanged



75

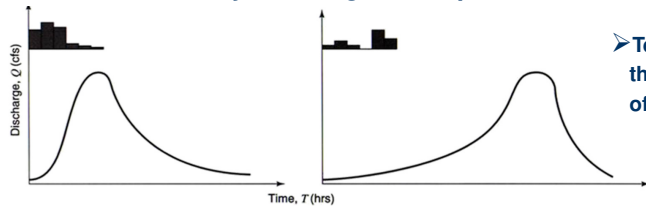
Factors related to the time of concentration .. with all other conditions remaining unchanged



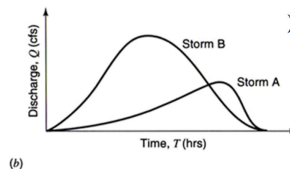
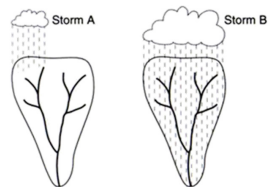
76

The physical characteristics of the watershed and of the river network that “delay” the water movement or that “promote” the natural water storage in the watershed (e.g., lateral flood plains) result in a decrease of the peak flood discharges and an increase of the duration of the flood hydrograph (the opposite also applies)

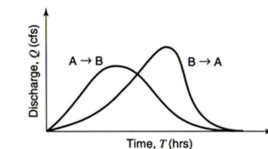
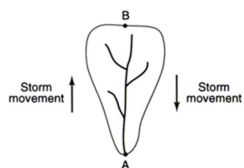
Factors directly affecting the shape of the flood hydrograph



➤ Temporal distribution of the rainfall in the shape of the flood hydrograph

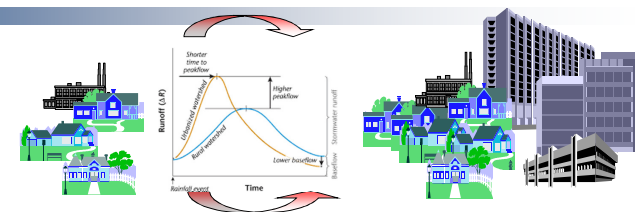


➤ Effect of the spatial distribution of the rainfall ... generally the models are lumped (... *agregados* ...), allowing to consider in each moment a kind of a average temporal distribution of the rainfall over the entire watershed and not different temporal rainfall patterns among regions

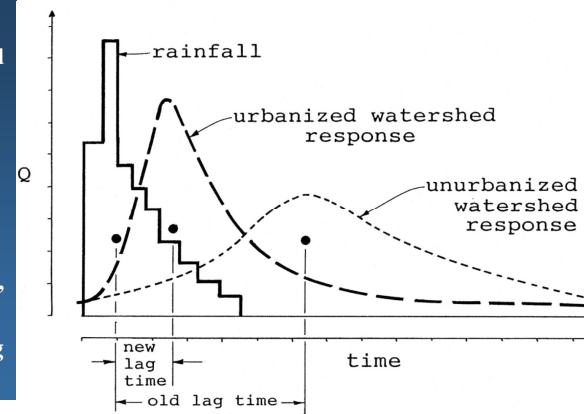


Mays, L. W (1st ed.), *Water Resources Engineering*, John Wiley and Sons, Inc., 2001

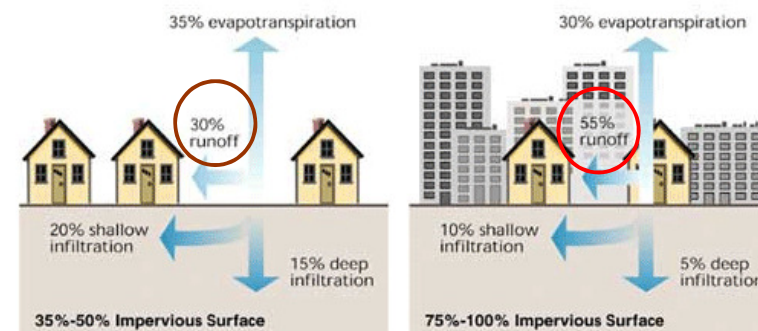
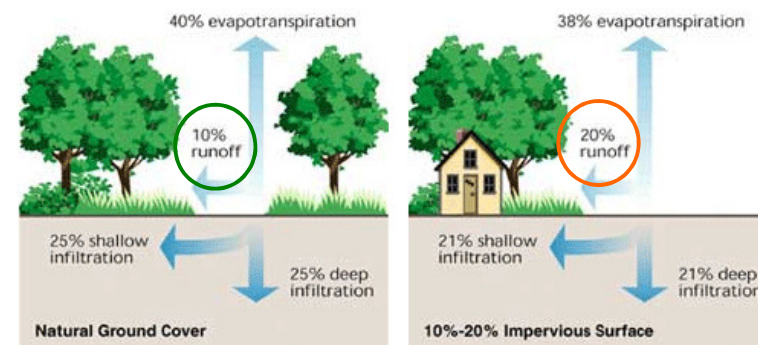
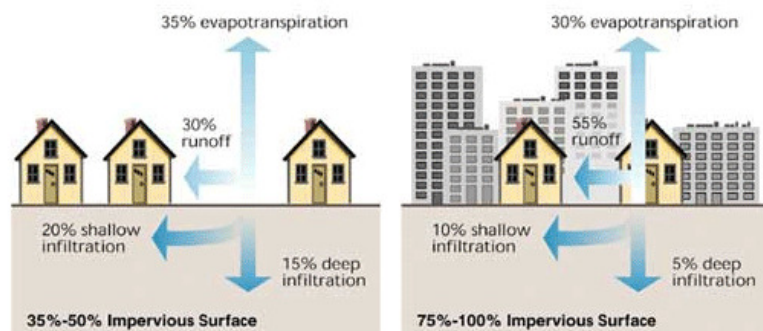
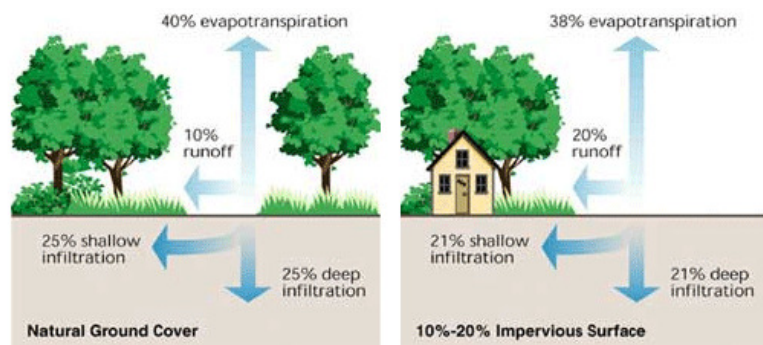
Effect of the floods due to the increase in the urbanized areas

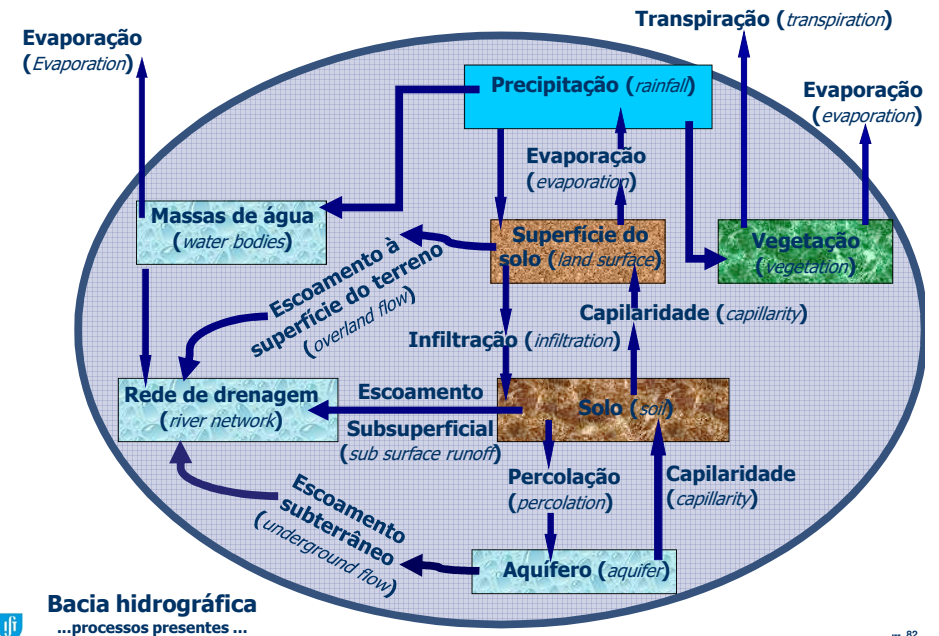
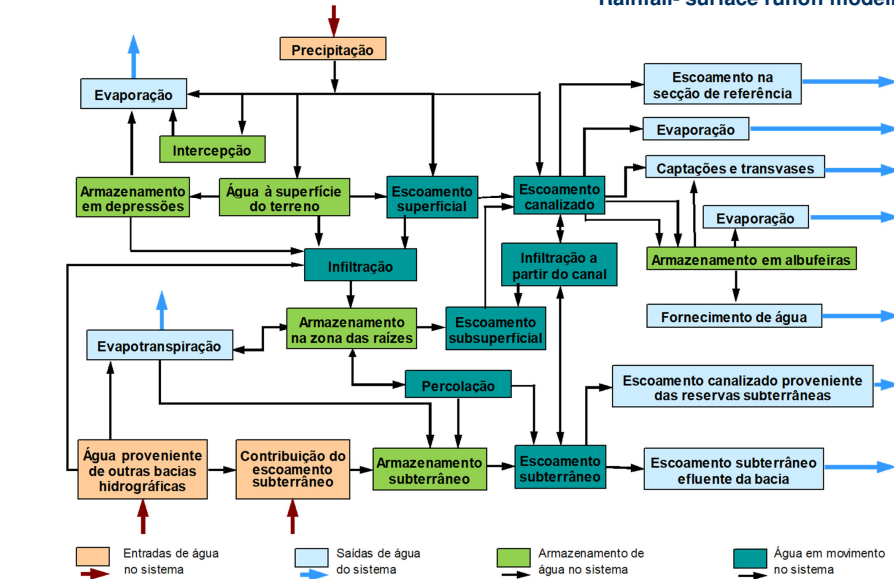


It acts by decreasing the precipitation losses (due to the infiltration decrease) and by increasing the flow velocity (due to the surface roughness decrease) thus reducing the time of concentration, increasing the design rainfalls intensities and, consequently, increasing the peak flood discharges and anticipating the its occurrence



78

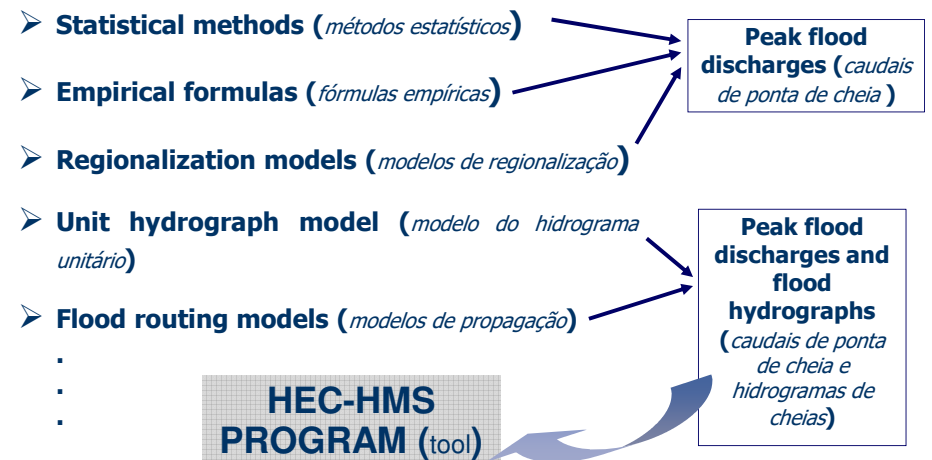


Conceptual model of the hydrological processes at the watershed level
 Rainfall- surface runoff modelling


The unit hydrograph model is particularly relevant to obtain flood hydrographs; in fact when only peak floods discharges are required there are other approaches, widely known, easier to apply and with tested results all around the world ➡ only applicable to rainfall-runoff modelling under extreme hydrological conditions ➡ floods

O modelo do hidrograma unitário tem particular interesse quando é determinante a obtenção de hidrogramas de cheia, pois a estimação somente de caudais de ponta de cheia pode utilizar outros métodos, amplamente divulgados, de aplicação mais expedita e com resultados de algum modo testados.

Approaches to estimate peak flood discharges or/and floods hydrographs (métodos de avaliação de caudais de cheia e de hidrogramas de cheia)



The return period, T, and the non-exceedance probability, F, provide the same design criteria that will be “translated” into design values

(water depth, water velocity, discharge, ...)

$$T = \frac{1}{1-F}$$

The return period, T, as a function of the non-exceedance probability, F

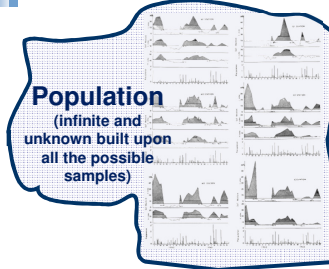
$$F = 1 - \frac{1}{T}$$

The non-exceedance probability, F, as a function of the return period, T

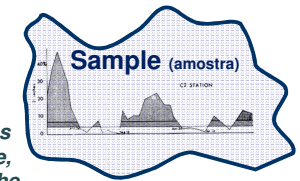


RETURN PERIOD (RECURRENCE INTERVAL), T	NON-EXCEEDANCE PROBABILITY, F	EXCEEDANCE PROBABILITY OR PROBABILITY OF OCCURRENCE IN ANY GIVEN YEAR
2	0.500	0.500
5	0.800	0.200
10	0.900	0.100
25	0.960	0.040
50	0.980	0.020
100	0.990	0.010
250	0.996	0.004
500	0.998	0.002
1000	0.999	0.001

89



... Sample
(only one or a few samples are drawn from the infinite, yet unknown, samples of the population)



Objective

Based on a sample of a given hydrological variable ... to estimate the design values with return periods much larger than those of the sample Identify and set up the mathematical model able of representing the variable...

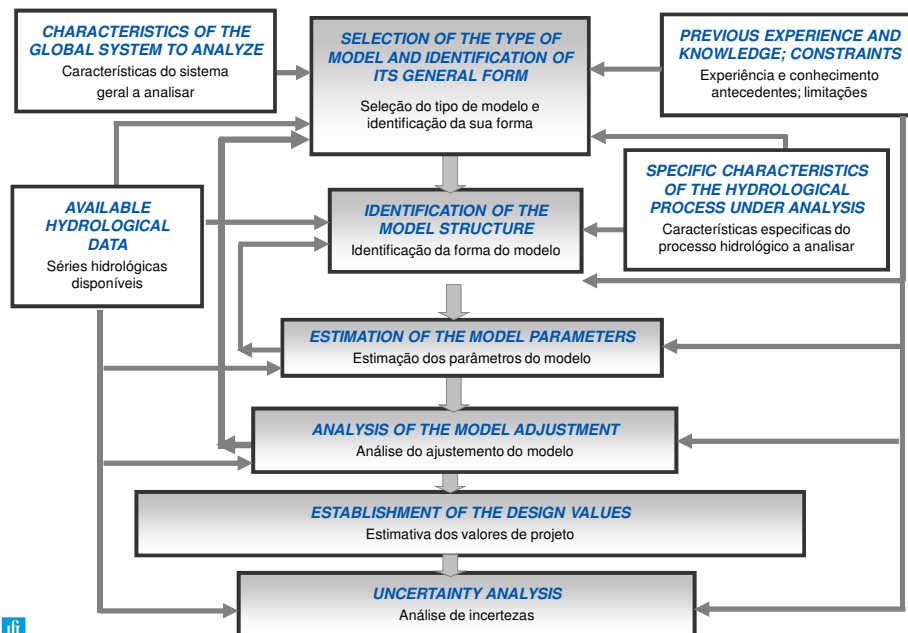
(sample: annual maximum instantaneous discharges, one value per year ... random variable; data base snirh.apamabinte.pt, SNIRH – Sistema Nacional de Informação de Recursos Hídricos)

Objetivo

Com base numa amostra de uma dada variável de hidrológica ... estabelecer valores de projeto, com períodos de retorno muito para além dos períodos de retorno abarcados pela amostraidentificar e “estabelecer” um modelo matemático estatístico capaz de representar uma aquela variável ...

(amostra: caudais instantâneos máximos anuais, um valor por ano Variável intrinsecamente aleatória, embora reflectindo as características fisiográficas e climáticas ocorrente na bacia; base de dados: SNIRH - snirh.apamabinte.pt SNIRH – Sistema Nacional de Informação de Recursos Hídricos)

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ADJUSTMENT OF STATISTICAL LAWS AND QUANTIL ESTIMATES: STEPWISE APPROACH

1 – GETTING THE SAMPLE (... one should always keep in mind that the sample is nothing but one sample out of the infinite number of samples that can be extracted from population/universe)

20) 92

ADJUSTMENT OF STATISTICAL LAWS AND QUANTIL ESTIMATES: STEPWISE APPROACH

1 – GETTING THE SAMPLE (... one should always keep in mind that the sample is nothing but one sample out of the infinite number of samples that can be extracted from population/universe)

2 – COMPUTATION OF THE SAMPLE STATISTICS aiming at to get from the sample as much information as possible

Average (média)

$$\bar{X} = \frac{X_1 + X_2 + \dots + X_i + \dots + X_n}{n} = \frac{\sum_{i=1}^n X_i}{n}$$

Variance with bias correction (variância com correção do viés)

$$s^2 = \frac{(X_1 - \bar{X})^2 + (X_2 - \bar{X})^2 + \dots + (X_i - \bar{X})^2 + \dots + (X_n - \bar{X})^2}{n-1} = \frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n-1}$$

Coefficient of variation (coeficiente de variação)

$$C_V = \frac{s'}{\bar{X}}$$

Skewness coefficient with bias correction (coeficiente de assimetria com correção do viés)

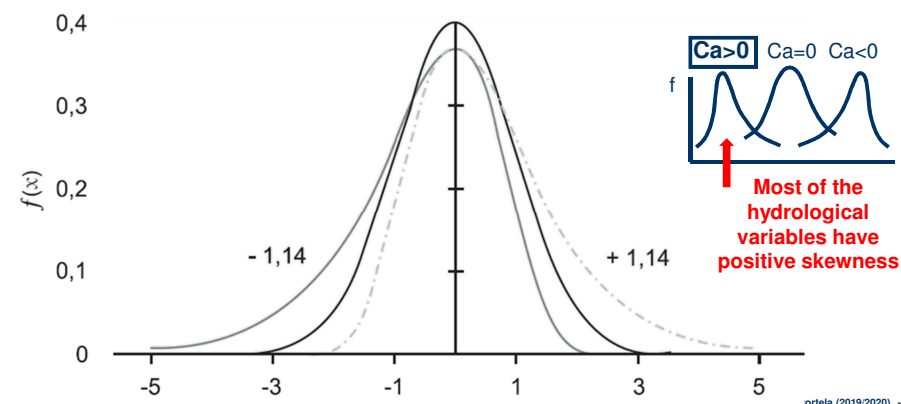
$$C_a = \frac{\sum_{i=1}^n (X_i - \bar{X})^3}{(n-1)(n-2)s'^3}$$

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Skewness coefficient without and with bias correction – dimensionless coefficient (coeficiente de assimetria sem e com correção do viés - adimensional)

$$g = \frac{\sum_{i=1}^N (x_i - \bar{X})^3}{N s^3}$$

$$g' = \frac{N \sum_{i=1}^N (x_i - \bar{X})^3}{(N-1)(N-2)s'^3}$$



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ADJUSTMENT OF STATISTICAL LAWS AND QUANTIL ESTIMATES: STEPWISE APPROACH

1 – GETTING THE SAMPLE (... one should always keep in mind that the sample is nothing but one sample out of the infinite number of samples that can be extracted from population/universe)

2 – COMPUTATION OF THE SAMPLE STATISTICS aiming at to get from the sample as much information as possible

3 – ASSUMPTION (... “postular” ...) **OF THEORETICAL STATISTICAL DISTRIBUTION** that expectable will be able to represent the distribution of the sampling values ... in the extreme events domain .. laws for the extremes

4 – SELECTION OF THE LAW WITH BEST ADJUSTMENT based on the a diagram with representation, over a probability paper, of the sampling points and of different theoretical laws ... eventually complemented by the application of statistical tests like the Chi-squared test or the Kolmogorov-Smirnov test. The theoretical laws are obtained by applying the probability factors’ approach

CONCEITOS GERAIS – Modelos estatísticos / GENERAL CONCEPTS – statistical models (cont.)

4 – SELECTION OF THE LAW WITH BEST ADJUSTMENT

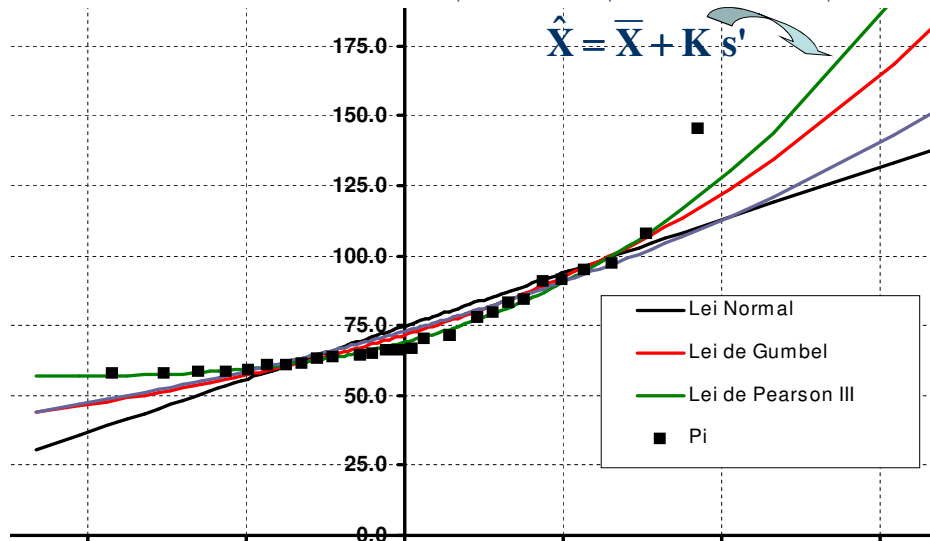
SELEÇÃO DA LEI COM MELHOR AJUSTAMENTO

Número de ordem i	Caudal instantâneo máximo anual Cima (m³/s)	Probabilidade empírica de não-excedência F	Normal reduzida Z
1	22.5	0.0278	-1.9145
2	60.6	0.0556	-1.5932
3	74.3	0.0833	-1.3830
4	82.9	0.1111	-1.2206
5	112.0	0.1389	-1.0853
6	120.0	0.1667	-0.9674
7	124.0	0.1944	-0.8616
8	165.0	0.2222	-0.7647
9	182.0	0.2500	-0.6745
10	196.0	0.2778	-0.5895
11	213.0	0.3056	-0.5095
12			
13			
14			

F	T (anos)	Probability factor			Peak flood discharge estimates			
		Z (-)	KG (-)	kP (-)	L. Normal (m³/s)	L. Gumbel (m³/s)	L. Pearson (m³/s)	L. Goodrich (m³/s)
0.030	1.0	-1.88079	-1.42828	-1.68138	24.2	129.1	70.4	81.6
0.050	1.1	-1.64485	-1.30552	-1.50644	78.9	157.5	111.0	113.3
0.070	1.1	-1.47579	-1.21262	-1.37659	118.1	179.0	141.1	138.7
0.090	1.1	-1.34076	-1.13522	-1.27014	149.4	197.0	165.7	160.6
0.110	1.1	-1.22653	-1.06737	-1.17817	175.8	212.7	187.0	180.2
0.130	1.1	-1.12639	-1.00601	-1.09609	199.0	226.9	206.0	198.2
0.150	1.2	-1.03643	-0.94931	-1.02117	219.9	240.0	223.4	214.9
0.170	1.2	-0.95417	-0.89609	-0.95168	238.9	252.4	239.5	230.7
0.190	1.2	-0.87790	-0.84555	-0.88641	256.6	264.1	254.6	245.7
0.210	1.3	-0.80642	-0.79708	-0.82451	273.1	275.3	269.0	260.1
0.230	1.3	-0.73885	-0.75026	-0.76532	288.8	286.2	282.7	274.0
0.250	1.3	-0.67449	-0.70472	-0.70835	303.7	296.7	295.9	287.5
0.270	1.4	-0.61281	-0.66018	-0.65319	318.0	307.0	308.6	300.6
0.290	1.4	-0.55338	-0.61642	-0.59953	331.8	317.2	321.1	313.5
0.310	1.4	-0.49585	-0.57324	-0.54710	345.1	327.2	333.2	326.1

Schematic representation of the different theoretical statistical laws by computing, for different non-exceedance probabilities, the theoretical values of the random variable based on the probability factor approach

Representação gráfica das leis teóricas: para sucessivas probabilidades de não-excedência, cálculo do valor teórico mediante recurso ao fator de probabilidade correspondente a essa lei e a essa probabilidade



Probability factor, K, and estimates according to the method of the moments

$$\hat{X} = \bar{X} + K s'$$

Normal law

Excel function - NORMSINV()

Gumbel law

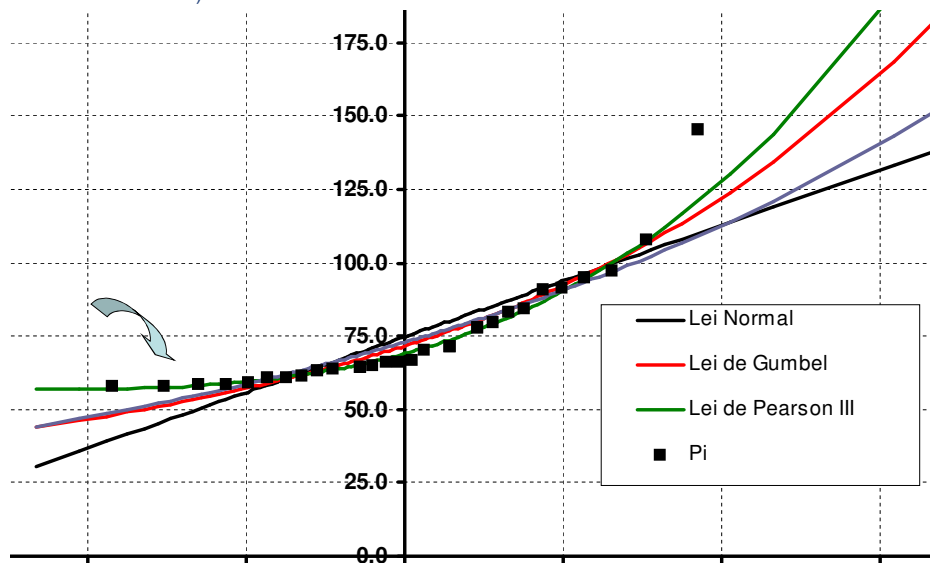
$$K_G = -\frac{\sqrt{6}}{\pi} \left\{ 0.577216 + \ln \left[\ln \left(\frac{T}{T-1} \right) \right] \right\} = -\frac{\sqrt{6}}{\pi} \left\{ 0.577216 + \ln \left[\ln \left(\frac{1}{F} \right) \right] \right\}$$

Pearson III law

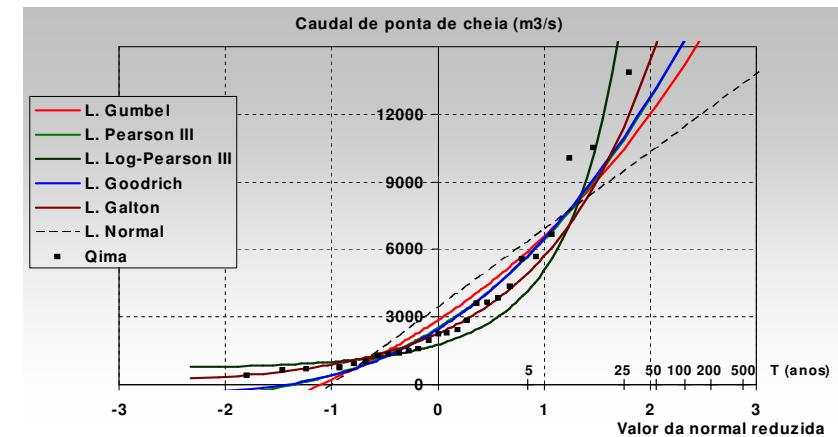
$$K_P = \frac{2}{g} \left\{ \left[\left(z - \frac{g}{6} \right) \frac{g}{6} + 1 \right]^3 - 1 \right\}$$

g – skewness coefficient
z – standard normal variable

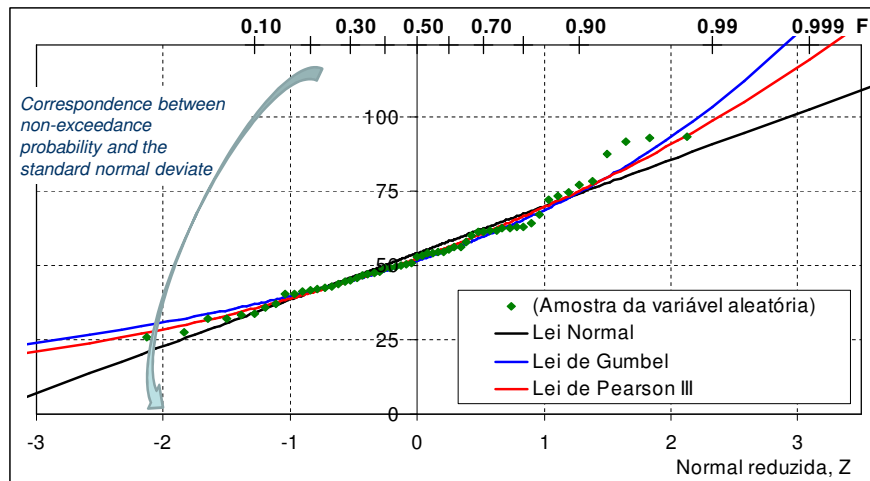
- Representation of the sample by assigning to each point its empirical non-exceedance probability or plotting-position (... probabilidade empírica de não-excedência ...)



Visual adjustment by representing, over a probability paper (more often, normal probability paper), the sample and the theoretical laws aiming at identifying the law with best adjustment.

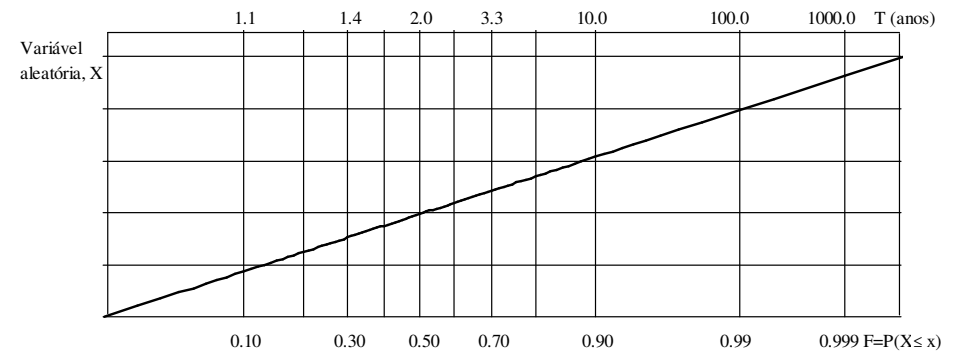


Normal probability paper: the horizontal axis is graduated in terms of the standard normal deviate or standard normal variable or standard normal random variable (papel de probabilidade da lei normal: eixo dos xx graduado em valores da normal reduzida).

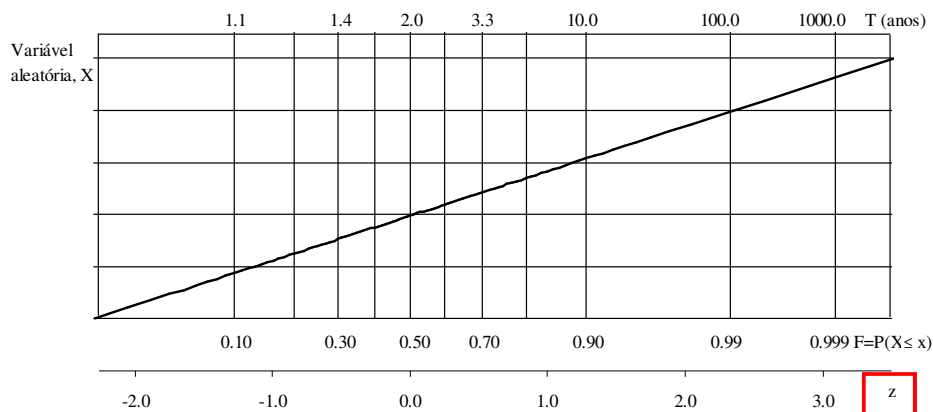


Normal probability paper: the horizontal axis is graduated in terms of the standard normal deviate or standard normal variable or standard normal random variable (papel de probabilidade da lei normal: eixo dos xx graduado em valores da normal reduzida).

Probability paper for a given statistical law – the scale of the horizontal is such that it linearizes the representation of the distribution probability function to which the probability paper refers



Probability paper for a given statistical law – the scale of the horizontal is such that it linearizes the representation of the distribution probability function to which the probability paper refers



Probability paper for the normal law - the horizontal axis is a linear scale of the values of the standard normal, z, for the different non-exceedance probabilities

Representation of the sample

Rank i	Instantaneous maximum discharge (ranked sample) Q _{ima} (m ³ /s)	Empirical non-exceedance probability or plotting position F	standard normal variable z
1	22.5	0.0278	-1.9145
2	60.6	0.0556	-1.5932
3	74.3	0.0833	-1.3830
4	82.9	0.1111	-1.2206
5	112.0	0.1389	-1.0853
6	120.0	0.1667	-0.9674
7	124.0	0.1944	-0.8616
8	165.0	0.2222	-0.7647
9	182.0	0.2500	-0.6745
10	196.0	0.2778	-0.5895
11	213.0	0.3056	-0.5085
12	221.0	0.3333	-0.4307
13	233.0	0.3611	-0.3555
14	265.0	0.3889	-0.2822

Empirical non-exceedance probability – in the example, given by Weibull formula

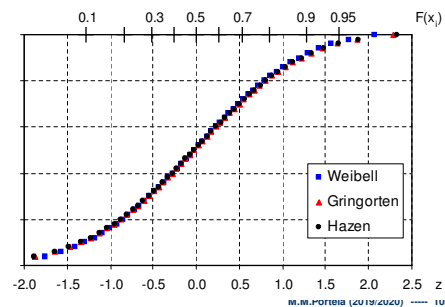
$$F = P(X \leq x) = \frac{i}{N+1}$$

Plotting position formula for the empirical non-exceedance probability

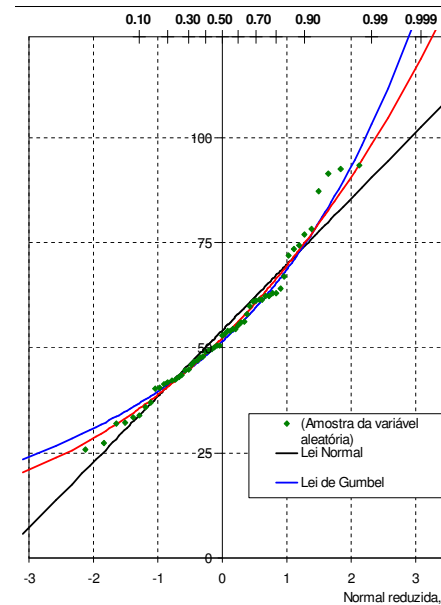
$$F(x) = P(X \leq x) = \frac{i - \theta}{n + 1 - 2\theta} \quad 0 \leq \theta \leq 1$$

θ equal to 0.00, 0.44 e 0.50 in the Weibull, Gringorten and Hazen, respectively ... example for a sample with 50 values ... the differences can only be perceived for the extreme values

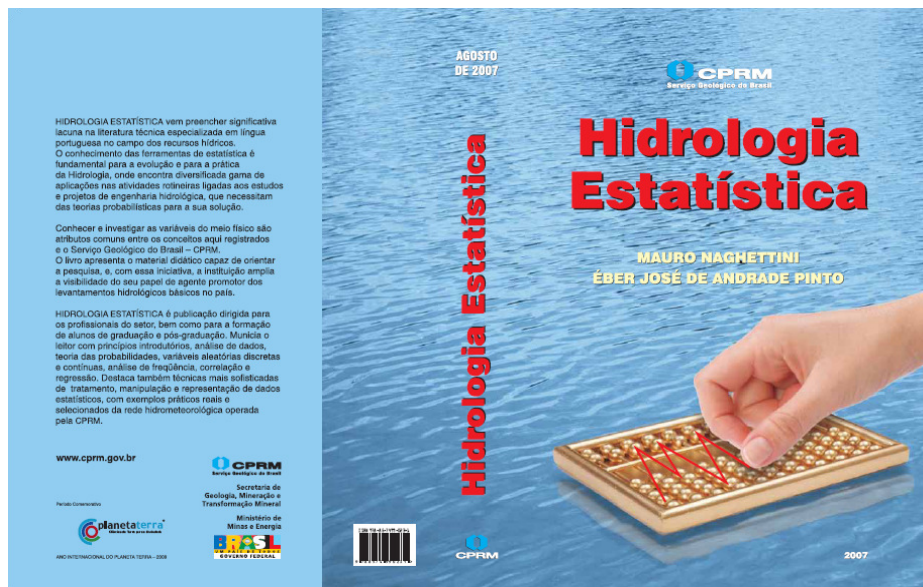
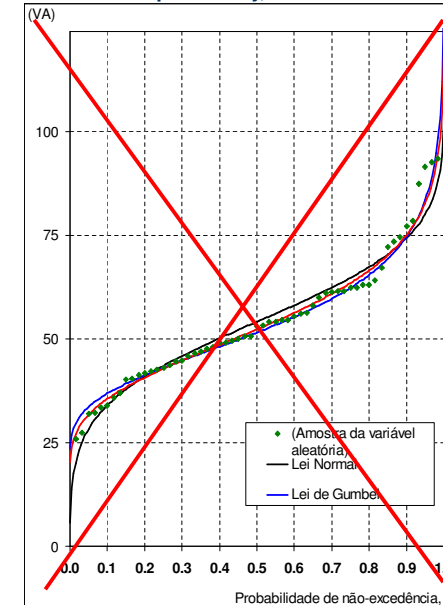
Rank i	Instantaneous maximum discharge (ranked sample) Q _{ima} (m ³ /s)	Empirical non-exceedance probability or plotting position F	standard normal variable z
1	22.5	0.0278	-1.9145
2	60.6	0.0556	-1.5932
3	74.3	0.0833	-1.3830
4	92.9	0.1111	-1.2206
5	112.0	0.1389	-1.0853
6	120.0	0.1667	-0.9674
7	124.0	0.1944	-0.8616
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9	182.0	0.2500	-0.6745
10	196.0	0.2778	-0.5895
11	213.0	0.3056	-0.5085
12	221.0	0.3333	-0.4307
13	233.0	0.3611	-0.3555
14	265.0	0.3889	-0.2822



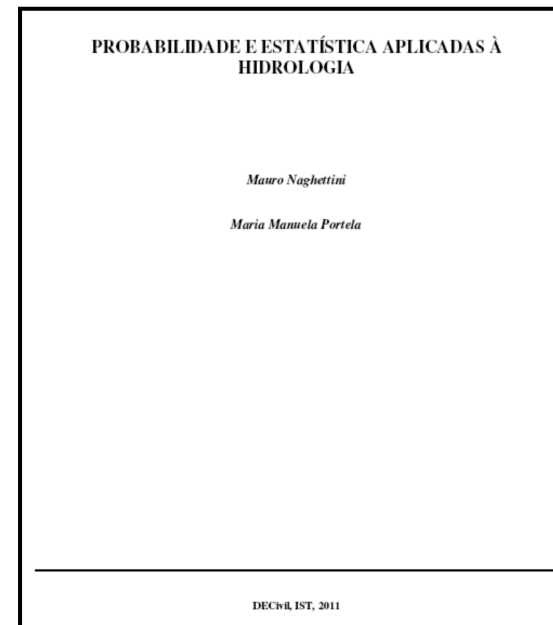
Probability paper for the Normal law linear scale for z



Linear scale for the non-exceedance probability, F



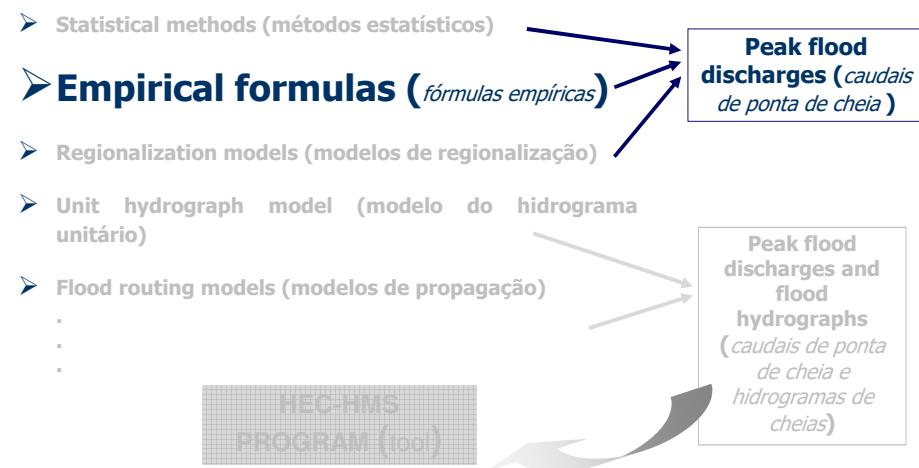
Naghettini, M.; Andrade Pinto, E.J., 2007, *Hidrologia estatística*. Belo Horizonte: CPRM, 2007 (disponível na internet)



Sample		Representation of the sample					Representation of the theoretical laws							
Hydrological year (starting October 1st)	Q (m³/s)	Rank	Q ⁽¹⁾	Empirical non-exceedence probability or plotting position, F	Return period, T	Standard normal variable, z ⁽²⁾	F	T	Normal law		Gumbel law		Pearson III law	
		i	m³/s		(years)			(anos)	z	Q _{NO} (m³/s)	K _G	Q _{GU} (m³/s)	K _P	Q _{PE} (m³/s)
1		1					0.0100							
2		2					0.0200							
3		3					0.0300							
4		4					0.0400							
5		5					0.0500							
6		6					0.0600							
7		7					0.0700							
8		8					0.0800							
9		9					0.0900							
10		10					0.1000							
11		11					0.1100							
12		12					0.1200							
13		13					0.1300							
14		14					0.1400							
15		15					0.1500							
16		16					0.1600							
17		17					0.1700							
18		18					0.1800							
19		19					0.1900							
20		20					0.2000							
21		21					0.2100							
22		22					0.2200							
23		23					0.2300							
24		24					0.2400							
25		25					0.2500							
26		26					0.2600							
27		27					0.2700							
28		28					0.2800							
29		29					0.2900							
30		30					0.3000							
.....														
.....														
.....														
.....														
Average (m3/s)							0.9700							
S. deviation (m3/s)							0.9800							
V. coefficient							0.9900							
Skewness c.							0.9950							
							0.9990							
							0.9995							
							0.9999							

DEPARTAMENTO DE ENGENHARIA
CIVIL, ARQUITETURA E CONSTRUÇÃO

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Q = C i A homogenous formula

The **rational method** is one of the most widely used methods to compute peak flood discharges in **small** to **medium** size watersheds, for all the return periods adopted as design criteria

Q: estimate of the peak discharge for a given return period (m^3/s)

C: coefficient related to the precipitation losses and depending on the type of soil, the soil use, and the return period

i: average intensity of the rainfall with duration equal to t_c and with the same recurrence interval (m/s)

A: watershed area (m^2)

A FÓRMULA RACIONAL é uma das fórmulas mais amplamente divulgadas e utilizadas para determinar caudais de ponta de cheia em pequenas e médias bacias hidrográficas para os períodos de retorno adotados como critério de projeto [Q: estimativa do caudal de ponta de cheia com dado período de retorno, m³/s; C: coeficiente que depende do tipo e uso de solo e do período de retorno; i: intensidade média da precipitação com duração igual ao tempo de concentração e aquele mesmo período de retorno (m/s); A: área da bacia hidrográfica (m²)]

$$Q = C i A$$

... from an hydrologic point of view, **a small to medium size watershed** is such that:

- ↳ the design rainfalls can be considered approx. **constant** over **time** and **space**, so they can be characterized by their average intensities;
- ↳ the surface runoff occurs mainly as **overland flow**;
- ↳ the **water storage capacity** of the river network is neglectable ... to prevent the diffusion effects.

The formula is valid **ONLY FOR RAINFALL DURATIONS EQUAL TO THE TIME OF CONCENTRATION, t_c .**

... do ponto de vista hidrológico, bacia com pequena a média aquela em que é aproximadamente válido admitir que:

- ☞ as precipitações determinantes em termos de gênese de cheias são uniformes no tempo e no espaço e consequentemente suscetíveis de serem caracterizadas pela sua intensidade média;
- ☞ o escoamento ocorre essencialmente sob a forma de escoamento à superfície do terreno;
- ☞ o armazenamento de água na rede de drenagem é negligenciável;
- ☞ as durações da precipitação são necessariamente iguais a tc.



$$Q = C i A$$

Most of the time is quite difficult to decide about the value of C.

It accounts for the **rainfall losses** (due to infiltration, interception and retention) and for the **diffusion** of the surface flow (which is progressively more important as the slope of the surface decreases). C is also a function of the **return period** because most probably as the return period increases the watershed becomes progressively saturated (wet antecedent moisture conditions) and, therefore, the rainfall losses, namely by infiltration, will decrease.

De um modo geral, é grande a indeterminação associada à fixação do valor do coeficiente C. O mesmo tem essencialmente em conta as perdas de precipitação (fundamentalmente por interceção, infiltração e retenção superficial) e a difusão do escoamento (que é tanto mais importante quanto menor é o declive do terreno). O coeficiente C é também função do período de retorno (aumenta com o aumento daquele período, de modo a traduzir a diminuição das perdas de precipitação)



$$Q = C i A$$

Several authors presented values for C as a functions of the most important factors that affect the rainfall losses (like the land use and occupation), the surface flow diffusion (slope of the surface) and of the return period.

However those values **were never validated for the Portuguese hydrological conditions.**

Diversos autores propõem valores para o coeficiente C em função de fatores determinantes das perdas de precipitação (uso e ocupação do solo), da difusão do escoamento (declive da superfície do terreno) e do período de retorno.

Tais valores não foram objeto de validação para as condições ocorrentes em Portugal.



$$C = 0,175 t^{1/3}$$

... t, rainfall duration (duração da chuva)



$$C = C_{\max} \left(\frac{T}{100} \right)^n$$

... T, Return period (período de retorno)



$$C = 0,364 \log t + 0,0042 r - 0,145$$

... r, % of impervious área (% de área impermeável)



$$C = 7,2 (10^{-7}) CN^3 T^{0,05} \left[(0,01 CN)^{0,6} \right] - S^{0,2} (0,001 CN^{1,48})^{0,15-0,1} i \left[(R+1)/2 \right]^{0,7}$$

...i, average rainfall intensity; S, average slope of the ground surface; R, percentage of impervious area; CN, curve number, CN

... i, intensidade média da precipitação; S, declive médio da superfície; R, percentagem de área impermeável; CN, número de escoamento

Table 1 Runoff Coefficients for the Rational Method

	FLAT	ROLLING	HILLY	
Pavement & Roofs	0.90	0.90	0.90	(Fonte: ODOT Hydraulics Manual, 2011 ftp://ftp.odot.state.or.us/techserv/geo-environmental/Hydraulics/Manual/Table_of_Contents_rev_Nav.pdf)
Earth Shoulders	0.50	0.50	0.50	
Drives & Walks	0.75	0.80	0.85	
Gravel Pavement	0.85	0.85	0.85	
City Business Areas	0.80	0.85	0.85	
Apartment Dwelling Areas	0.50	0.60	0.70	
Light Residential: 1 to 3 units/acre	0.35	0.40	0.45	
Normal Residential: 3 to 6 units/acre	0.50	0.55	0.60	
Dense Residential: 6 to 15 units/acre	0.70	0.75	0.80	
Lawns	0.17	0.22	0.35	
Grass Shoulders	0.25	0.25	0.25	
Side Slopes, Earth	0.60	0.60	0.60	
Side Slopes, Turf	0.30	0.30	0.30	
Median Areas, Turf	0.25	0.30	0.30	
Cultivated Land, Clay & Loam	0.50	0.55	0.60	
Cultivated Land, Sand & Gravel	0.25	0.30	0.35	
Industrial Areas, Light	0.50	0.70	0.80	
Industrial Areas, Heavy	0.60	0.80	0.90	
Parks & Cemeteries	0.10	0.15	0.25	
Playgrounds	0.20	0.25	0.30	
Woodland & Forests	0.10	0.15	0.20	
Meadows & Pasture Land	0.25	0.30	0.35	
Unimproved Areas	0.10	0.20	0.30	

Table 2 Runoff Coefficient Adjustment Factors

Note:

- **Impervious surfaces in bold**
- **Rolling** = ground slope between 2 percent to 10 percent
- **Hilly** = ground slope greater than 10 percent

RECURRENCE INTERVAL	RUNOFF COEFFICIENT ADJUSTMENT FACTOR
10 years or less	1.0
25 years	1.1
50 years	1.2
100 years	1.25

Table 1: Runoff coefficients for the Rational method

Hydrologic Soil Group	A			B			C			D		
Recurrence Interval	5	10	100	5	10	100	5	10	100	5	10	100
Land Use Or Surface Characteristics												
Business:												
A. Commercial Area	.75	.80	.95	.80	.85	.95	.80	.85	.95	.85	.90	.95
B. Neighborhood Area	.50	.55	.65	.55	.60	.70	.60	.65	.75	.65	.70	.80
Residential:												
A. Single Family	.25	.25	.30	.30	.35	.40	.40	.45	.50	.45	.50	.55
B. Multi-Unit (Detached)	.35	.40	.45	.40	.45	.50	.45	.50	.55	.50	.55	.65
C. Multi-Unit (Attached)	.45	.50	.55	.50	.55	.65	.55	.60	.70	.60	.65	.75
D. 1/2 Lot Or Larger	.20	.20	.25	.25	.25	.30	.35	.40	.45	.40	.45	.50
E. Apartments	.50	.55	.60	.55	.60	.70	.60	.65	.75	.65	.70	.80
Industrial												
A. Light Areas	.55	.60	.70	.60	.65	.75	.65	.70	.80	.70	.75	.90
B. Heavy Areas	.75	.80	.95	.80	.85	.95	.80	.85	.95	.80	.85	.95
Parks, Cemeteries												
Playgrounds	.10	.10	.15	.20	.20	.25	.30	.35	.40	.35	.40	.45
Schools	.30	.35	.40	.40	.45	.50	.45	.50	.55	.50	.55	.65
Railroad Yard Areas	.20	.20	.25	.30	.35	.40	.40	.45	.45	.45	.50	.55
Streets												
A. Paved	.85	.90	.95	.85	.90	.95	.85	.90	.95	.85	.90	.95
B. Gravel	.25	.25	.30	.35	.40	.45	.40	.45	.50	.40	.45	.50
Drives, Walks, & Roofs												
A. 50%-75% Grass (Fair Condition)	.85	.90	.95	.85	.90	.95	.85	.90	.95	.85	.90	.95
B. 75% Or More Grass (Good Condition)												
A. Flat (0-1%)	.04	.09		.07	.12		.11	.16		.15	.20	
B. Average (2-6%)	.09	.14		.12	.17		.16	.21		.20	.25	
C. Steep	.13	.18		.18	.24		.23	.31		.28	.38	

¹ Undeveloped Surface Definition: Forest and agricultural land, open space.

² Source: Storm Drainage Design Manual, Erie and Niagara Counties Regional Planning Board.

(Fonte: Iowa Stormwater Management Manual

<http://www.iowadnr.gov/Environmental-Protection/Water-Quality/NPDES-Storm-Water/Storm-Water-Manual>)

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For Portugal ... a study based on the comparison of the estimates of the peak flood discharges given by (1) the statistical analysis of the flood records and (2) the rational formula at 19 river gauges stations aiming at establishing the values of the C coefficient applicable to Portugal mainland. (PORTELA, M. M.; HORA, G. R., 2002, "Aplicação da fórmula racional à análise de cheias em Portugal Continental: valores do coeficiente C", Tecnologia da Água, n.º 2, Edição I, pp. 47-60, Ed.: Elsevier Informação Profissional, S.A., ISSN 0211 8173, Portugal)

Estação hidrométrica			Rio		Coordenadas cartográficas		Altitude (m)	Período com registo de máximas instantâneas máximas anuais	
Código (s)	Nome (s)	Bacia principal (s)	Nome (s)	Área da bacia (km²)	M (m)	P (m)		Número De anos (s)	Período (s)
03Q/01	Boicais	Douro	Sabor	425	319 433	537 564	510	20	1970/71-1989/90
03Q/01	Gimonde		Beca	77	235 305	526 809	745	33	1957/58-1989/90
03P/01	Vinhais - Quinta da Ranca		Tuela	455	294 670	538 211	400	30	1960/61-1989/90
04R/01	Ponte de Pinelo		Magias	585	329 742	520 521	470	23	1967/68-1989/90
05Q/01	Santa Maria do Alvão		Louredo	52	231 455	503 127	835	33	1955/56-1989/90
05Q/01	Azibo		Azibo	281	310 864	489 667	220	18	1978/79-1989/90
06Q/01	Ermião do Corgo		Corgo	201	232 167	473 328	40	33	1956/57-1989/90
07Q/01	Cabriz		S. Paio	17	201 684	455 672	250	23	1966/67-1989/90
08Q/01	Castro d'Aire		Pavia	291	216 905	435 732	450	45	1945/46-1989/90
08Q/01	Quinta do Rape		Távora	170	252 257	435 590	500	20	1978/79-1989/90
08Q/01	Vale Trevo	Vouga	Massareme	390	284 045	438 229	305	32	1957/58-1989/90
08Q/01	Ponte de Vale Maior		Camã	188	172 088	445 770	18	35	1958/59-1989/90
11Q/01	Manteigas	Tejo	Zesere	28	249 000	378 440	800	31	1949/50-1989/90
18Q/01	Couto de Andreiros		Seda	244	245 529	255 562	201	23	1964/65-1989/90
19Q/01	Monforte		Aviz	136	259 064	231 411	220	25	1963/64-1989/90
20Q/01	Pavia		Terra	610	211 538	214 181	124	30	1959/60-1989/90
24Q/01	Torrão do Alentejo	Sado	Amarral	400	191 432	347 900	30	28	1968/69-1989/90
27Q/01	Entradas	Guadiana	Targis	52	209 908	68 330	100	19	1971/72-1989/90



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For Portugal ... a study based on the comparison of the estimates of the peak flood discharges given by (1) the statistical analysis of the flood records and (2) the rational formula at 19 river gauges stations aiming at establishing the values of the C coefficient applicable to Portugal mainland. (PORTELA, M. M.; HORA, G. R., 2002, "Aplicação da fórmula racional à análise de cheias em Portugal Continental: valores do coeficiente C", Tecnologia da Água, n.º 2, Edição I, pp. 47-60, Ed.: Elsevier Informação Profissional, S.A., ISSN 0211 8173, Portugal)

It did not allow to establish relationships between C and physiographic/morphologic parameters of the watersheds applicable to Portugal mainland

Código (s)	Nome (s)	Bacia principal (s)	Nome (s)	Área da bacia (km²)	M (m)	P (m)	Altitude (m)	Número De anos (s)	Período (s)
03Q/01	Boicais	Douro	Sabor	425	319 433	537 564	510	20	1970/71-1989/90
03Q/01	Gimonde		Beca	77	235 305	526 809	745	33	1957/58-1989/90
03P/01	Vinhais - Quinta da Ranca		Tuela	455	294 670	538 211	400	30	1960/61-1989/90
04R/01	Ponte de Pinelo		Magias	585	329 742	520 521	470	23	1967/68-1989/90
05Q/01	Santa Maria do Alvão		Louredo	52	231 455	503 127	835	33	1955/56-1989/90
05Q/01	Azibo		Azibo	281	310 864	489 667	220	18	1978/79-1989/90
06Q/01	Ermião do Corgo		Corgo	201	232 167	473 328	40	33	1956/57-1989/90
07Q/01	Cabriz		S. Paio	17	201 684	455 672	250	23	1966/67-1989/90
08Q/01	Castro d'Aire		Pavia	291	216 905	435 732	450	45	1945/46-1989/90
08Q/01	Quinta do Rape		Távora	170	252 257	435 590	500	20	1978/79-1989/90
08Q/01	Vale Trevo	Vouga	Massareme	390	284 045	438 229	305	32	1957/58-1989/90
08Q/01	Ponte de Vale Maior		Camã	188	172 088	445 770	18	35	1958/59-1989/90
11Q/01	Manteigas	Tejo	Zesere	28	249 000	378 440	800	31	1949/50-1989/90
18Q/01	Couto de Andreiros		Seda	244	245 529	255 562	201	23	1964/65-1989/90
19Q/01	Monforte		Aviz	136	259 064	231 411	220	25	1963/64-1989/90
20Q/01	Pavia		Terra	610	211 538	214 181	124	30	1959/60-1989/90
24Q/01	Torrão do Alentejo	Sado	Amarral	400	191 432	347 900	30	28	1968/69-1989/90
27Q/01	Entradas	Guadiana	Targis	52	209 908	68 330	100	19	1971/72-1989/90



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General guideline for Portugal

C values of about 0.80 should result in reliable estimates of the 100-year peak flood discharges (T ~ 100 years) in watersheds with areas up to than 500 km² (QUINTELA, 1984, p. 686 e 687)

$$Q = C i A \quad A \leq 500 \text{ km}^2 \quad C \sim 0.80$$

QUINTELA, 1984, p. 686 e 687, coeficientes C da ordem de 0,80 devam conduzir a estimativas suficientemente seguras dos caudais de ponta de cheia com T~100 anos e bacias hidrográficas com área inferior a 500 km².

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$$Q = C i A$$

The **rational method** is valid only for **uniform design rainfalls** (uniform hyetographs) with **durations equal to the times of concentration** of the watersheds

... additional research work for Portugal presenting scaling factors that allow to account for the temporal variability of the rainfall ...

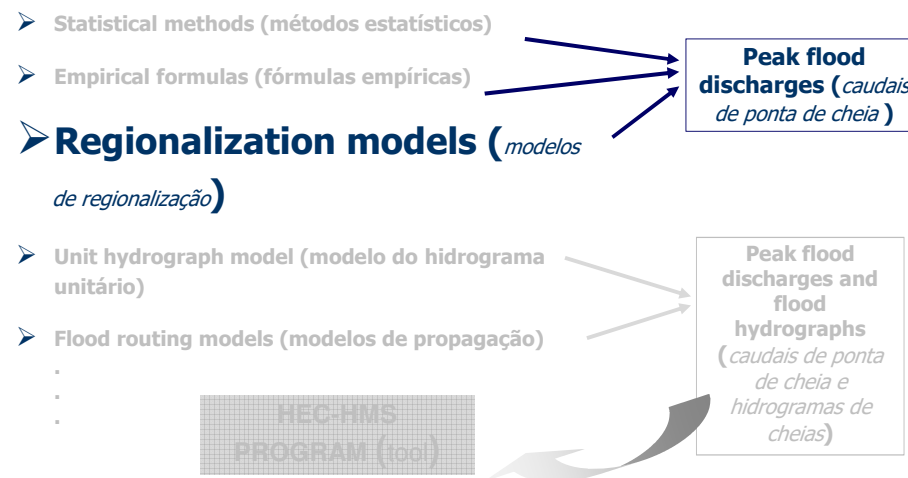
... HIPÓLITO, J. R.; SANTOS, E. G.; PORTELA, M. M., 2006, "Contribuição para o estabelecimento de um factor de majoração para a fórmula racional". *Recursos Hídricos*, Vol 27(2), pp. 47-53. Número Temático: Hidrologia e Modelação Hidrológica, Lisboa) estabelecendo um factor de majoração a aplicar à fórmula racional de modo a ter em conta a não uniformidade temporal da precipitação.

... there are problems such those related to flood routing in artificial reservoirs that must considered rainfall with durations greater than t_c and variable along time ... ?

A FÓRMULA RACIONAL só é aplicável a precipitações de projecto com duração igual ao tempo de concentração das bacias hidrográficas e descritas por meio das respectivas intensidades médias (hietogramas uniformes).

... Amortecimento de ondas de cheia em de albufeiras para precipitações, P, com durações múltiplas do tempo de concentração, t_c ... Hietogramas não uniformes ... ?

Approaches to estimate peak flood discharges or/and floods hydrographs (*métodos de avaliação de caudais de cheia e de hidrogramas de cheia*)



Often, the **samples of instantaneous maximum discharges** at the river gage stations have very reduced lengths, incompatible with the application of statistical methods aiming at establishing design values, namely when very high return periods are envisaged.

As amostras disponíveis de caudais instantâneos máximos anuais, Q_{inst} , em estações hidrométricas (EHs) de Portugal Continental têm frequentemente reduzida dimensão, comprometendo o recurso a métodos estatísticos tendo em vista obter estimativas fiáveis de caudais de ponta de cheia, especialmente quando referentes a períodos de retorno, T , elevados

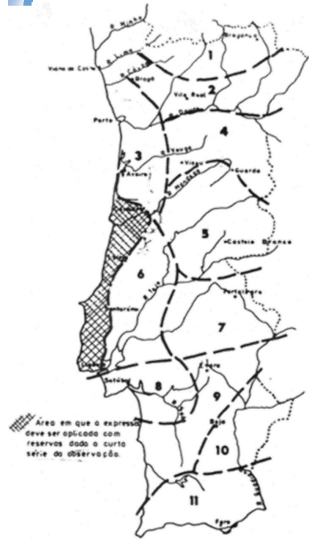
Ways to overcome the insufficient or non-existing flow data:

- ✓ by applying correlation models among the instantaneous maximum annual discharges and physiographic characteristics of the watersheds
- ✓ by applying regional models established based on watersheds with similar hydrological behaviour

Formas de contornar a insuficiência ou ausência de dados hidrométricos

- ✓ Utilização de correlações entre caudais instantâneos máximos anuais e as características fisiográficas e hidrológicas da bacia hidrográfica
- ✓ Utilização de informação regional estabelecida para bacias hidrográficas com comportamento hidrológico semelhante

Regionalization of peak flood discharges/ regionalização de caudais instantâneos máximos anuais



Loureiro's Formula $Q_p = C A^Z$

Zonas	Valor de Z	Valor de C para diferentes períodos de retorno - anos						
		5	10	25	50	100	500	1000
1	0.807	2.85	3.72	4.53	5.27	6.10	7.54	8.57
2	0.694	5.44	6.97	8.58	9.67	10.98	13.91	15.63
3	0.510	24.93	30.50	39.14	43.49	49.50	57.05	64.83
4	0.489	11.68	16.79	19.19	22.31	26.20	33.13	38.52
5	0.375	31.30	40.07	50.22	58.07	66.89	80.51	94.38
6	0.466	19.17	26.26	34.69	42.22	48.27	66.24	72.29
7	0.761	3.66	4.49	5.58	6.02	8.45	9.60	11.03
8	0.816	1.66	2.09	2.58	2.98	3.37	4.27	4.75
9	0.738	3.39	4.28	5.54	6.44	7.40	9.50	10.68
10	0.745	2.38	3.06	3.68	4.12	4.94	6.23	7.72
11	0.784	3.45	4.40	5.40	6.24	7.09	8.97	9.88

The Loureiro's formula is supported by the well-known and very old Myer formula

$$Q = \beta A^\alpha$$

where Q is the peak flood discharge (m^3/s), A , the watershed area (km^2), α an exponent comprehended between 0.4 and 0.8 (often set equal to 0.5), and β , a coefficient that depends on the watershed characteristics

LOUREIRO, J. M., 1984. Expressão para o Cálculo do Caudal de Cheia em Cursos de Água de Portugal, Recursos Hídricos, 5(1), pp. 53-78.

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$$Q_p = C A^Z \quad Q = \beta A^\alpha$$

The Portuguese Loureiro's formula, as well as the very old Myers's formula, which theoretically supports the former, although no longer directly applied, are very useful to transpose the peak flood discharges obtained for a given watershed based on reliable hydrological data to another watershed were such information is not available or even does not exist

A fórmula proposta por Loureiro, 1984, tal como a fórmula de Meyer, têm como principal utilidade o facto de permitirem transpor para uma bacia hidrográfica com características análogas a estimativa do caudal de ponta de cheia com dado período de retorno obtido para outra bacia mediante um método de maior confiança, como seja a análise estatística de caudais instantâneos máximos anuais.

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Loureiro $Q_p = C A^Z$ $Q = \beta A^\alpha$ Meyrs

Assuming that the exponent that relates the peak flood discharges with the watershed areas is similar in the two watersheds (because they belong to the same homogenous regions or because they are geographically close), the next equation is obtained, where A and A_1 stand for the areas of the two watersheds (expressed in the same units) and Q and Q_1 for the corresponding peak floods discharges (also in the same units). By this way, if Q and A related to the gauged watershed, the flood discharges at the ungauged watershed, Q_1 , can be estimated based solely on the knowledge of the corresponding area, A_1 (for Portugal based on Z , for other countries based on specific studies or in the average value of α of 0.5).

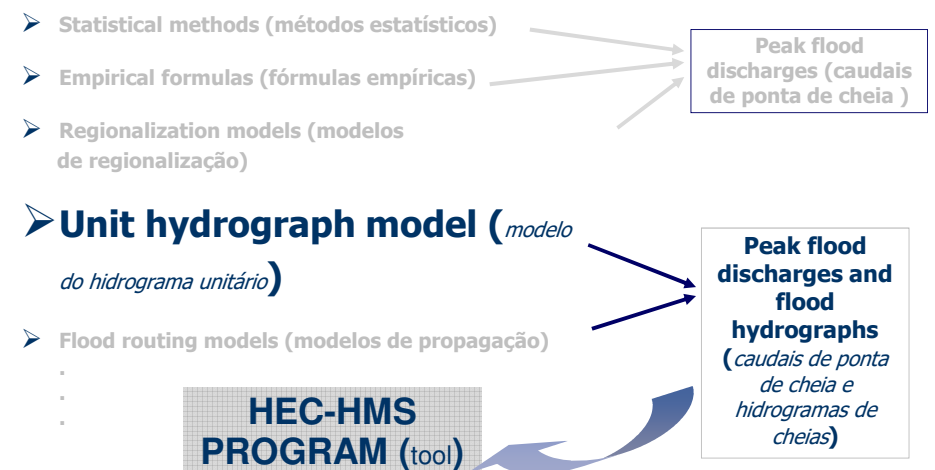
$$\frac{Q}{Q_1} = \left(\frac{A}{A_1} \right)^Z$$

$$\frac{Q}{Q_1} = \left(\frac{A}{A_1} \right)^\alpha$$

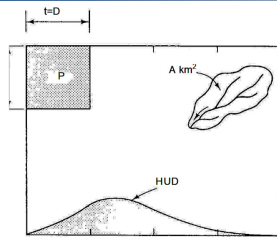
Nestas circunstâncias, admitindo que o expoente que afeta a área A é igual nas duas bacias hidrográficas consideradas na transposição, obtém-se a equação anterior em que A e A_1 representam as áreas das bacias hidrográficas entre as quais se processa a transposição (expressas nas mesmas unidades) e Q e Q_1 os correspondentes caudais de ponta de cheia (também nas mesmas unidades).

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Approaches to estimate peak flood discharges or/and floods hydrographs (*métodos de avaliação de caudais de cheia e de hidrogramas de cheia*)



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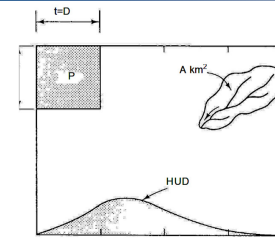
Unite hydrograph with duration D, UHD

Hidrograma unitário com duração D, (HUD)

A unit hydrograph (UH) is the hypothetical unit response of a watershed (in terms of peak discharge, runoff volume and timing) to a unit input of rainfall. It can be defined as the direct runoff hydrograph resulting from one unit (e.g., one mm or one inch) of effective rainfall occurring uniformly over that watershed at a uniform rate over a unit period of time, D. As a UH is applicable only to the direct runoff component of a hydrograph (i.e., surface runoff), a separate determination of the baseflow component is required.

Hidrograma do escoamento direto provocado numa secção de um curso de água por uma precipitação útil ou efetiva, considerada unitária, com intensidade constante no tempo e aproximadamente uniforme sobre toda a bacia hidrográfica e com duração D.

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Unite hydrograph with duration D, UHD

ELEMENTARY CONCEPTS

A unit hydrograph (UH) is the hypothetical unit response of a watershed (in terms of peak discharge, runoff volume and timing) to a unit input of rainfall. It can be defined as the direct runoff hydrograph resulting from one unit (e.g., one mm or one inch) of effective rainfall occurring uniformly over that watershed at a uniform rate over a unit period of time, D. As a UH is applicable only to the direct runoff component of a hydrograph (i.e., surface runoff), a separate determination of the baseflow component is required.

Hidrograma do escoamento direto provocado numa secção de um curso de água por uma precipitação útil ou efetiva, considerada unitária, com intensidade constante no tempo e aproximadamente uniforme sobre toda a bacia hidrográfica e com duração D.

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Components of the observed flood hydrograph. Models to separate the direct runoff from the baseflow

After a rainfall event, the discharge at a given river section is not totally caused by that event. In fact, most of the time, before the rainfall event there was already some discharges → not all the river discharges are directly caused by the rainfall events that occurred in a given instant → two components are identified in the flood hydrograph caused by a rainfall event: the **direct runoff** which is a direct consequence of the rainfall event that is taking place and the **baseflow** which is due to rainfall events that occurred before, sometimes with a considerable delay

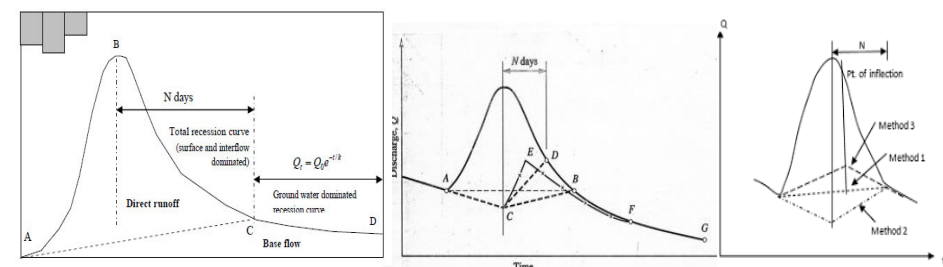
Componentes do hidrograma de cheia observado numa secção de um curso de água. Modelos de separação dos escoamentos direto e de base

Geralmente, o caudal que atravessa a secção transversal de um curso de água na sequência de um dado acontecimento pluvioso intenso não provém, na totalidade, da precipitação que atingiu a bacia hidrográfica, tanto mais que frequentemente existe escoamento no curso de água antecedendo a ocorrência da precipitação e que tal escoamento se mantém após o termo da precipitação. Distinguem-se, assim, duas componentes fundamentais no hidrograma de cheia associado àquele acontecimento pluvioso: o escoamento de base e o escoamento direto

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COMPONENTS OF THE OBSERVED FLOOD HYDROGRAPH MODELS TO SEPARATE THE DIRECT RUNOFF FROM THE BASEFLOW

Componentes do hidrograma de cheia observado numa secção de um curso de água
modelos de separação do escoamento direto e do escoamento de base



Let us consider a rainfall event after a long period without rainfall in order to be possible to accept that the contribution, in terms of surface runoff, from the previous rainfall events is null (there is no longer water moving over the surface towards the river network).

At the beginning and except for the parcel that falls directly into the river, the rainfall does not contribute to increase the river discharge because $\Rightarrow$ it is intercepted by obstacles, stored in the depressions and other irregularities of the surface and infiltrated, contributing to the increase in water content of the soil (**initial rainfall losses**).

Considere-se a ocorrência de uma precipitação significativa após um intervalo considerável de tempo sem chuva, por forma a que já não exista água em trânsito sobre o terreno e na rede hidrográfica decorrente de chuvadas anteriores (detenção superficial nula).

... Inicialmente a precipitação caída sobre a bacia hidrográfica não contribui para o aumento do caudal que se escoia $\Rightarrow$ interceção por obstáculos (vegetação e outros); armazenamento em depressões e irregularidades da superfície e infiltração no solo, aumentando o teor de humidade deste último.

The time delay between the beginning of the rainfall event and the increase of the river discharge depends on the intensity of the rainfall and on the “water deficit” in the watershed – antecedent moisture and water storage conditions.

In Portugal, such “deficit” decreases and the exceptionality of the rainfall event increases because very exceptional rainfall events normally occur after periods with very high rainfall

Under these conditions

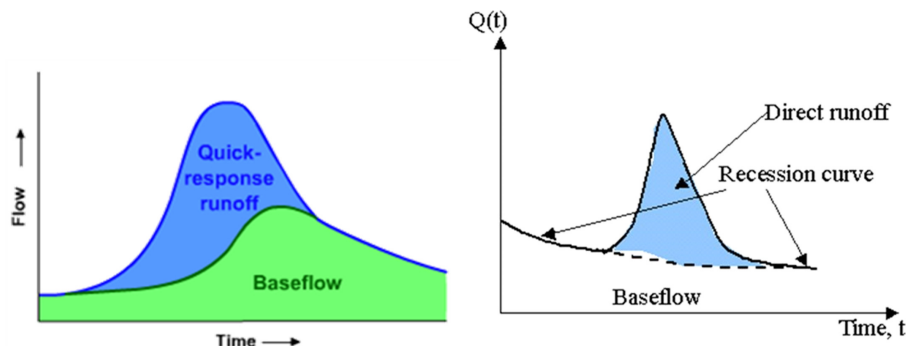
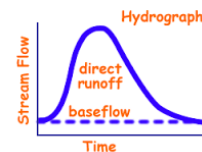
Intervalo de tempo entre os inícios da precipitação e da elevação do nível da superfície da água no rio $\Leftrightarrow$ do “défice de humidade” na bacia hidrográfica em relação às condições de saturação da bacia hidrográfica, anteriormente à ocorrência da chuva – *condições antecedentes de humidade e de armazenamento de água na bacia, incluindo na zona não permanentemente saturada* – e da própria intensidade da precipitação.

Em Portugal, tal “défice” será tanto menor quanto maior for a exceção da ocorrência pluviosa por, *normalmente, acontecimentos pluviosos muito excepcionais serem antecedidos por períodos com elevada precipitação.*)

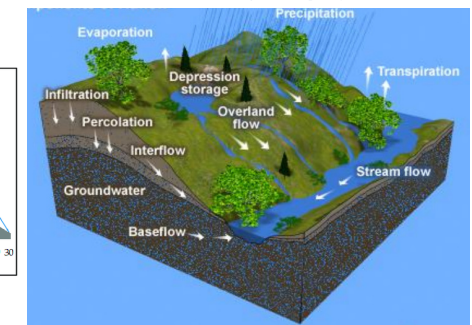
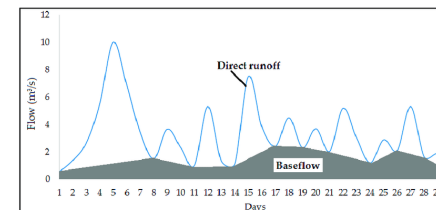
Nestas condições ... - 134

✓ **Baseflow** (escoamento de base)

✓ **Direct runoff** (escoamento direto)



✓ **Baseflow**: The longer-term discharge derived from natural water storages, i.e., the portion of stream flow that results from the slowly seepage of water from the ground into a river



Escoamento de base (baseflow): escoamento que, antecedendo a ocorrência de precipitação, se verifica num curso de água. Resulta da contribuição para o hidrograma observado das reservas subterrâneas (provém do esgotamento gradual das reservas subterrâneas). Depende do armazenamento disponível naquelas reservas que, por sua vez, depende das condições antecedentes de ocorrência de precipitação e das características morfológicas, fisiográficas, geológicas e geotécnicas da bacia hidrográfica que favorecem ou determinam a alimentação subterrânea e a própria existência de reservas subterrâneas. A contribuição do escoamento de base para o hidrograma de cheia observado como resultado de uma precipitação excepcional é, em termos relativos e em geral, pouco significativa, embora passe a representar a totalidade do escoamento observado após longos períodos com ausência de precipitação

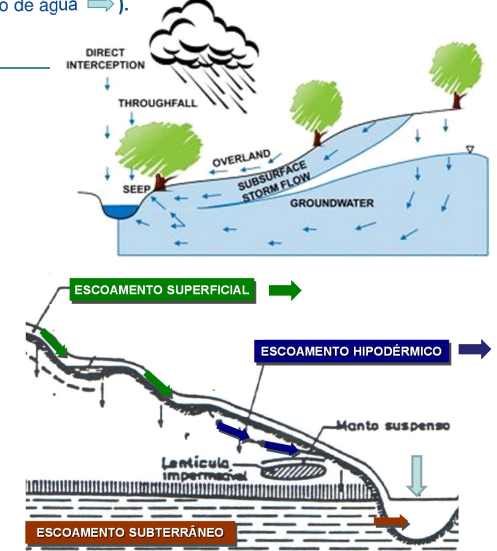
- ✓ **Baseflow:** The longer-term discharge derived from natural water storages, i.e., the portion of stream flow that results from the slowly seepage of water from the ground into a river
- ✓ It depends on the water storage in the watershed which in turn depends on the previous rainfall events and on the different characteristics of the watershed (from physiographic to geological) regarding the natural water storages.
- ✓ Compared to the contribution of the rainfall to a flood hydrograph caused by an exceptional rainfall event, the one from the baseflow is generally very small or even neglectable; however the baseflow is the primary source of running water in a stream during dry season.

Escoamento de base (baseflow): escoamento que, antecedendo a ocorrência de precipitação, se verifica num curso de água. Resulta da contribuição para o hidrograma observado das reservas subterrâneas (provém do esgotamento gradual das reservas subterrâneas). Depende do armazenamento disponível naquelas reservas que, por sua vez, depende das condições antecedentes de ocorrência de precipitação e das características morfológicas, fisiográficas, geológicas e geotécnicas da bacia hidrográfica que favorecem ou determinam a alimentação subterrânea e a própria existência de reservas subterrâneas. A contribuição do escoamento de base para o hidrograma de cheia observado como resultado de uma precipitação excepcional é, em termos relativos e em geral, pouco significativa, embora passe a representar a totalidade do escoamento observado após longos períodos com ausência de precipitação

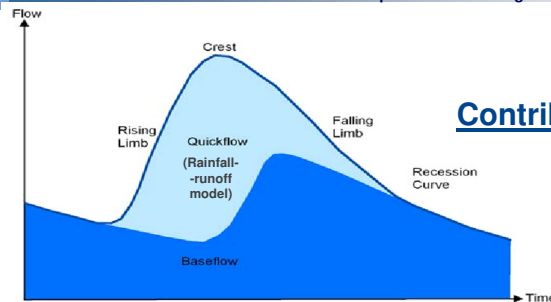
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Escoamento direto: acréscimo de caudal que se verifica no curso de água em resultado da ocorrência da precipitação. Representa a contribuição da precipitação caída sobre a bacia hidrográfica para o acréscimo, relativamente ao escoamento de base, do caudal que se escoou na secção do curso de água que define a bacia hidrográfica em consideração (escoamento superficial → + escoamento hipodérmico → + precipitação diretamente caída no curso de água →).

Direct runoff (quickflow): the stream flow that represents the direct response to a rainfall event (the water that reaches the river shortly after the rainfall event beginning) it includes the overland flow (runoff) →, the lateral movement of the water in the soil profile (interflow or subsurface flow) → and direct rainfall onto the stream surface →.



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Contribution of the baseflow to the flood hydrograph

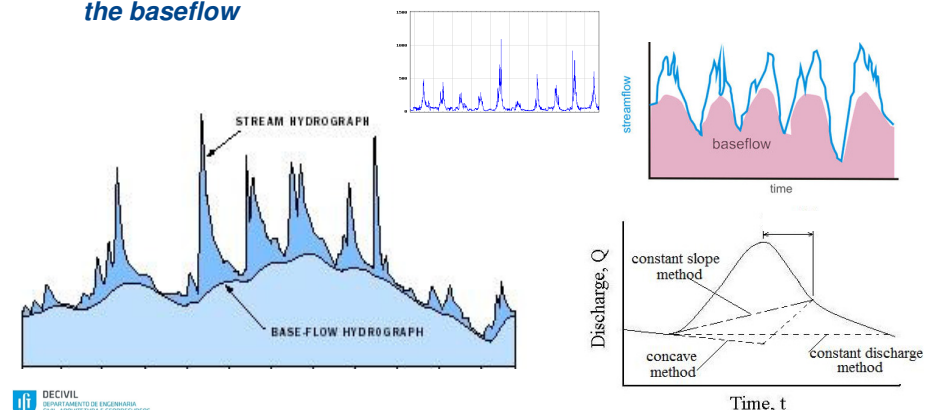
Theoretically, the baseflow needs to be “added” to the design flood discharges given by a rainfall – runoff model because the model only provides the discharges and the volume of the direct runoff (... any design rainfall event can be combined with different antecedent natural water storages in the watershed, i.e., with different baseflows, because the baseflow are not directly connected to the rainfall event and so the models can not account for it).

Contribuição do escoamento de base para o hidrograma de cheia

... componente a adicionar às cheias de projeto fornecidas pela generalidade dos modelos de transformação da precipitação em escoamento em condições de cheia (... apenas conduzem a caudais de ponta ou a hidrogramas do escoamento direto).

Objetivo: Tendo por base hidrogramas de cheia observados, modelos de separação dos escoamentos direto e de base, logo, de identificação das parcelas representativas daquelas escoamentos

Objective: Based on observed hydrographs at a given watershed, models that can be applied to separate the direct runoff from the baseflow, i.e., models that allow to characterize the baseflow



Model for the baseflow: recession curve for the baseflow given by Horton – exponential decay:

$$Q_t = Q_0 e^{-(t-t_0)/k}$$

Q_0 e Q_t – baseflow discharges at the initial time t_0 and at the time t , after t_0 ; k recession constant (time units)

The equation assumes that the baseflow is the result from a series of linear reservoirs; from a mathematical point of view, a reservoir is said to be linear if in each instant the outflow from the reservoir is proportional to the volume stored in the same, the constant of proportionality being the recession constant $\forall(t) = \kappa O(t)$

Modelação do escoamento de base: curva de recessão do escoamento de base descrita por Horton (exponencial negativa)

Q_0 e Q_t - caudais do escoamento de base nos instantes t_0 e t após ter ocorrido Q_0 ; k - constante de recessão ou de esgotamento (em unidades de tempo).

A anterior equação admite conceitualmente que o caudal proveniente da contribuição das reservas subterrâneas pode ser aproximado pela descarga de um conjunto de sucessivos reservatórios lineares; um reservatório diz-se linear quando, em cada instante o caudal efluente do reservatório é proporcional ao volume nele armazenado, sendo a constante de proporcionalidade a constante de armazenamento.

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Model for the baseflow: recession curve for the baseflow given by Horton – exponential decay:

$$Q_t = Q_0 e^{\frac{t-t_0}{k}}$$

$$\ln Q_t = \ln Q_0 - \frac{t-t_0}{k}$$

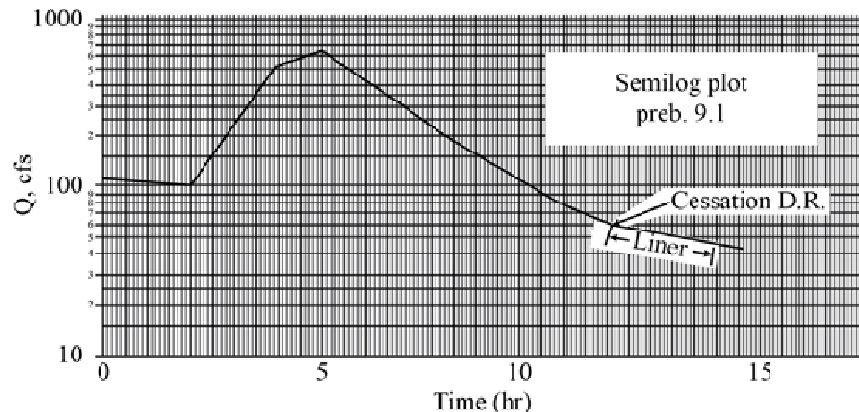
Linear equation on a semilog plot $\ln Q$ versus t

After the end of the direct runoff – i.e., when only baseflow occurs – the variation of $\ln Q$ with time should be approximately linear

$$Q_t = Q_0 e^{\frac{t-t_0}{k}}$$

$$\ln Q_t = \ln Q_0 - \frac{t-t_0}{k}$$

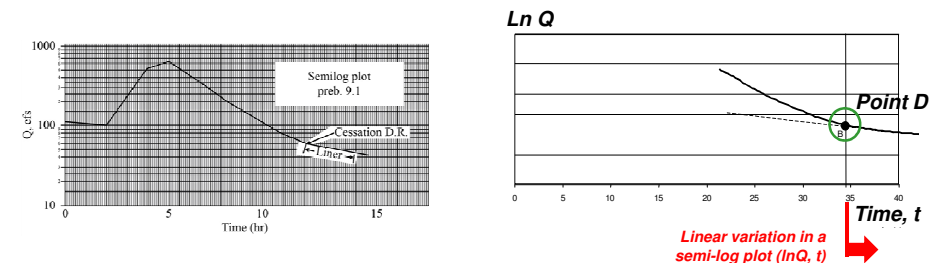
Linear equation on a semilog plot $\ln Q$ versus t

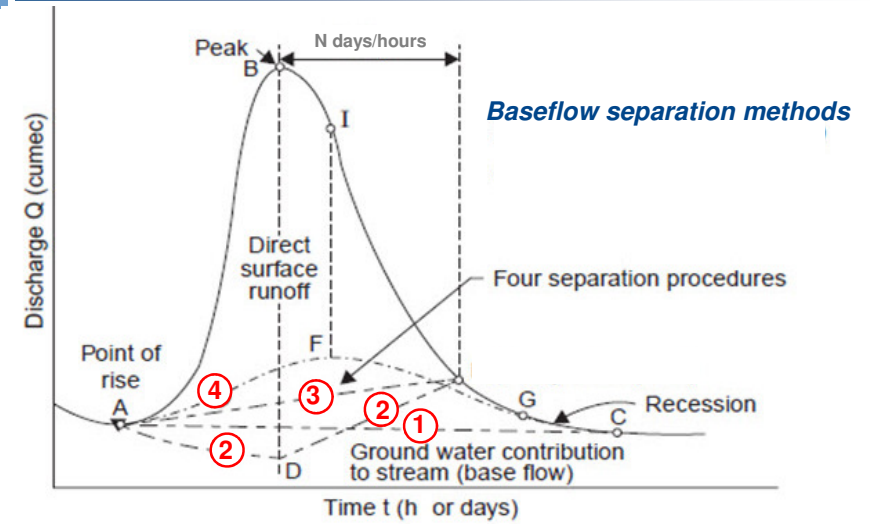
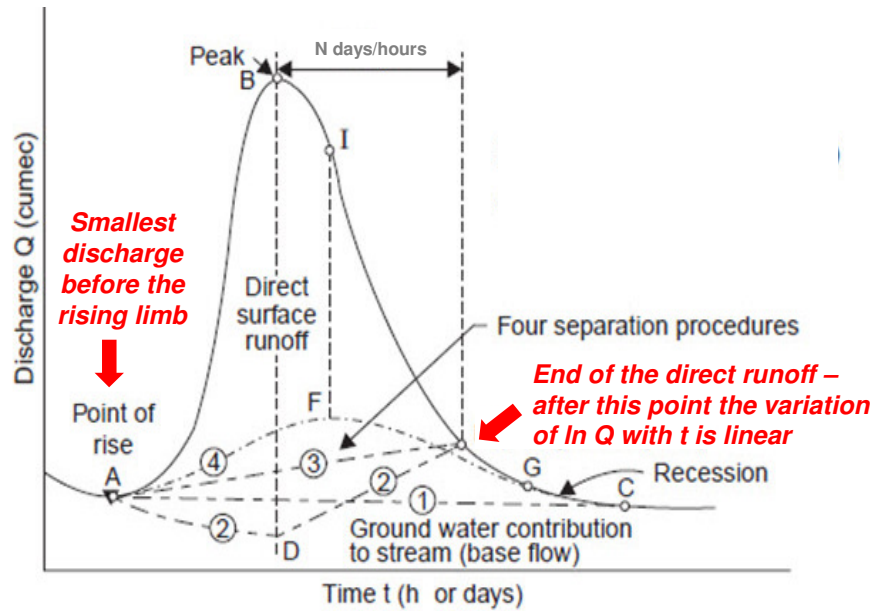


Separação do escoamento de base / separation of the baseflow (cont.)

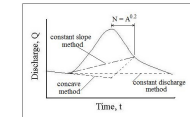
Estimativa da constante de esgotamento numa dada secção de um curso de água por representação do hidrograma de cheia observado num gráfico semi-logarítmico e análise dos trechos representativos de períodos com ausência de precipitação e afastados da ocorrência anterior de escoamento superficial ... períodos de esgotamento dos aquíferos da bacia hidrográfica

The recession constant can be computed by representing the flood hydrograph in a semi log plot ($\ln Q$; t) and by analyzing the periods without rainfall events with linear decay ... after a considerable interval without precipitation in order to ensure that the observed flow is only due to the baseflow.

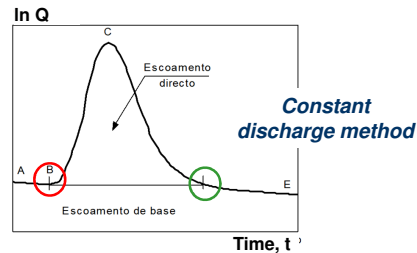
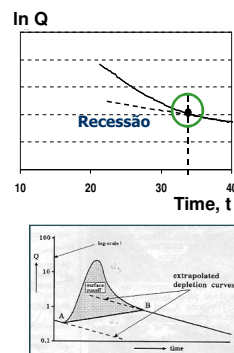




- 1 – constant discharge method
- 2 – concave method
- 3 – constant slope method
- 4 – mix method

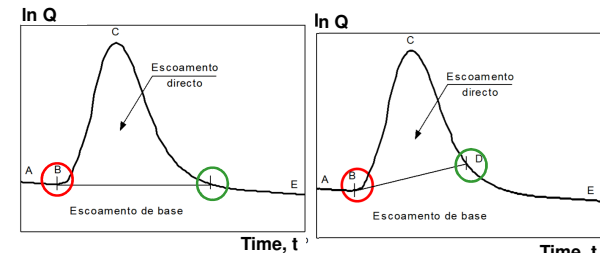
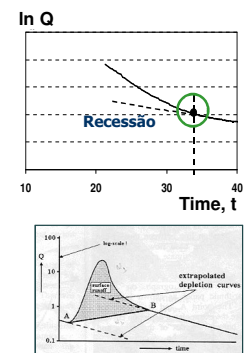


Separação do escoamento de base / separation of the baseflow (cont.)

Semi-log ($\ln Q$, t) plot

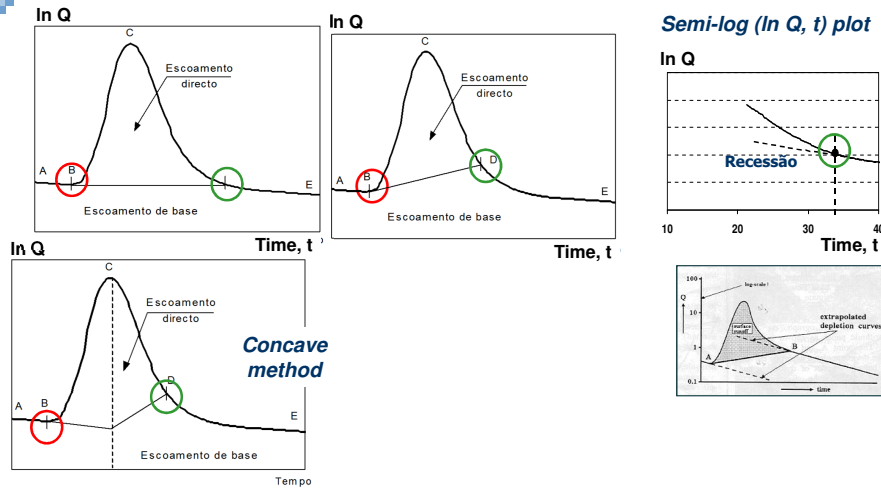
B the smallest discharge before the rising limb of the hydrograph (point of rise)

Separação do escoamento de base / separation of the baseflow (cont.)

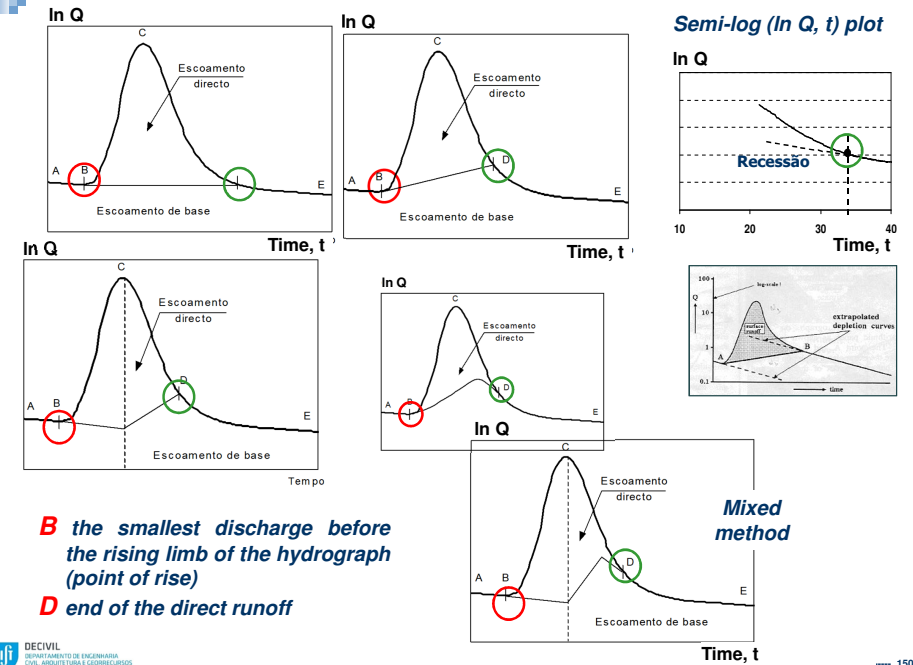
Semi-log ($\ln Q$, t) plot

B the smallest discharge before the rising limb of the hydrograph (point of rise)

D end of the direct runoff



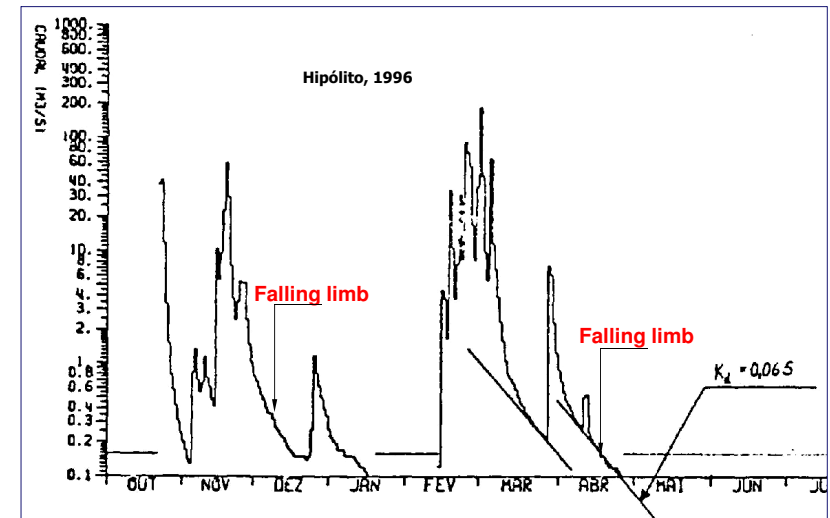
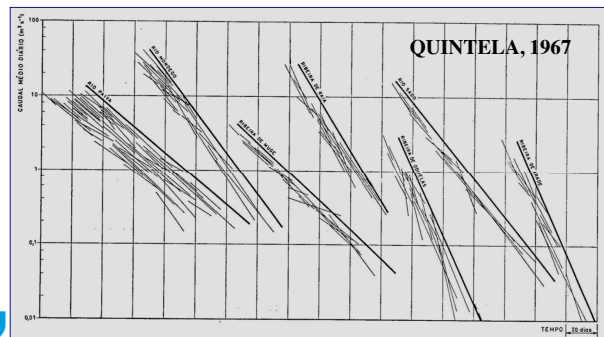
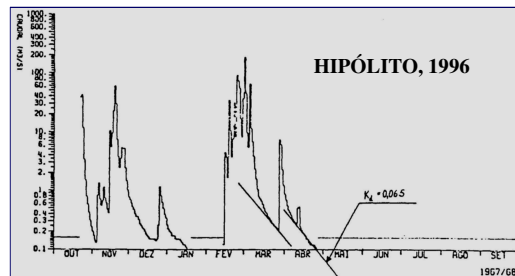
B the smallest discharge before the rising limb of the hydrograph (point of rise)
D end of the direct runoff



B the smallest discharge before the rising limb of the hydrograph (point of rise)
D end of the direct runoff

Curvas de esgotamento em cursos de água de Portugal Continental

Recession curves for mainland Portugal



... Floods clearly spaced in time to ensure that the falling limbs of the hydrographs represent periods under recession, i.e., only with baseflow and not influenced by any kind of surface runoff. When only recession applies the slope of the falling limbs of the different hydrograph should be approx. the same

Master depletion curve method

(R. H. McCuen. Hydrologic Analysis and Design. Prentice Hall, Upper Saddle River, New Jersey, 07458, 3rd edition, 2004. ISBN 0-13-142424-6. URL <http://www.prenhall.com>).

