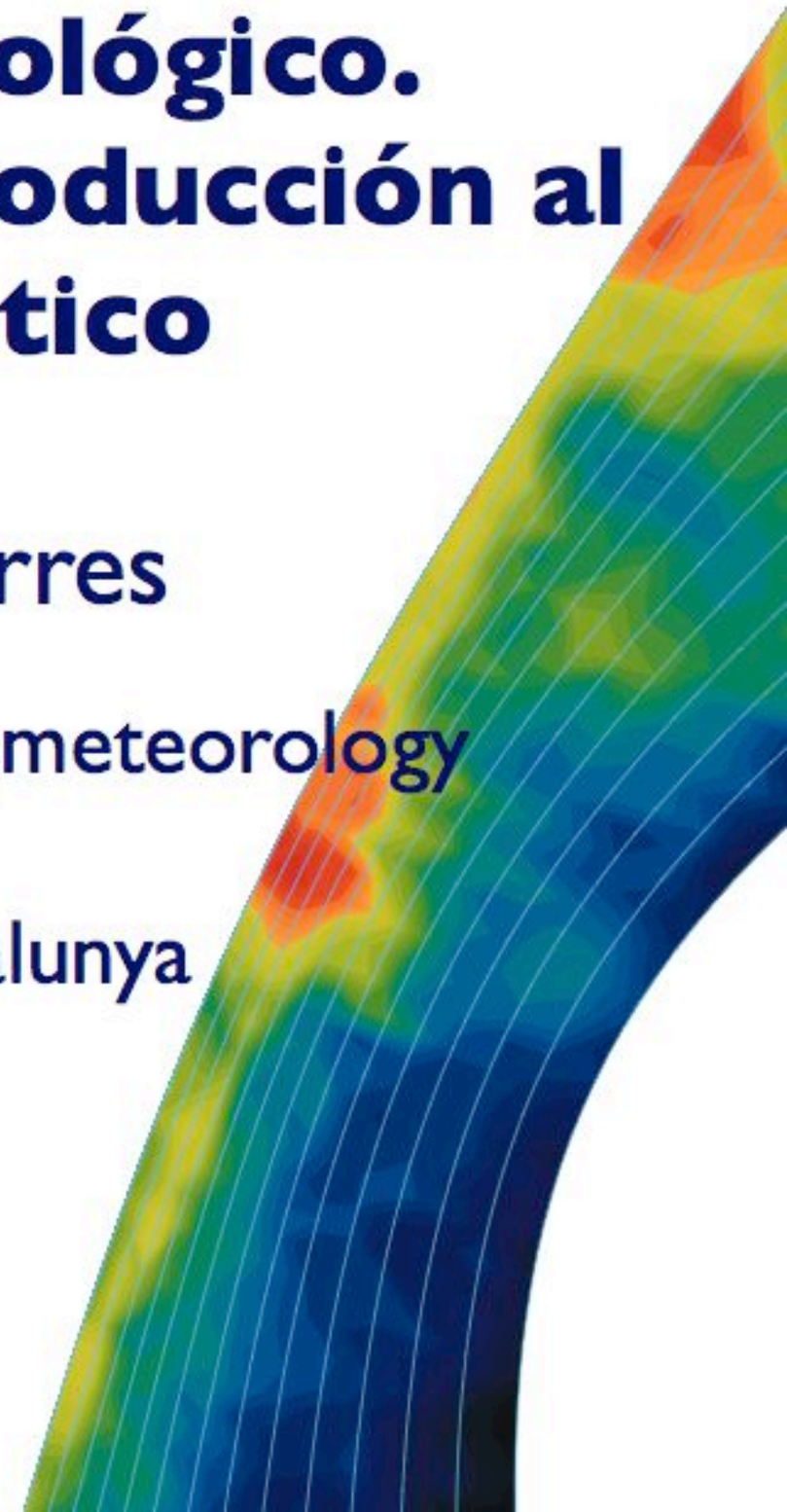
Pronóstico Hidrometeorológico. Revisión de conceptos e introducción al pronostico probabilístico

Prof. Daniel Sempere Torres

Centre for Applied Research in Hydrometeorology
CRAHI
Universitat Politècnica de Catalunya
Barcelona



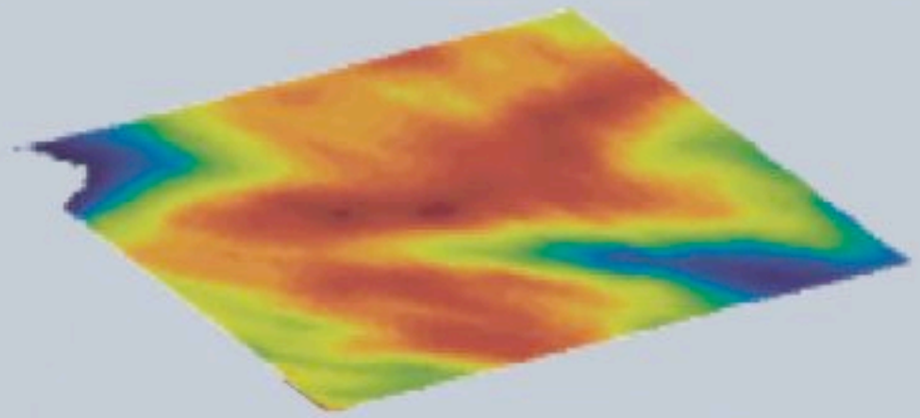
Coupled hydrometeorological forecasting







Coupled hydrometeorological forecasting



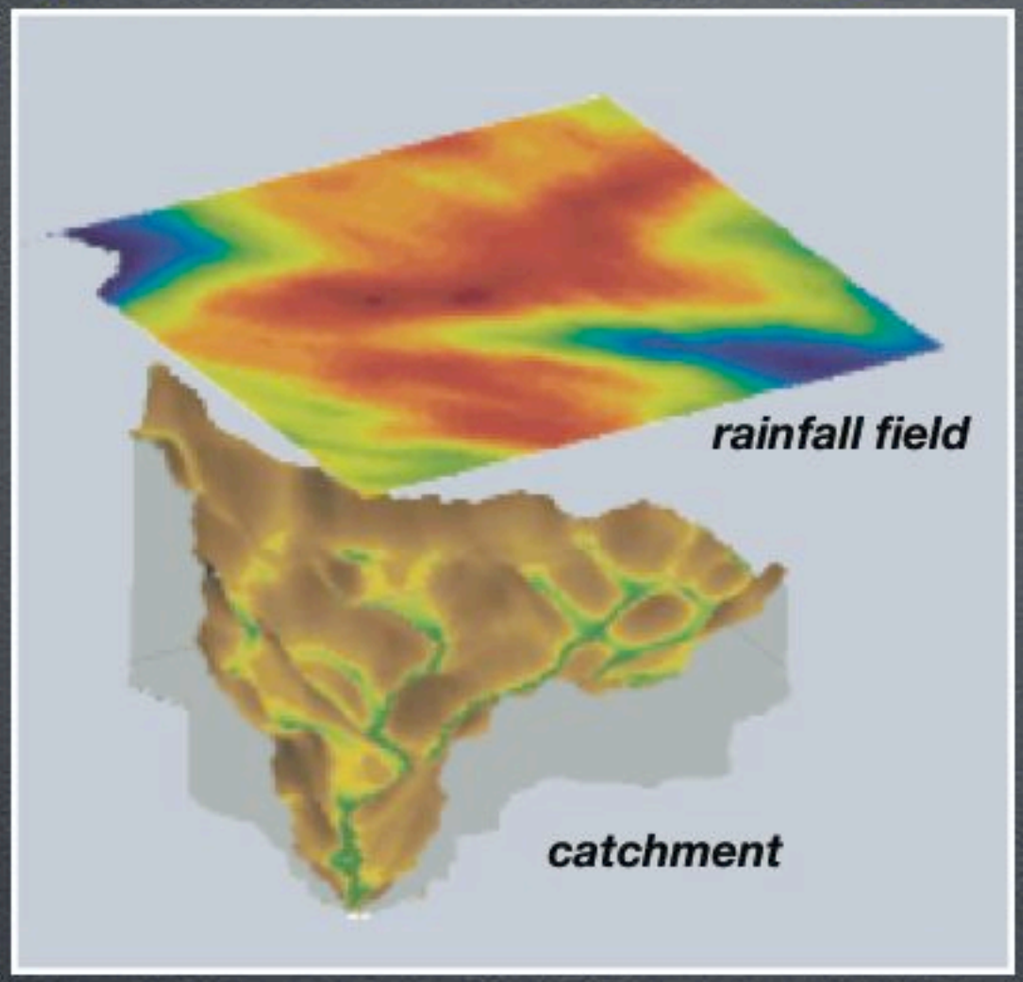
rainfall field

TECNIO
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Coupled hydrometeorological forecasting

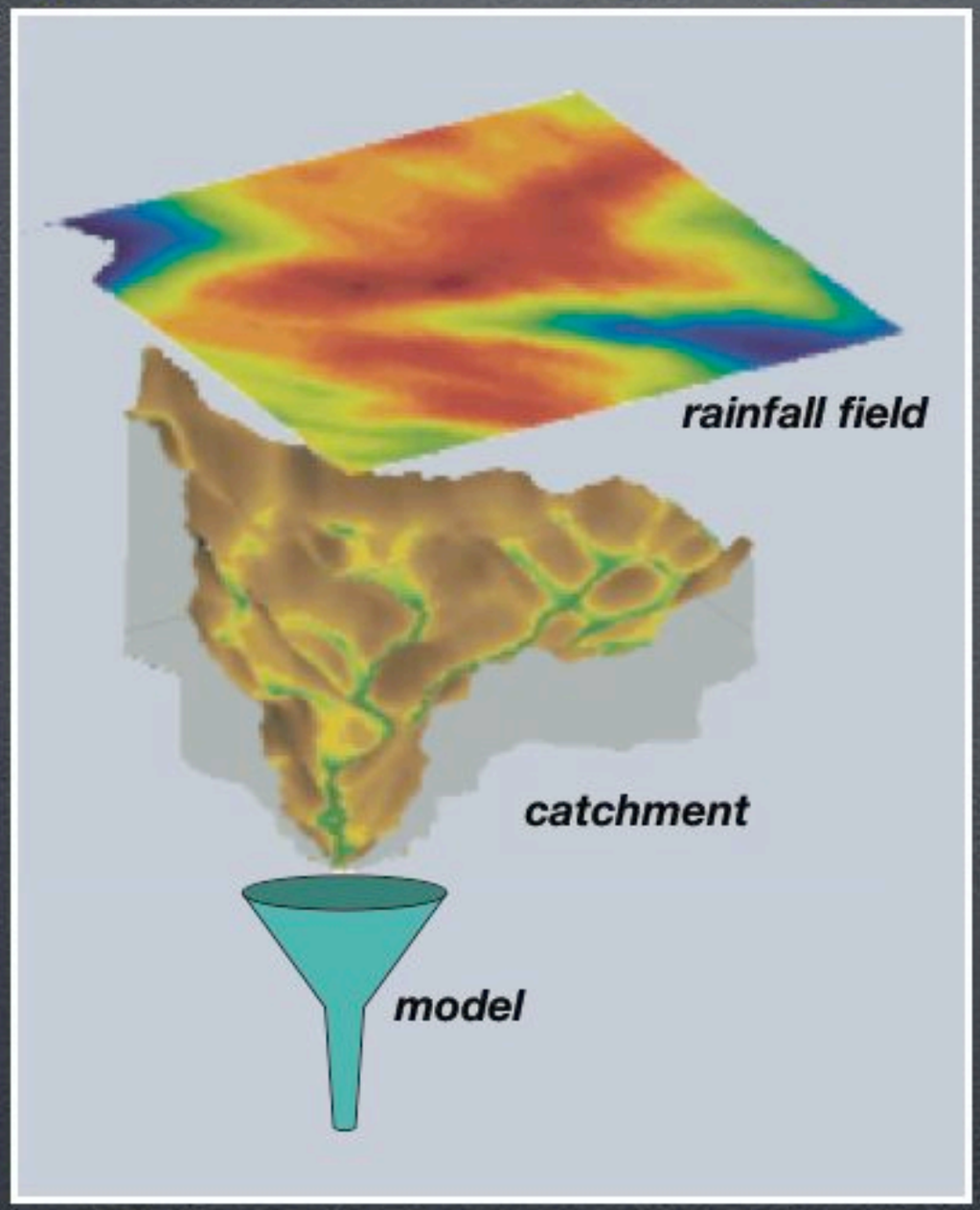


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Coupled hydrometeorological forecasting

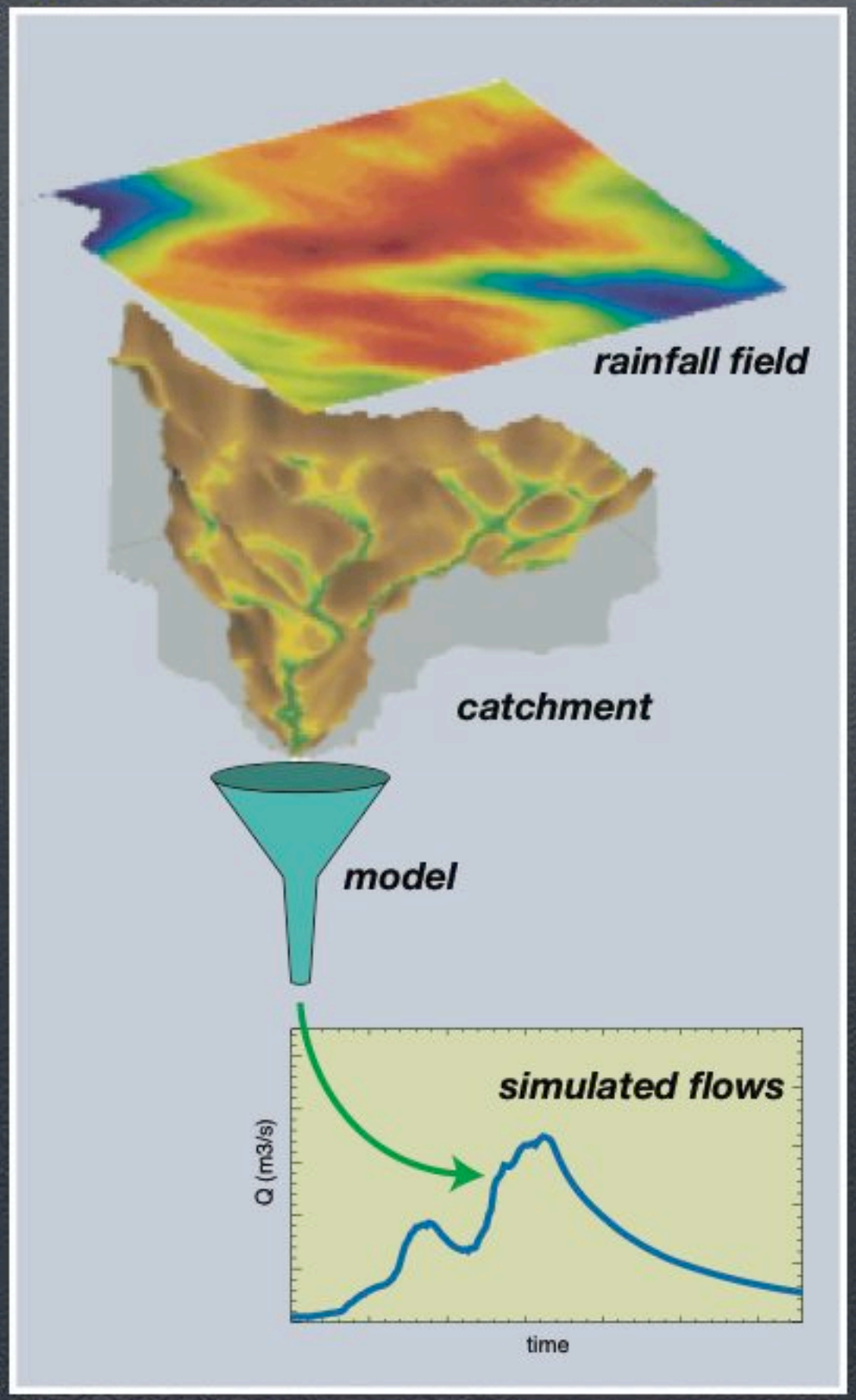


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Coupled hydrometeorological forecasting



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Integrated system for operational hydrological forecasting in Catalunya

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EHIMI

Radar network

volumetric information

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Radar network

volumetric information

GenRad

corrections

processed images

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Radar network

volumetric information

GenRad

corrections

processed images

rainfall field for hydrological use

merging

Raingauge network

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Raingauge network

short term rainfall forecasting

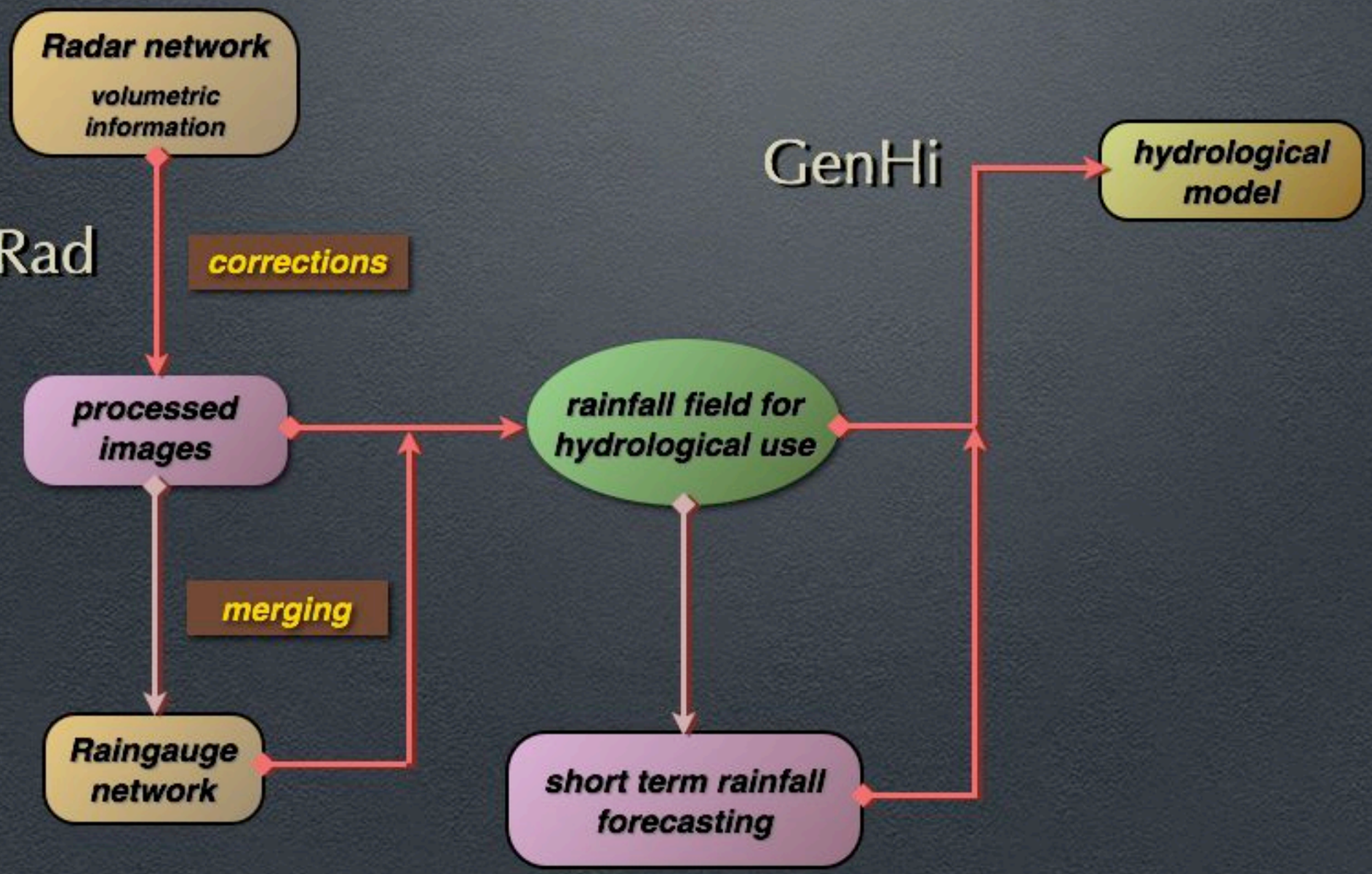
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Integrated system for operational hydrological forecasting in Catalunya

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EHIMI

Radar network

volumetric information

GenRad

corrections

processed images

merging

Raingauge network

GenHi

rainfall field for hydrological use

short term rainfall forecasting

hydrological model

Q(t)

VisHid

WARNING

TECNIO Be tech. Be competitive

CRAHI UPC

Integrated system for operational hydrological forecasting in Catalunya

CRAHI UPC meteocat

EHIMI

Radar network

volumetric information

GenRad

corrections

processed images

merging

Raingauge network

GenHi

rainfall field for hydrological use

short term rainfall forecasting

hydrological model

Q(t)

VisHid

WARNING

Ensemble Forecasting

TECNIO Be tech. Be competitive

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Integrated system for operational hydrological forecasting in Catalunya

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EHIMI

Probabilistic Forecasting

Radar network
volumetric information

GenRad

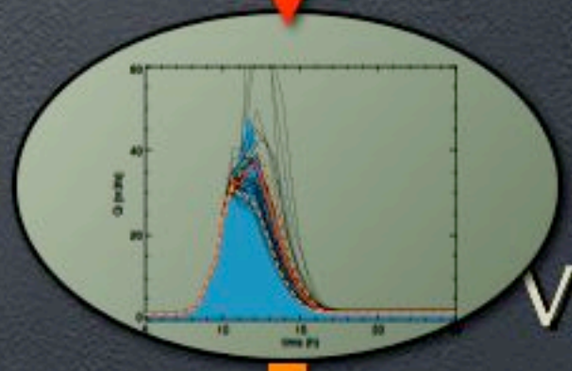
corrections

processed images

rainfall field for hydrological use

GenHi

hydrological model



VisHid

merging

Raingauge network

short term rainfall forecasting

WARNING

Ensemble Forecasting

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El pronóstico hidrometeorológico debe ser siempre FINALISTA



El pronóstico hidrometeorológico debe ser siempre FINALISTA

Depende del objetivo, de los datos disponibles y de la capacidad de gestión que se tenga para utilizar los resultados.



Pronóstico meteorológico

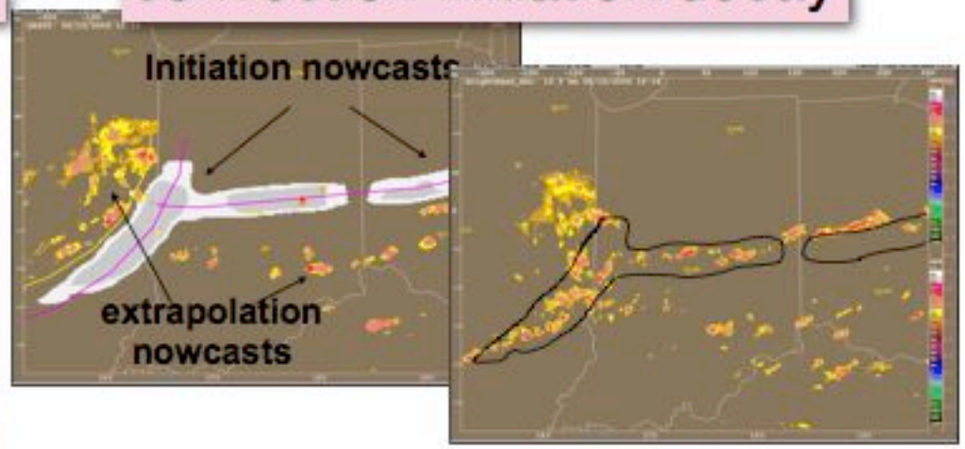
Precipitation forecasting

- ***Nowcasting***: short/range based on recent and current observations.

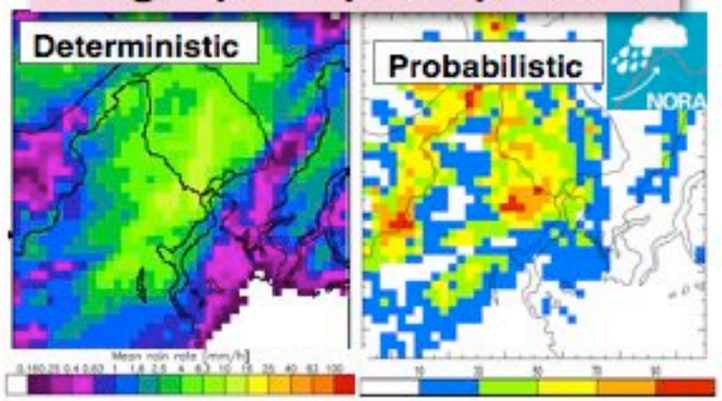
extrapolation of obs



convection initiation/decay



orographic precipitation

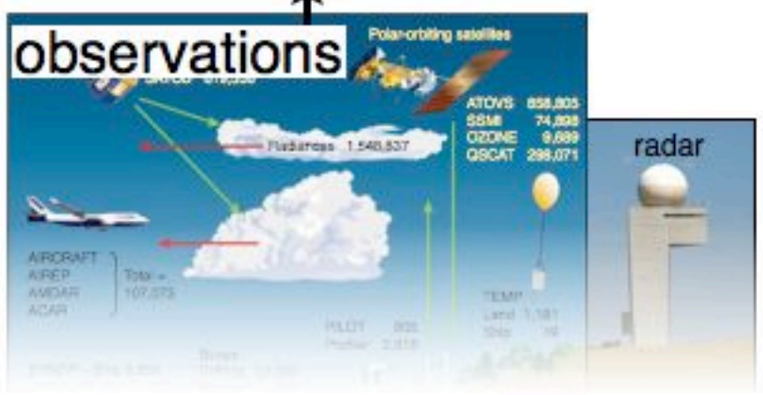


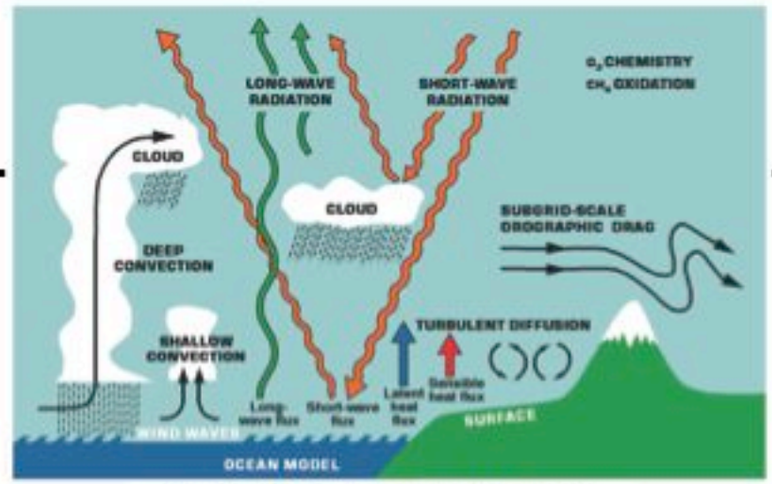
- ***Numerical Weather Prediction*** (NWP): three-dimensional models of the atmosphere.

NWP outputs

initial conditions

observations





model equations

3D forecasts of the atmosphere (u,v,w,T,P,RH,...)

Hydrometeorological processes and its interaction with the terrain

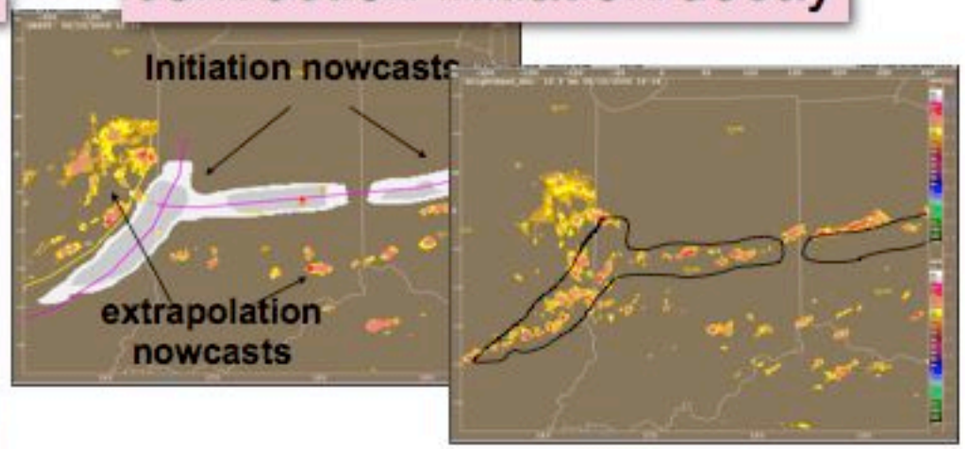
Precipitation forecasting

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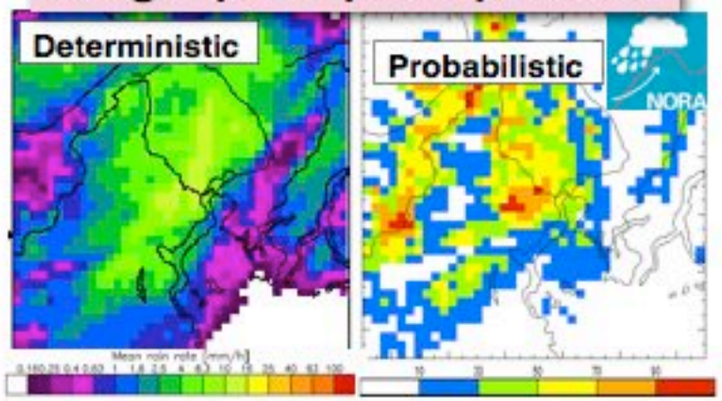
extrapolation of obs



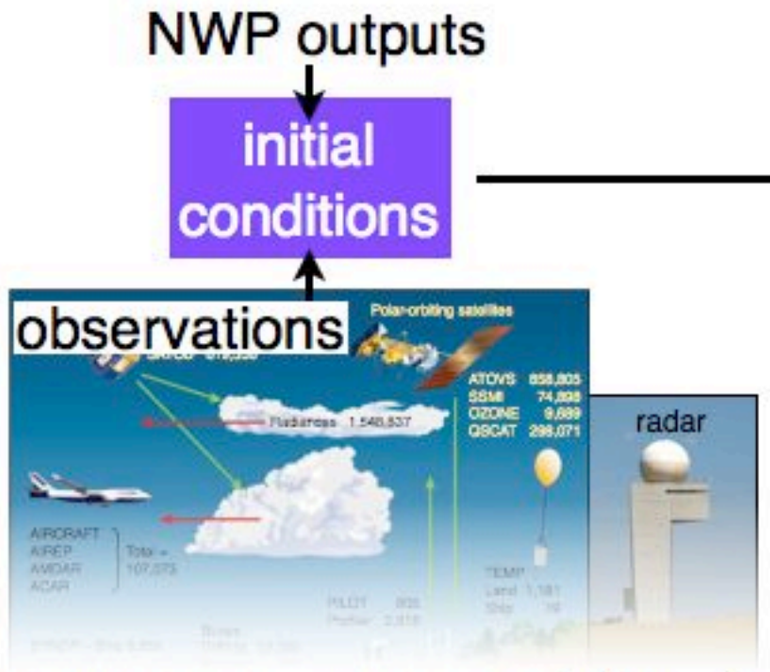
convection initiation/decay

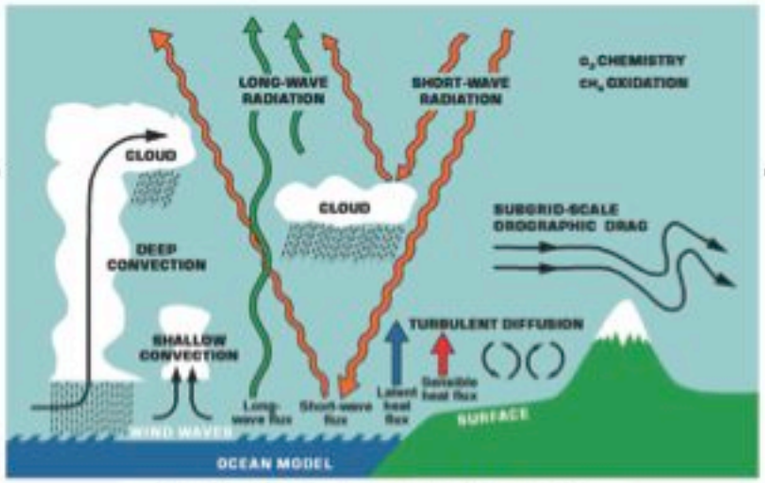


orographic precipitation



- ***Numerical Weather Prediction*** (NWP): three-dimensional models of the atmosphere.





model equations

3D forecasts of the atmosphere (u,v,w,T,P,RH,...)

- ***Statistical methods.*** More focused on seasonal forecasting of large-scale phenomena (El Niño Southern Oscillation, North Atlantic Oscillation,...).

Hydrometeorological processes and its interaction with the terrain

Increasing anticipation of heavy rainfalls

IMPRINTS



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Increasing anticipation of heavy rainfalls

IMPRINTS



Meteorological rainfall forecasting (NWP)

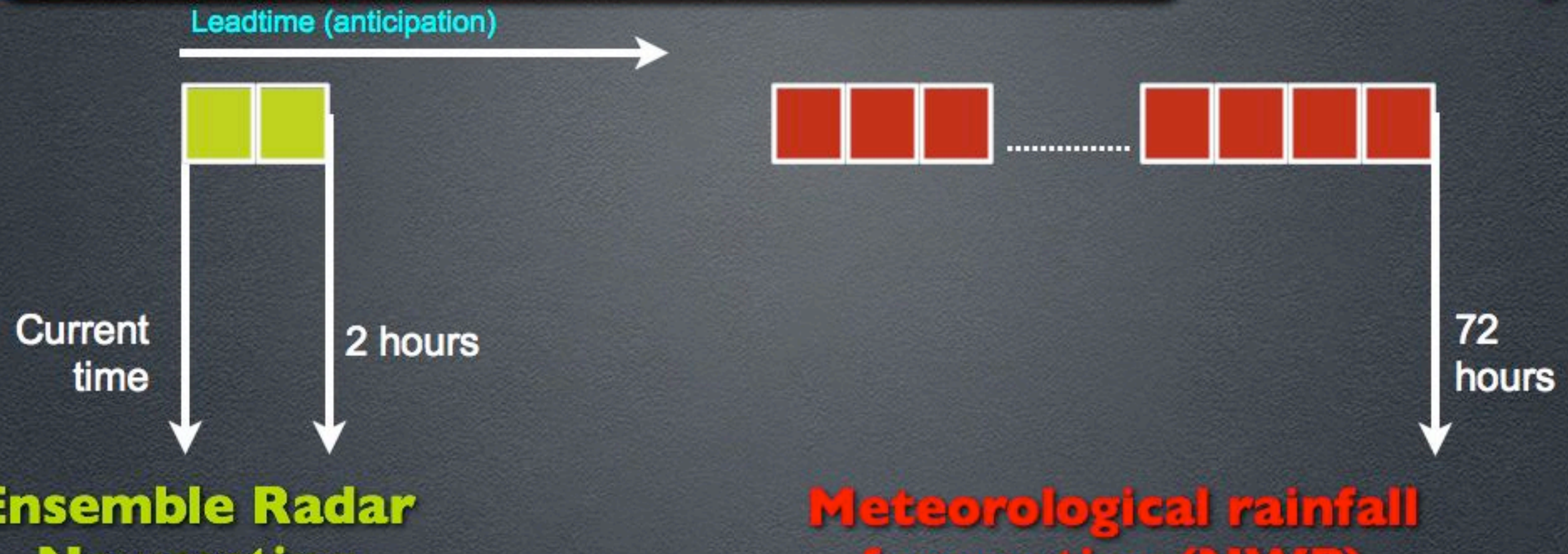
- **Adapting high-resolution meteorological model forecasts** to FF & DF early warnings **(from 6h to 72 h)**

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Increasing anticipation of heavy rainfalls

IMPRINTS



Ensemble Radar Nowcasting

Meteorological rainfall forecasting (NWP)

- **High resolution radar nowcasting probabilistic outputs** (ensembles) for FF & DF forecasting **(up to 2 h)**

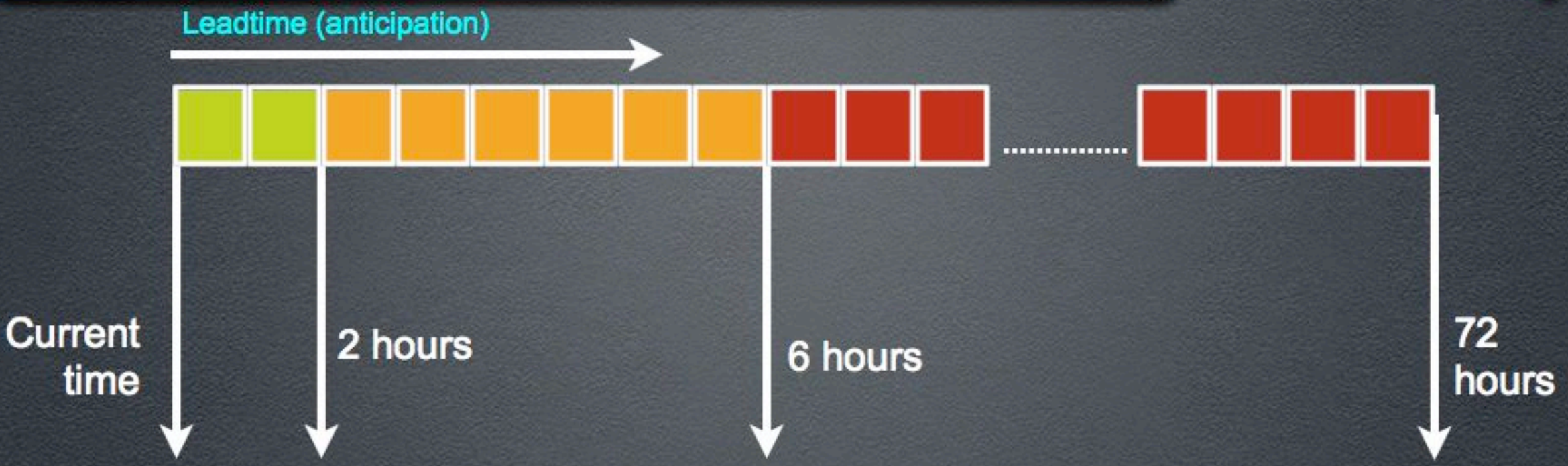
- **Adapting high-resolution meteorological model forecasts** to FF & DF early warnings **(from 6h to 72 h)**

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Increasing anticipation of heavy rainfalls

IMPRINTS



- **High resolution radar nowcasting probabilistic outputs** (ensembles) for FF & DF forecasting **(up to 2 h)**
- **Combining (blending) radar rainfall nowcasting with probabilistic NWP products (between 2h and 6h)**
- **Adapting high-resolution meteorological model forecasts** to FF & DF early warnings **(from 6h to 72 h)**

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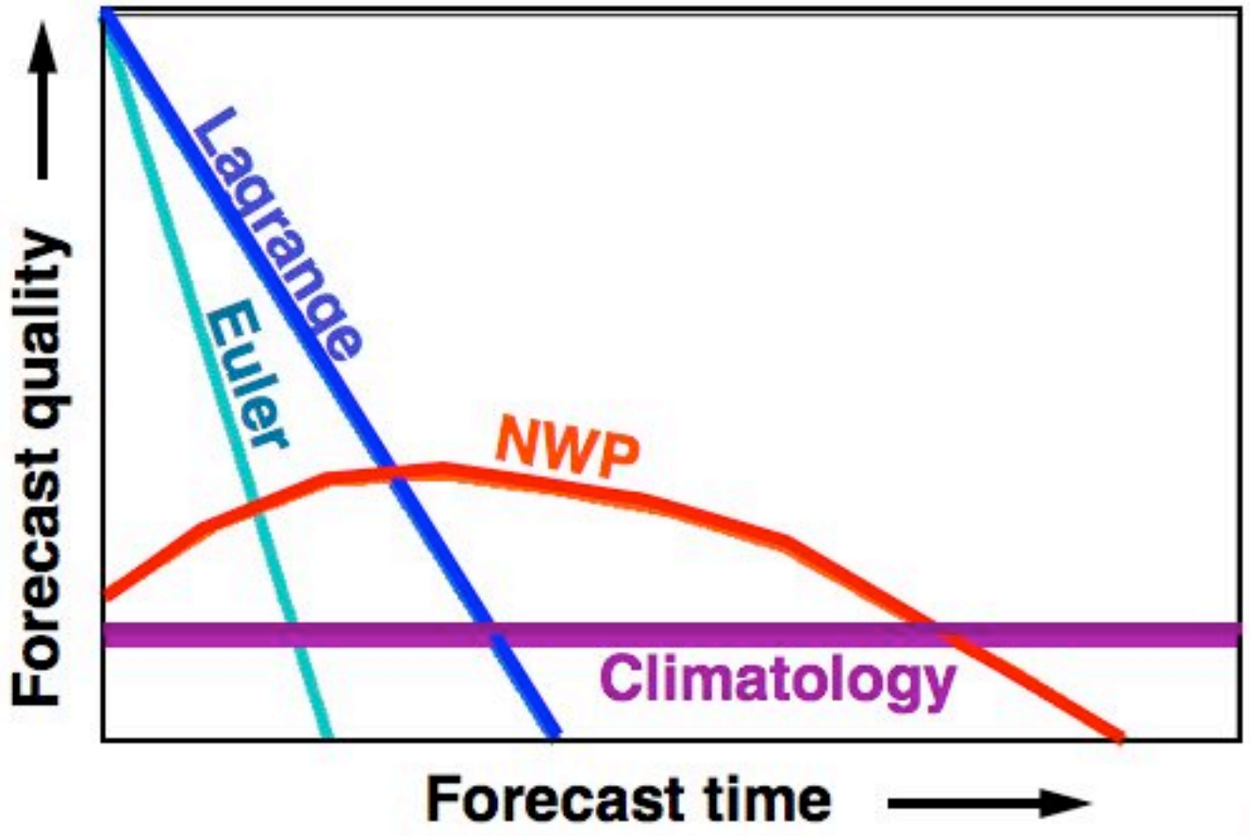
Precipitation forecasting

The types of meteorological forecasting outputs which are potentially useful include:

Quantative Preciptiation Forecasts (QPF).

And other variables such as temperature, wind, humidity,...

- ***Nowcasting***: short/range based on recent and current observations.
- ***Numerical Weather Prediction*** (NWP): three-dimensional models of the atmosphere.
- ***Statistical methods.***



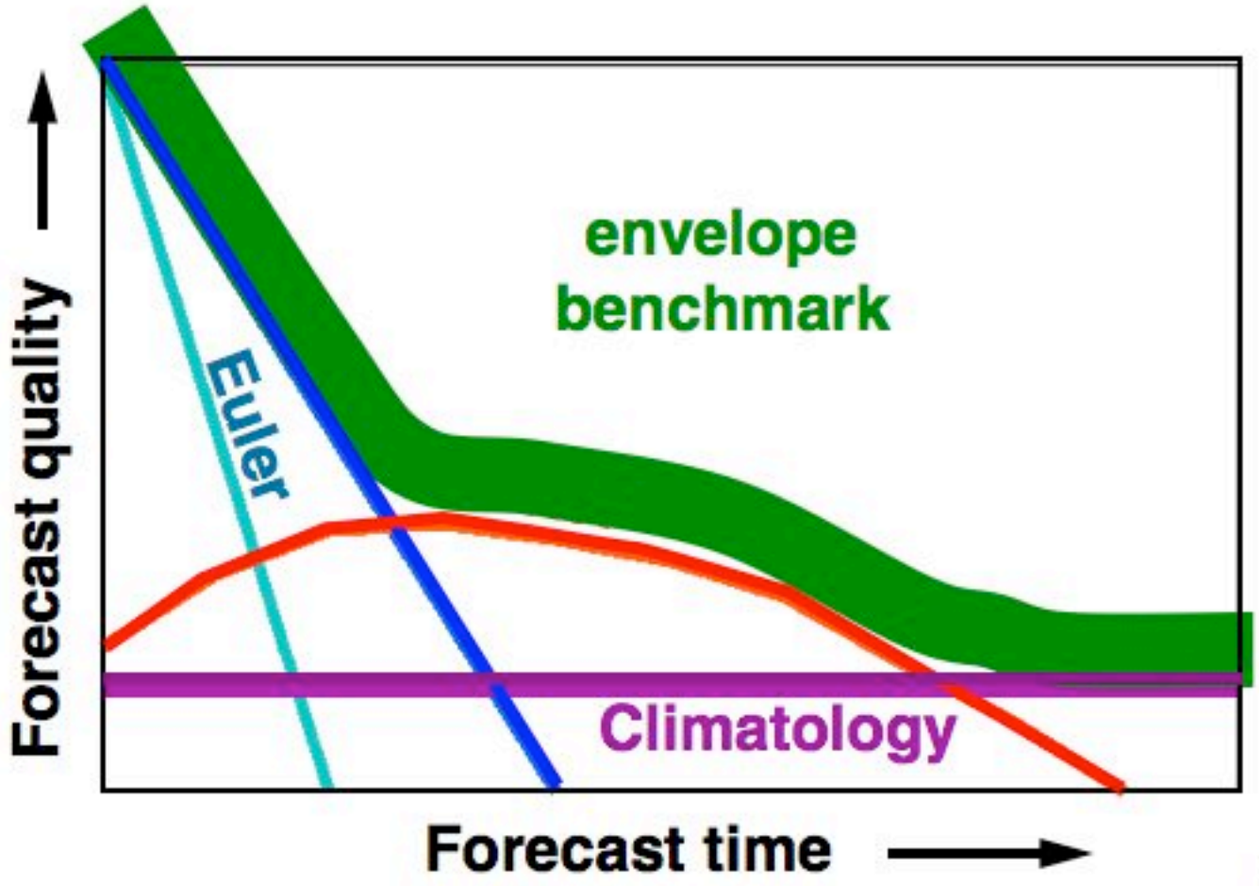
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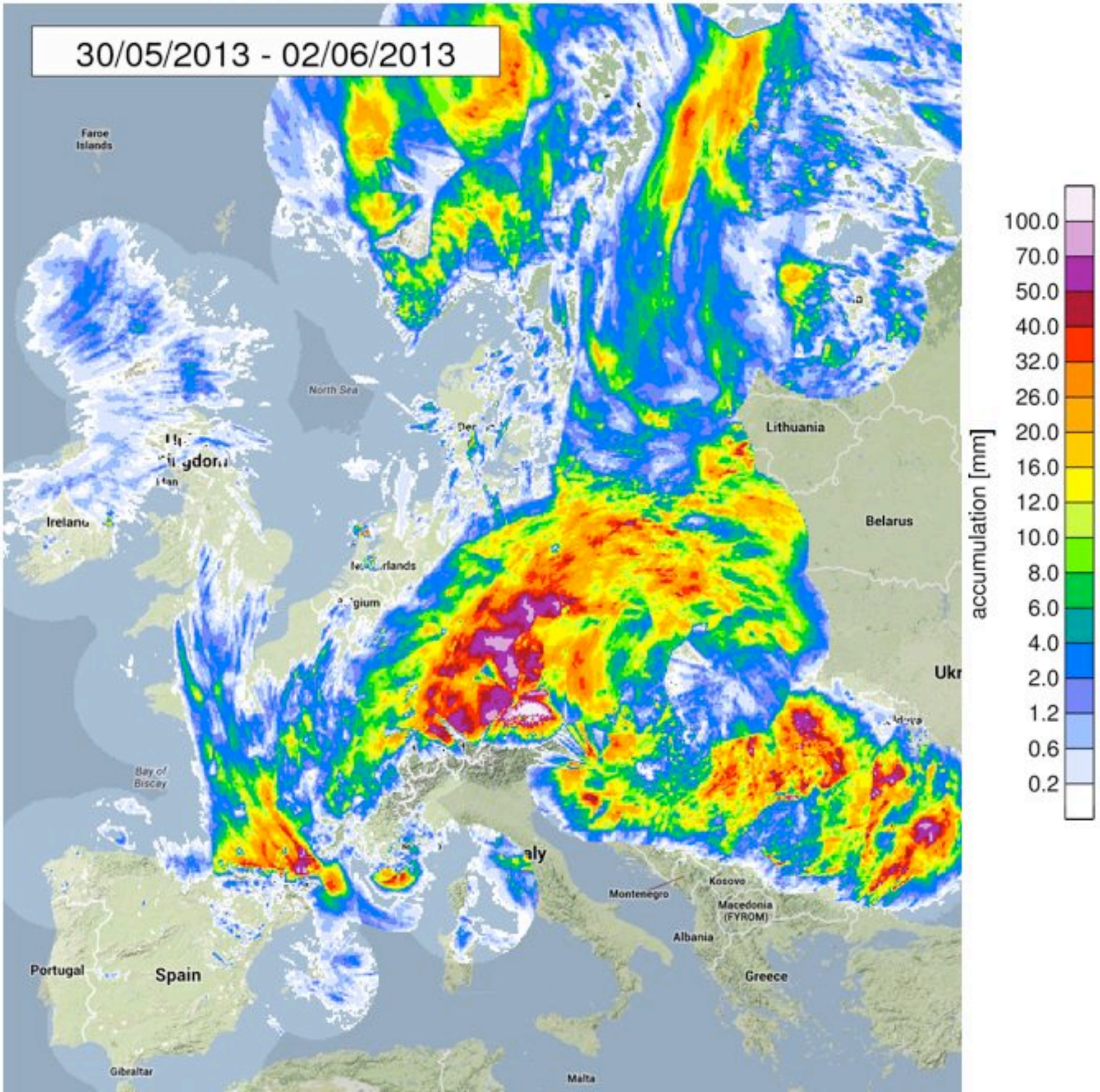
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- ***Statistical methods.***



Precipitation forecasting - Evaluation of nowcasts and NWP

01 June 2013 - 48 hour evaluation



Hydrometeorological processes and its interaction with the terrain

Precipitation forecasting - Evaluation of nowcasts and NWP

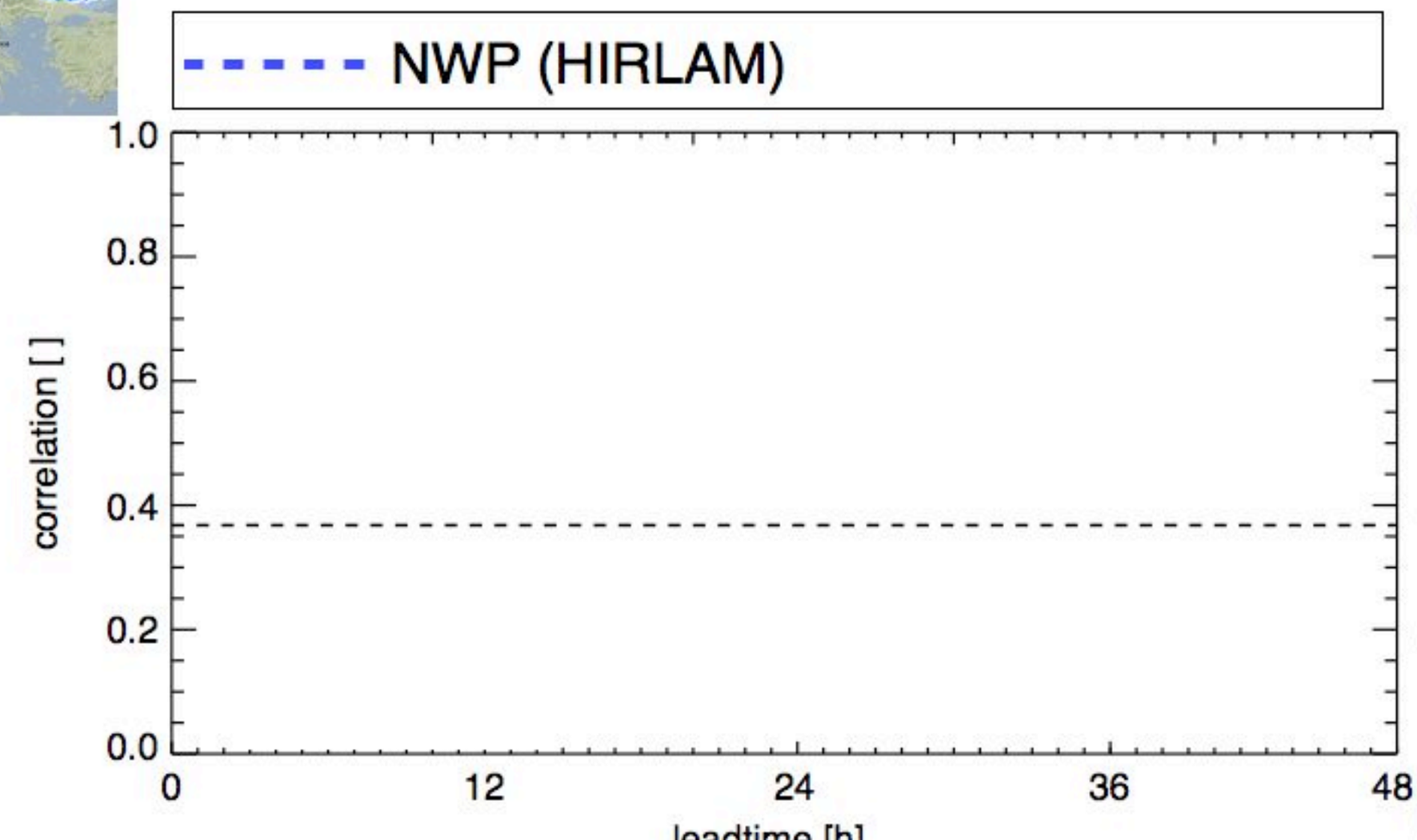


Comparison between rainfall forecasts and observations

Precipitation forecasting - Evaluation of nowcasts and NWP



Comparison between rainfall forecasts and observations

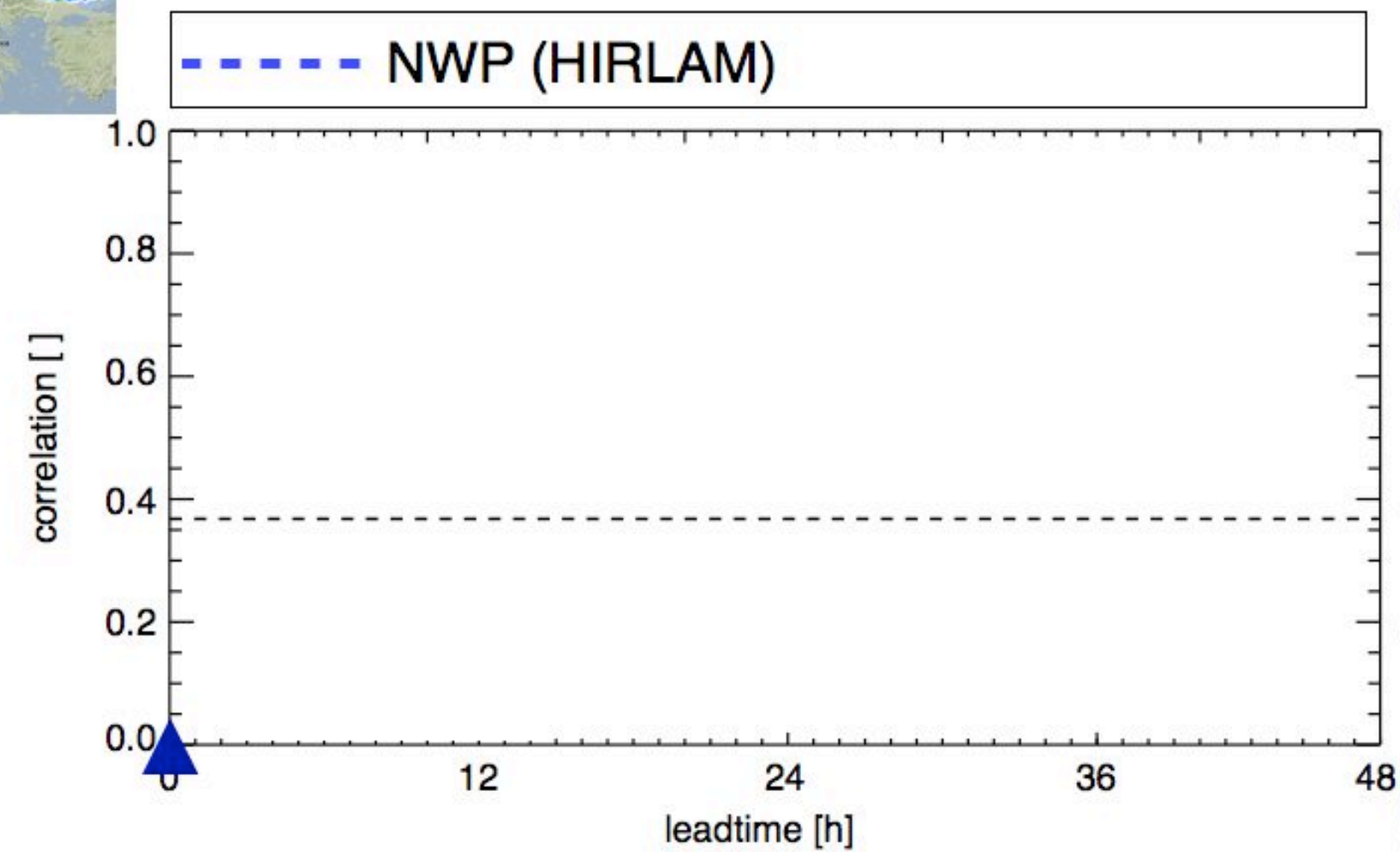


Hydrometeorological processes and its interaction with the terrain

Precipitation forecasting - Evaluation of nowcasts and NWP



Comparison between rainfall forecasts and observations

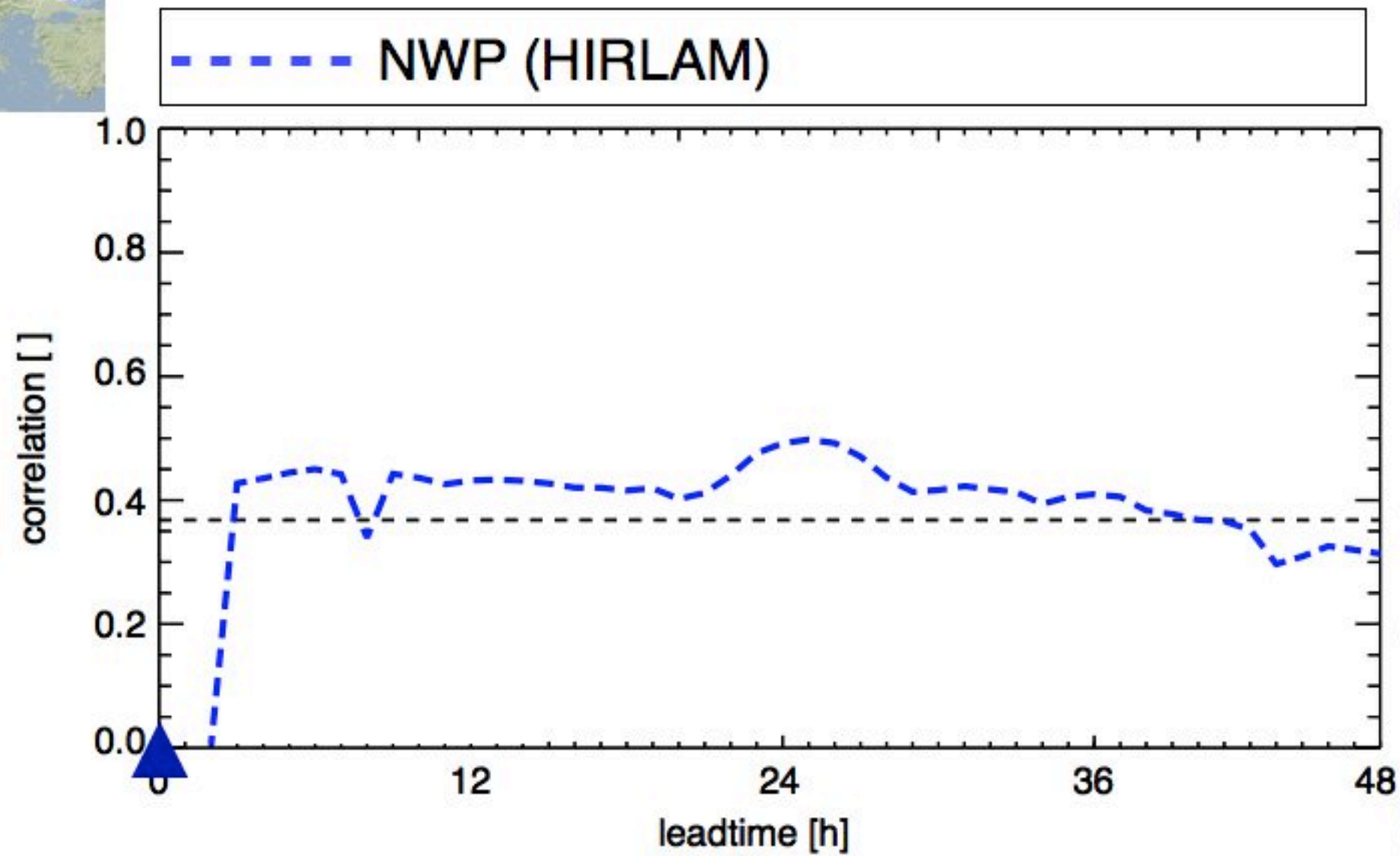


Hydrometeorological processes and its interaction with the terrain

Precipitation forecasting - Evaluation of nowcasts and NWP



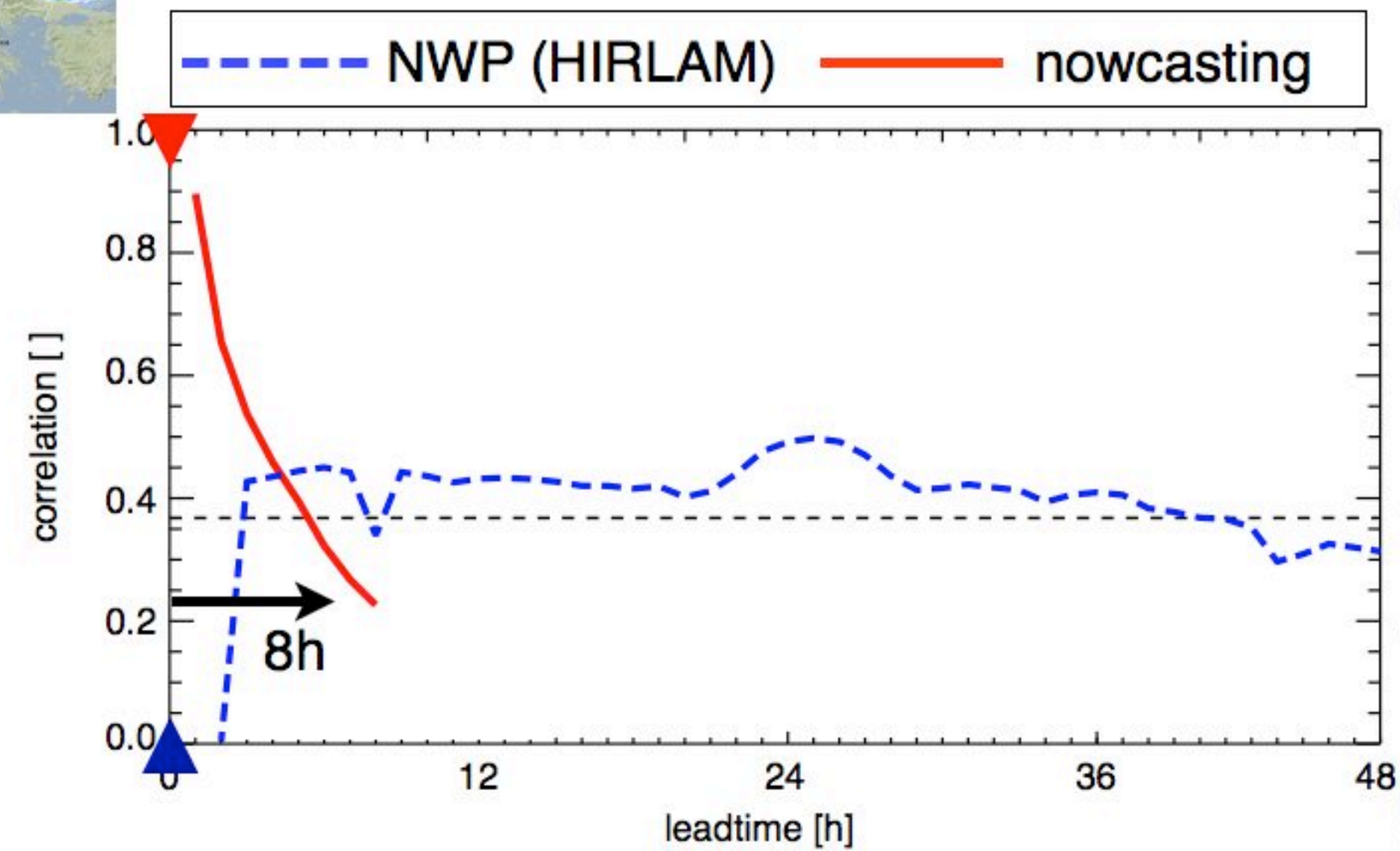
Comparison between rainfall forecasts and observations



Precipitation forecasting - Evaluation of nowcasts and NWP



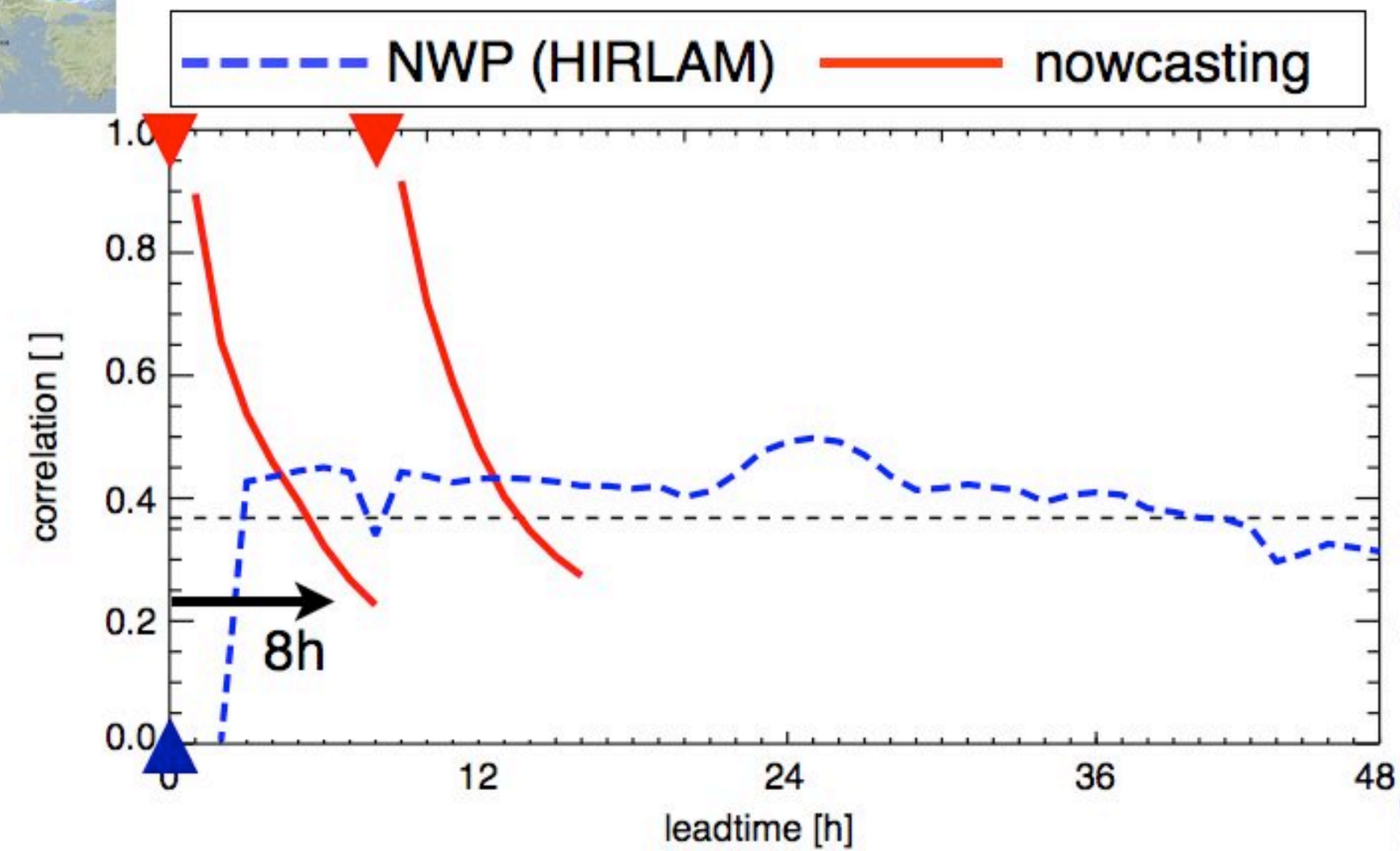
Comparison between rainfall forecasts and observations



Precipitation forecasting - Evaluation of nowcasts and NWP



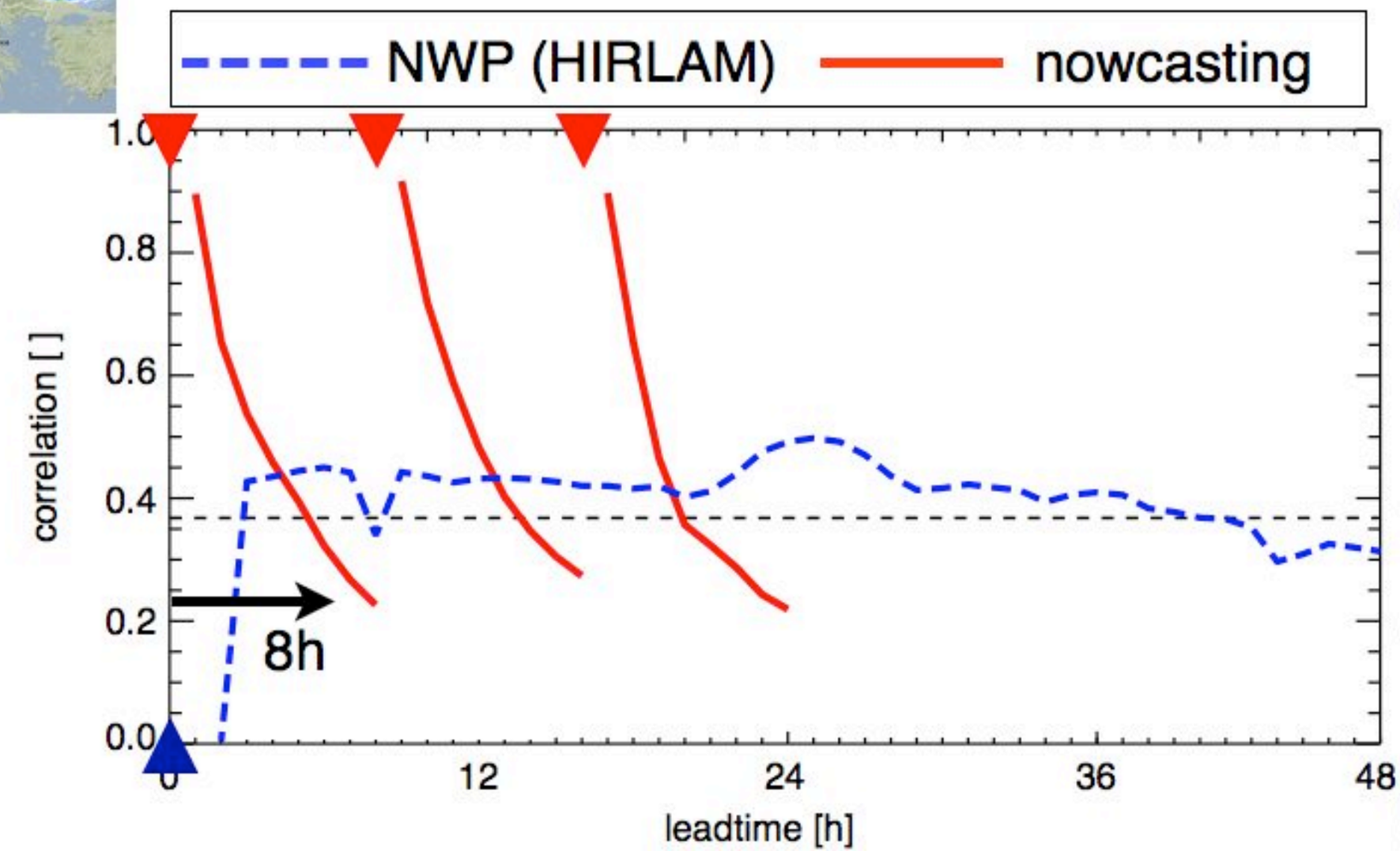
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Precipitation forecasting - Evaluation of nowcasts and NWP



Comparison between rainfall forecasts and observations

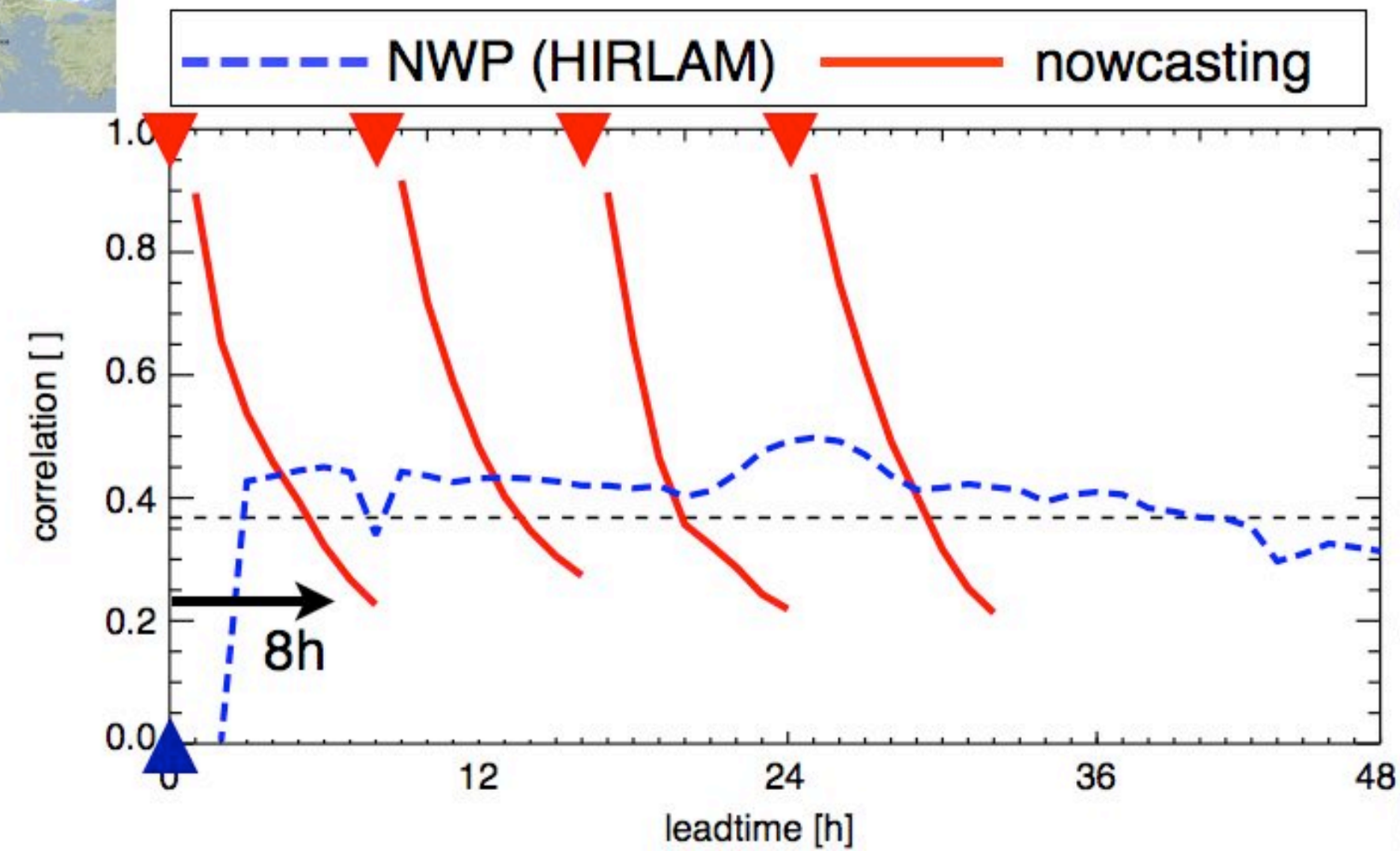


Hydrometeorological processes and its interaction with the terrain

Precipitation forecasting - Evaluation of nowcasts and NWP



Comparison between rainfall forecasts and observations

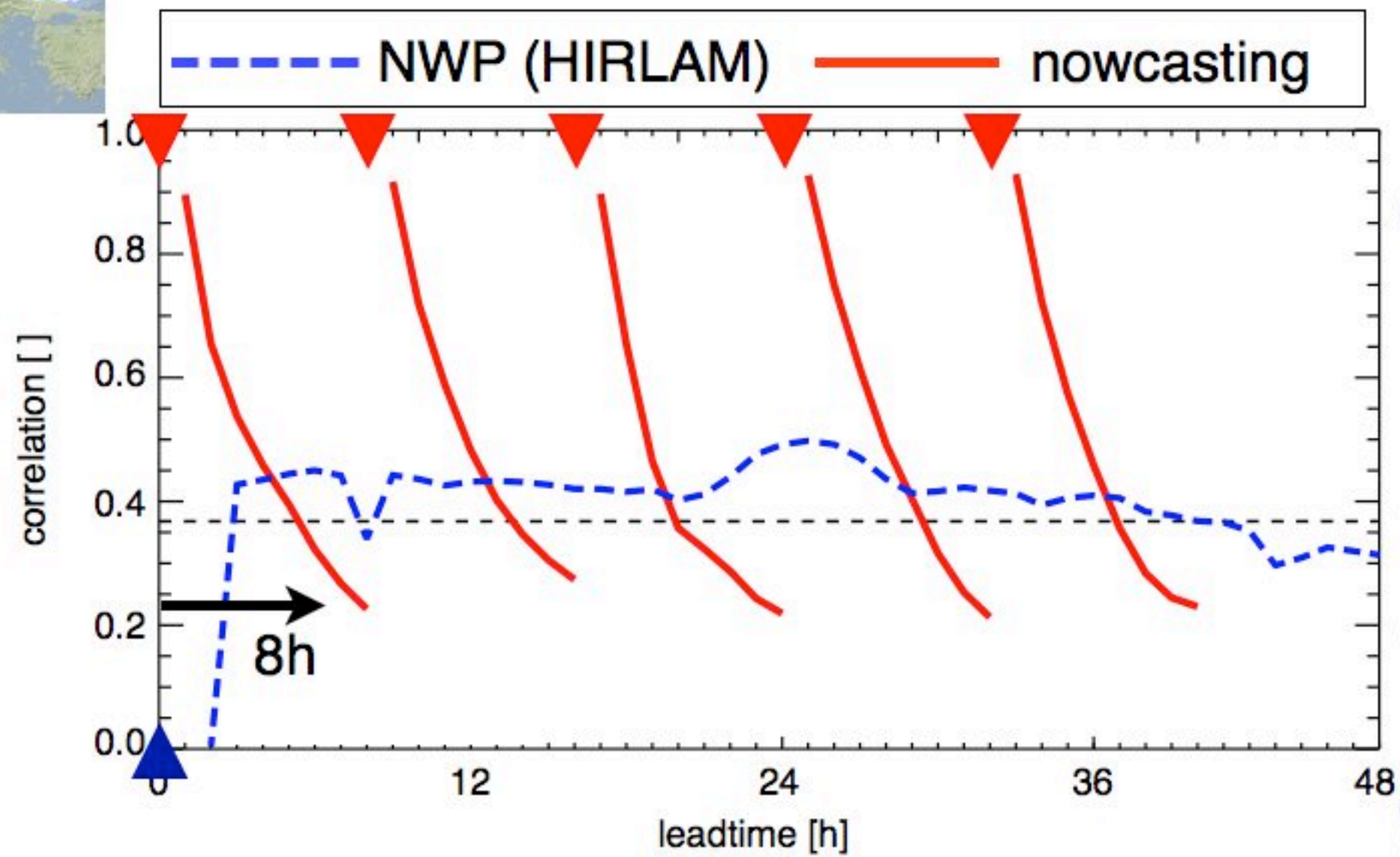


Hydrometeorological processes and its interaction with the terrain

Precipitation forecasting - Evaluation of nowcasts and NWP



Comparison between rainfall forecasts and observations

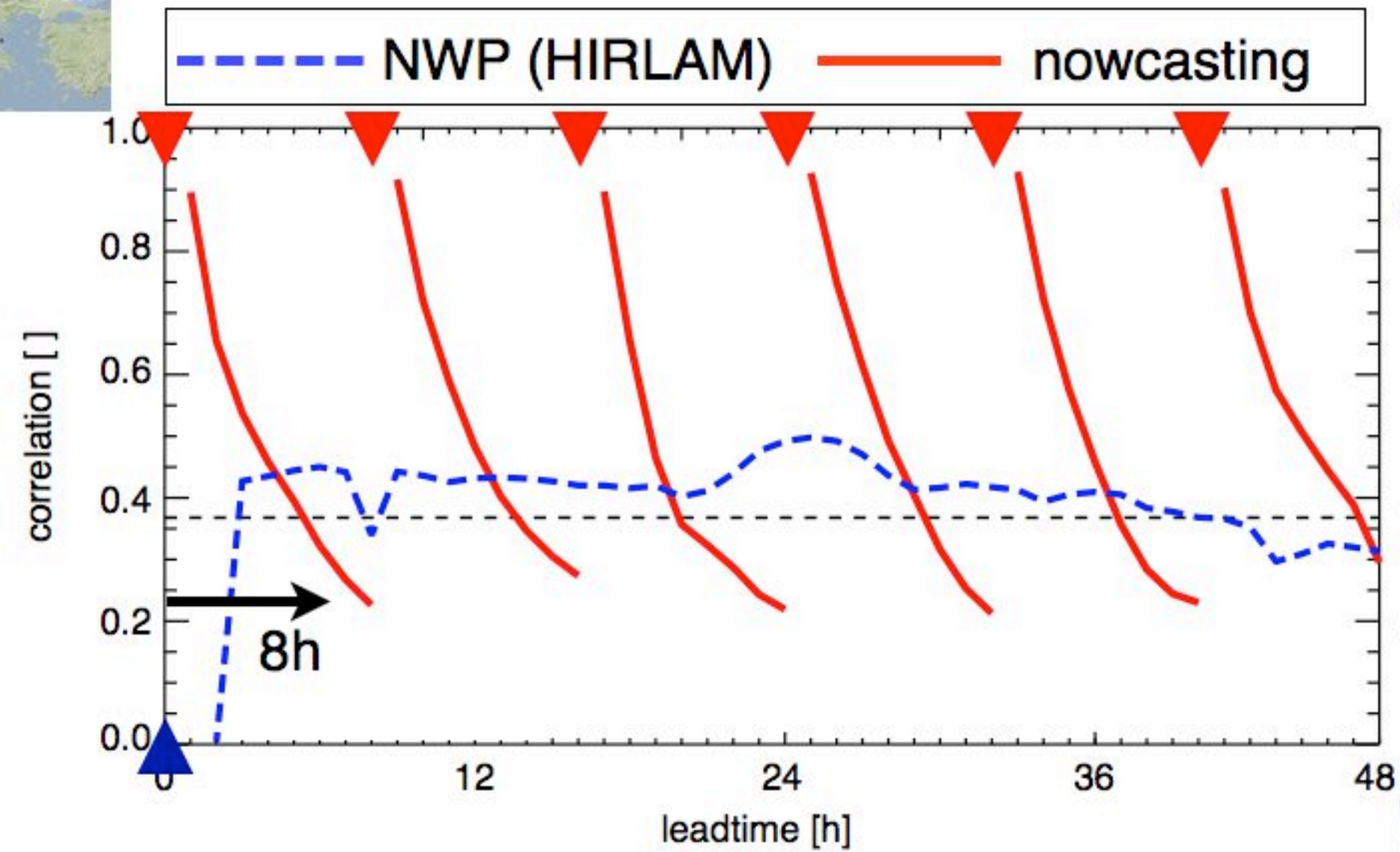


Hydrometeorological processes and its interaction with the terrain

Precipitation forecasting - Evaluation of nowcasts and NWP



Comparison between rainfall forecasts and observations



Hydrometeorological processes and its interaction with the terrain

CASE STUDY in The Netherlands (20 June 2013)

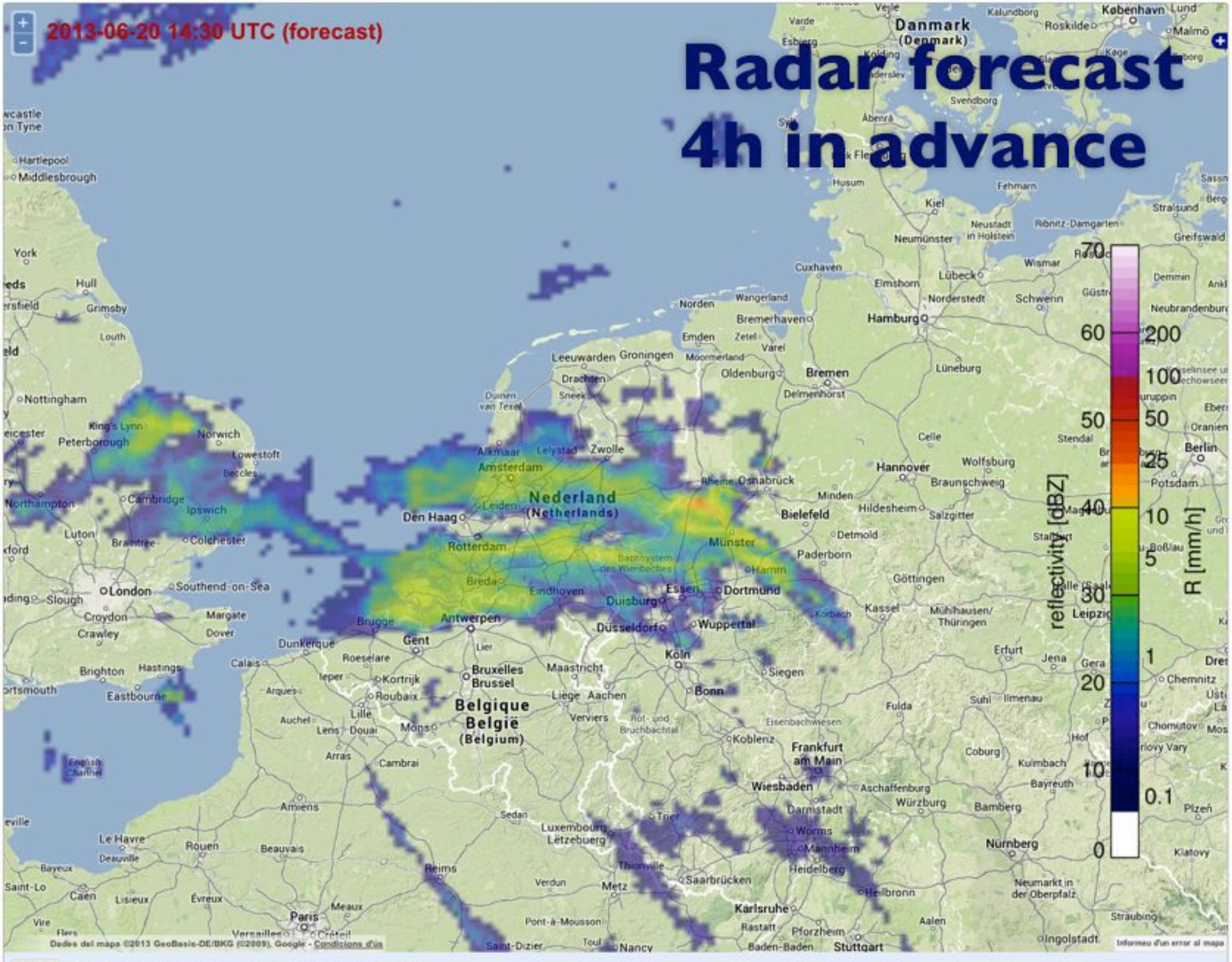
Ondertussen in het oosten van het land: zandzakken en rubberbootjes



Noodweer in Enschede. Screenshot van WeerGroningen.

2013-06-20 14:30 UTC (forecast)

Radar forecast 4h in advance



Real Time | Historical Episode

Jun 2013

Su	Mo	Tu	We	Th	Fr	Sa
						1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30						

Today

Number of Frames: 32

Hour/Minute: 24 : 00

Topographies
- Google Physical
- Google Streets
- Google Satellite
- Google Hybrid

Layers
- Convective cells
- Reflectivity (dBZ)
- FMI Product

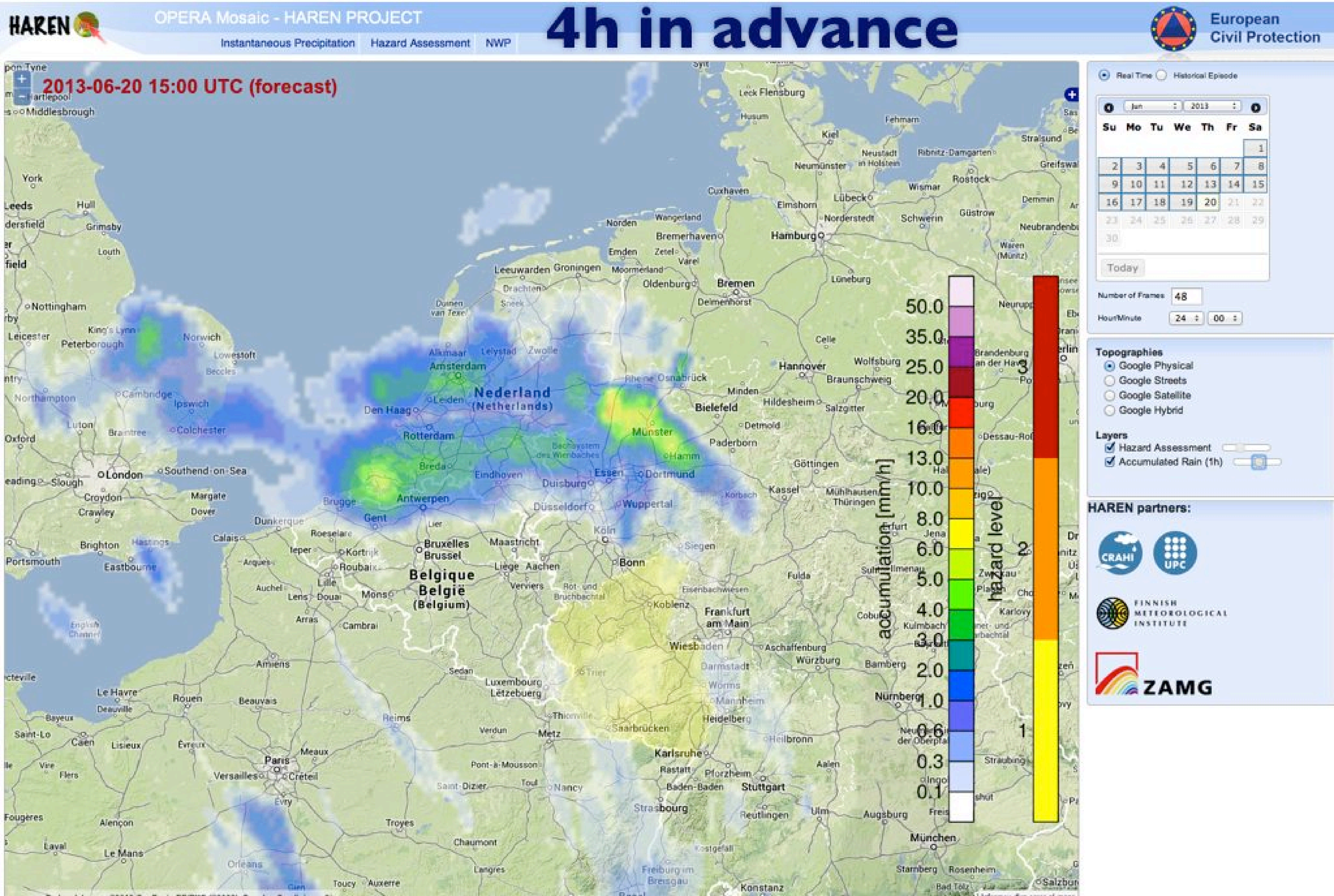
HAREN partners:

CRAHI | UPC | Finnish Meteorological Institute | ZAMG

Dades del mapa ©2013 GeoBasis-DE/BKG (©2009), Google - Condicions d'ús

Center Lon.:0.99 Lat.:54.81 X (Km utm):109844.92 Y (Km utm).:7324521.07

1h Radar Accumulation 4h in advance



1h Radar Accumulation

Observed

OPERA Mosaic - HAREN PROJECT

OPERA Mosaic - HAREN PROJECT

Instantaneous Precipitation | Hazard Assessment | NWP

European Civil Protectio

2013-06-20 15:00 UTC

Real Time | Historical Episode

Jun 2013

Su	Mo	Tu	We	Th	Fr	Sa
						1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30						

Today

Number of Frames 32

Hour/Minute forecasting time 15 00

View

Topographies
- Google Physical
- Google Streets
- Google Satellite
- Google Hybrid

Layers
- Hazard Assessment
- Accumulated Rain (1h)

HAREN partners:

CRAHI UPC FINNISH METEOROLOGICAL INSTITUTE ZAMG

accumulation [mm/h]: 50.0, 35.0, 25.0, 20.0, 16.0, 13.0, 10.0, 8.0, 6.0, 5.0, 4.0, 3.0, 2.0, 1.0, 0.6, 0.3, 0.1

hazard level: 3, 2, 1

Nederland (Netherlands)

Deutschland (Germany)

2013 GeoBasis-DE/BKG (©2009), Google, basado en BCN IGN España

Informeu d'un error al mapa

h.:0.22 Lat.:54.40 X (Km utm):24846.94 Y (Km utm).:7245638.06

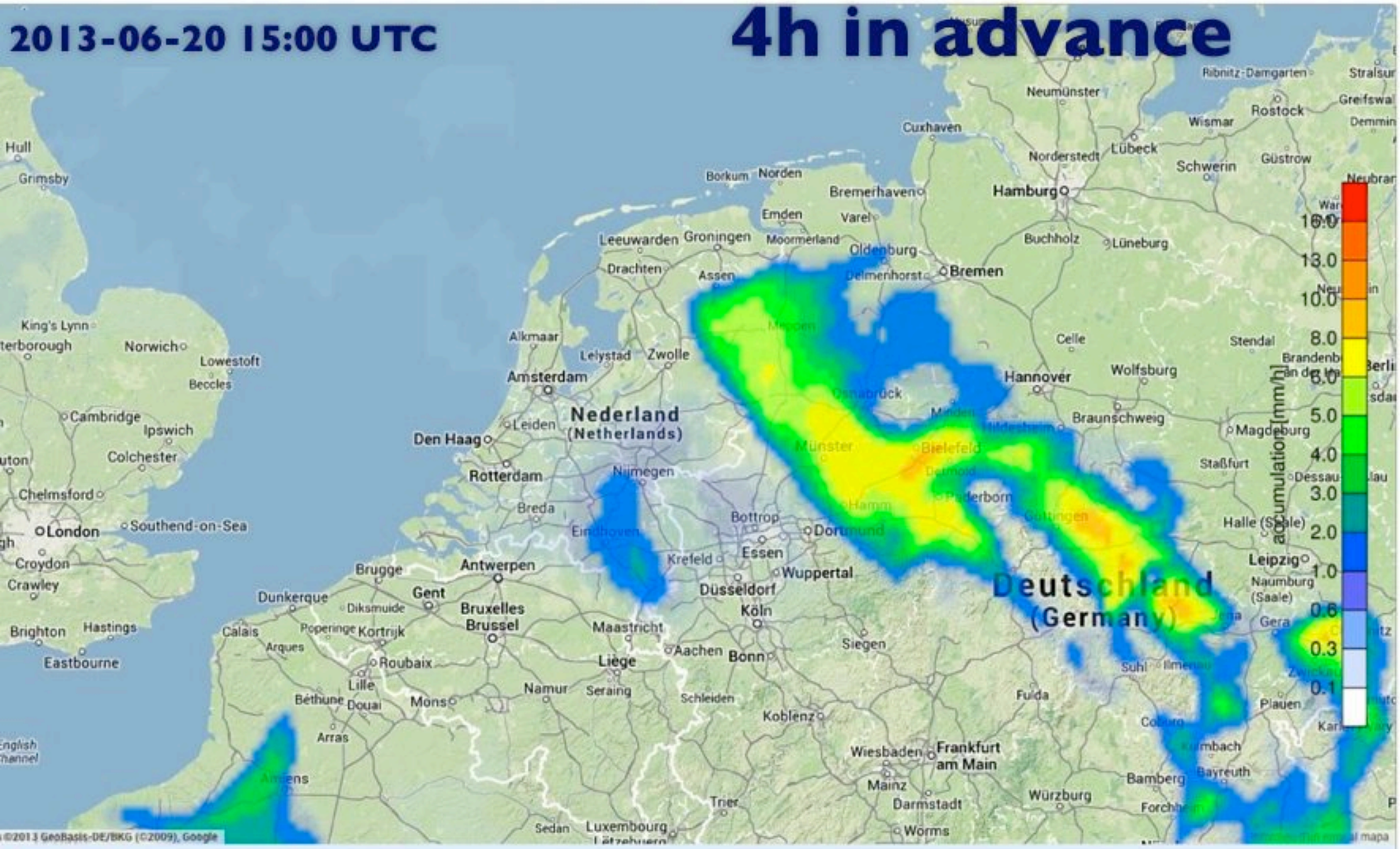
OPERA Mosaic - HAREN PROJECT

Instantaneous Precipitation | Hazard Assessment | NWP

Model forecast 4h in advance

Euro Civil

2013-06-20 15:00 UTC



©2013 GeoBasis-DE/BKG (©2009), Google

on.:8.81 Lat.:54.36 X (Km utm):981227.04 Y (Km utm).:7238911.60

2013-06-20 08:00 — 2013-06-21 15:00

Real Time | Historical Episode

Jun 2013

Su	Mo	Tu	We	Th	Fr
2	3	4	5	6	
9	10	11	12	13	
16	17	18	19	20	
23	24	25	26	27	
30					

Today

Number of Frames: 32

Hour/Minute forecasting time: 15 00

View

Topographies

- Google Physical
- Google Streets
- Google Satellite
- Google Hybrid

Layers

- NWP hourly accumulation
- %[R > 1mm]

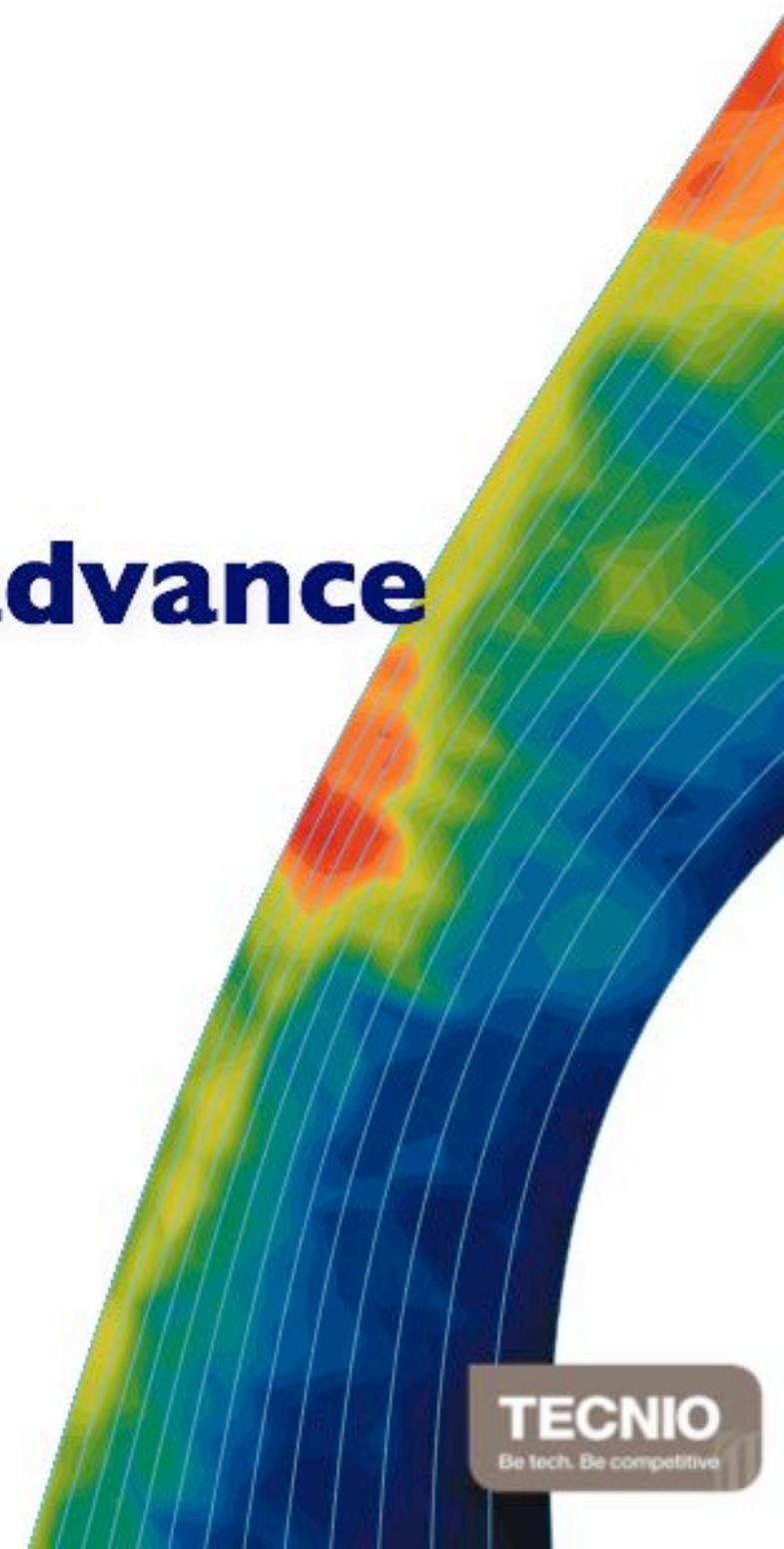
HAREN partners:

CRAHI | UPC | FINNISH METEOROLOGICAL INSTITUTE | ZAMG

HAREN

European Civil Protection

Flood warnings
From 6h to few days in advance

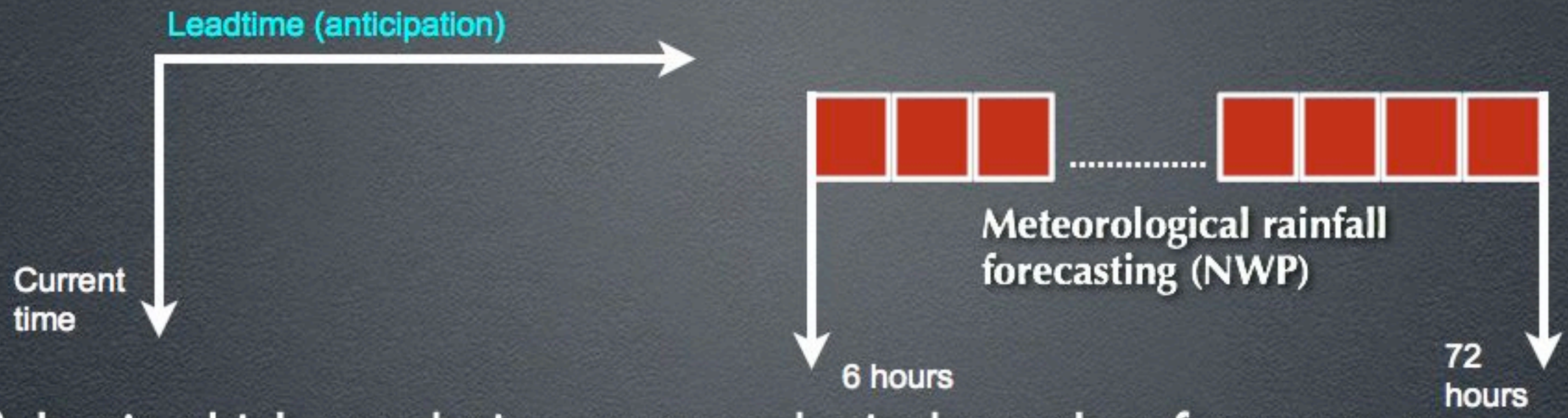


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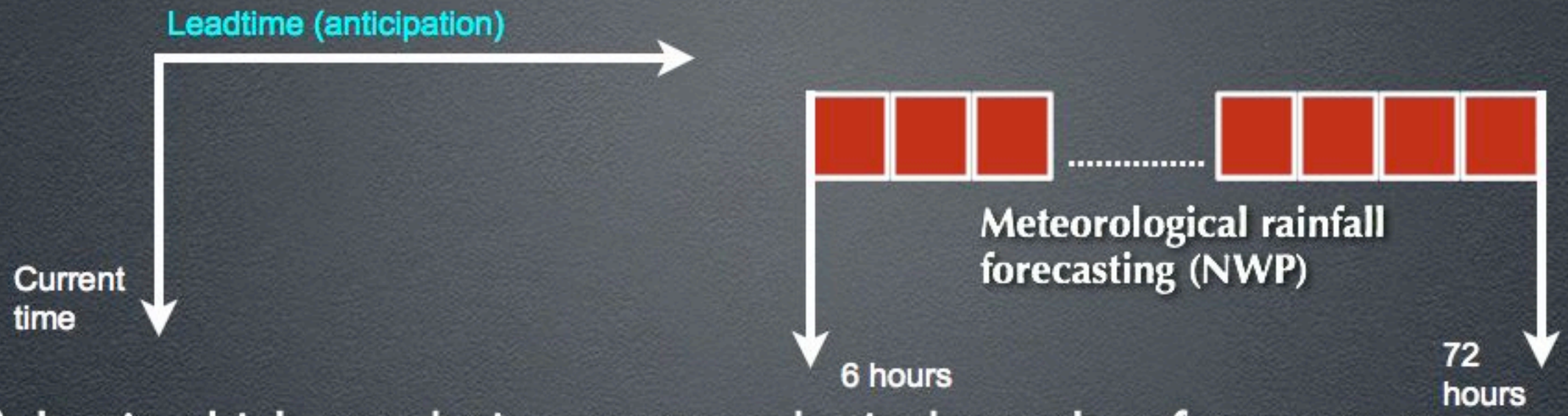
TECNIO
Be tech. Be competitive

Increasing anticipation of heavy rainfalls

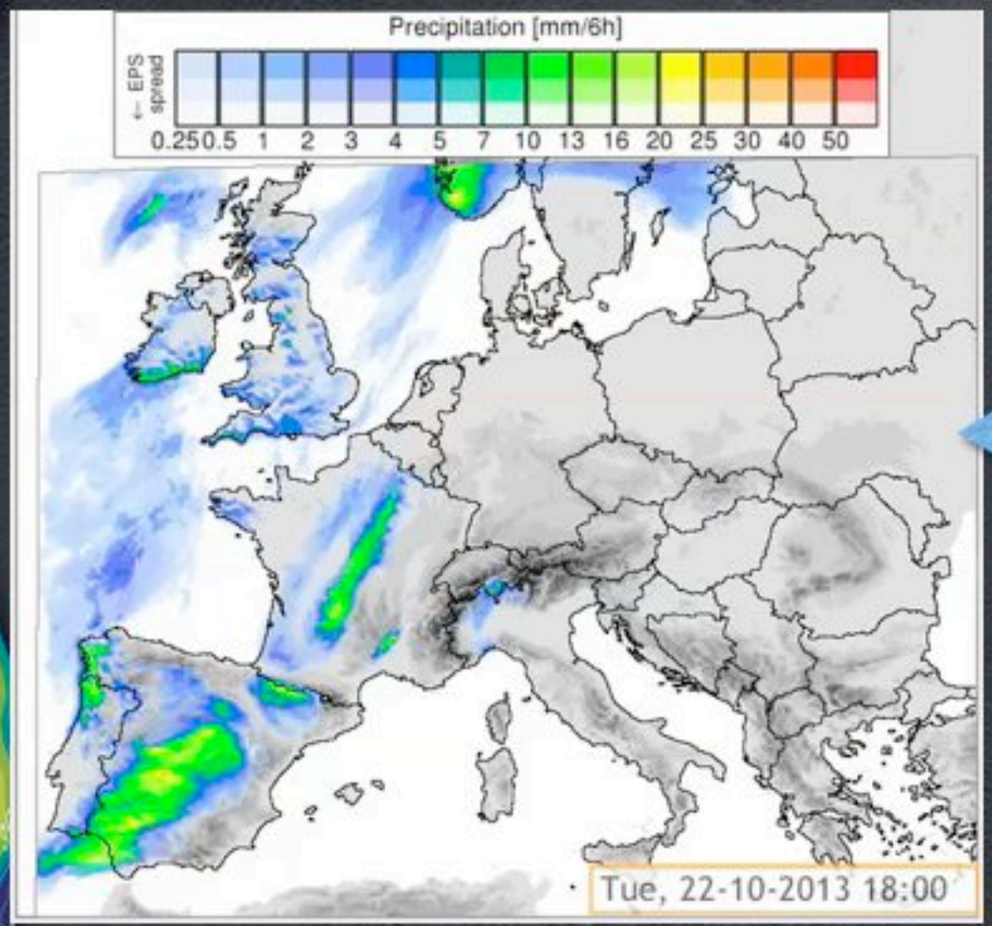


- Adapting high-resolution meteorological weather forecasts to their use for FF & DF early warnings (from 6h to 72 h)

Increasing anticipation of heavy rainfalls



- Adapting high-resolution meteorological weather forecasts to their use for FF & DF early warnings (from 6h to 72 h)



Initialisation with ECMWF-VAREPS
(15 days, 51 members, 32 km resolution)

Operational COSMO-LEPS 7
7 km spatial resolution
since Dec 2009

Probabilistic Forecast COSMO-LEPS
16 Ensembles

Source: MeteoSwiss-
COSMO Consortium

CRAHI

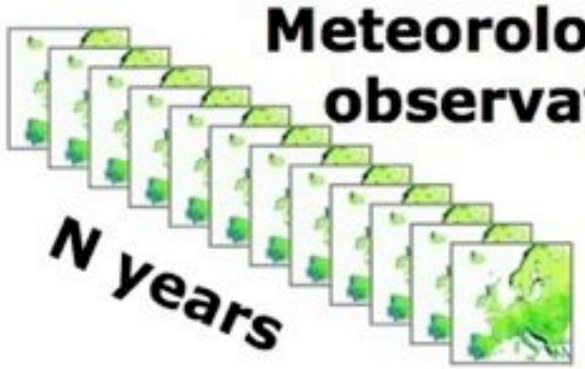
UPC

TECNIO

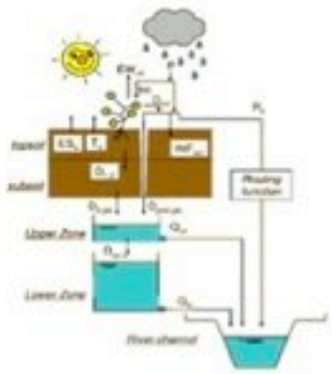
EUROPEAN FLOOD AWARENESS SYSTEM (EFAS)

Establish thresholds – from model climatology

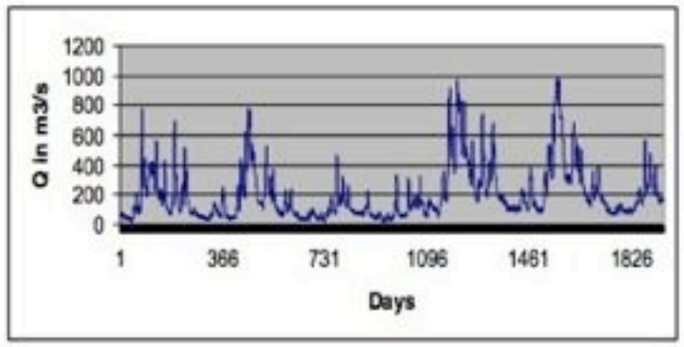
Meteorological observations



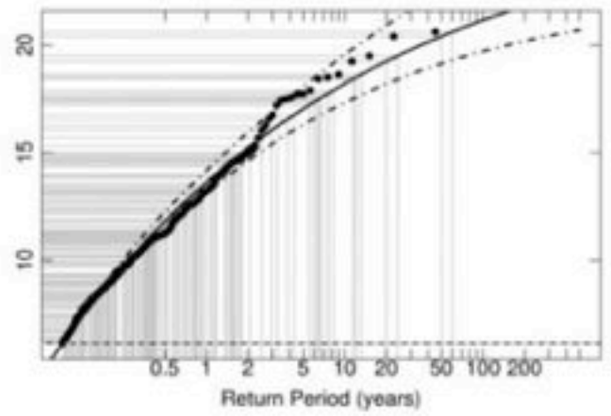
LISFLOOD



Discharge time series



Return period statistics



Thresholds

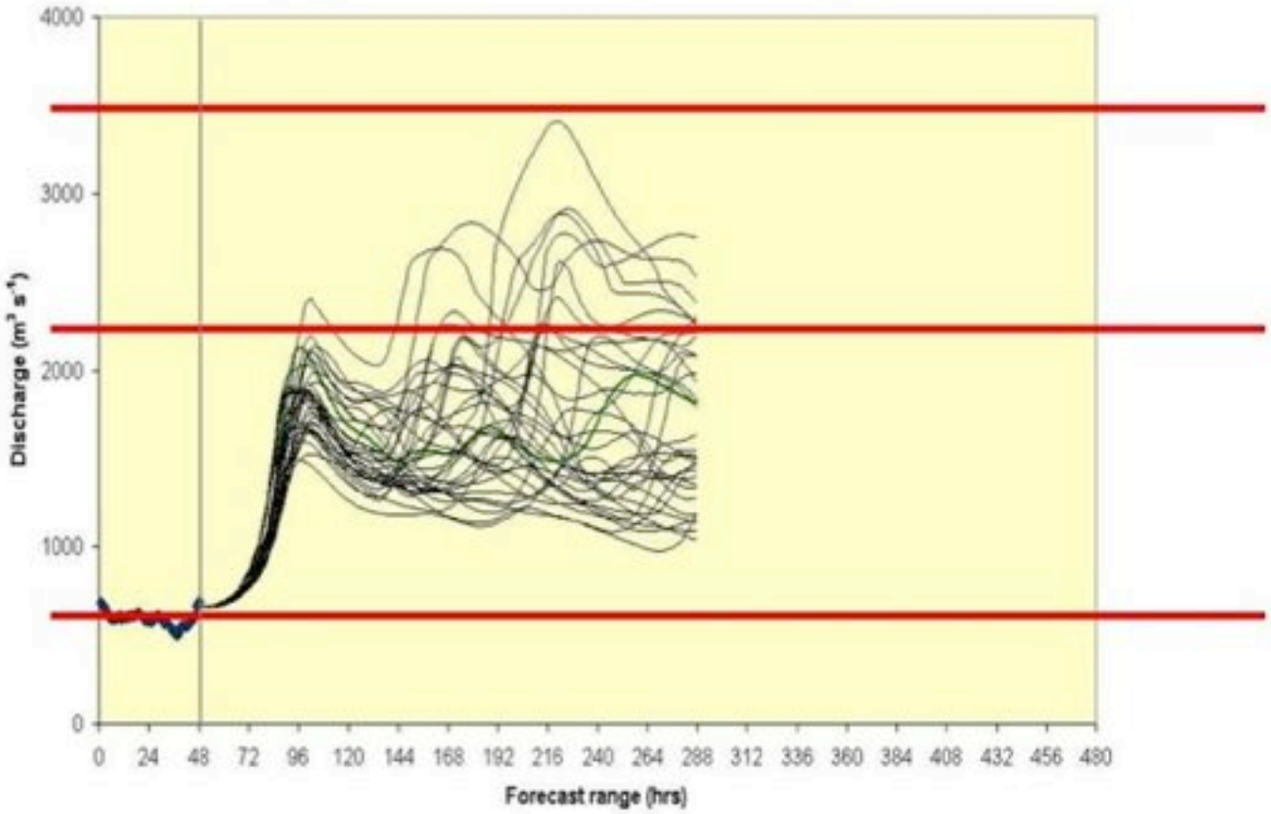
- Q20
- Q5
- Q2
- Q1.3

- **Thresholds are derived from simulated time series.**
- **The same model set-up and parameterisations are used in the forecasts to remain model consistent**

Joint Research Centre

Concept of threshold exceedance

For flood early warning we want to know if critical discharges are exceeded – not necessarily the discharges themselves

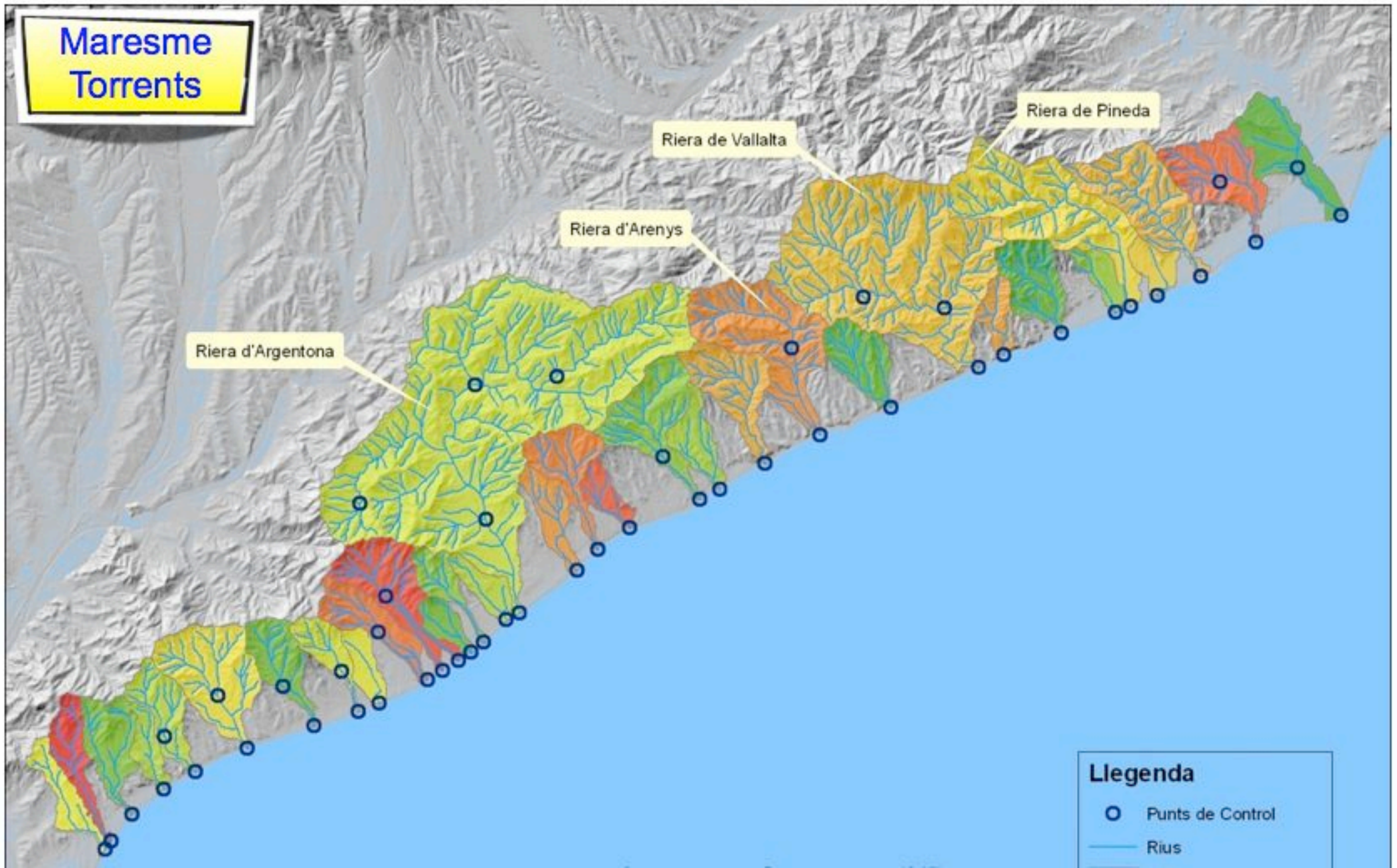


If the threshold for flooding is here, there is no problem

If the threshold for flooding is here, there might be a problem

If the threshold for flooding is here, there is almost certain a problem

In Flash Floods, the basins affected are small (tenths of Km^2) and show very quick responses (from 1/2 hour to few hours)



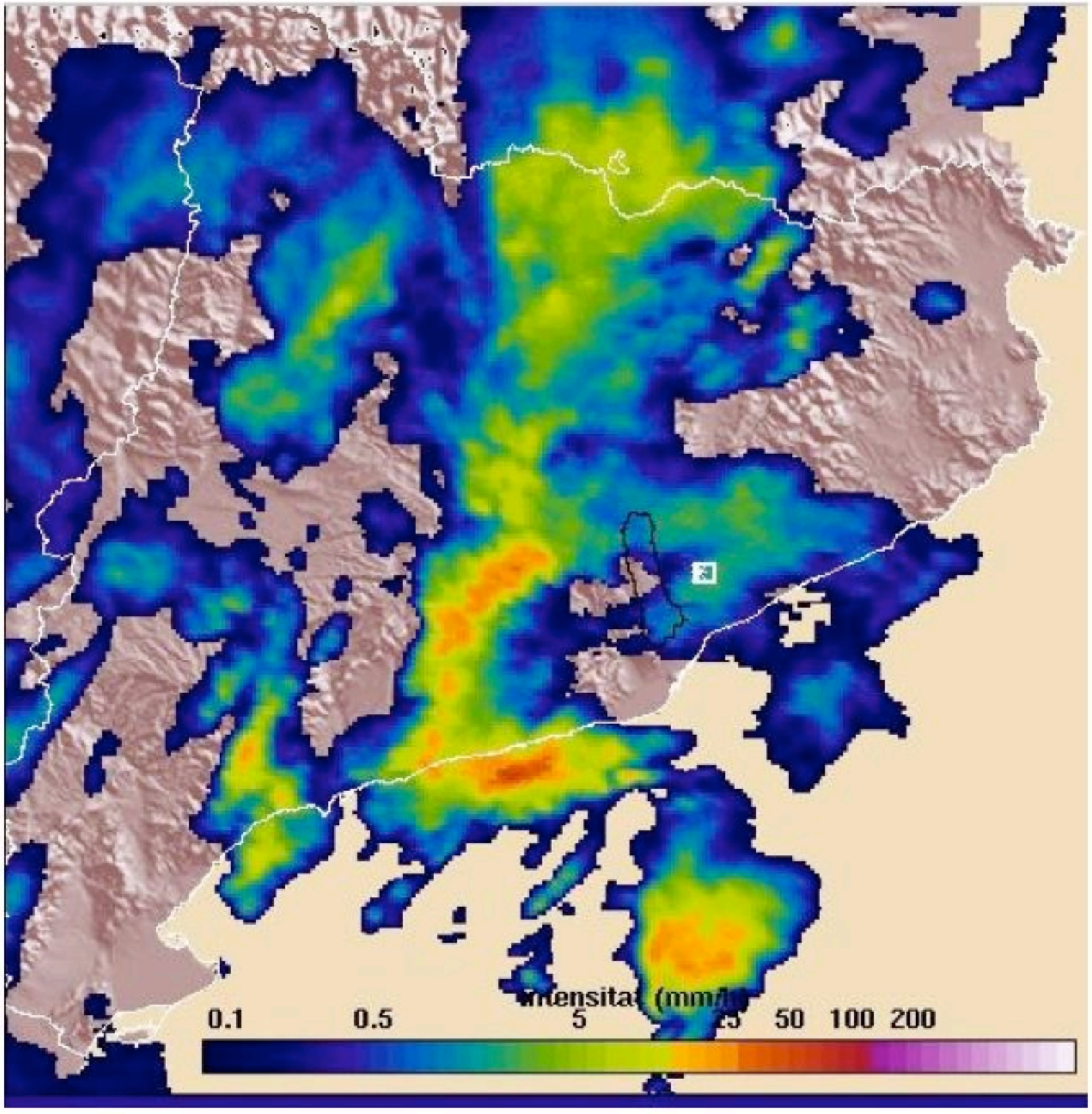
FF & DF early warning systems

IMPRINTS

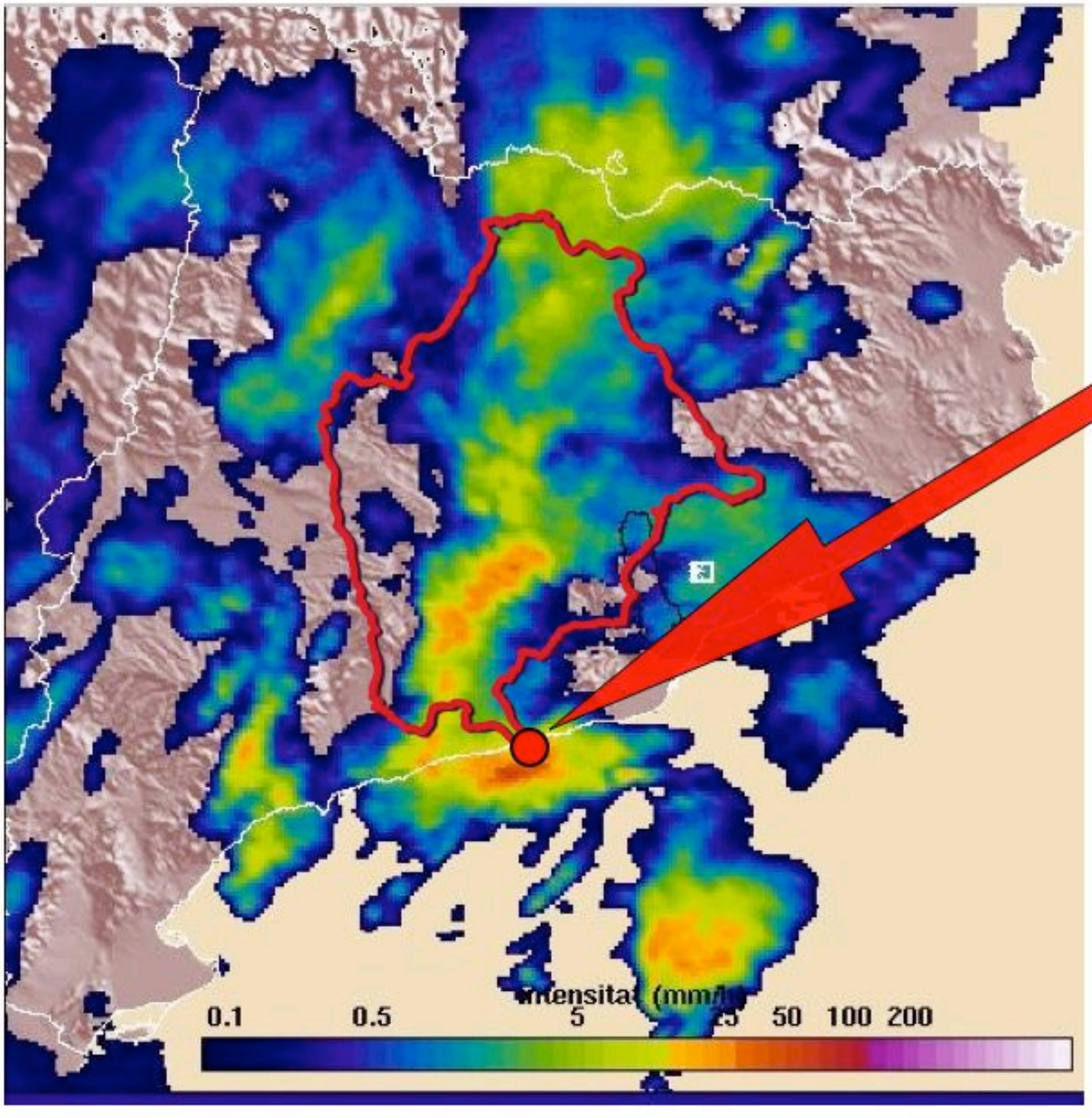
In Flash Floods, the basins affected are small (tenths of Km^2) and show very quick responses (from 1/2 hour to few hours)



Basin aggregated rainfall exceedances



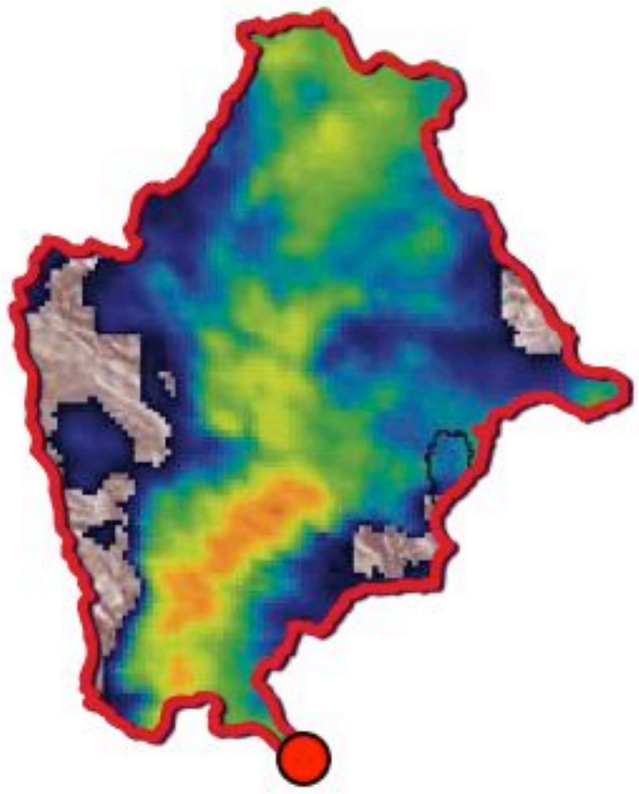
Basin aggregated rainfall exceedances



Given a point in the drainage system,

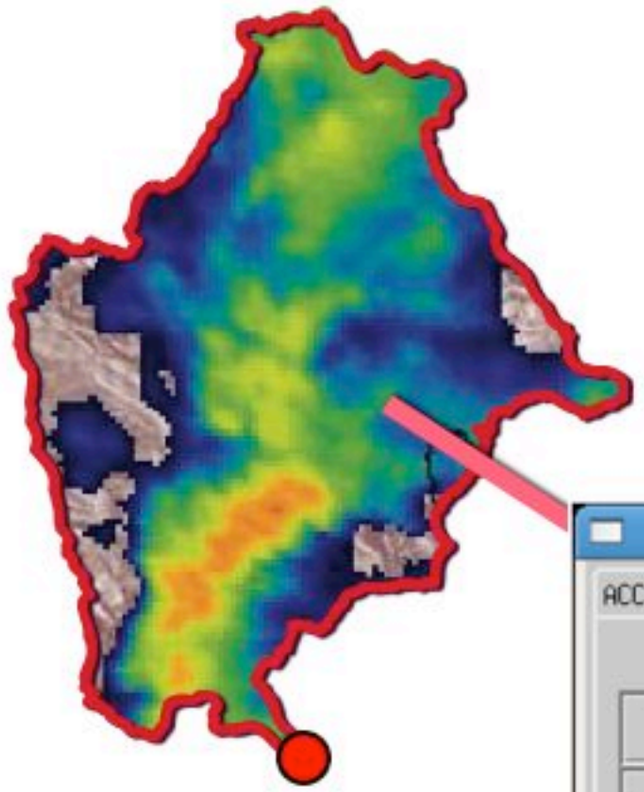
We can define the associated basin, and calculate the rainfall that will be collected by the selected point

Basin aggregated rainfall exceedances



This basin aggregated rainfall is accumulated over the hydrological characteristic time of the basin

Basin aggregated rainfall exceedances



This basin aggregated rainfall is accumulated over the hydrological characteristic time of the basin

And a **probability of Exceedance** is associated (return period in years)

Finestra stats 426, 4600

ACC30 | Cabal | Grafica IDF | Taula IDF

Return Period

	T2	T5	T10	T25	T50	T100	T200	T500
30m	41.3	59.2	72.9	90.8	106.6	122.4	139.0	163.0

Taula IDF (mm)

1h	27.5	39.4	48.6	60.5	71.0	81.6	92.6	108.6
2h	35.6	51.0	62.9	78.3	91.9	105.6	119.8	140.6
3h	40.8	58.5	72.1	89.8	105.4	121.0	137.4	161.2
4h	44.6	64.0	78.9	98.2	[illegible]	132.5	150.3	176.4
6h	50.2	72.0	88.7	110.4	129.7	148.9	169.0	198.3
12h	59.7	85.5	105.4	131.2	[illegible]	177.0	200.8	235.6
24h	68.3	97.9	120.6	150.2	176.4	202.6	229.9	269.7

Coordenades del punt (426.5,4600.5) Km

Duration

Accum Rainfall thresholds

EPIC: European Precipitation Index Climatology

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- **30 Years of COSMO-LEPS** reanalysis have been generated.

EPIC: European Precipitation Index Climatology

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- For any point in the river system (1 km^2) a **Climatology of its basin aggregated rainfall** is calculated.

EPIC: European Precipitation Index Climatology

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- A Precipitation Index based on Climatology is thus calculated at European scale (**EPIC**).

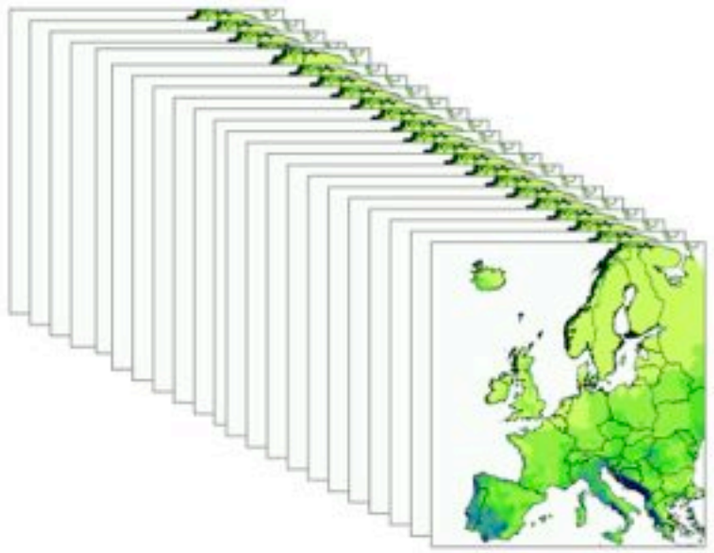
EPIC: European Precipitation Index Climatology

- **30 Years of COSMO-LEPS** reanalysis have been generated.
- For any point in the river system (1 km^2) a **Climatology of its basin aggregated rainfall** is calculated.
- A Precipitation Index based on Climatology is thus calculated at European scale (**EPIC**).
- For any new event the rainfall forecasted is used to calculate the **basin aggregated rainfall, and compared against the EPIC CLIMATOLOGY.**

FF & DF early warning systems

IMPRINTS

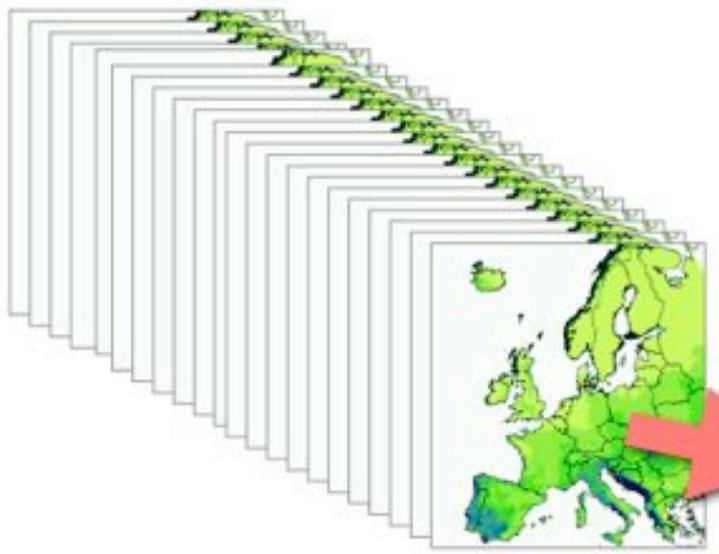
COSMO-LEPS Probabilistic Rainfall forecasts



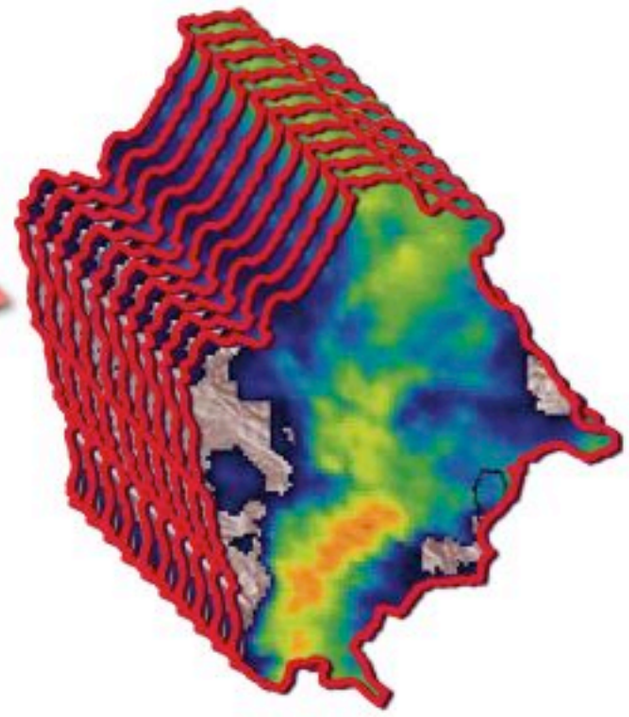
FF & DF early warning systems

IMPRINTS

COSMO-LEPS Probabilistic Rainfall forecasts



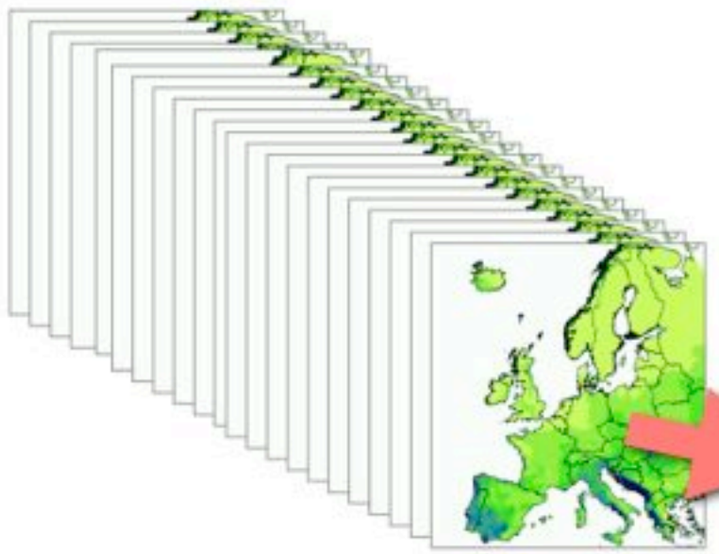
Probabilistic basin aggregated rainfall forecasts



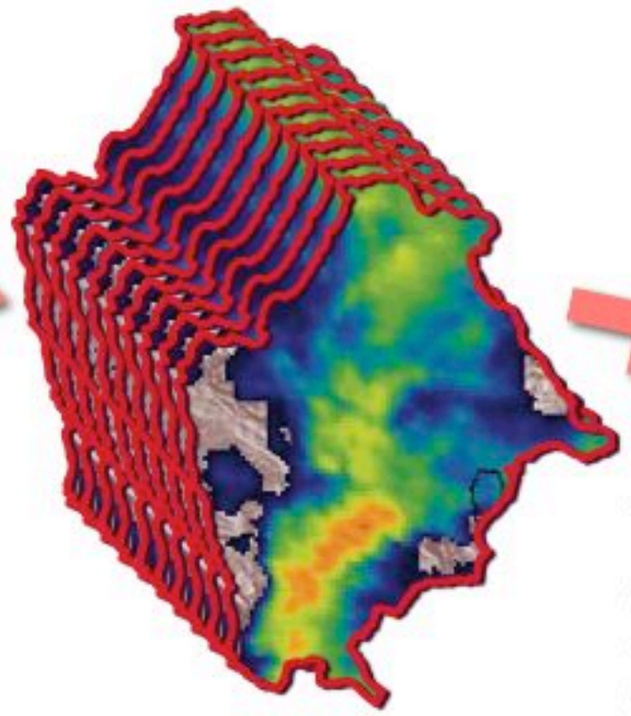
FF & DF early warning systems

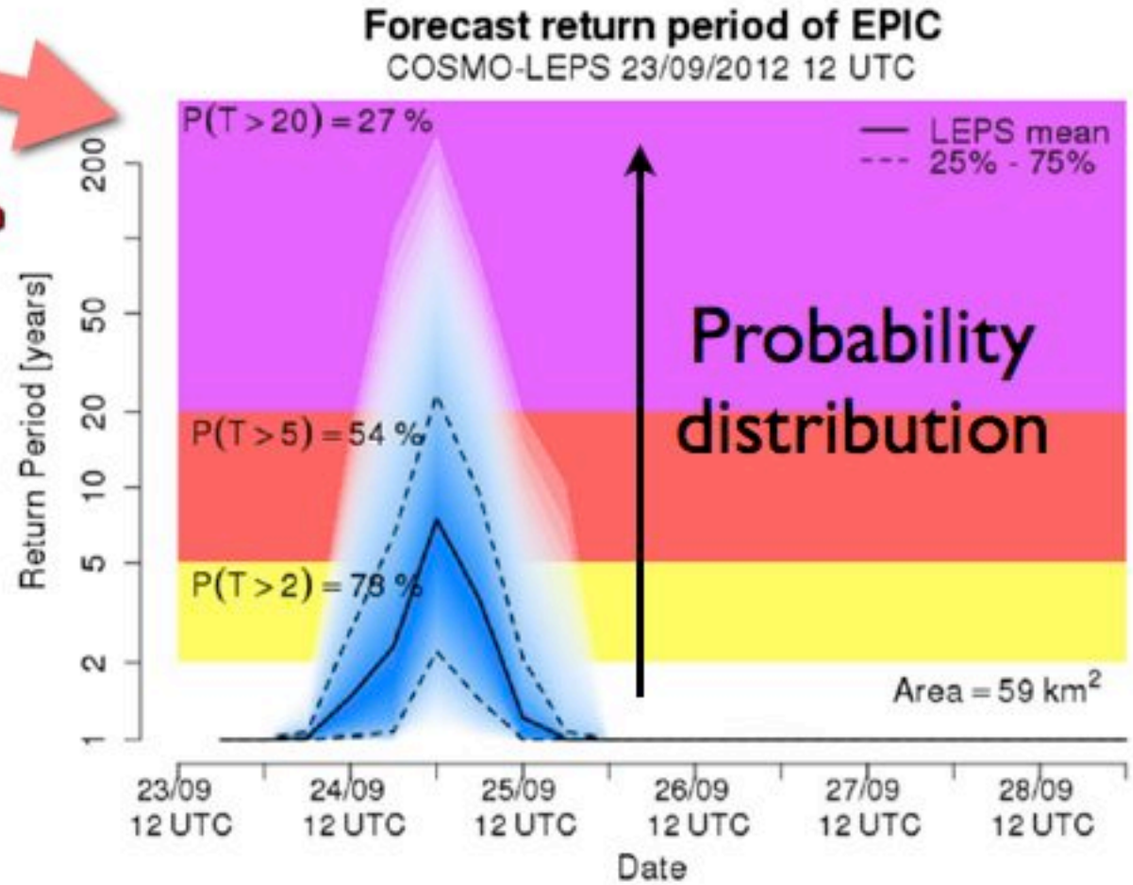
IMPRINTS

COSMO-LEPS Probabilistic Rainfall forecasts



Probabilistic basin aggregated rainfall forecasts

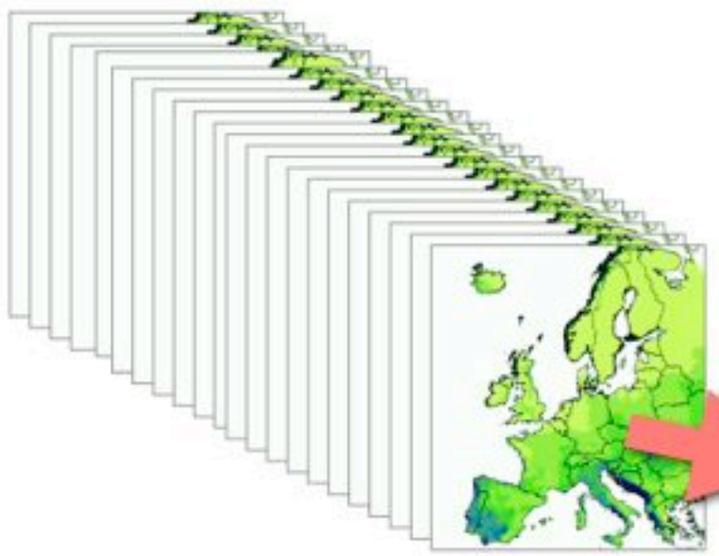




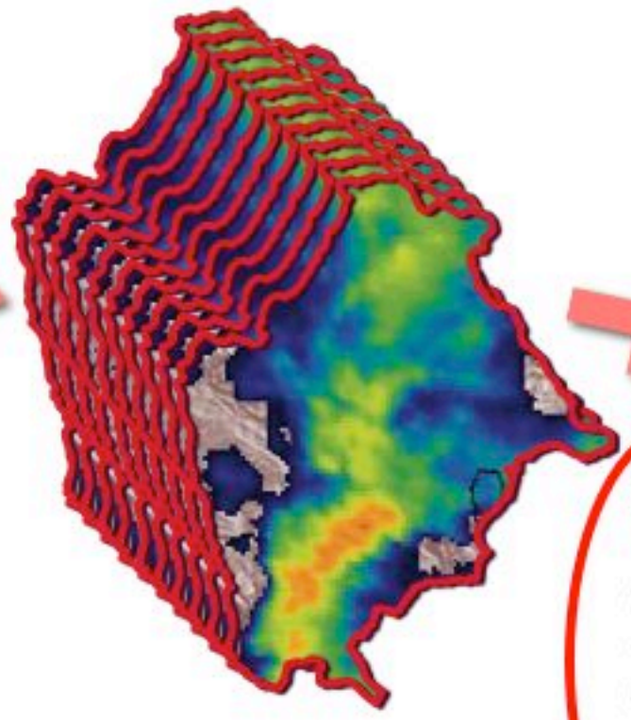
FF & DF early warning systems

IMPRINTS

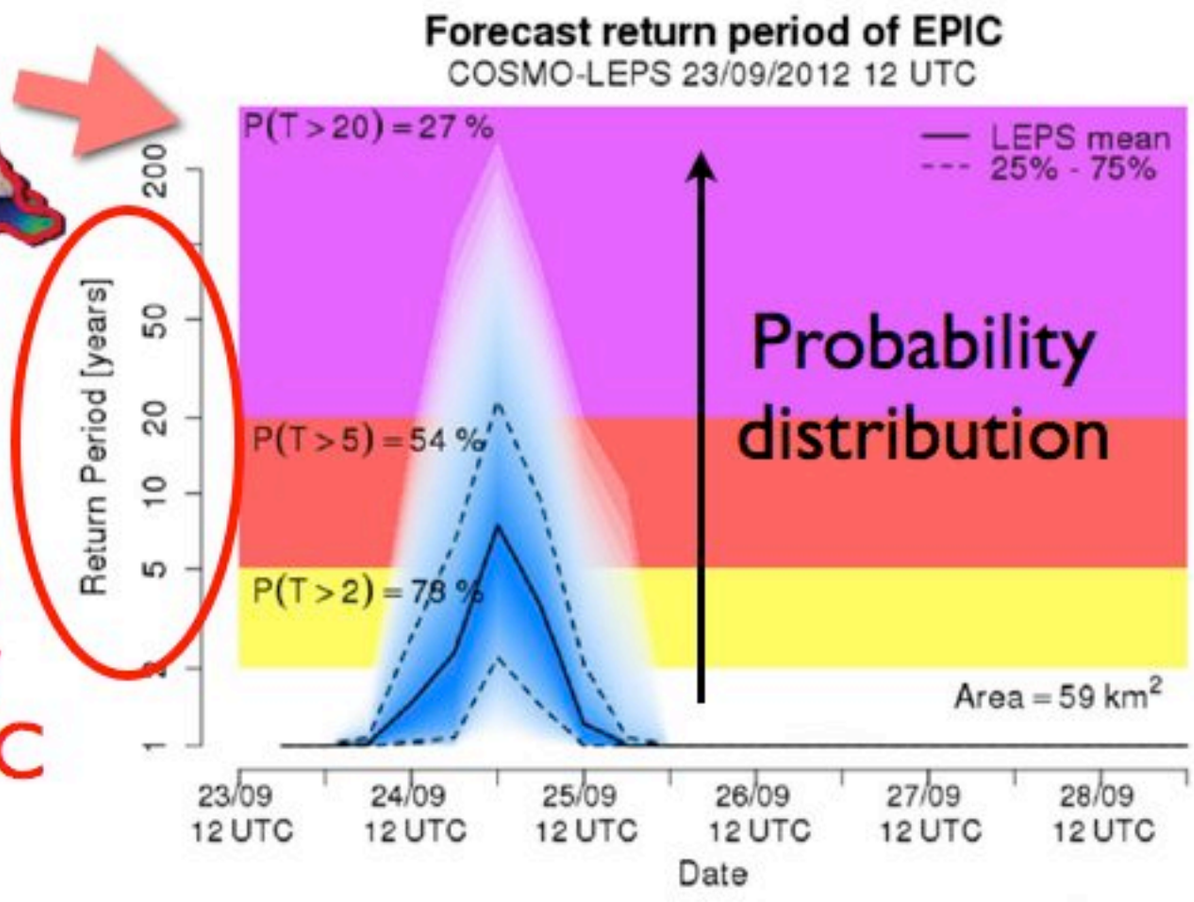
COSMO-LEPS Probabilistic Rainfall forecasts



Probabilistic basin aggregated rainfall forecasts



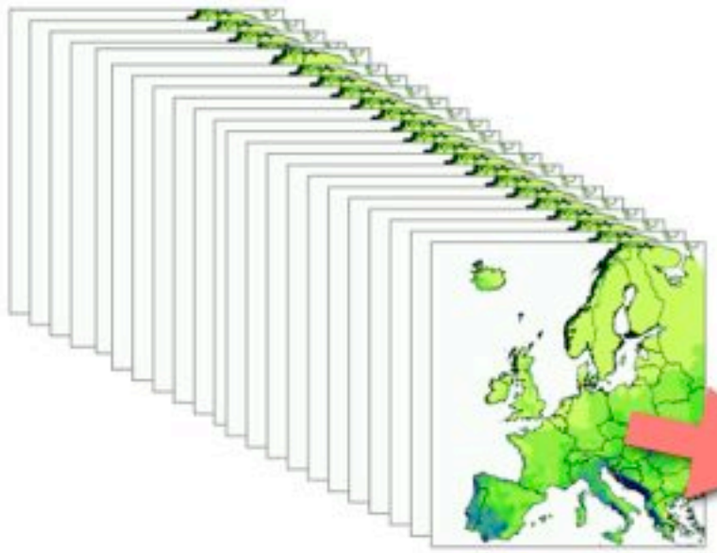
Return Period of any member calculated by comparison against EPIC climatology



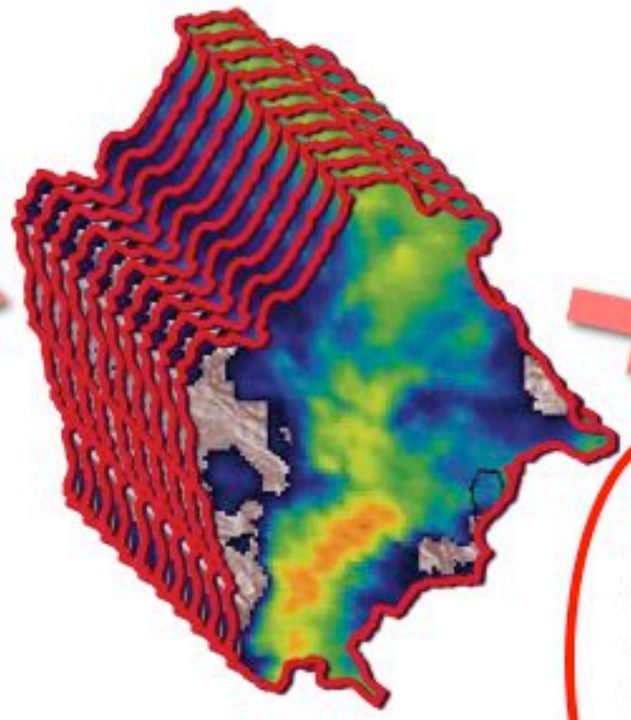
FF & DF early warning systems

IMPRINTS

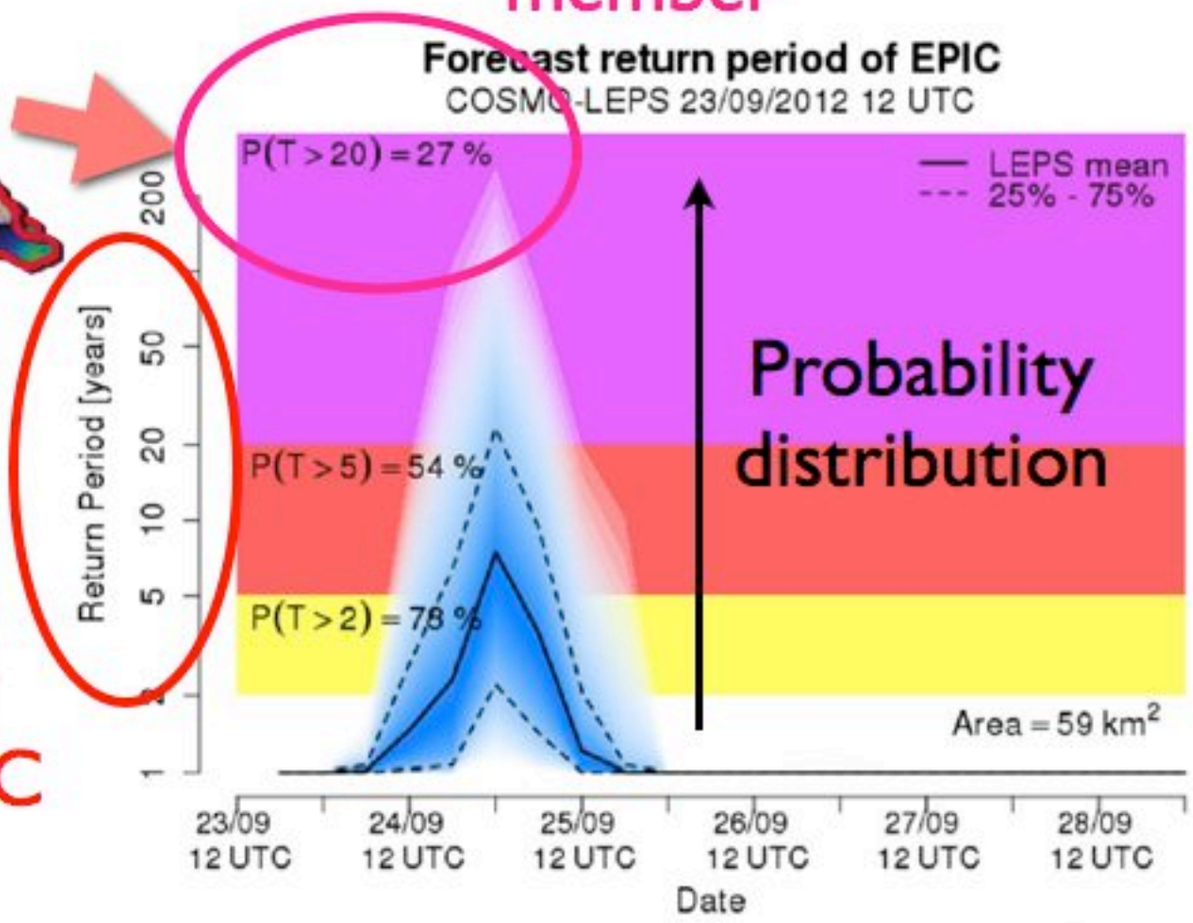
COSMO-LEPS
Probabilistic Rainfall
forecasts



Probabilistic basin
aggregated rainfall
forecasts



Warning code associated
to the 75% percentile
member



Return Period of any
member calculated by
comparison against EPIC
climatology

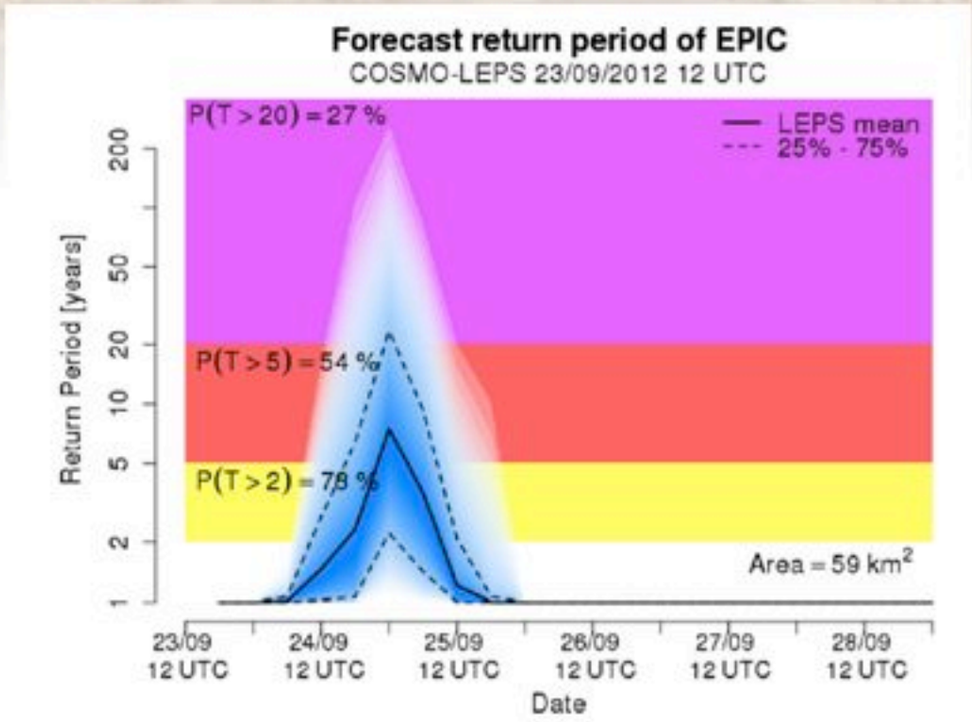
IMPRINTS

FF & DF early warning systems

Event of 2012-09-25 in Newcastle Upon Time (UK)

EPIC 2012-09-23 12:00





Forecast 48h in advance

Top story



Floods hit 300 homes in north England

26 Sep 2012: River defences under pressure in downpours, while fishing village is left covered in sea foam

Most recent



Looters of flooded shop condemned by police

26 Sep 2012: Newcastle upon Tyne cycle shop targeted as swollen rivers cause havoc in northern England

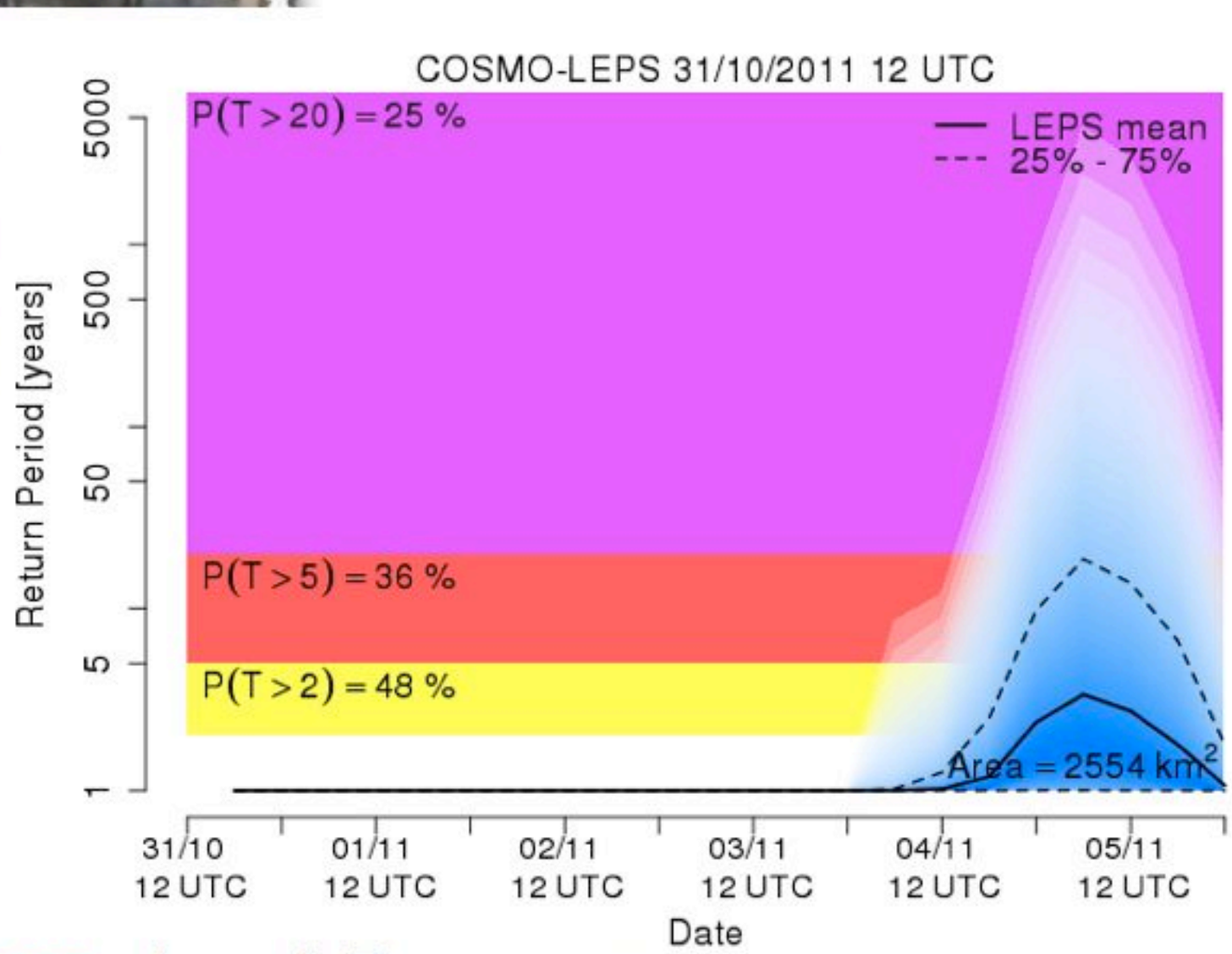
Genova (Italia) 4/11/2011



IMPRINTS

Genova (Italia) 4/11/2011



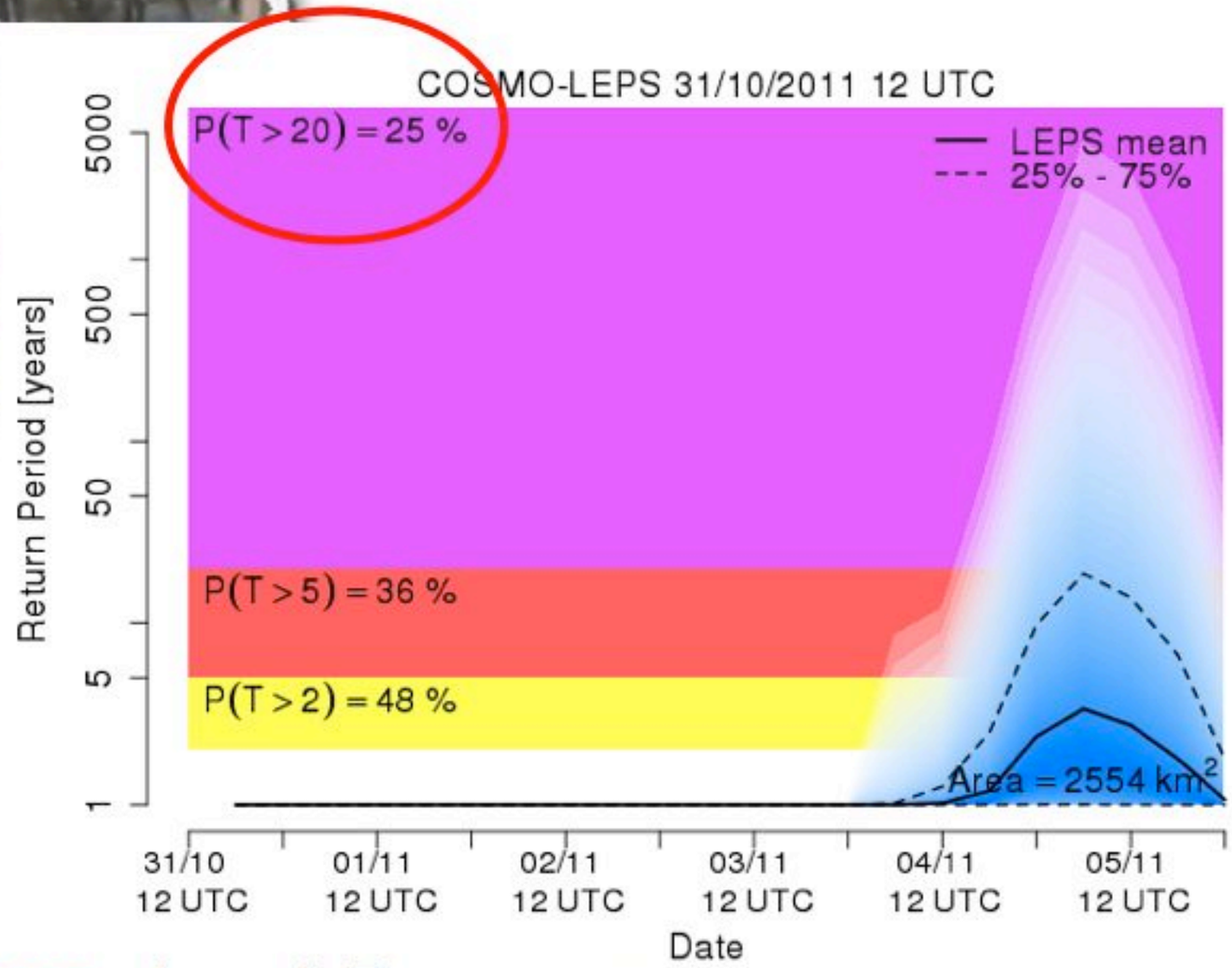


4 days ahead Forecast

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Genova (Italia) 4/11/2011



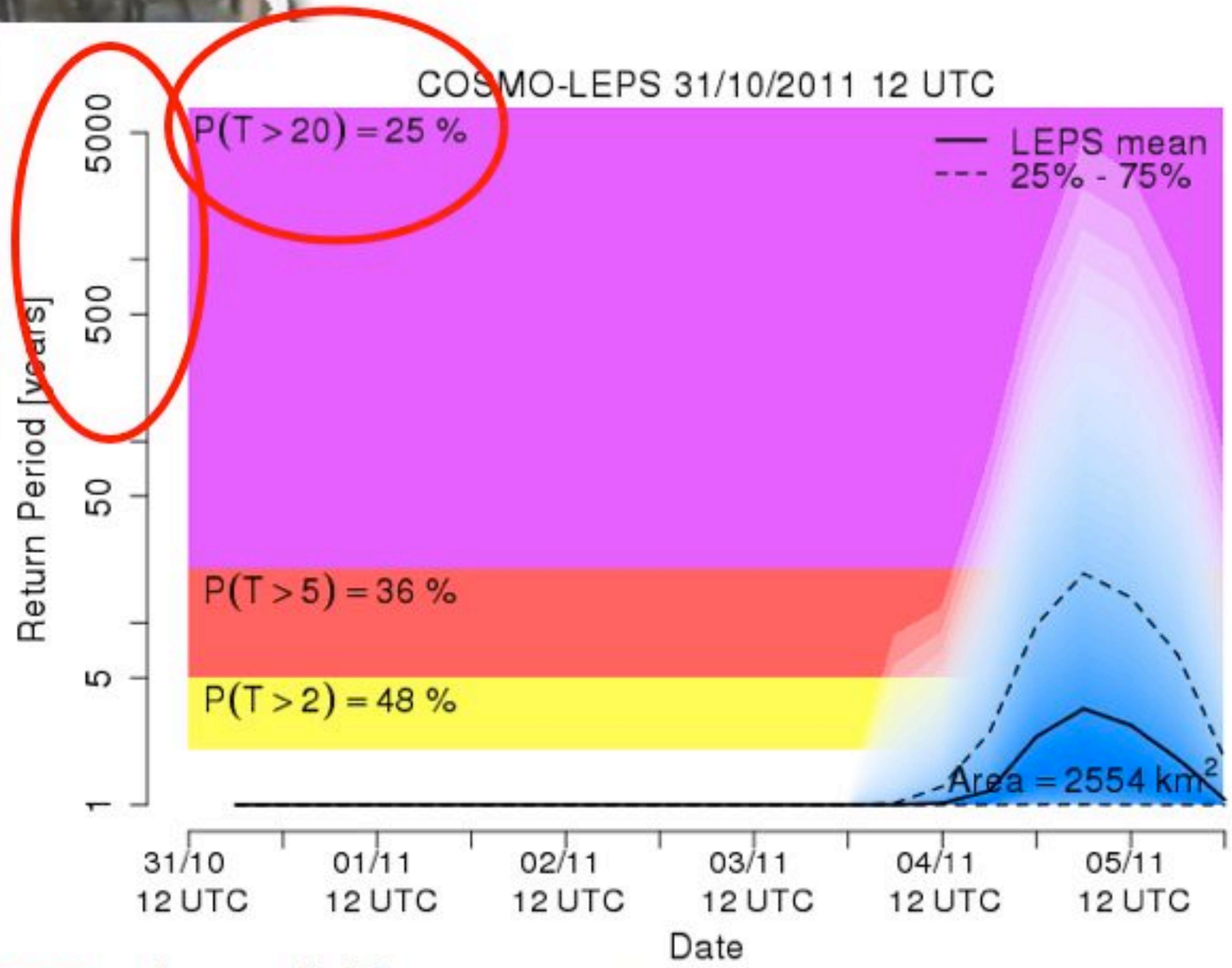


4 days ahead Forecast

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Genova (Italia) 4/11/2011





4 days ahead Forecast

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Genova (Italia) 4/11/2011



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EFAS forecasting

Forecasts available from 2009-05-01 to 2012-06-12 (12 UTC)

<< full screen opacity << 0.9 >> Print screenshot

search for location...

2011-11-02 (12 UTC) Disclaimer

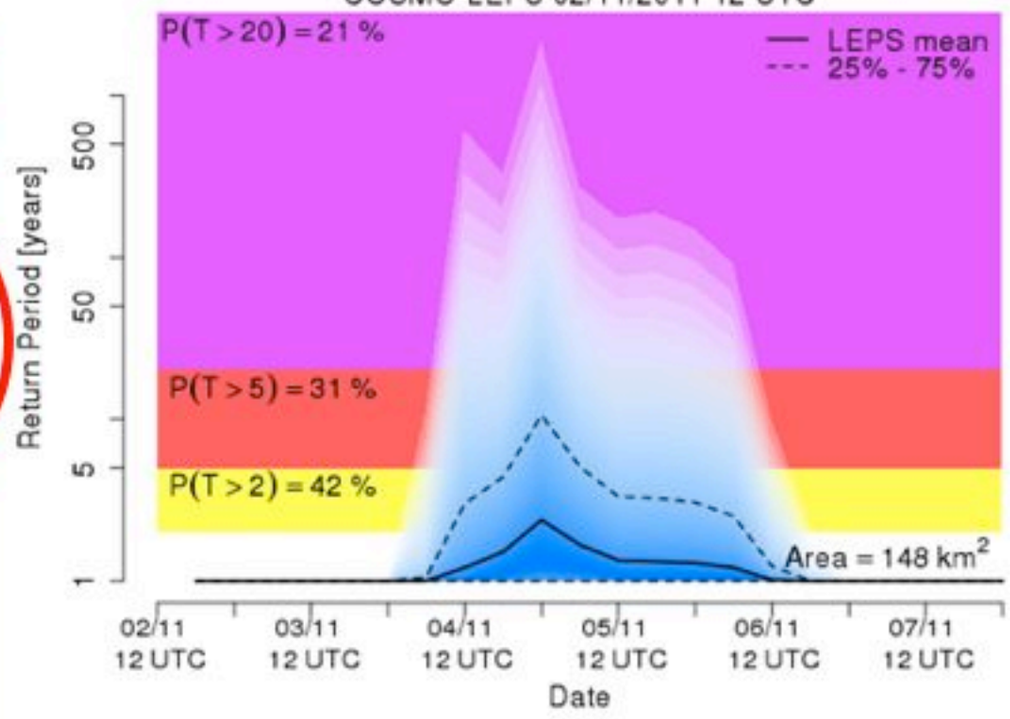
Select layers

2011-11-02 12

- Flood summary layers (0/10)
- Hydrological layers (0/7)
- Meteorological layers (0/7)
- Background layers (2/6)
- Flash flood layers (4/8)
  - IMPRINTS testbeds
  - No. COSMO Above Medium
  - No. COSMO Above High
  - No. COSMO Above Severe
  - Medium alert - T>2 years
  - High alert - T>5 years
  - Severe alert - T>20 years
  - EPIC above Medium

SELECTED POINT - Close all

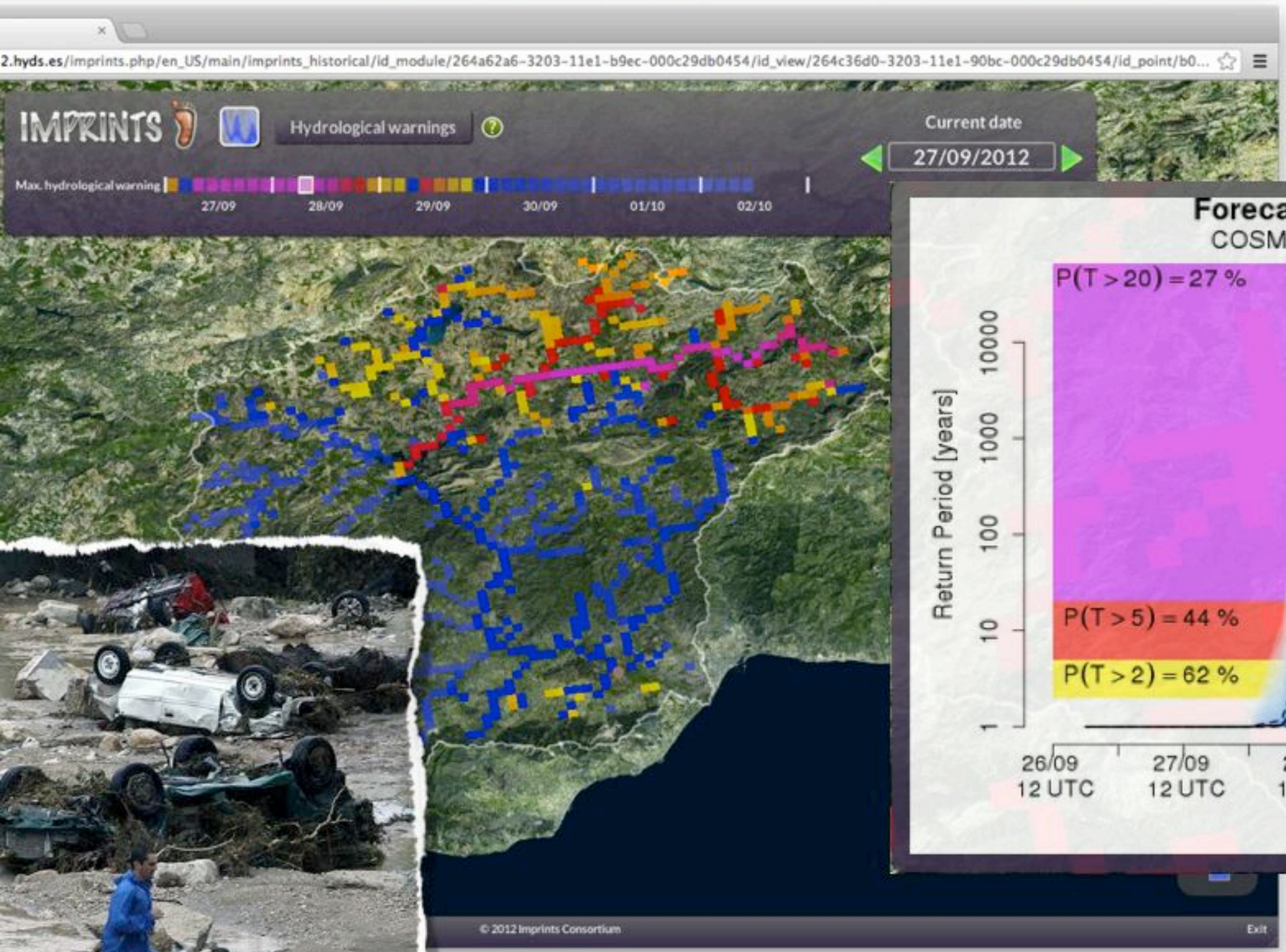
Report an error

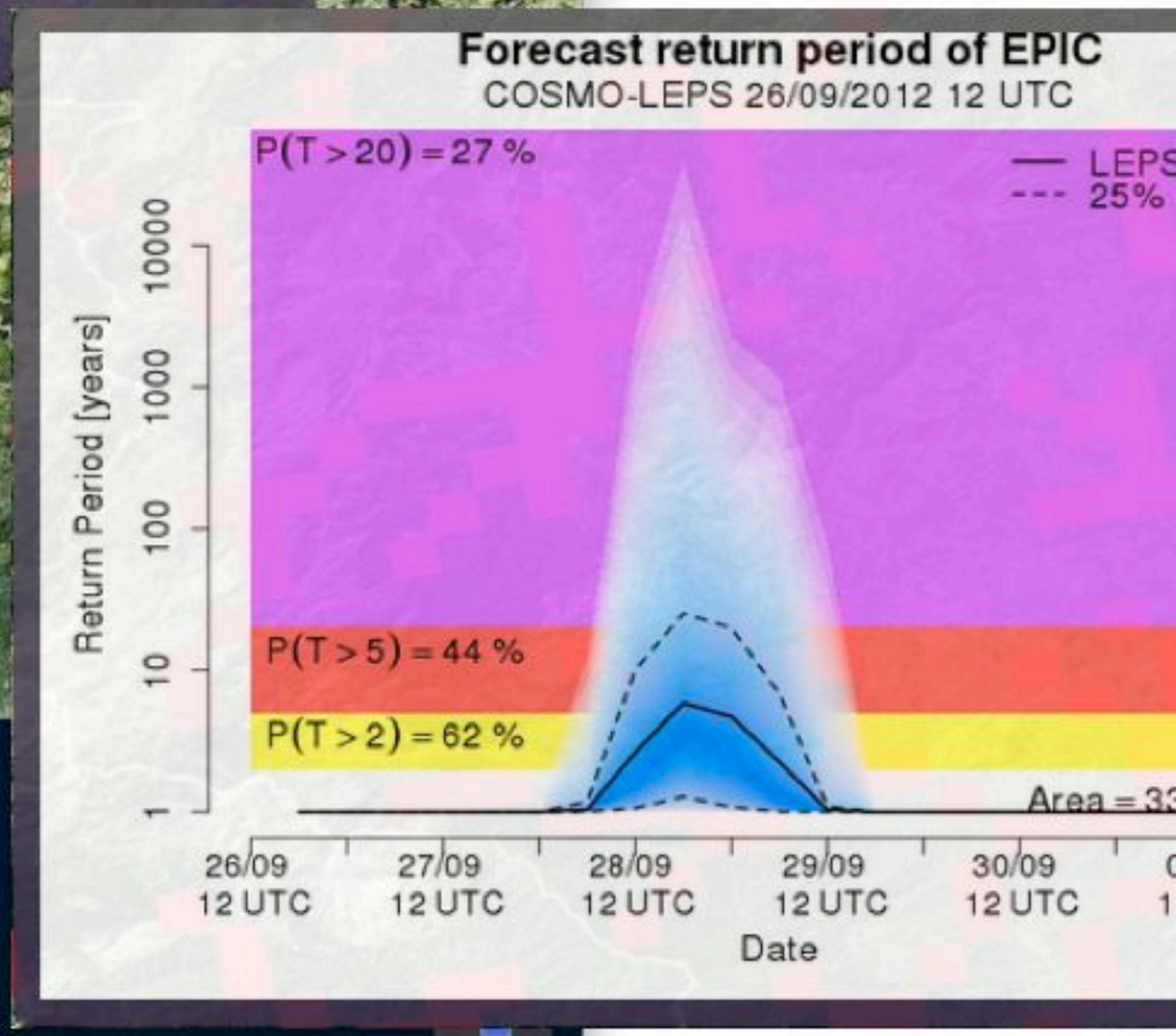


2 days ahead Forecast

IMPRINTS

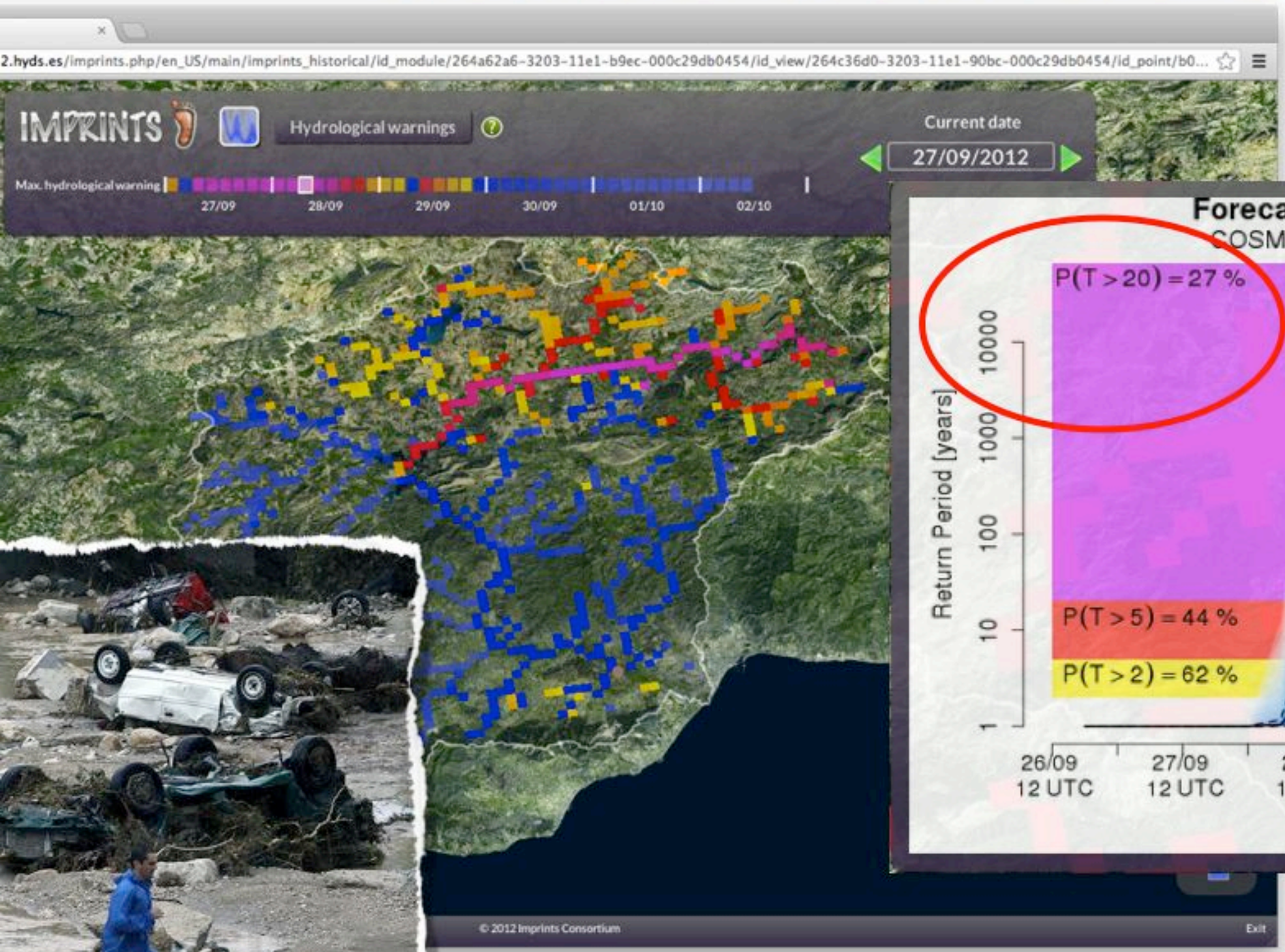
Guadalhorce 28/09/2012

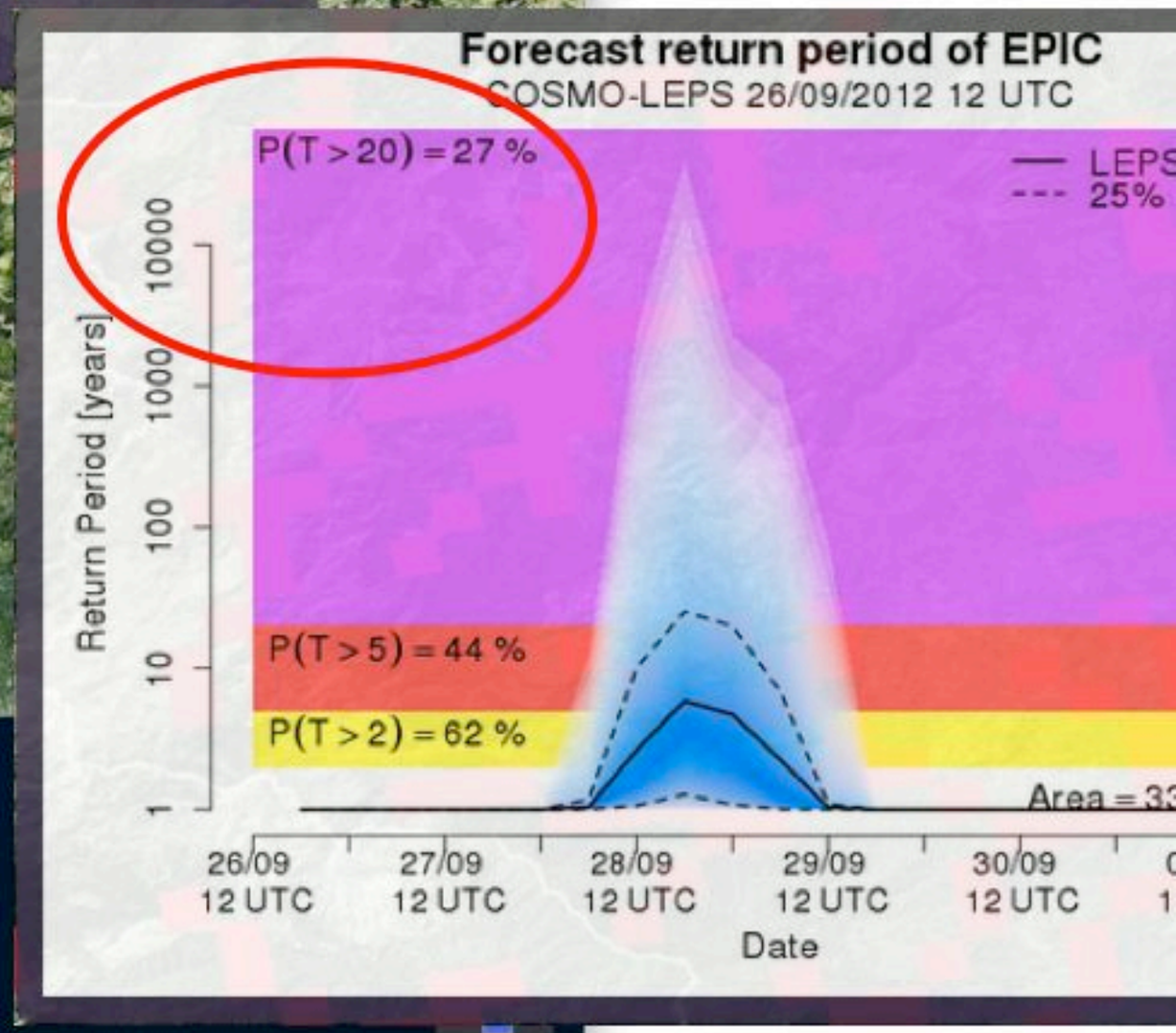




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Guadalhorce 28/09/2012





36 hours ahead Forecast

IMPRINTS

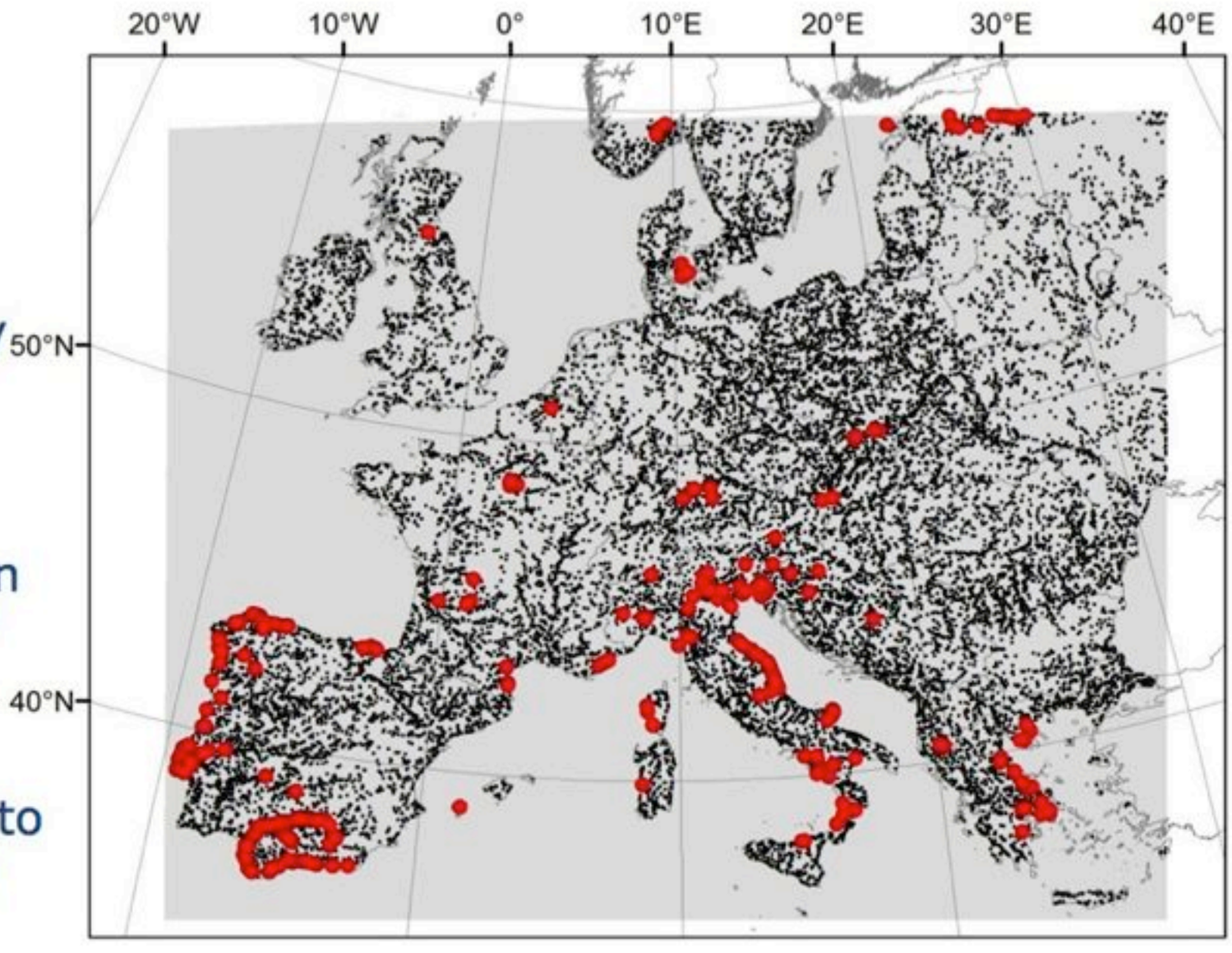
Performance of EPIC

22 months data starting on 1/12/2009.

We derived an alert criterion for extreme events of 60% probability of exceeding the 5-year return period.

363 points above the alert criterion were clustered in 50 events, 42 of which were confirmed events.

Out of 8 false alarms, 3 were due to boundary issues and can be easily recognized and removed



Course on tools to support the EU Flood Directive implementation on for Flash Flood prone areas

IMPRINTS

Català Castellano English

OPERATIONAL CENTER
Catalonian Water Agency

L'Aigua en temps real

Agència Catalana de l'Aigua

meteo.cat Servei Meteorològic de Catalunya

Dades d'avui | Pluja | Mapa d'avisos | Històrics

Mapa d'avisos

Detecció d'indrets on cal posar-hi una atenció especial.

Avisos Hidrològics

Aigua acumulada

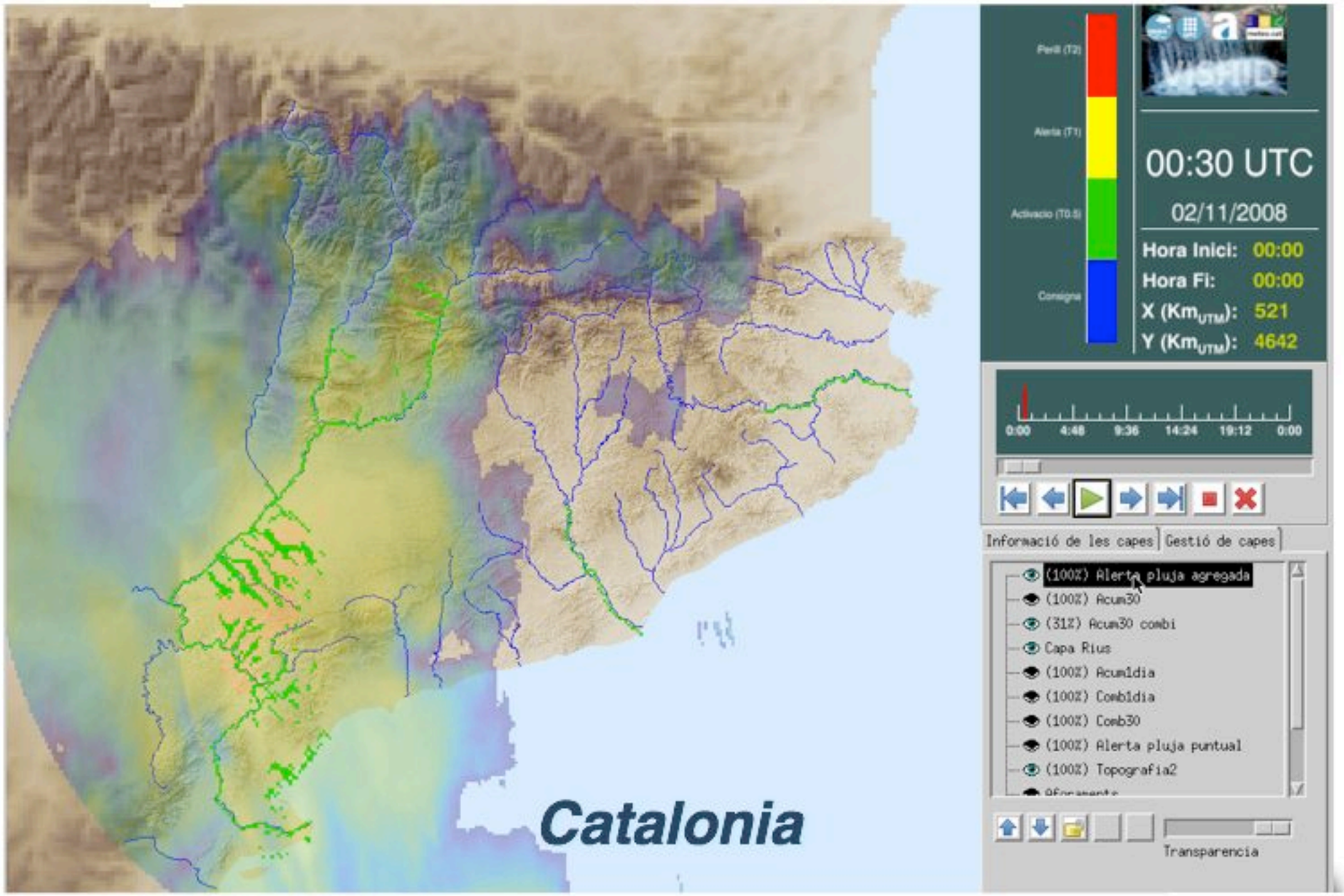
Aigua al riu

Avisos Meteorològics

Avisos (SMC)

Estat Hidrologia:

Normalitat | Precaució



Generalitat de Catalunya
Departament de Territori i Sostenibilitat

© 2000-2011 Agència Catalana de l'Aigua - Tots els drets reservats

Les dades són provisionals i estan subjectes a revisió.

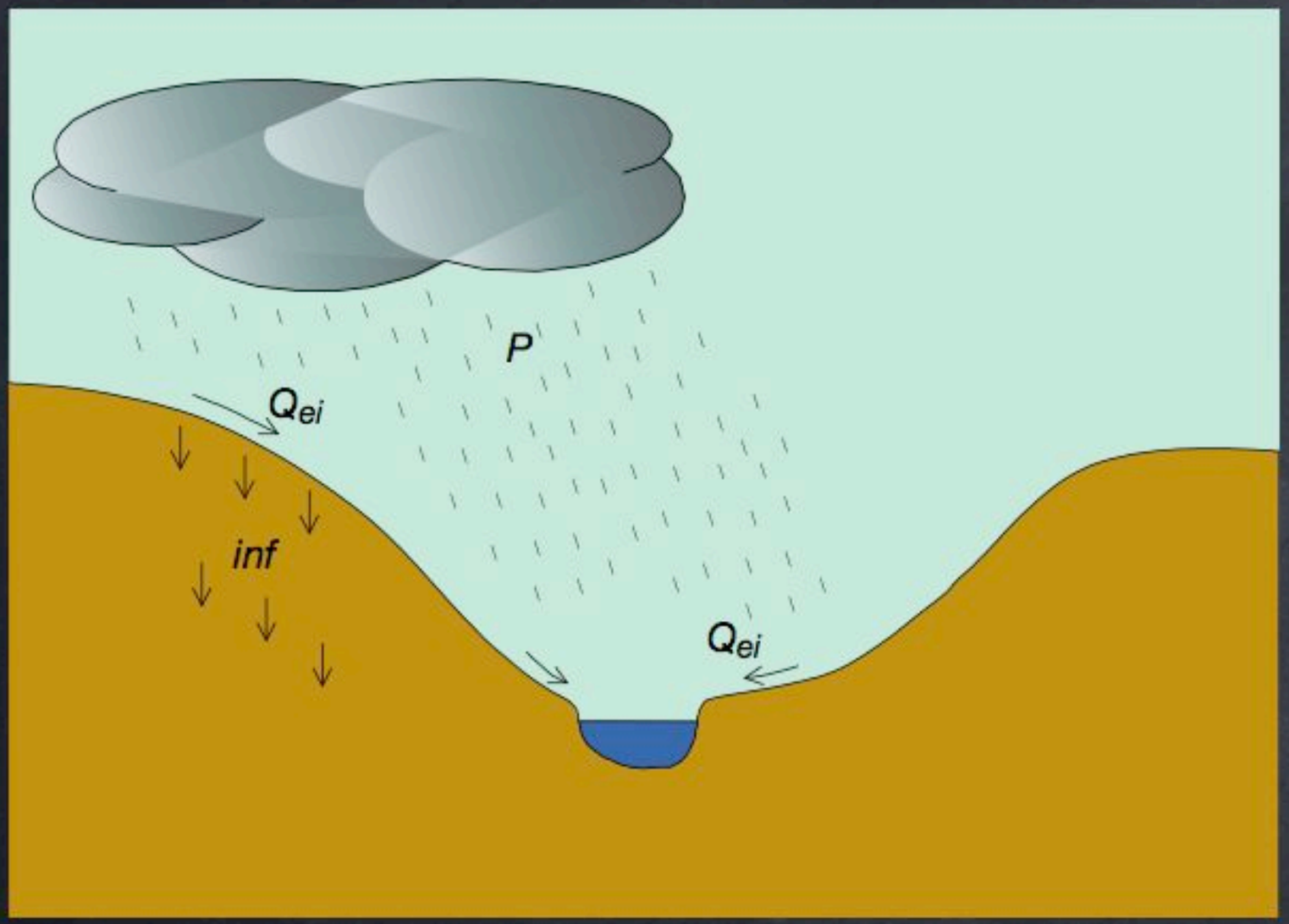
Modelos Hidrológicos

Introducción a Topmodel

Beven, K., Kirkby, M.J. (1979). A physically-based variable-contributing area model of basin hydrology. Hydrologic Science Bulletin, 24, p:27-53

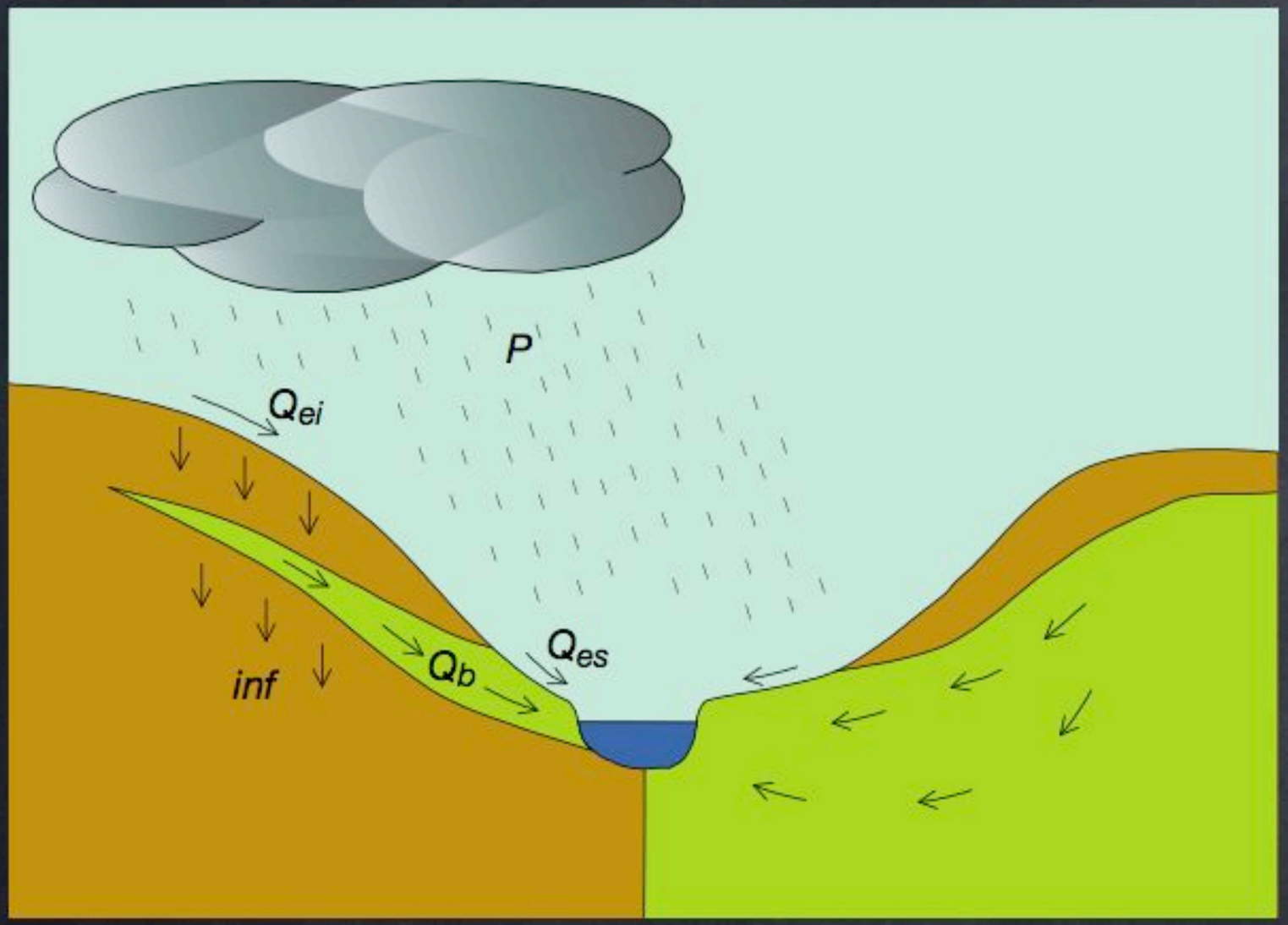
Introducción a Topmodel

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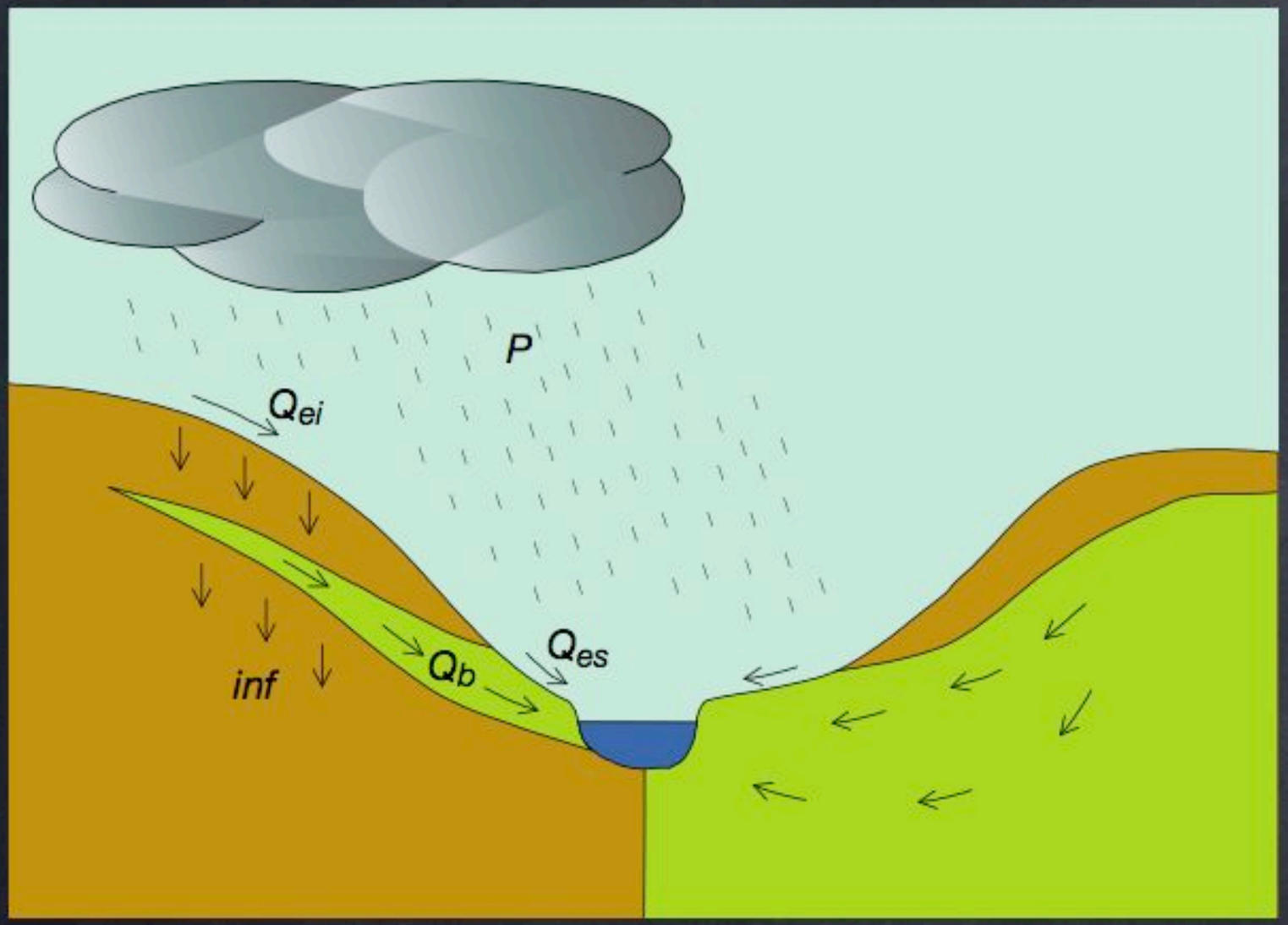
Introducción a Topmodel

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Introducción a Topmodel

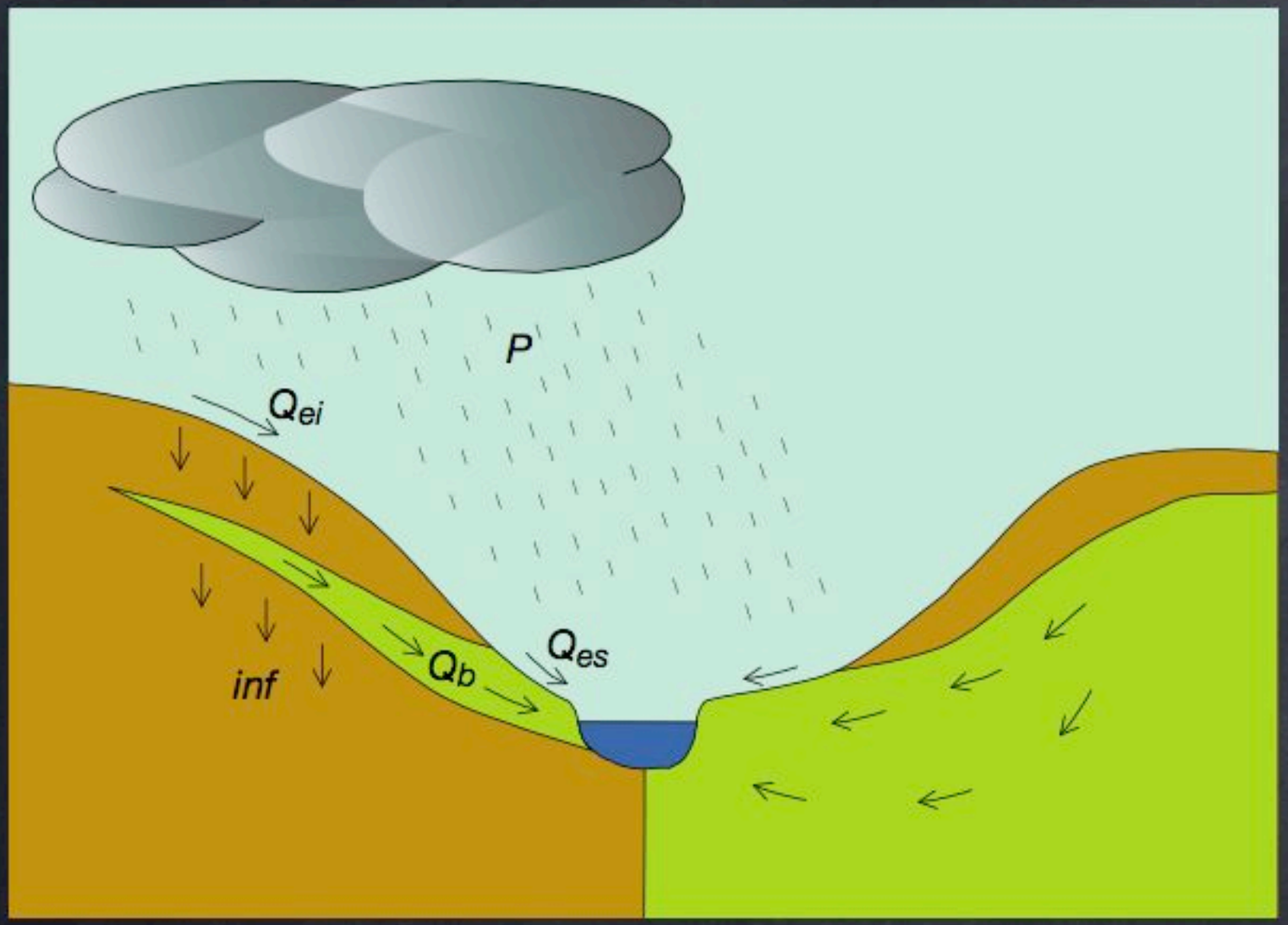
Beven, K., Kirkby, M.J. (1979). A physically-based variable-contributing area model of basin hydrology. Hydrologic Science Bulletin, 24, p:27-53



Tipos de flujo:

Introducción a Topmodel

Beven, K., Kirkby, M.J. (1979). A physically-based variable-contributing area model of basin hydrology. Hydrologic Science Bulletin, 24, p:27-53



Tipos de flujo:

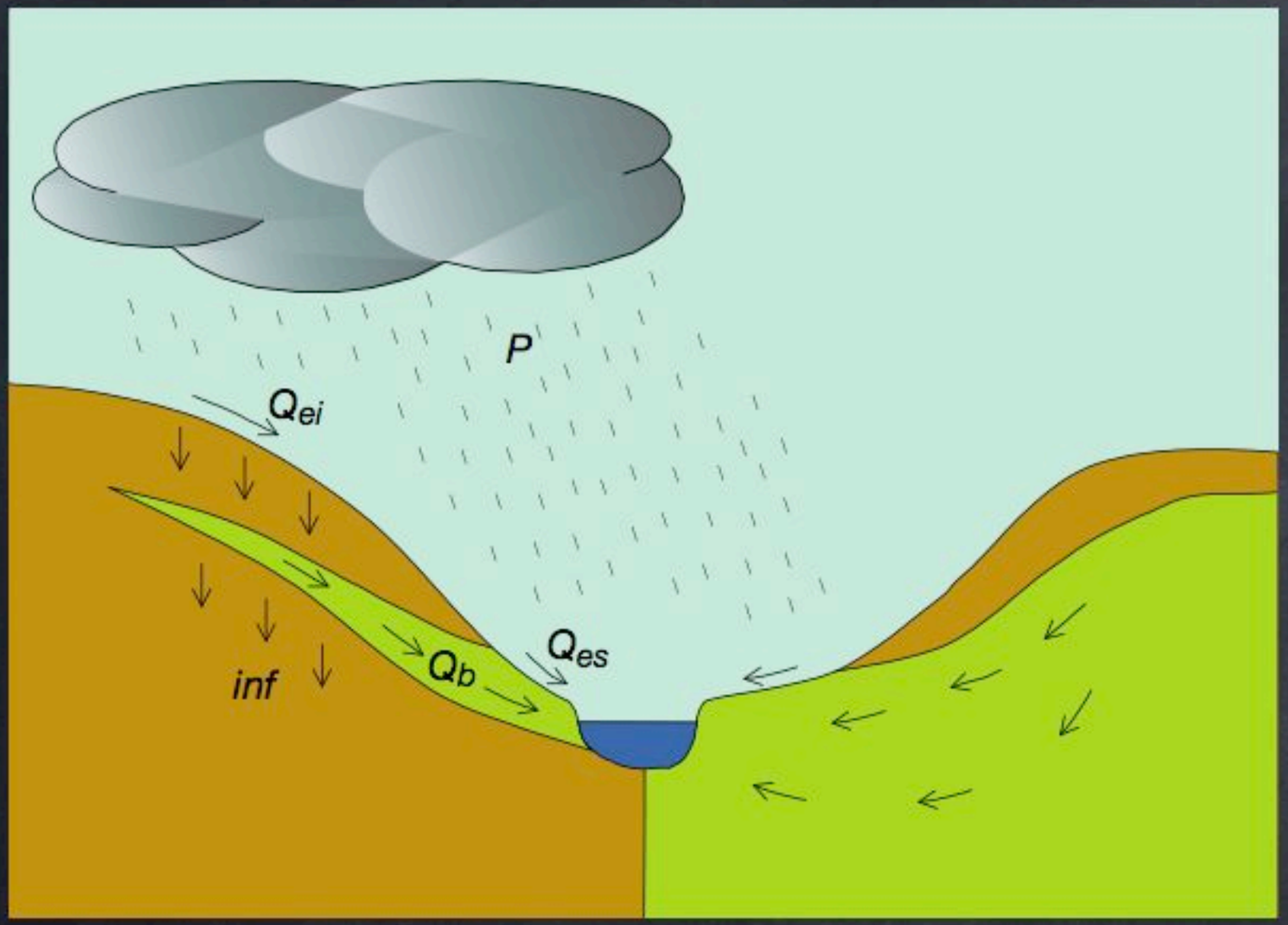
Flujo superficial (overland flow)

Qei: Exceso de infiltración o de Horton

Qes: Exceso de saturación o de Dunne

Introducción a Topmodel

Beven, K., Kirkby, M.J. (1979). A physically-based variable-contributing area model of basin hydrology. Hydrologic Science Bulletin, 24, p:27-53



Tipos de flujo:

Flujo superficial (overland flow)

Qei: Exceso de infiltración o de Horton

Qes: Exceso de saturación o de Dunne

Flujo base (base flow, return flow)

Flujo subsuperficial (interflow)

Flujo subterráneo

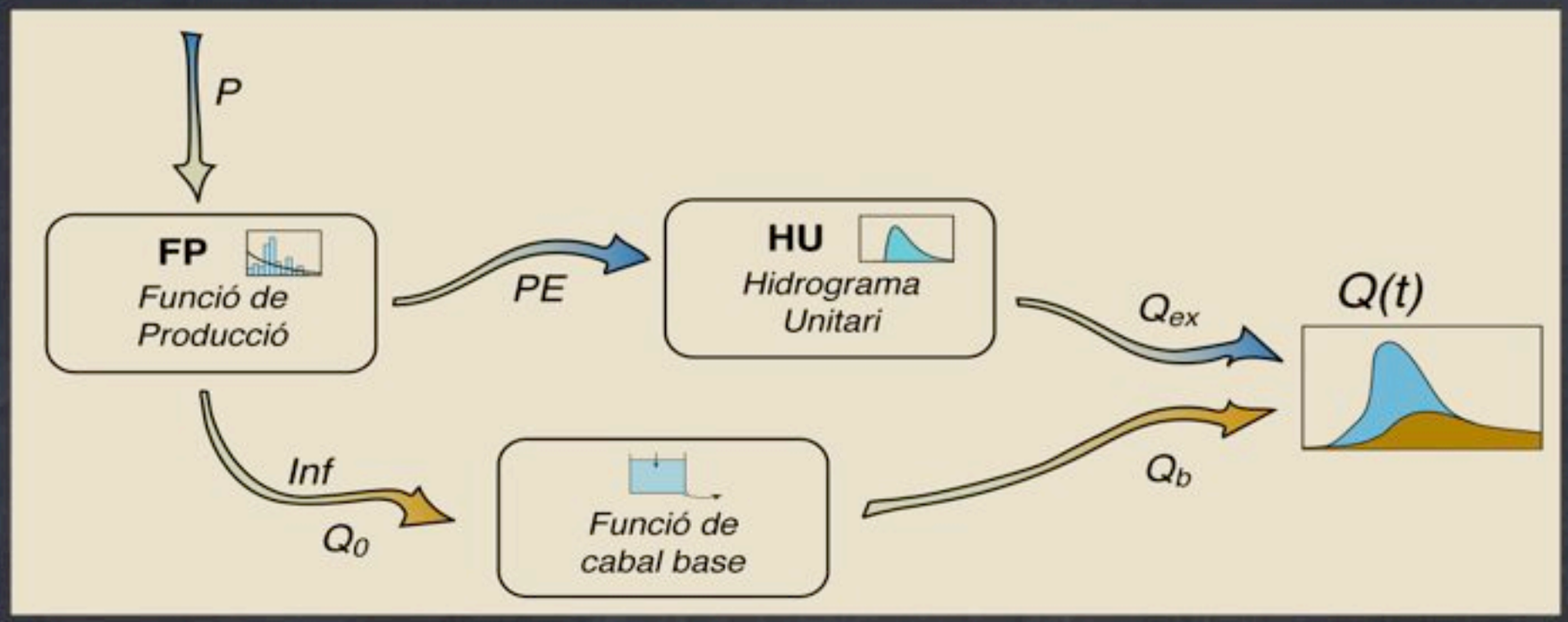
Tipus de models hidrològics

MODELOS GLOBALES → Entrada única P(t)

Tipus de models hidrològics

MODELOS GLOBALES → Entrada única P(t)

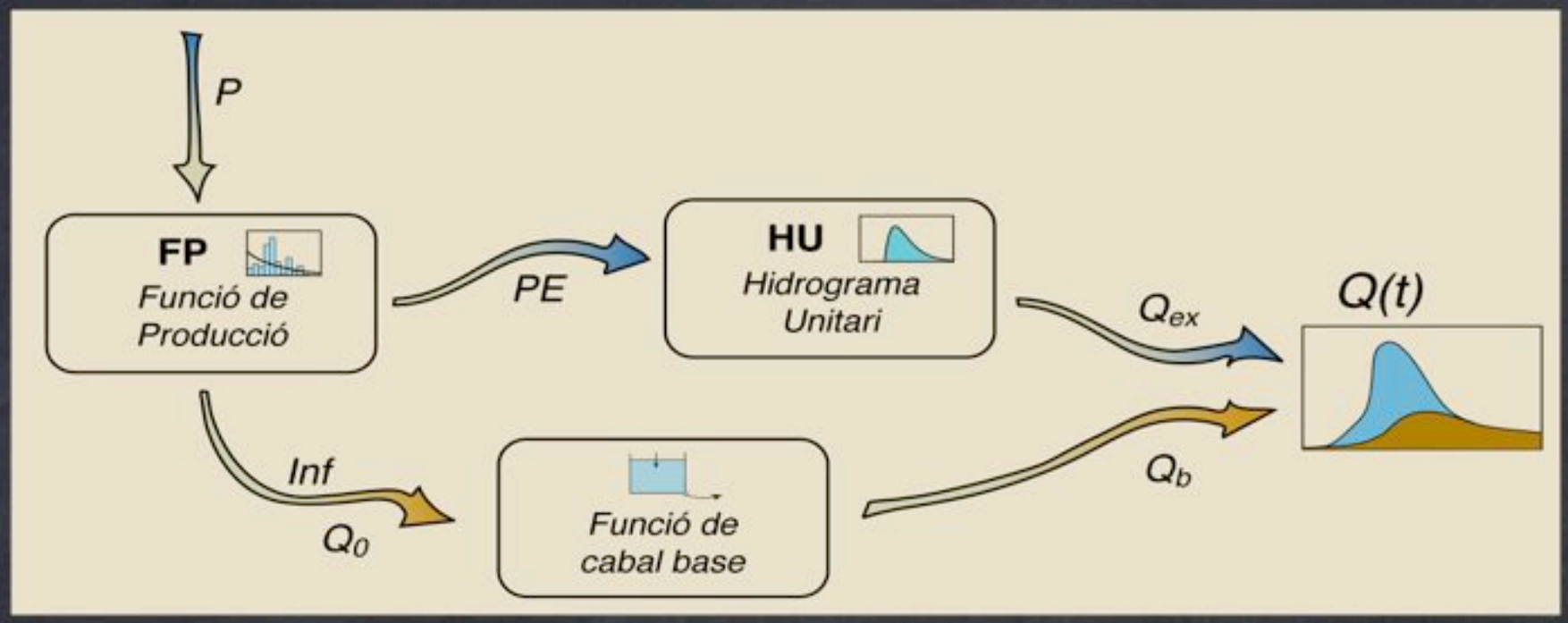
model clàssic: Funció de Pèrdues + Hidrograma Unitari



Tipus de models hidrològics

MODELOS GLOBALES → Entrada única P(t)

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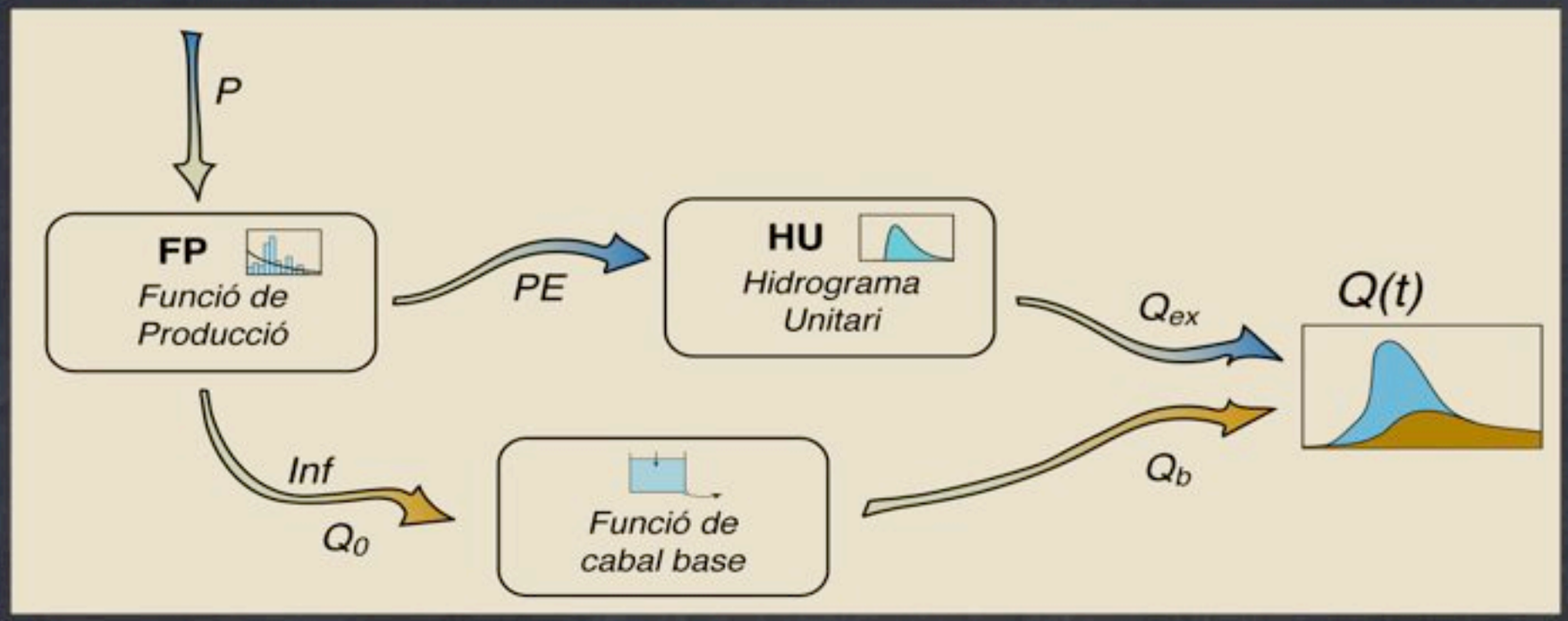


MODELOS CONCEPTUALES: conceptualització de la conca en un sistema senzill de modelitzar (pocs paràmetres)

Tipus de models hidrològics

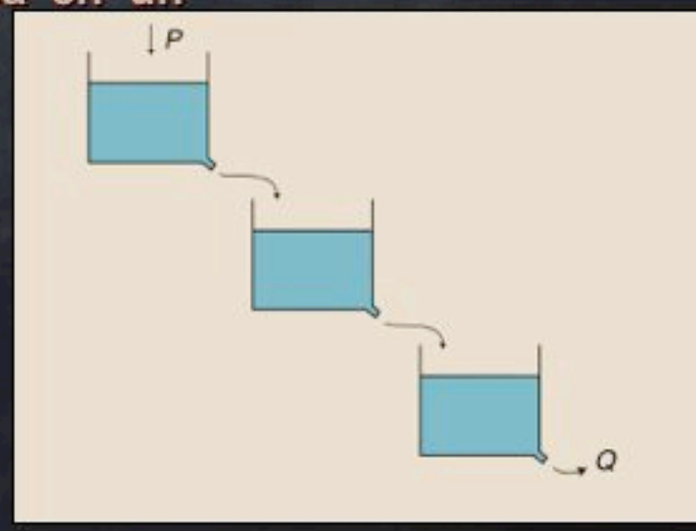
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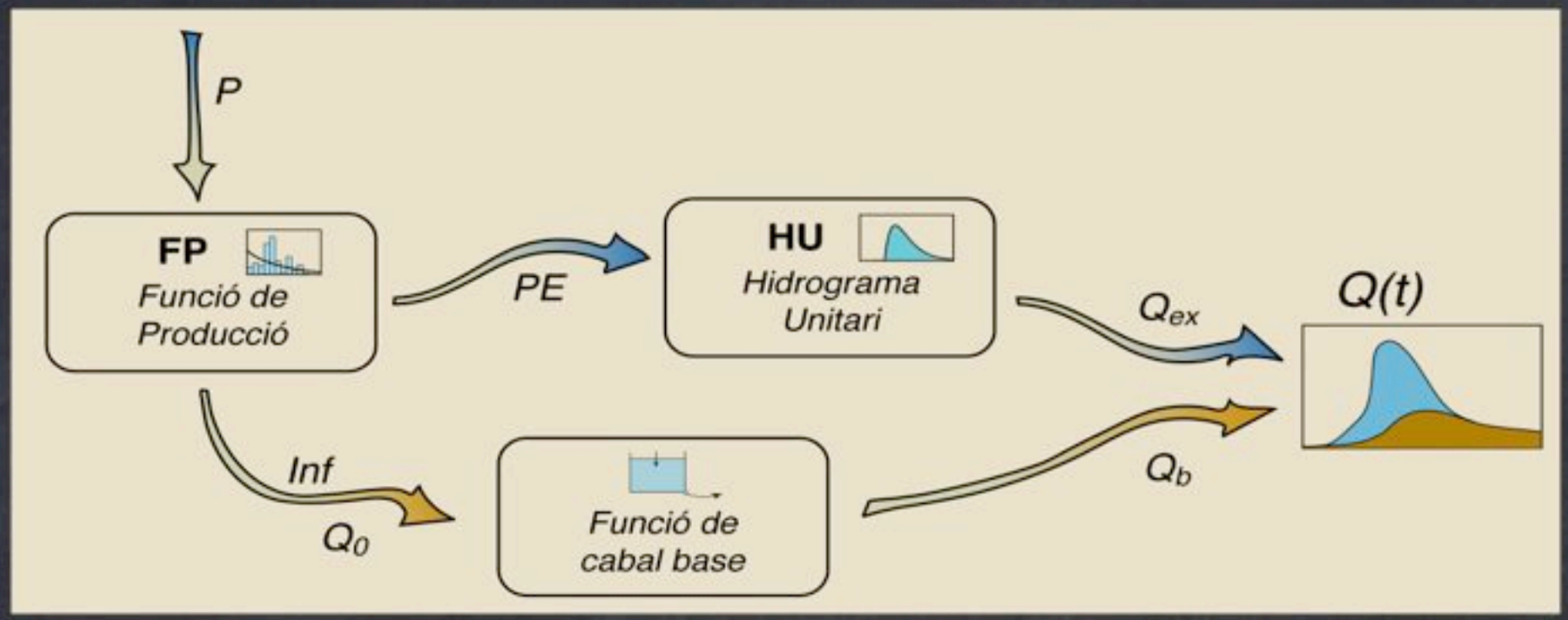


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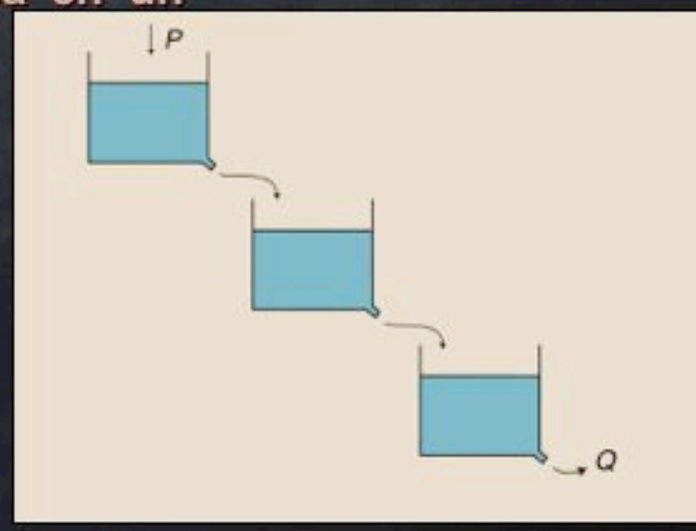
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MODELOS DE BASE FISICA: intent de reproduir els processos físics globalment (equacions físiques amb molts paràmetres)
comuns als anys 60

Tipus de models hidrològics

Models de caixa negra (black-box)

relacionen entrades i sortides sense cercar una base física



Tipus de models hidrològics

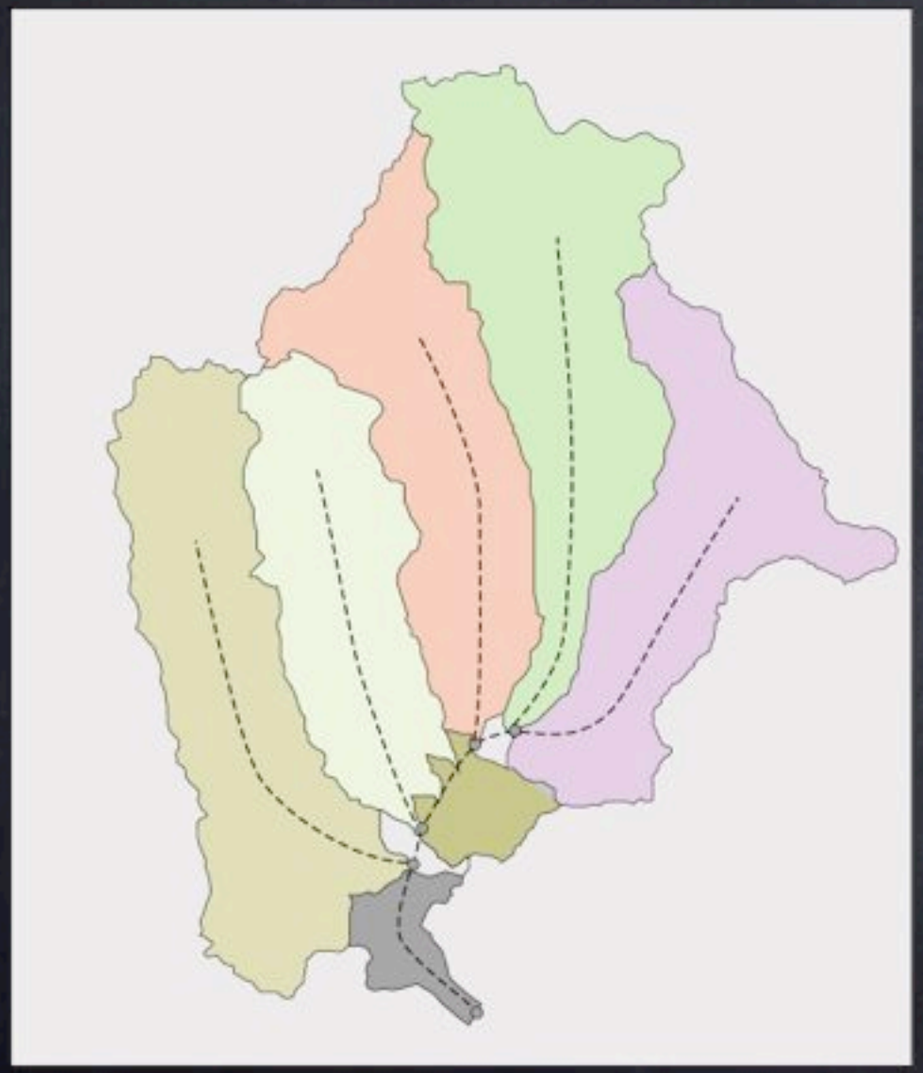
Models distribuïts

- divisió de la conca en subunitats

Tipus de models hidrològics

Models distribuïts

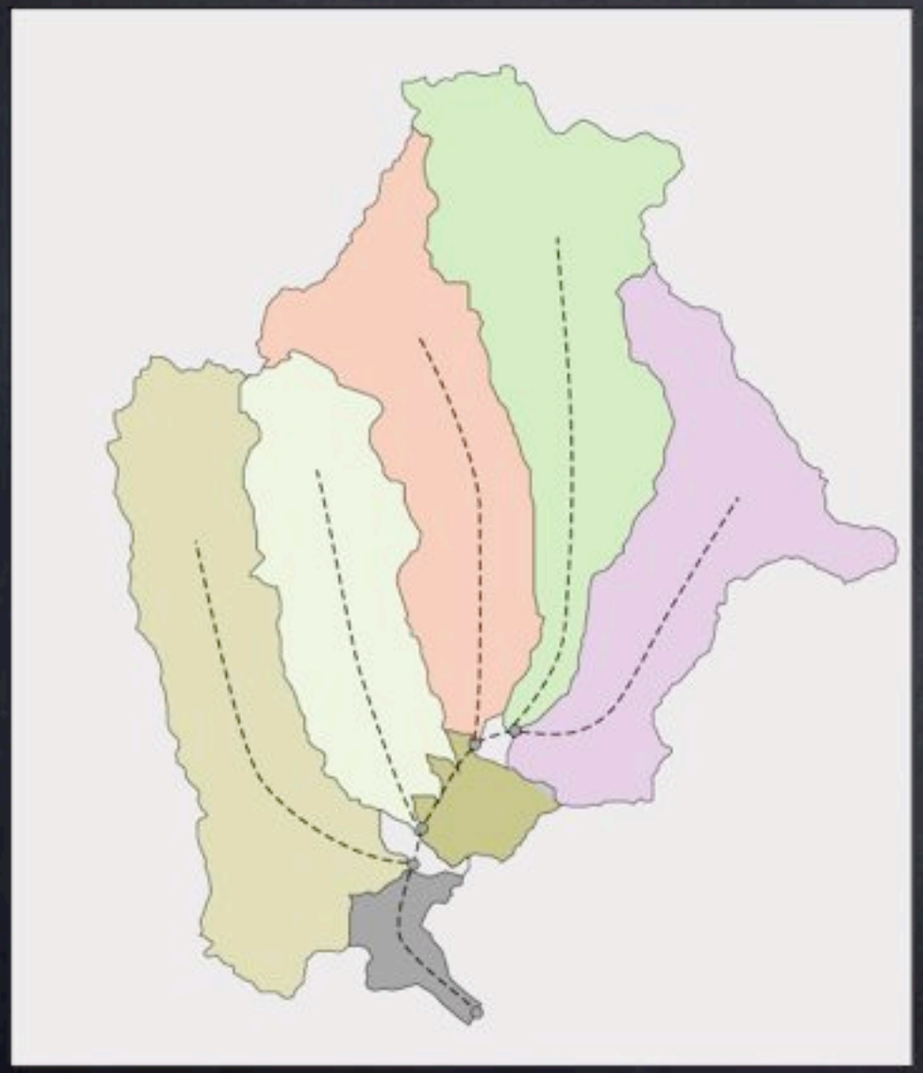
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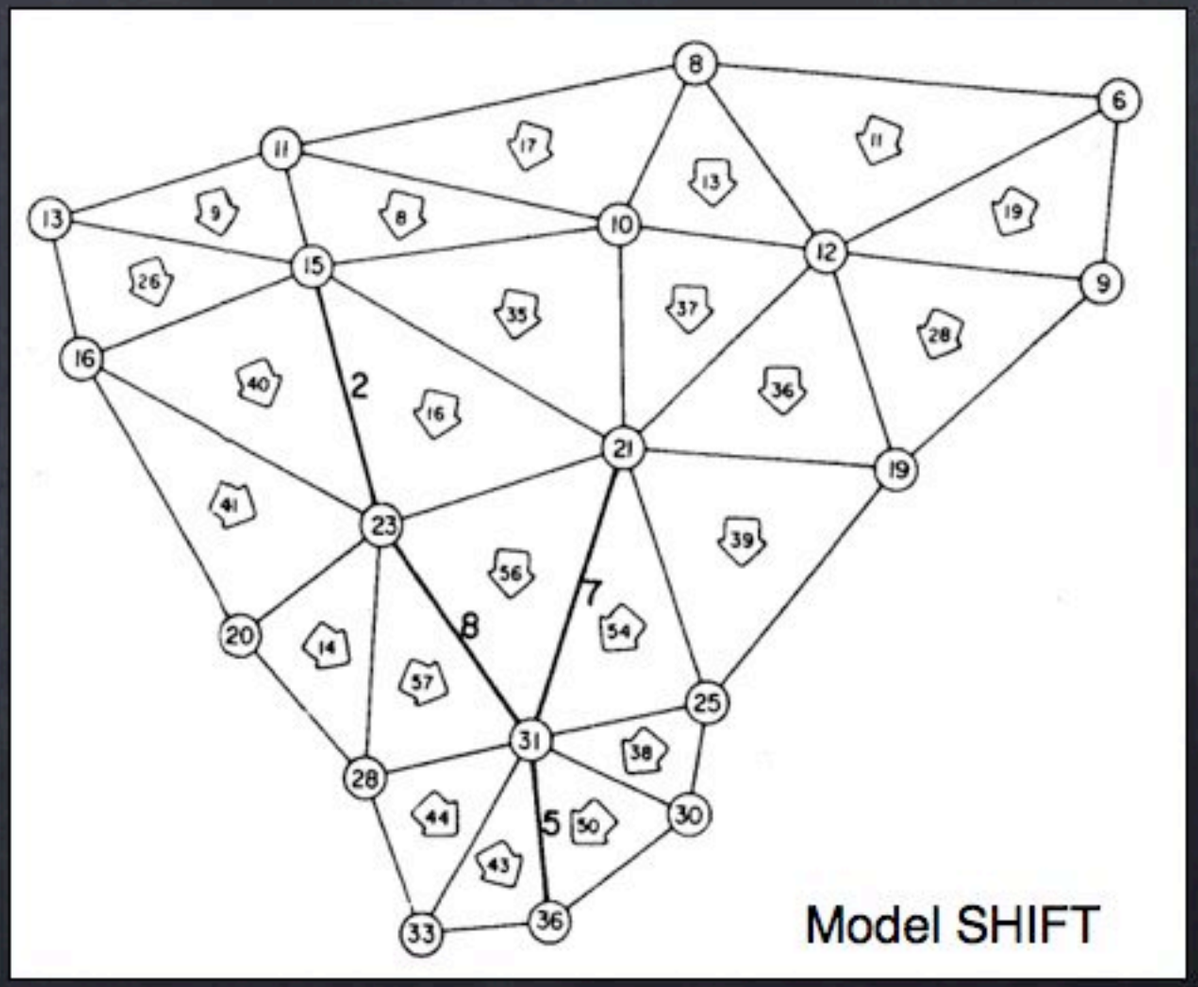


Tipus de models hidrològics

Models distribuïts

divisió de la conca en subunitats





Cómo es el modelo que queremos construir?

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Modelo de tipo distribuido

> ***Intento de integrar la variabilidad espacial de las variables***

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Intento de integrar la variabilidad espacial de las variables

características de la cuenca



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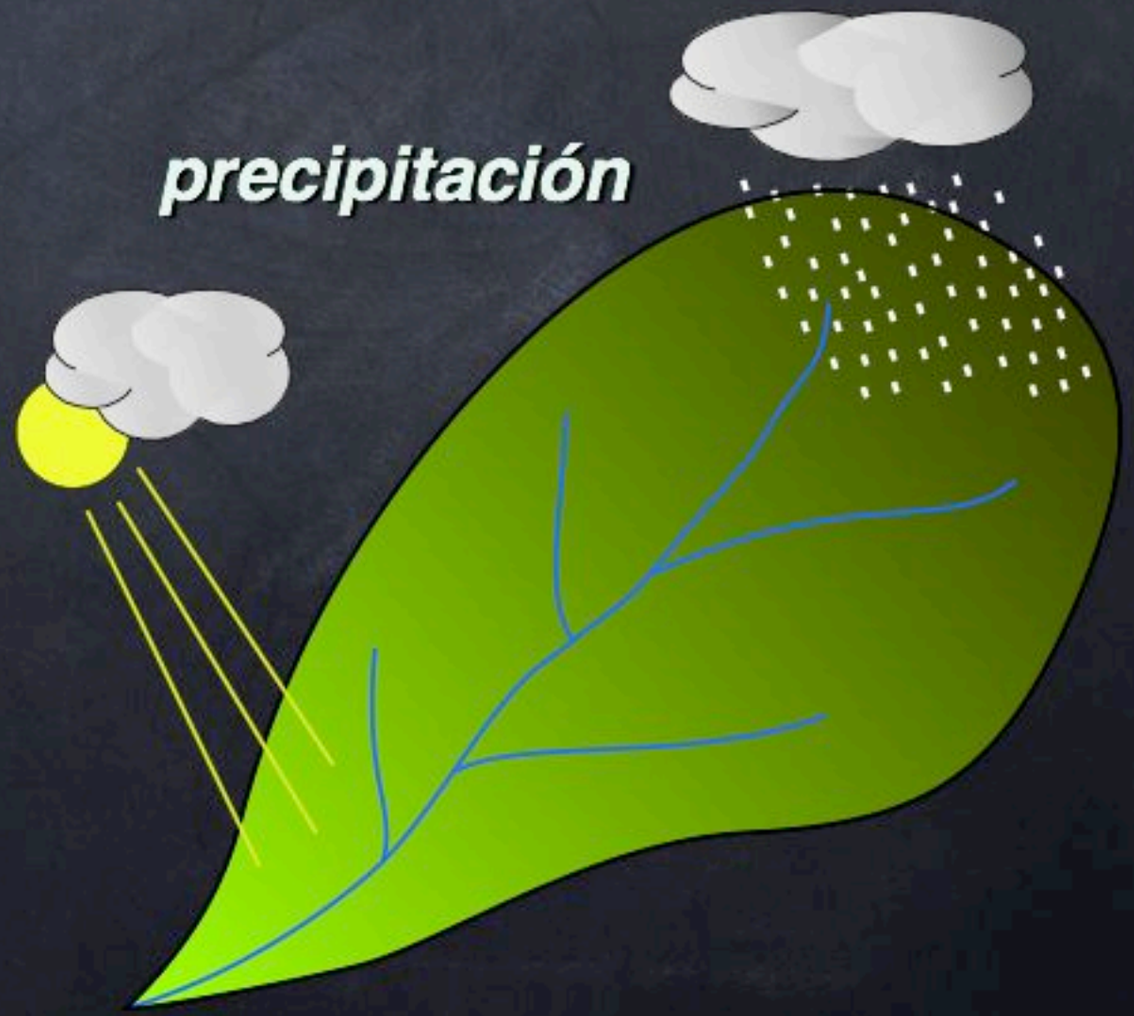
Modelo de tipo distribuido

Intento de integrar la variabilidad espacial de las variables

características de la cuenca

precipitación





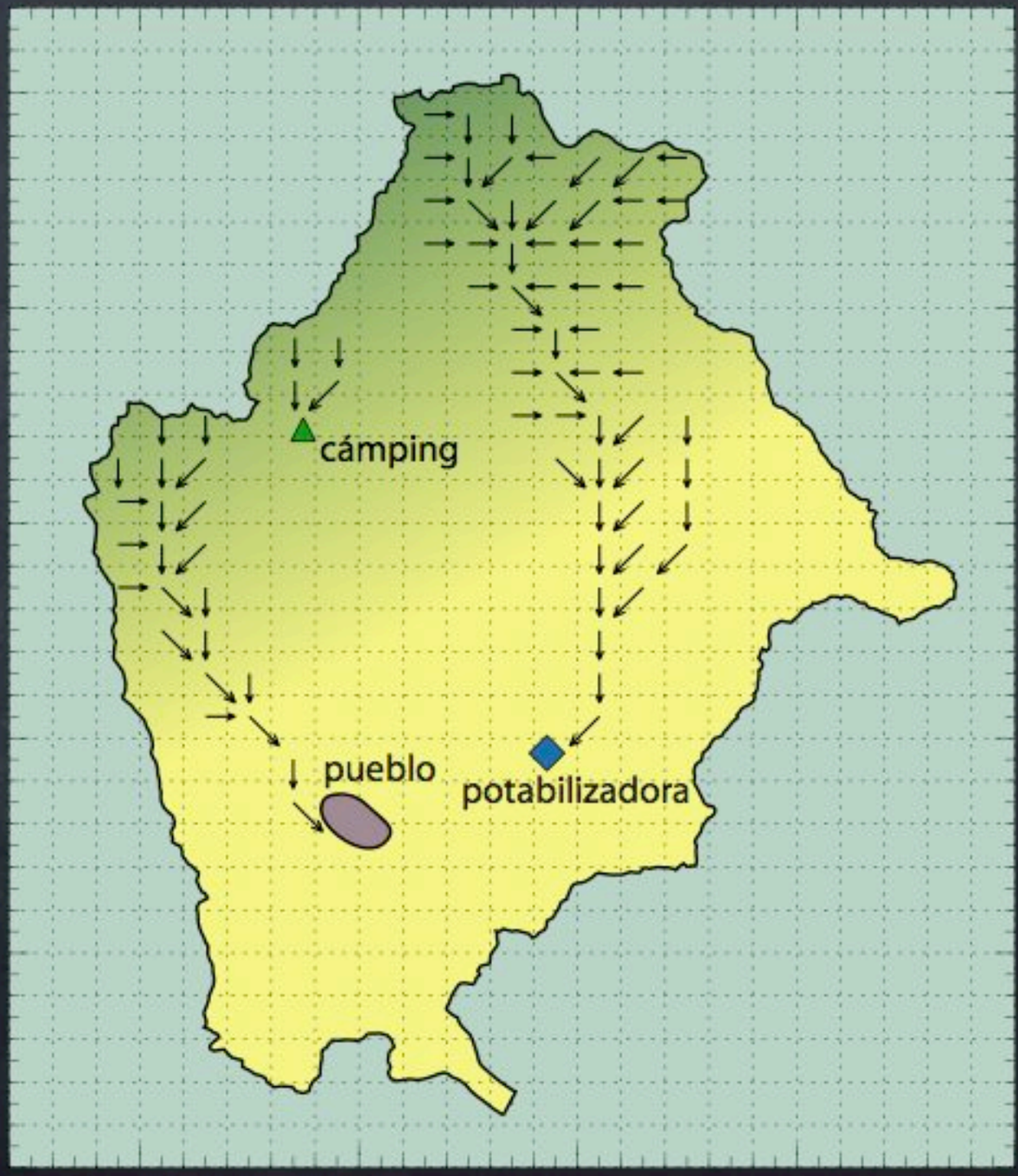
Qué le pedimos al modelo propuesto?

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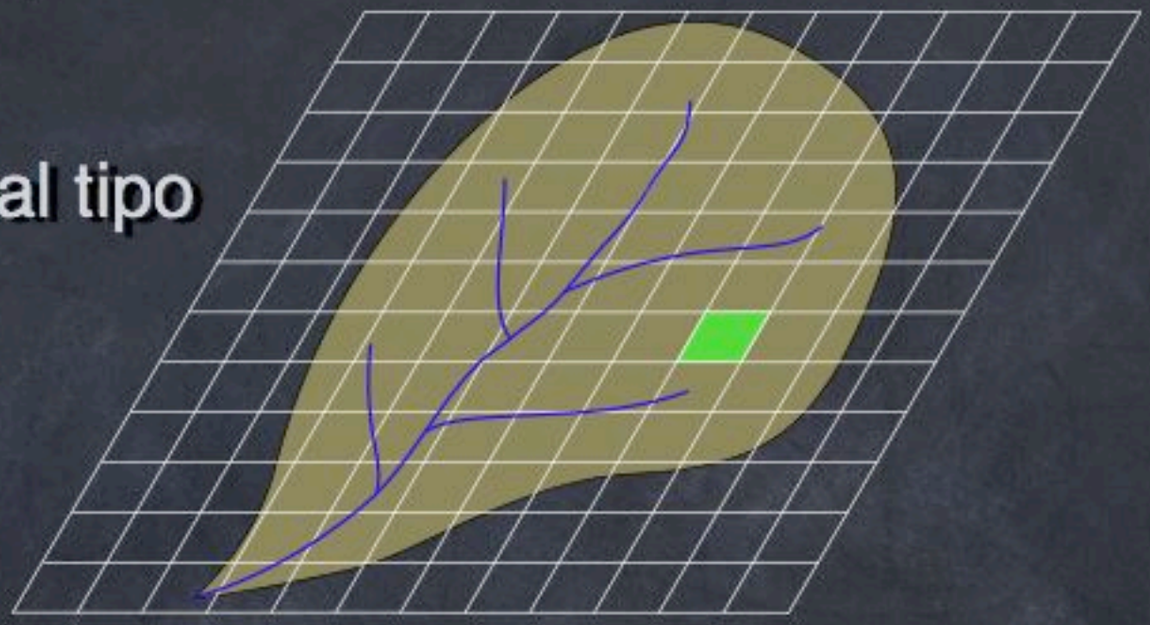
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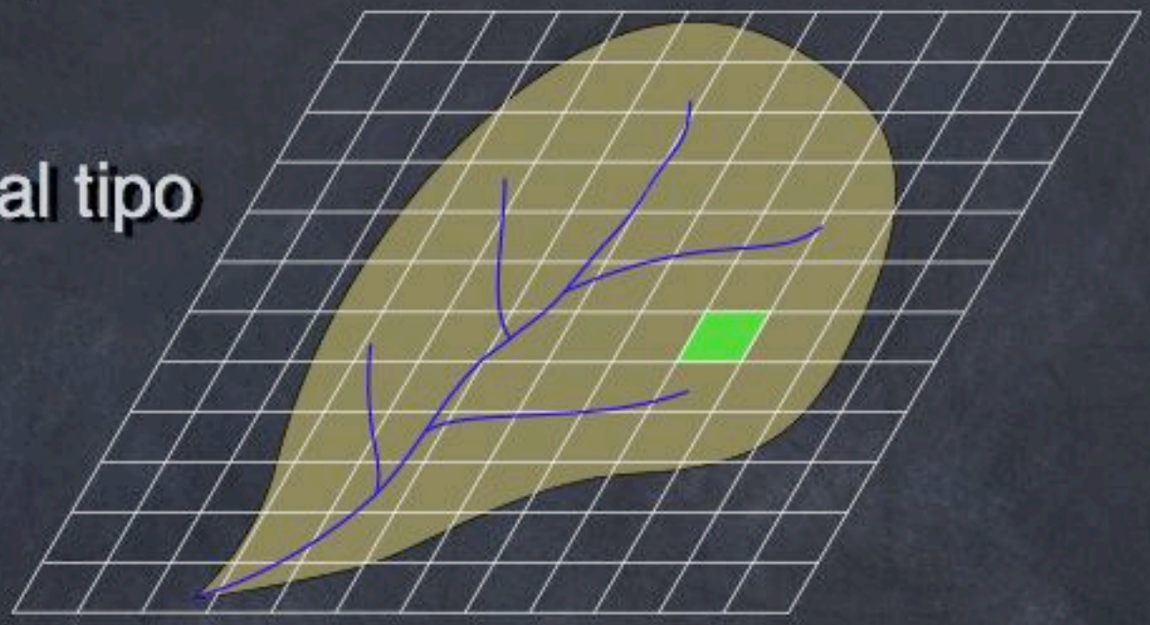
modelo conceptual tipo malla



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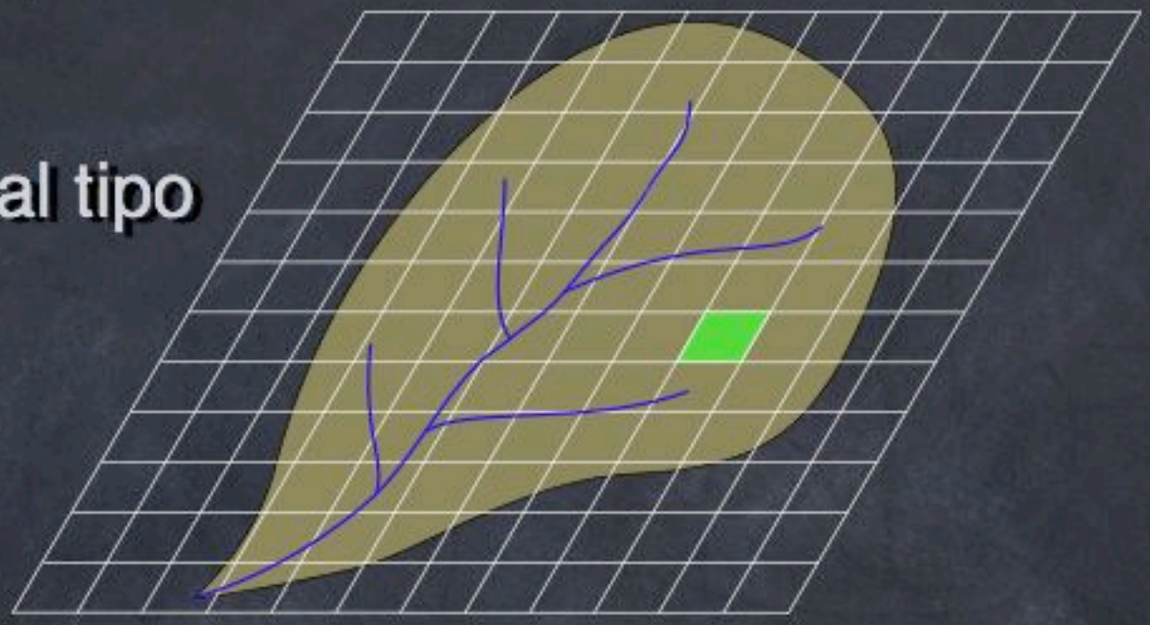


celda hidrológica

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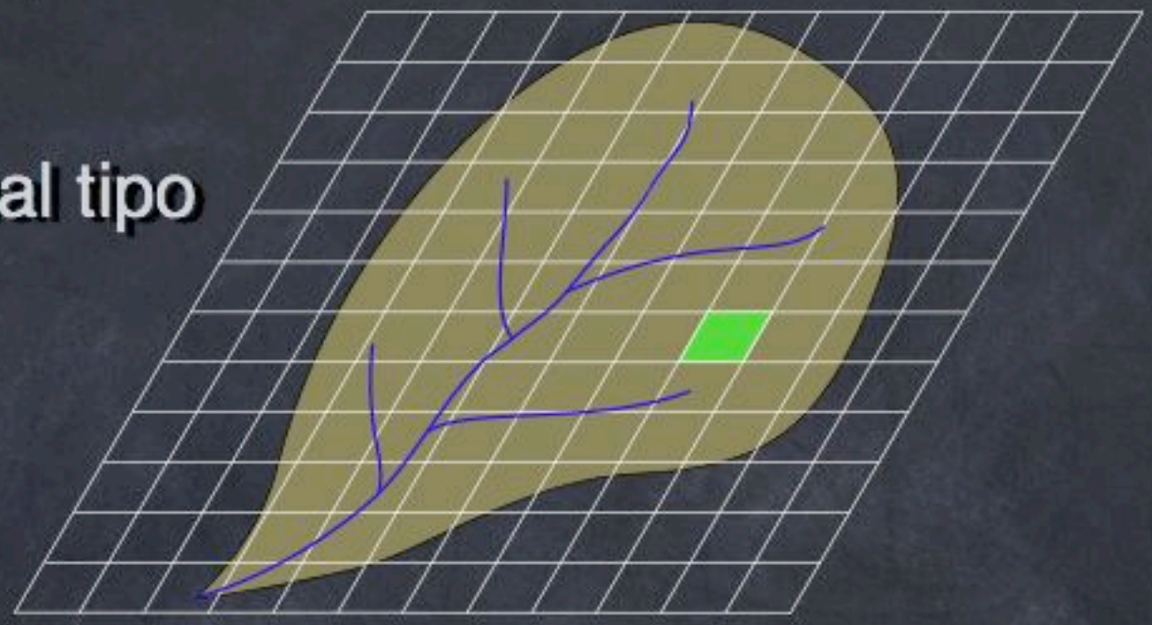
celda hidrológica

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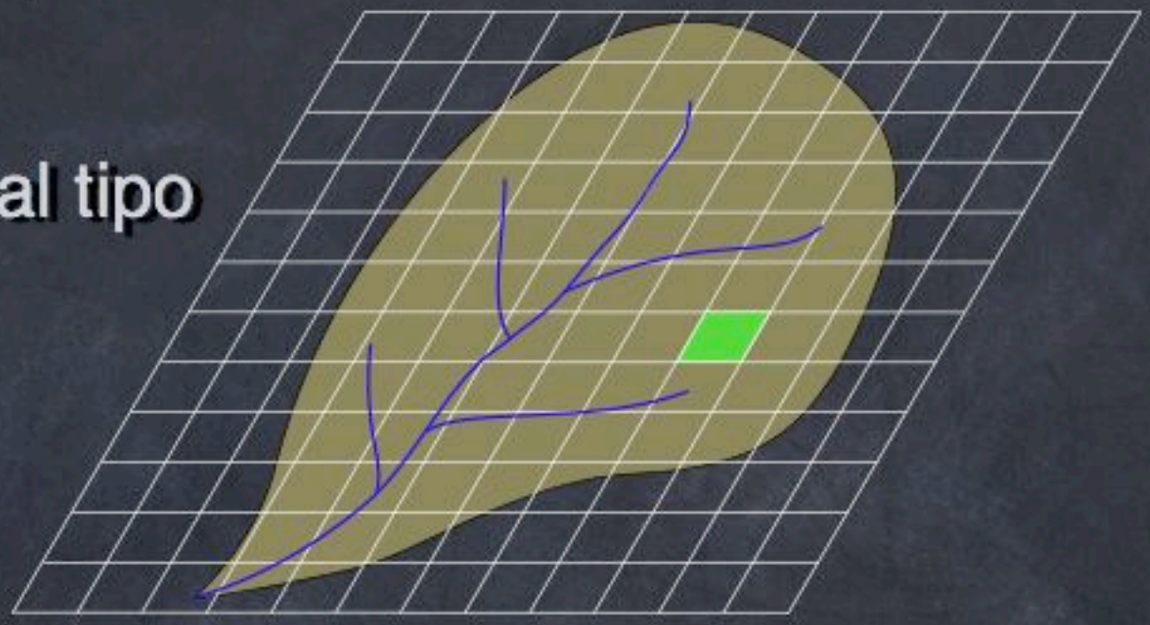
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- *características hidrológicas medias de la celda*
- *lluvia media*

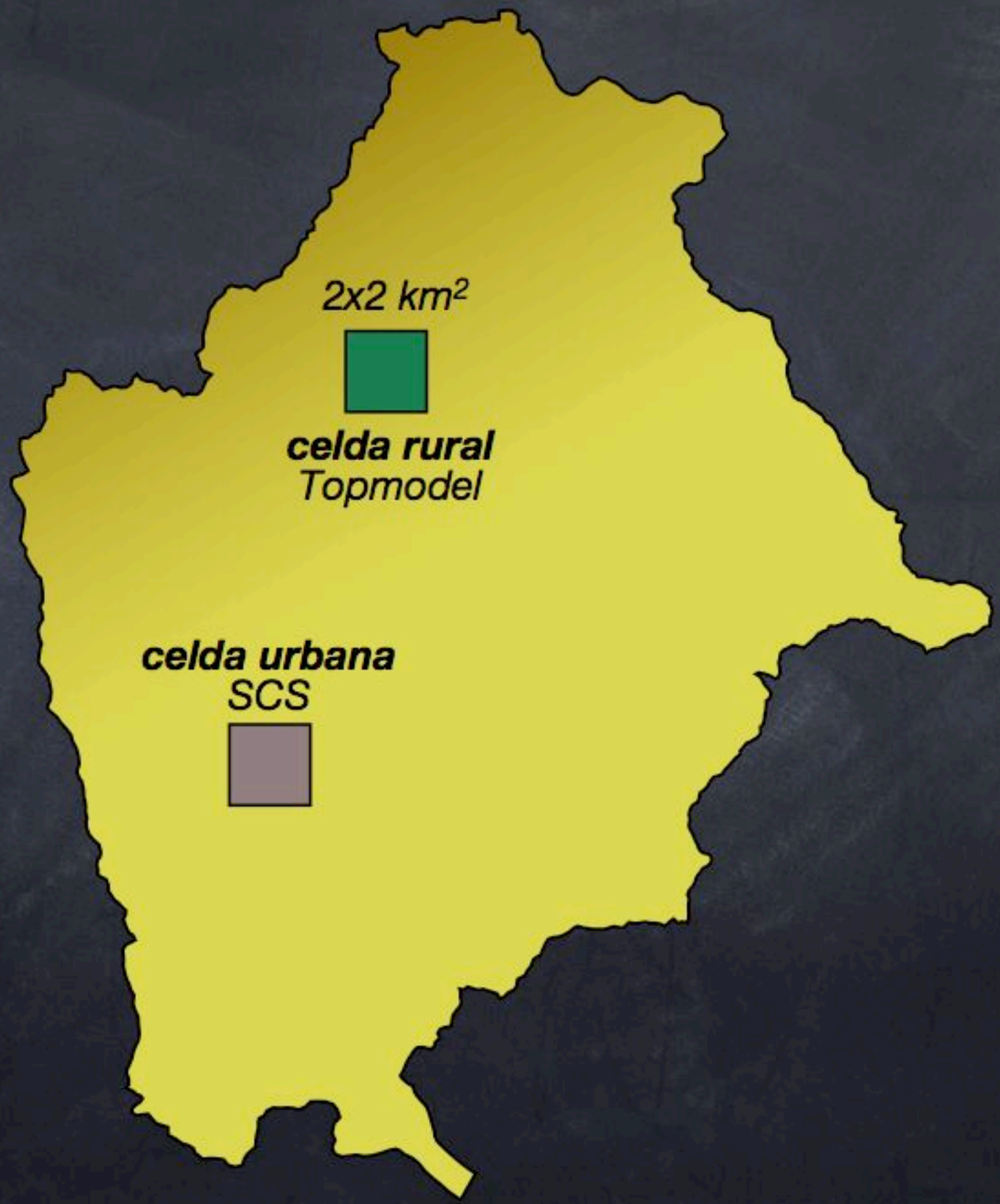
DiCHiTop

modelo Distribuido basado en Celdas Hidrológicas y en la Topografía



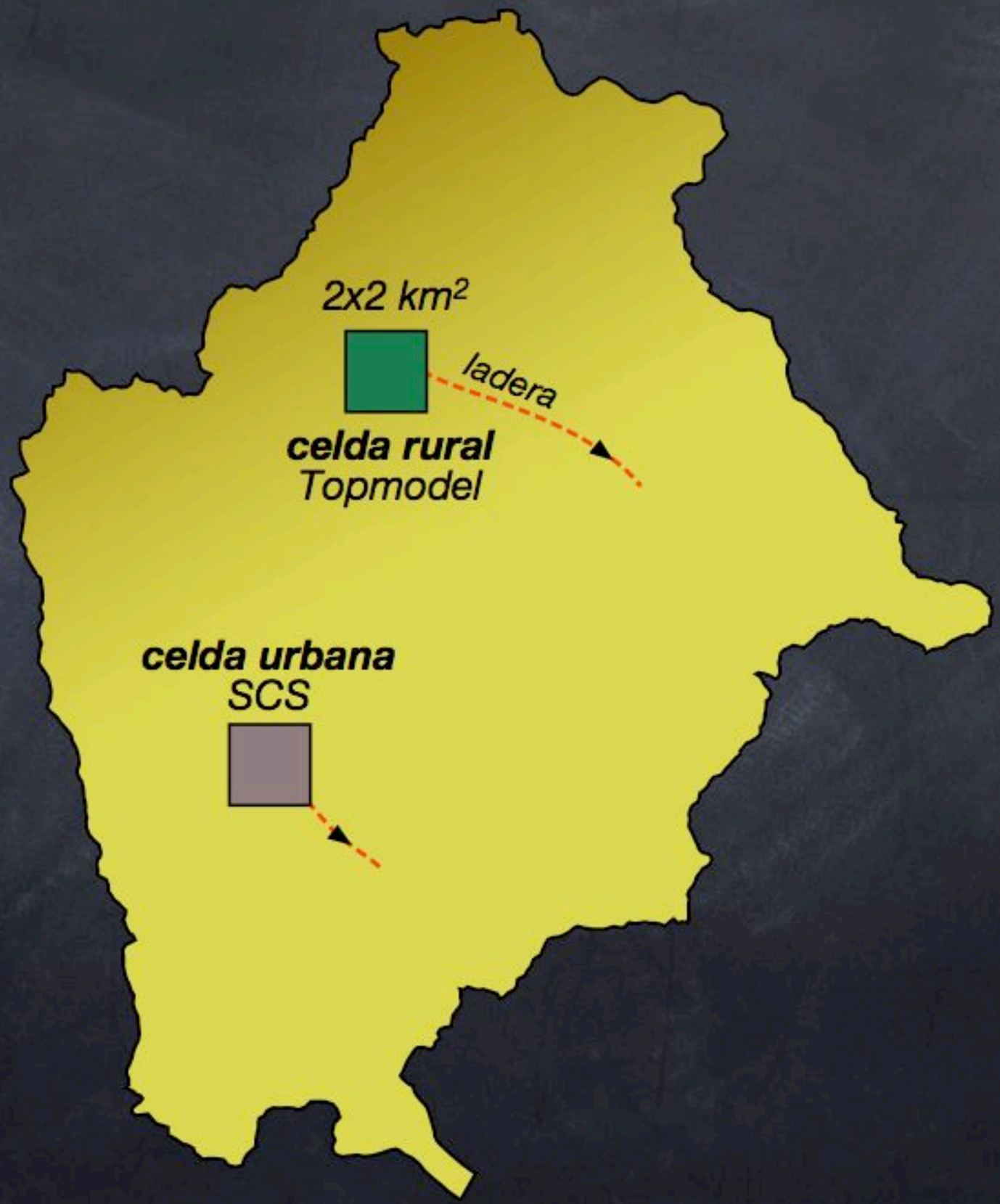
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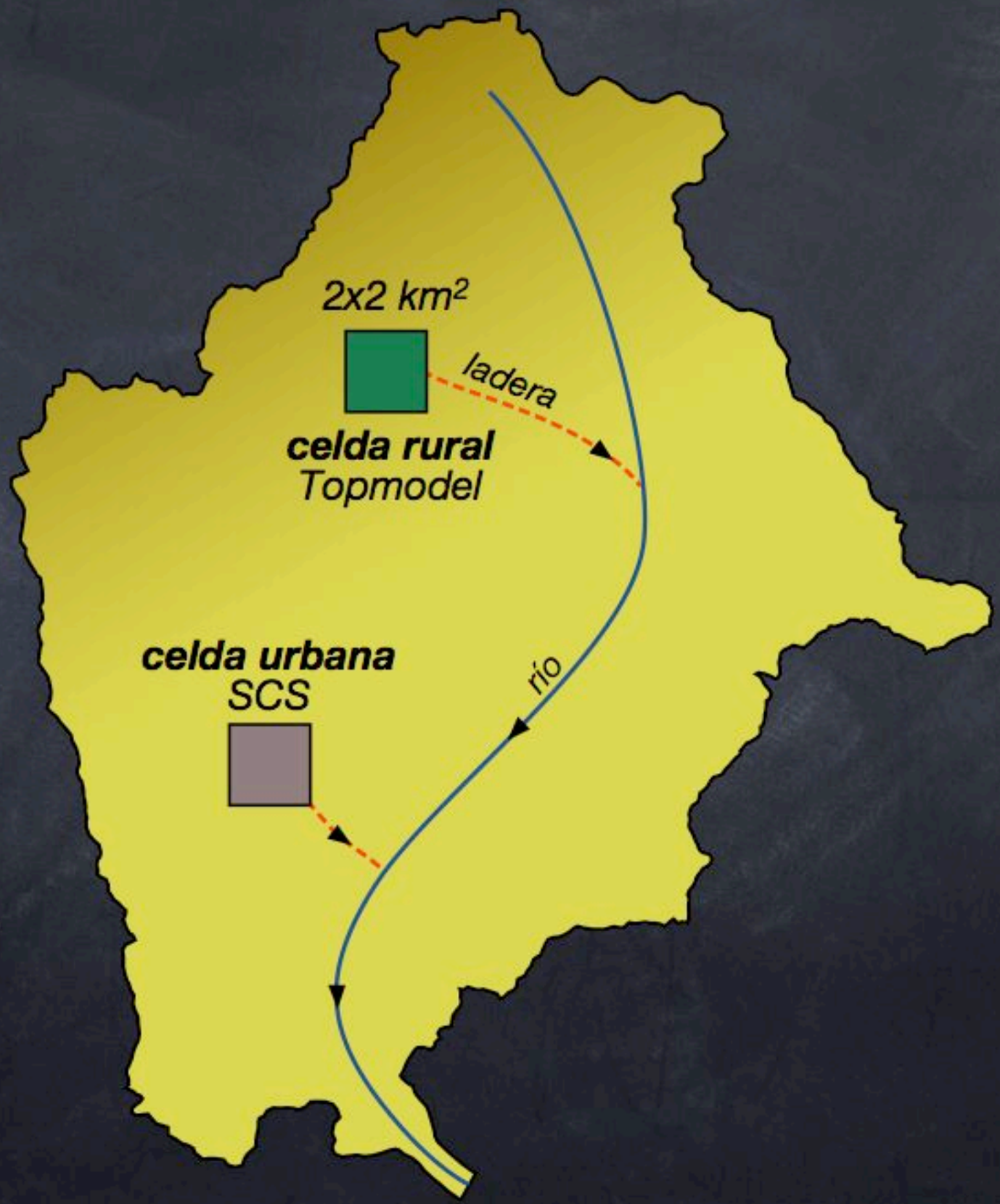
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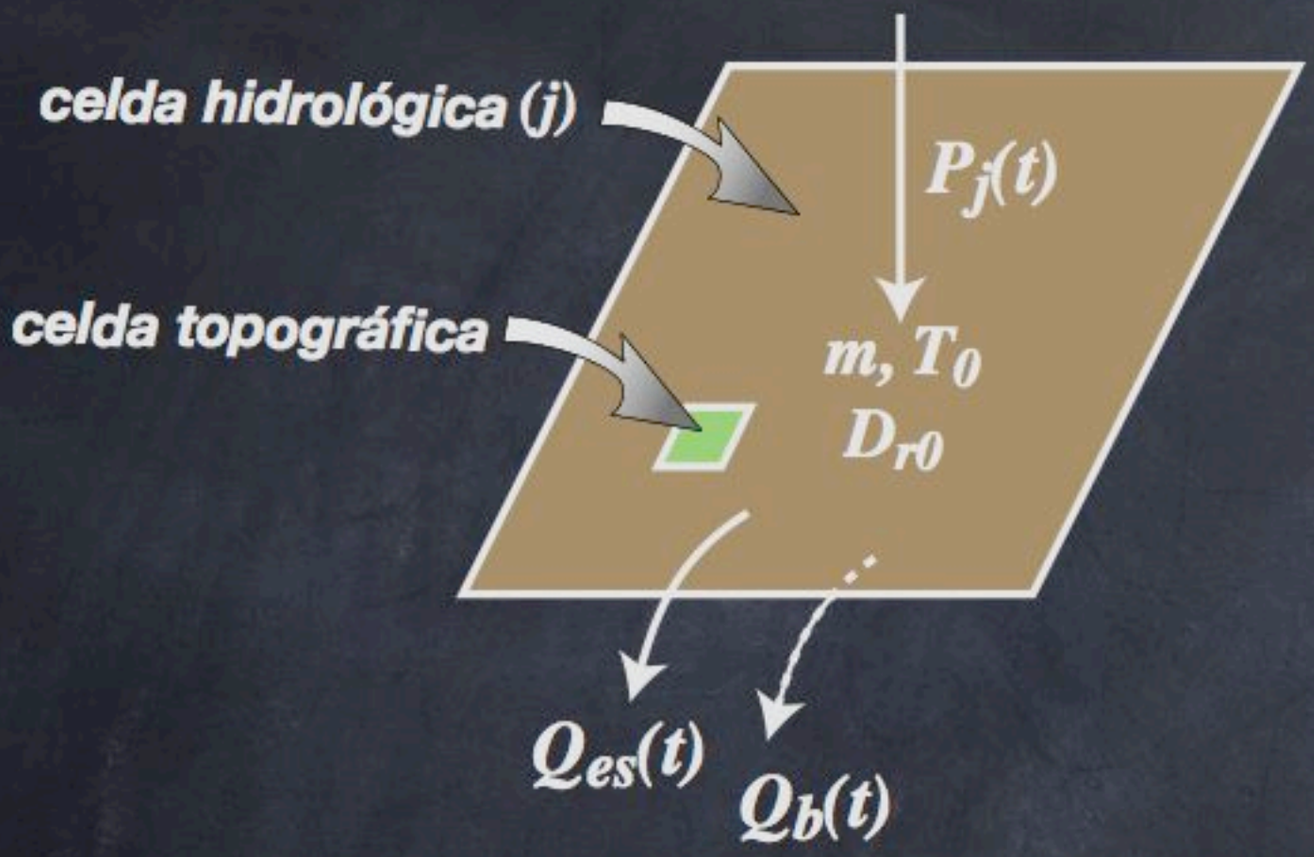


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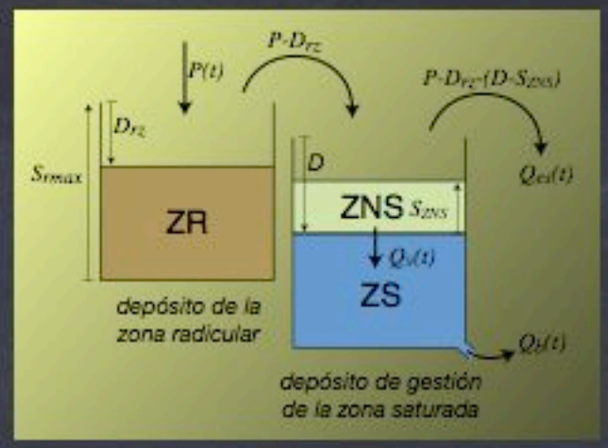
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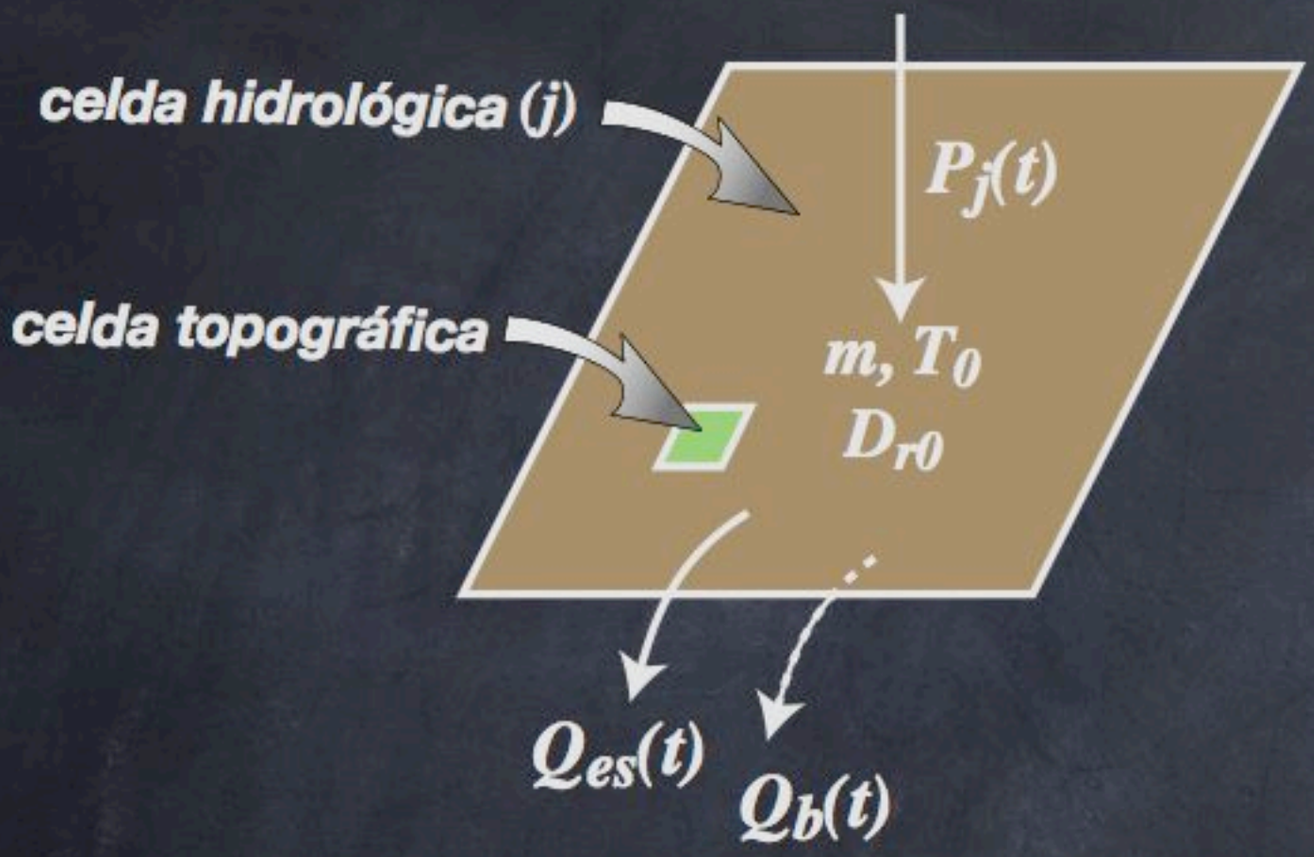


Topmodel a escala de celda hidrológica

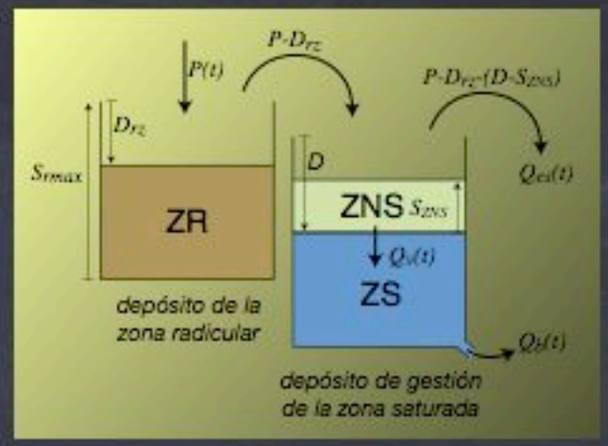


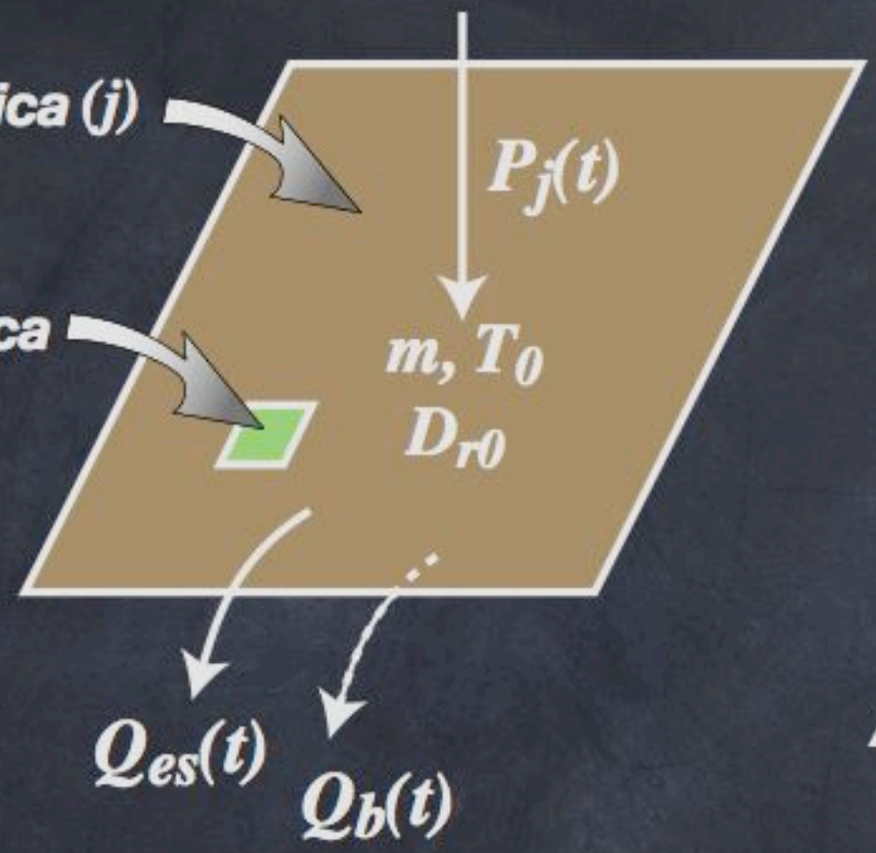
Topmodel a escala de celda hidrológica

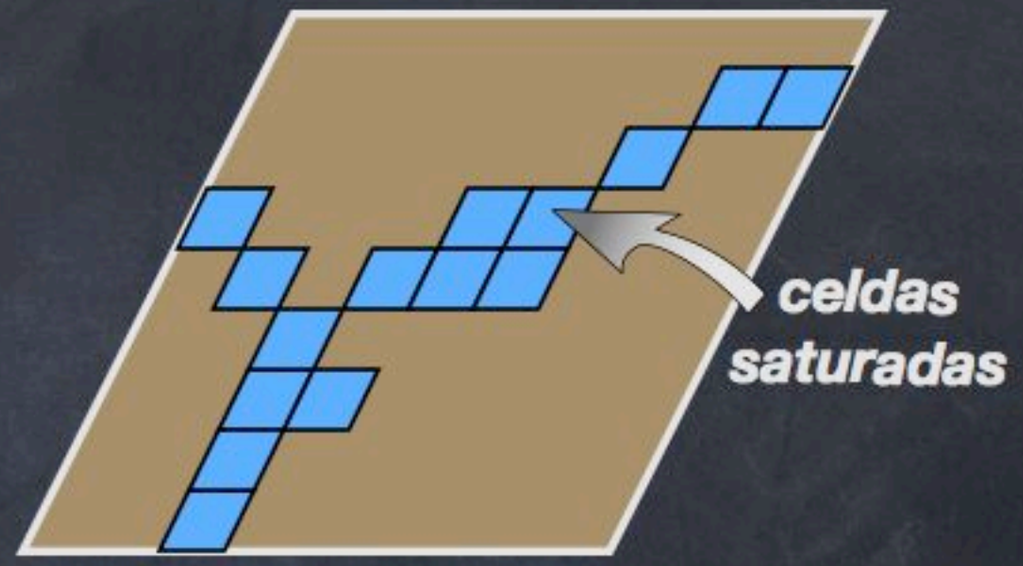




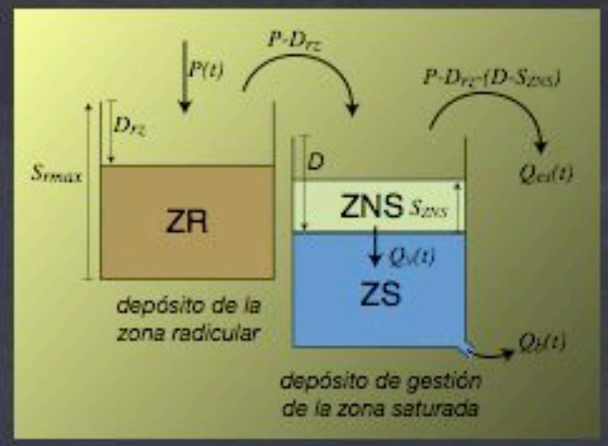
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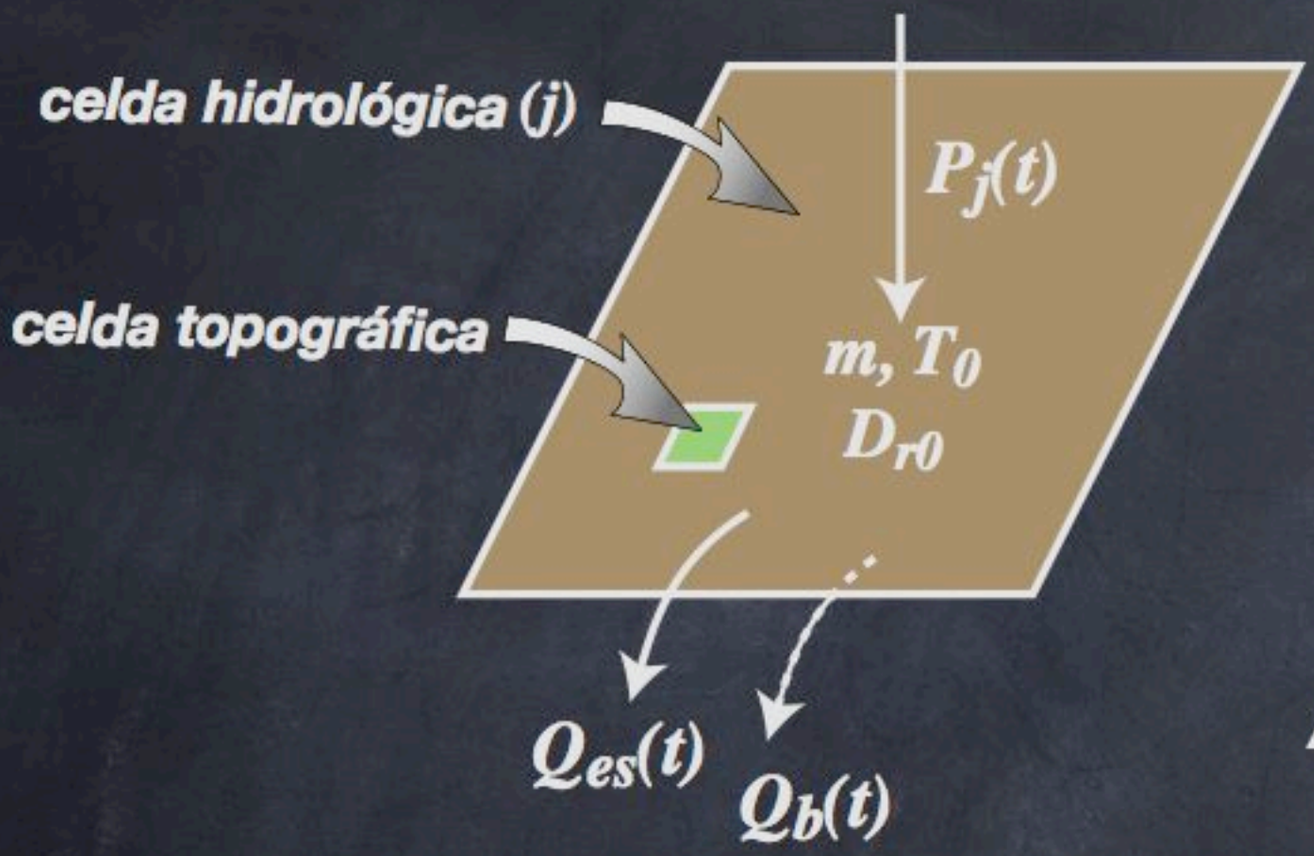


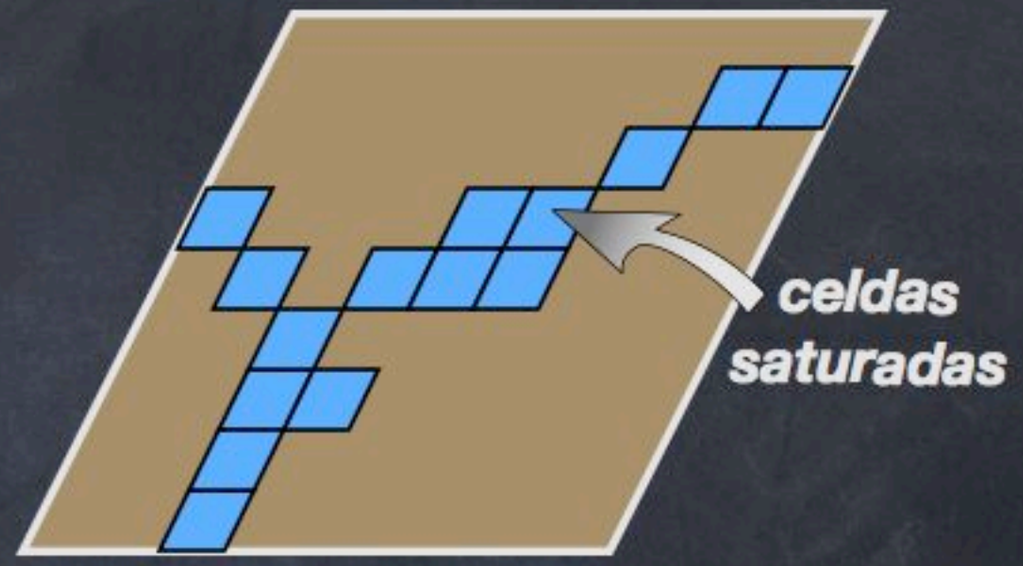




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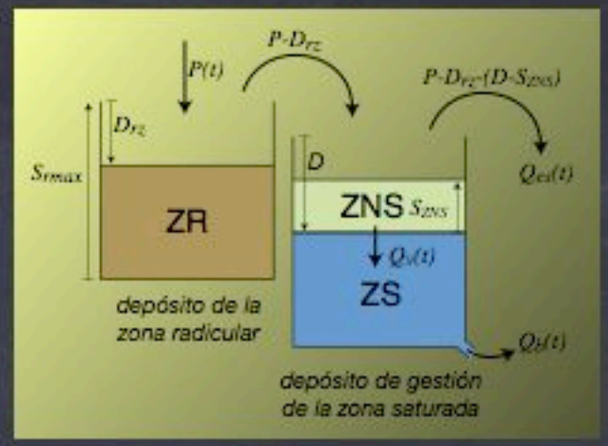


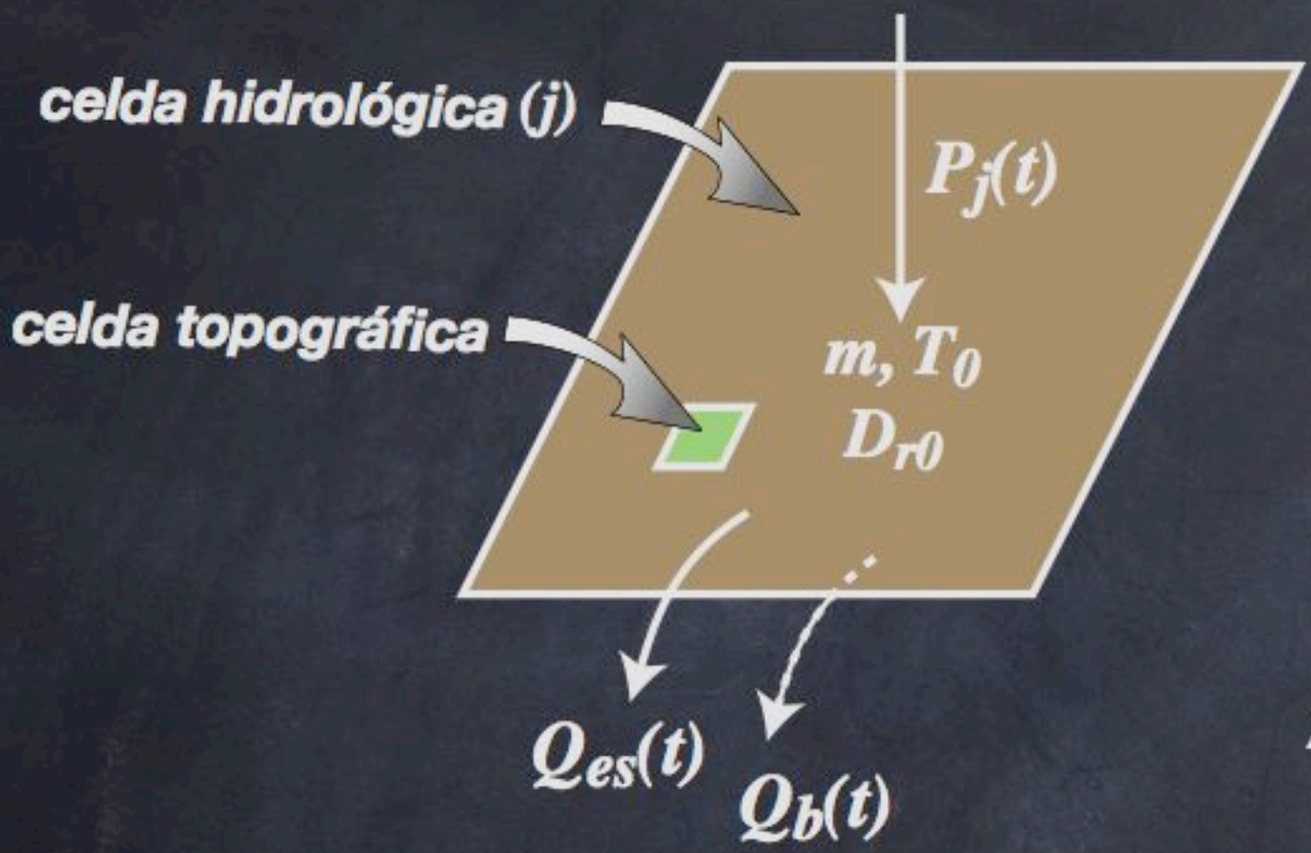


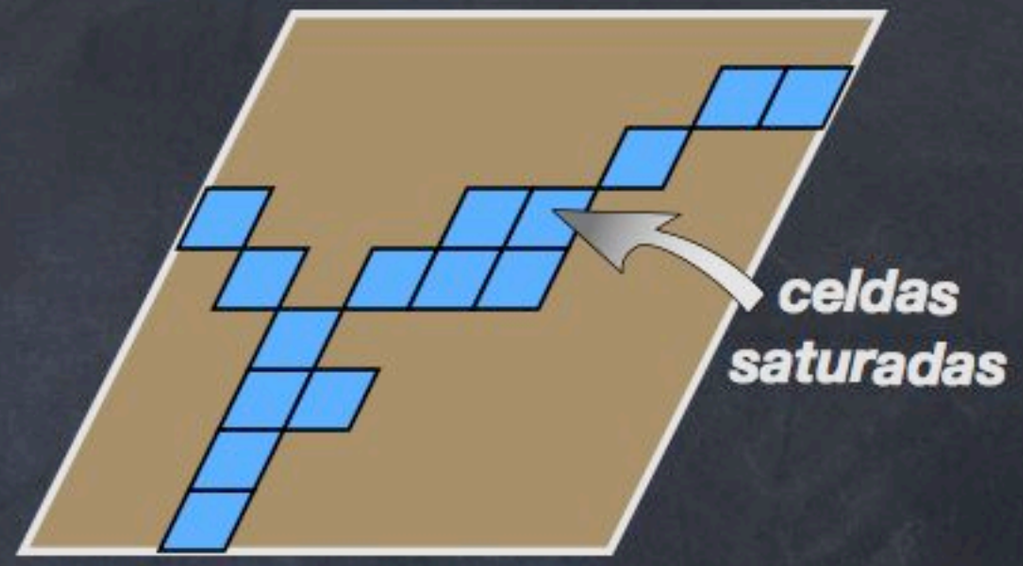


- 2 parámetros de cuenca (m, T_0)

Topmodel a escala de celda hidrológica



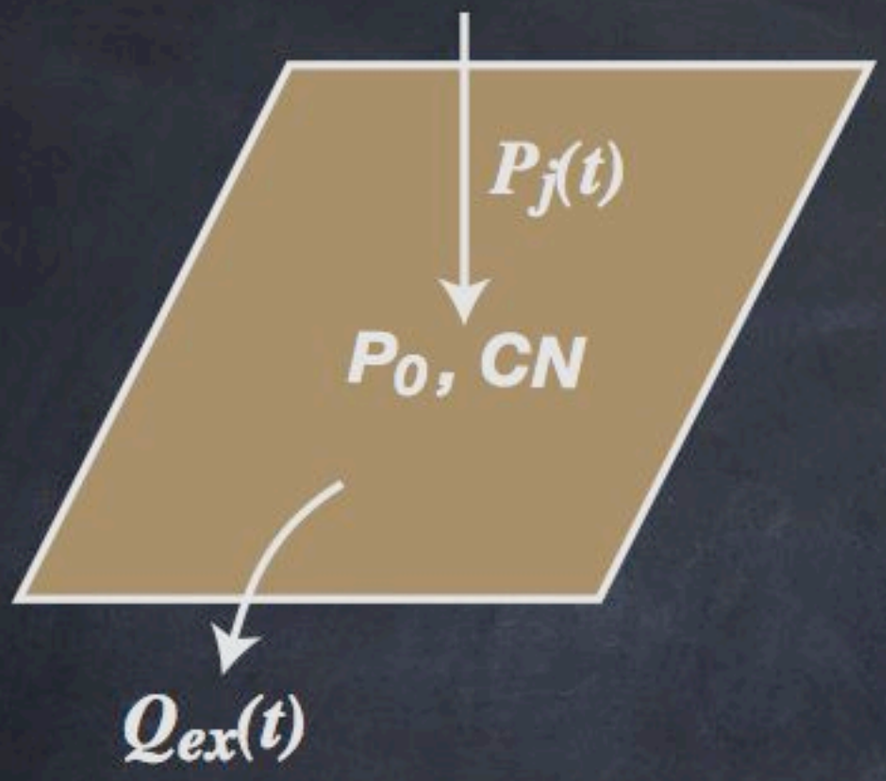




- 2 parámetros de cuenca (m, T_0)
- 1 parámetro de inicialización (D_{r0})

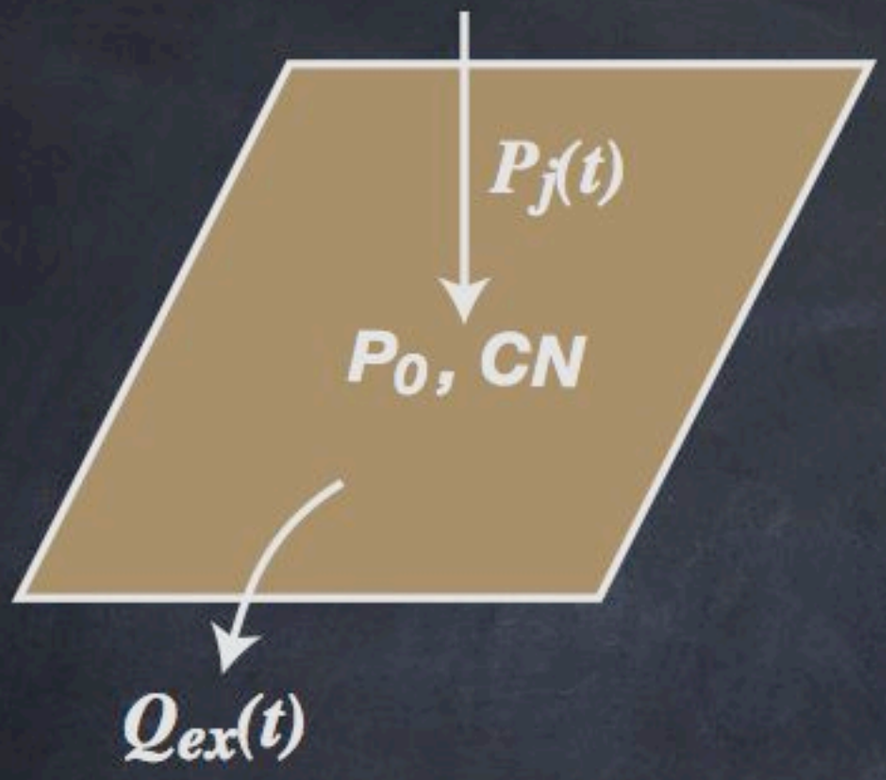
Generación de agua a escala de celda

celda urbana: función de pérdidas del SCS



Generación de agua a escala de celda

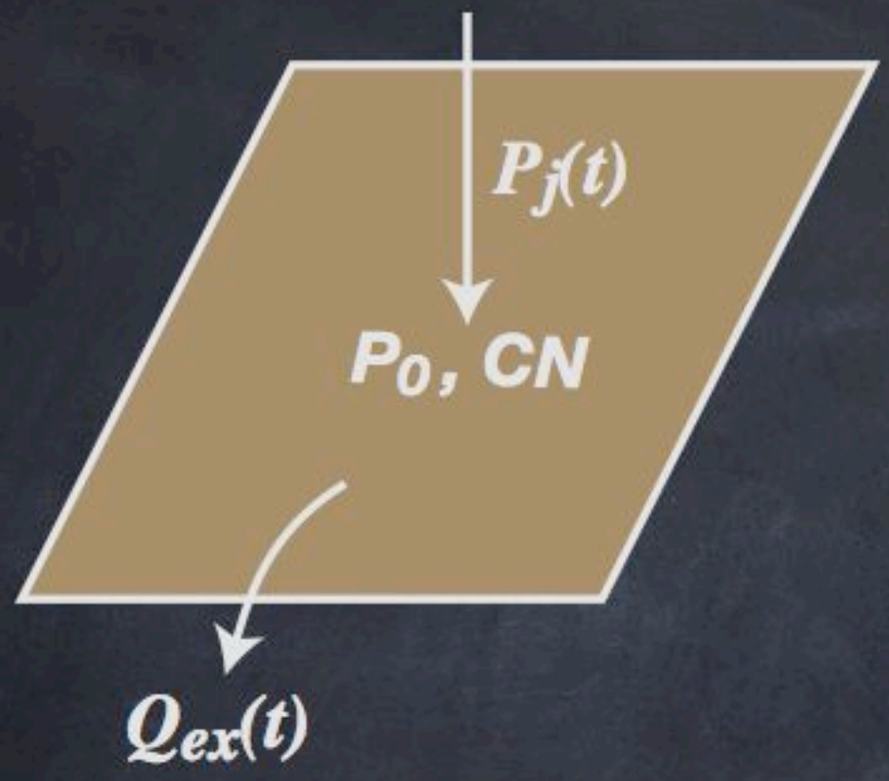
celda urbana: función de pérdidas del SCS



- *1 parámetro de cuenca (CN)*
- *1 parámetro de inicialización (P_0)*

Generación de agua a escala de celda

celda urbana: función de pérdidas del SCS

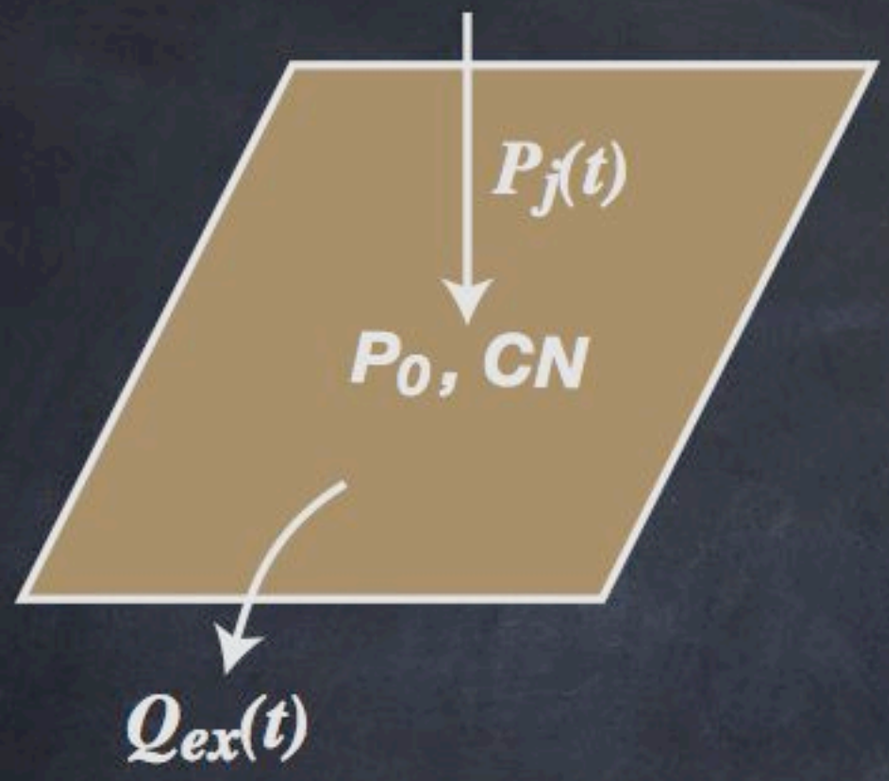


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- *CN' = FS · CN*

Determinación de las pérdidas iniciales

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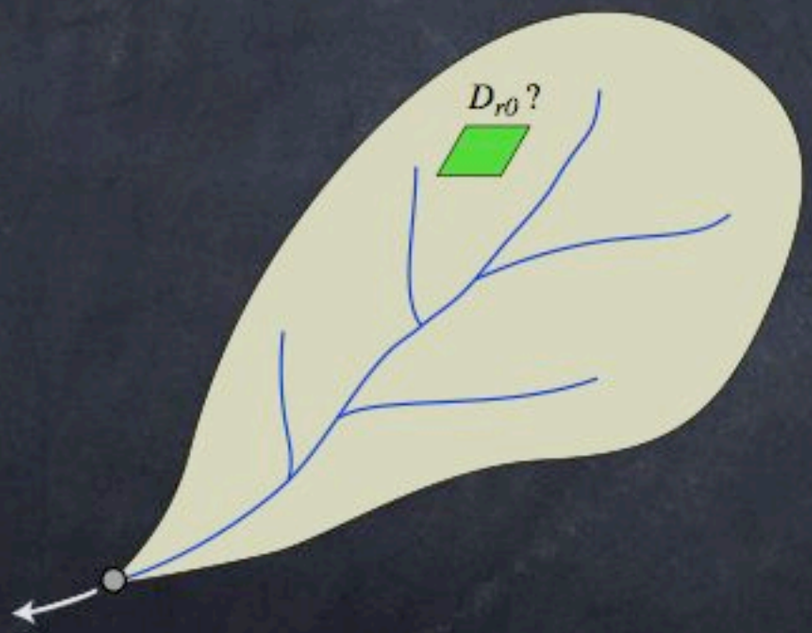
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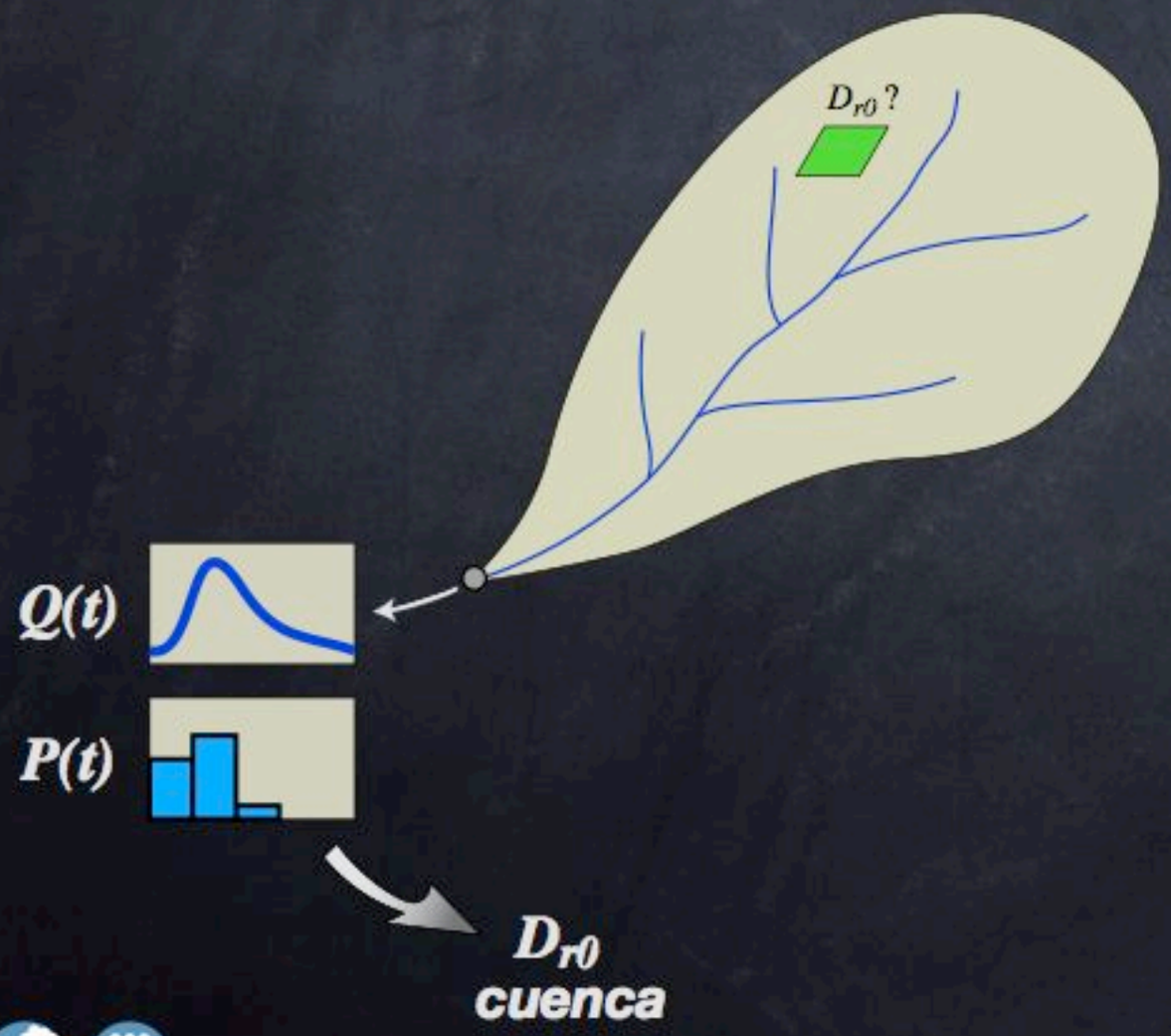
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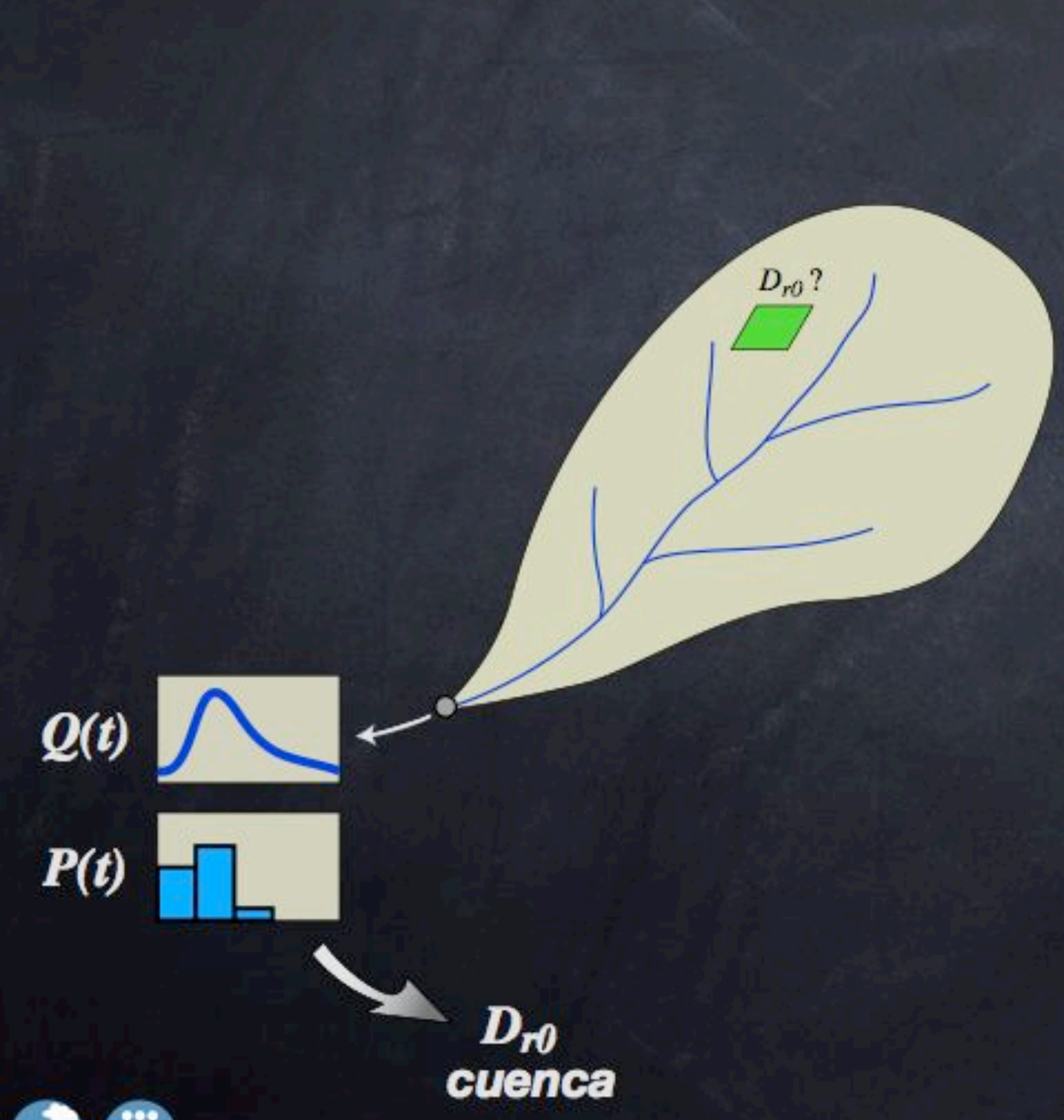
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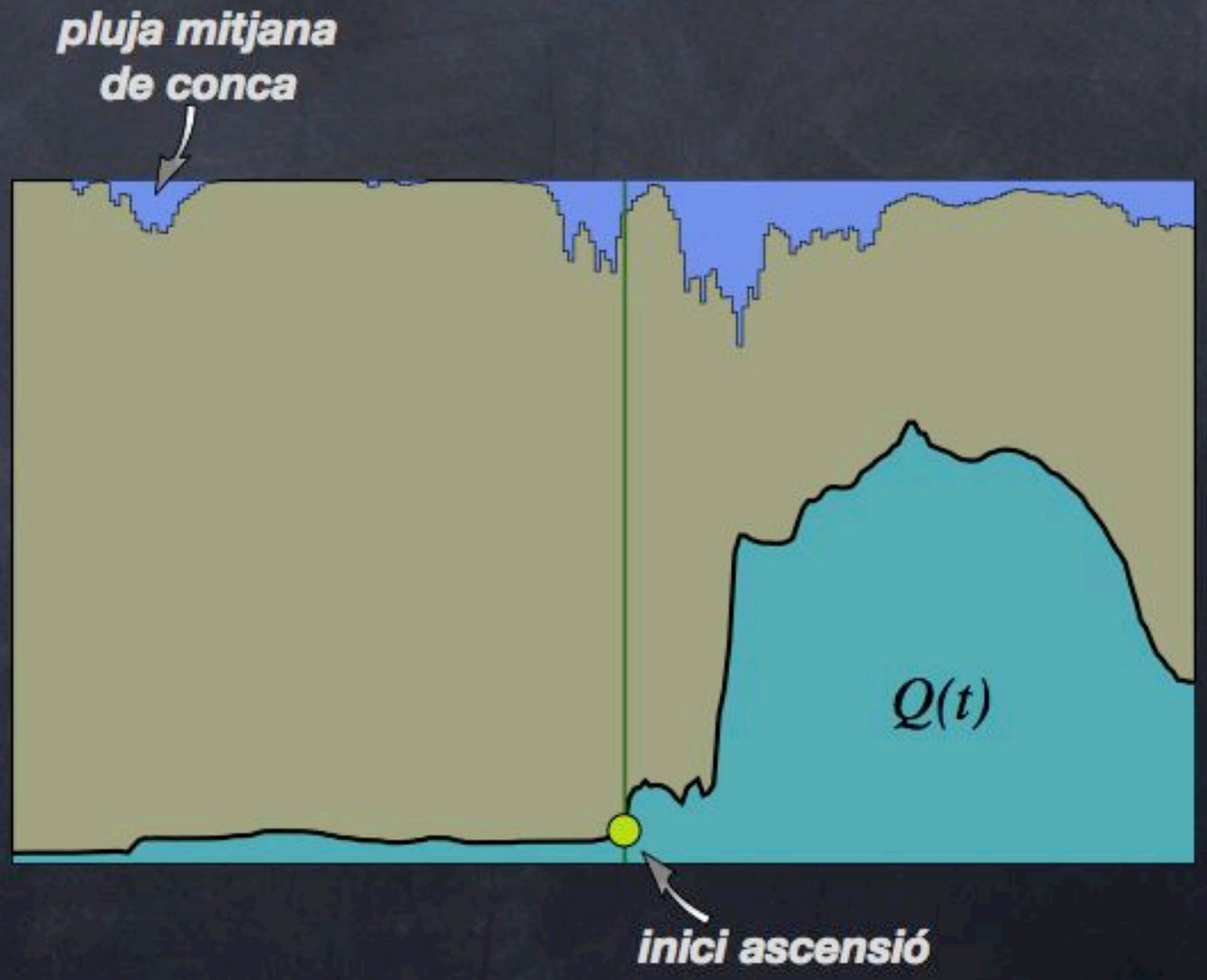
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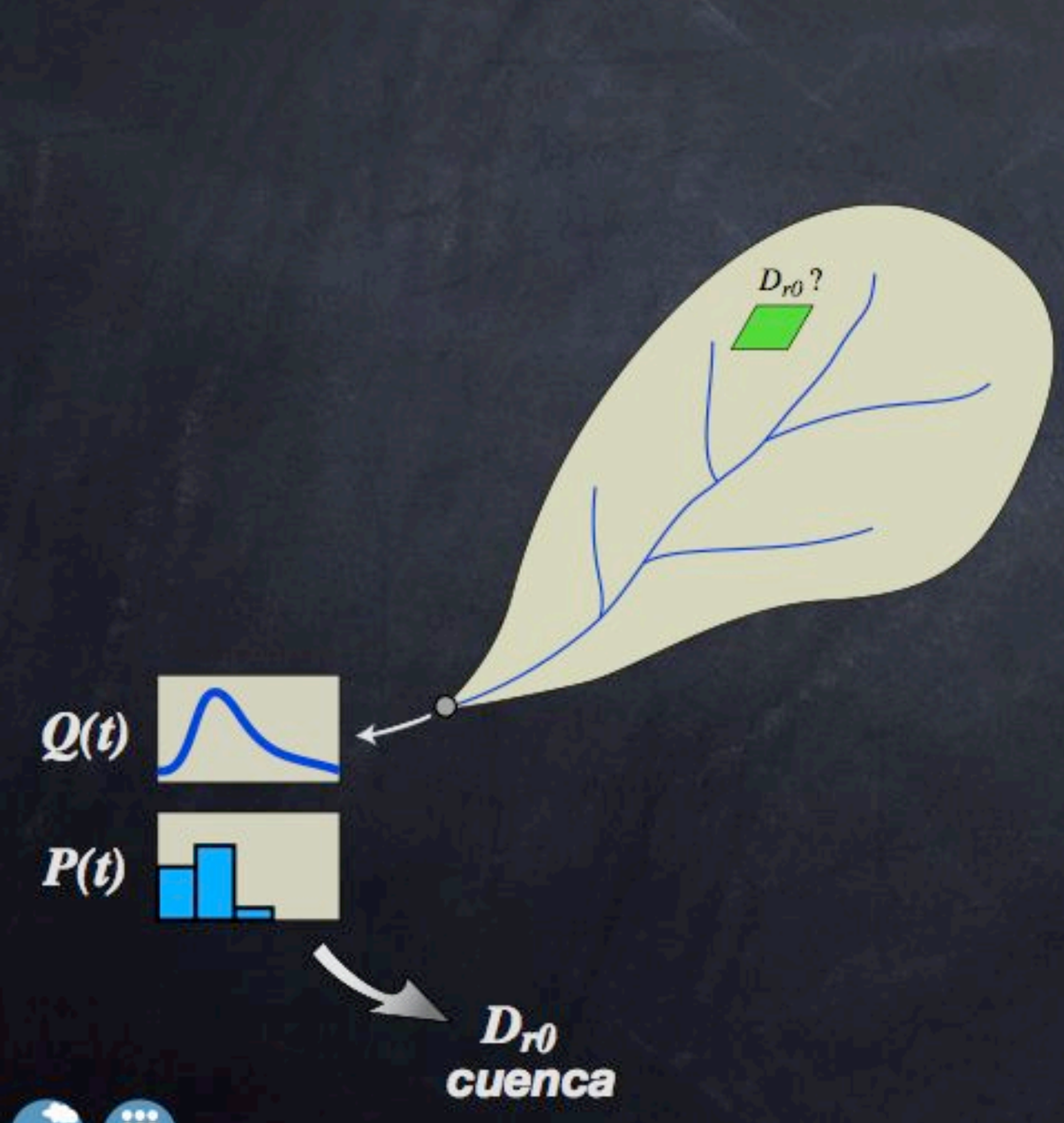
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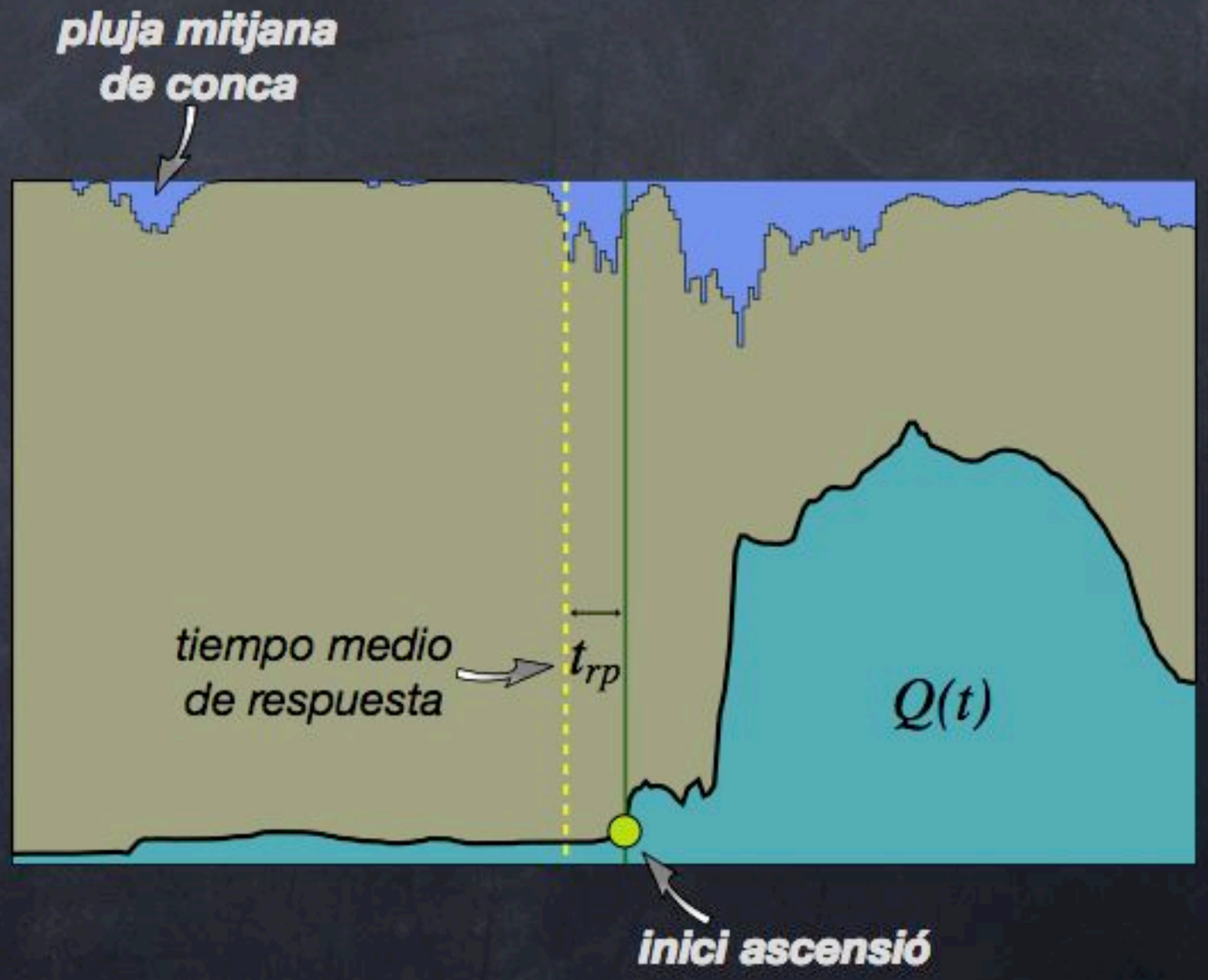




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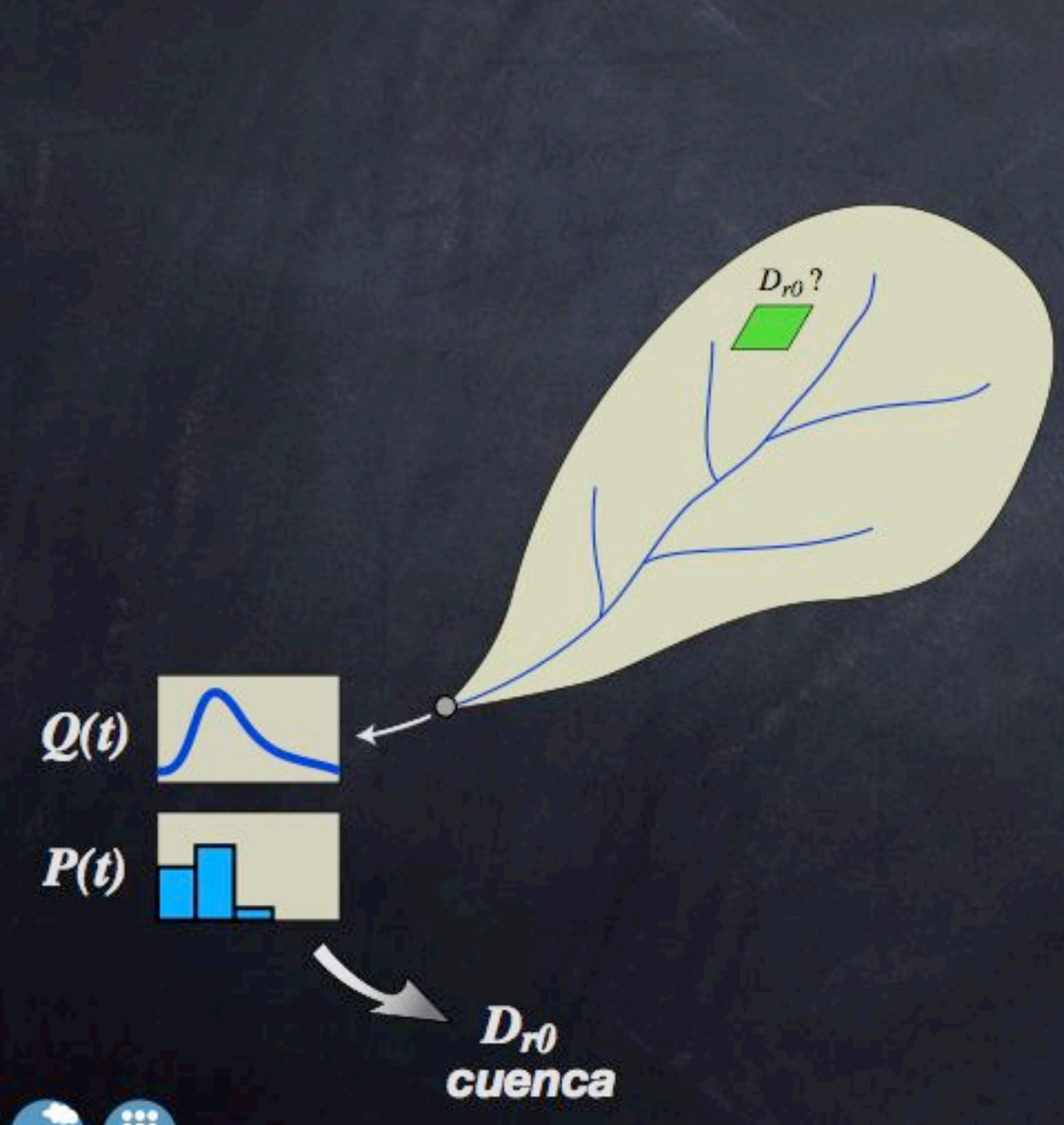
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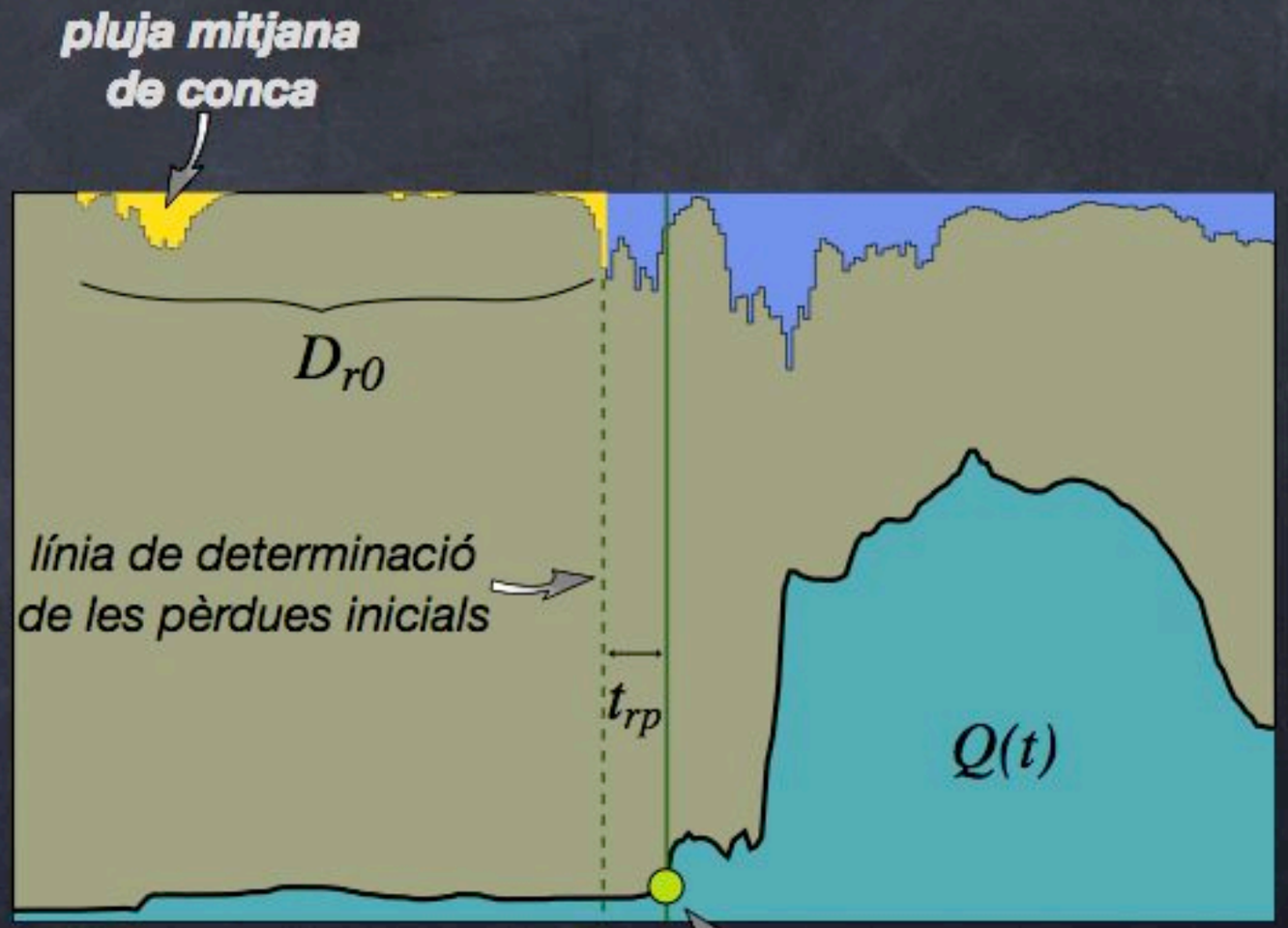




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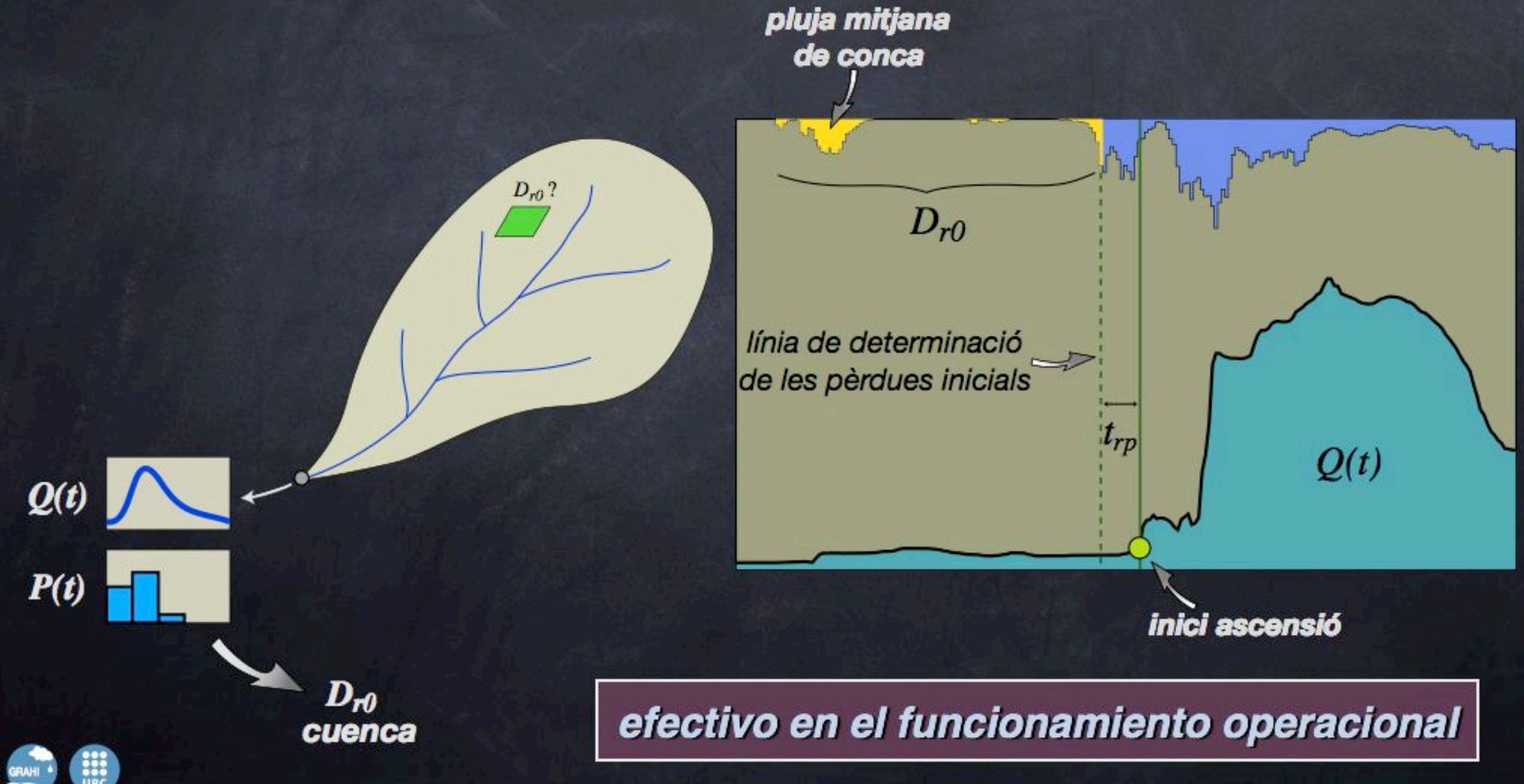
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efectivo en el funcionamiento operacional

Transporte del agua generada

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importancia de separar el flujo en vertiente / flujo en canal

Transporte del agua generada

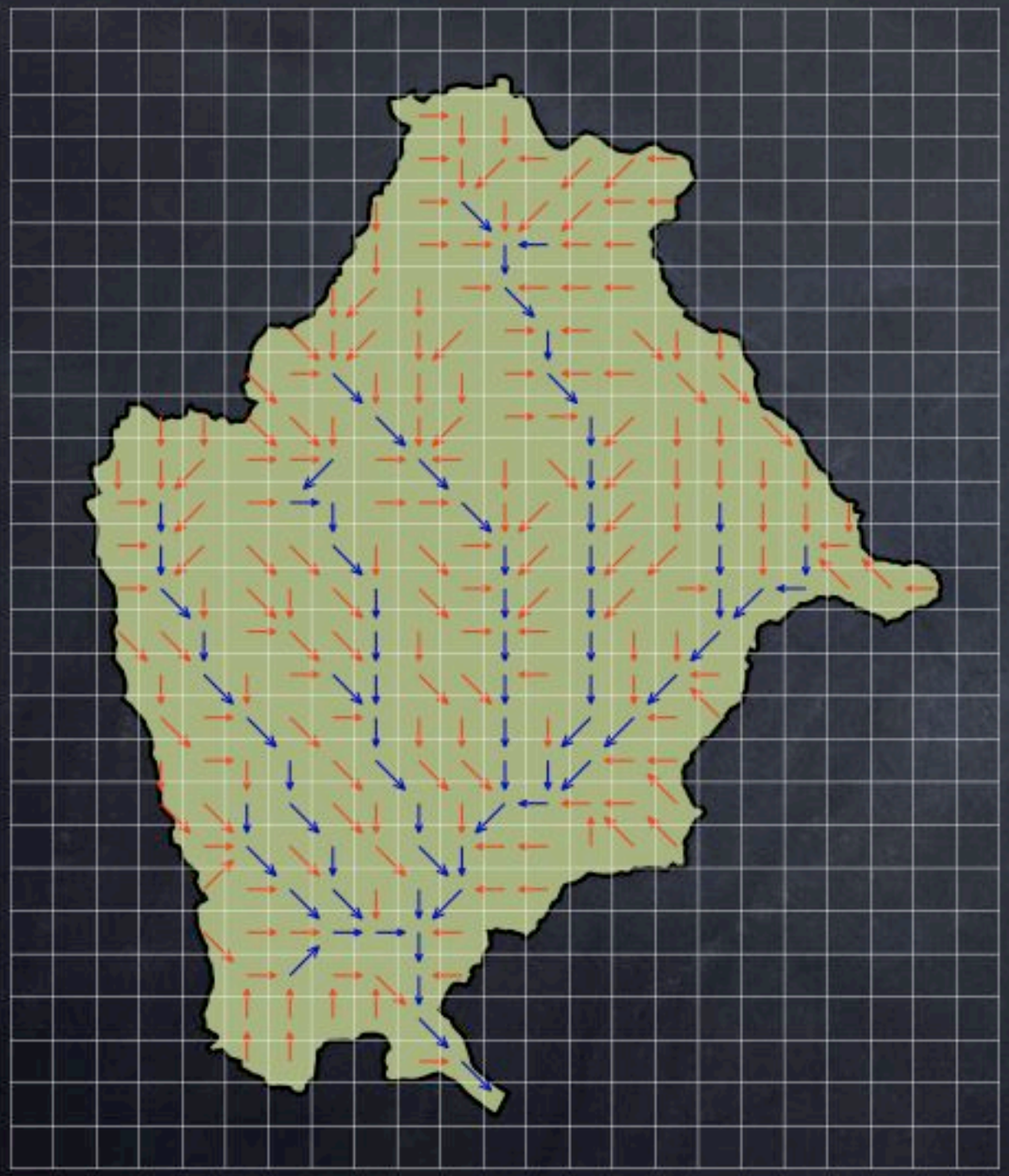
importancia de separar el flujo en vertiente / flujo en canal

río: área drenada superior a un umbral

Transporte del agua generada

importancia de separar el flujo en vertiente / flujo en canal

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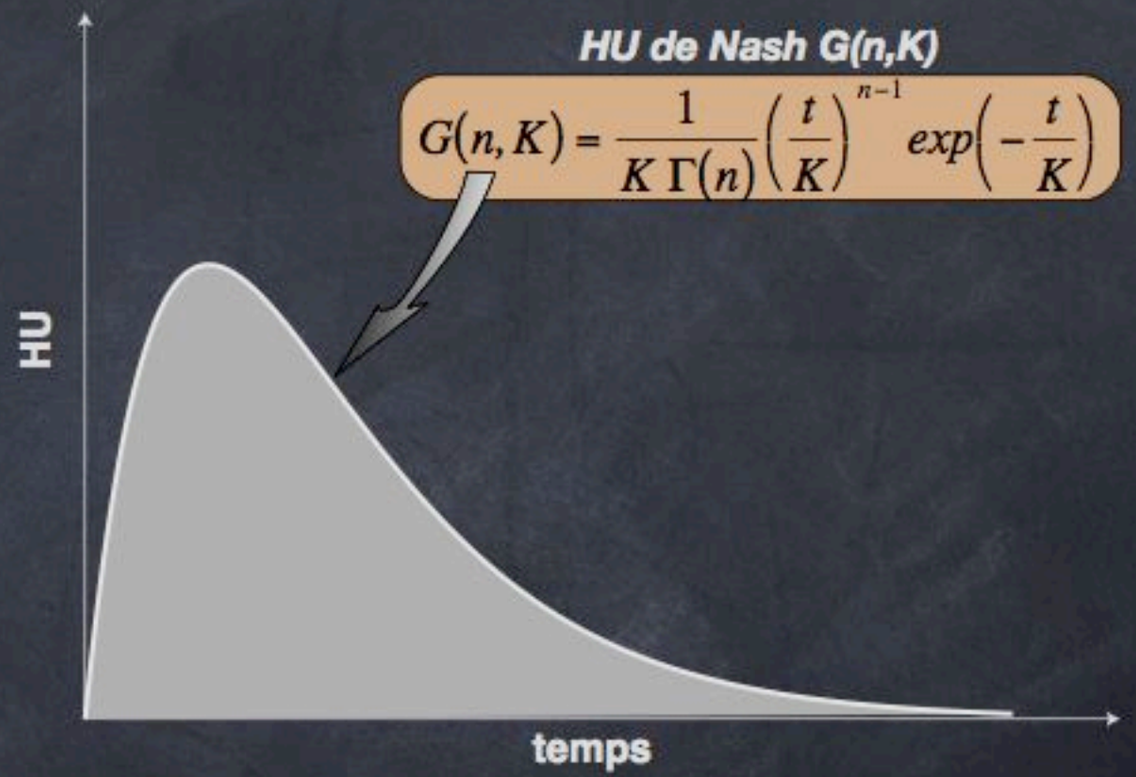


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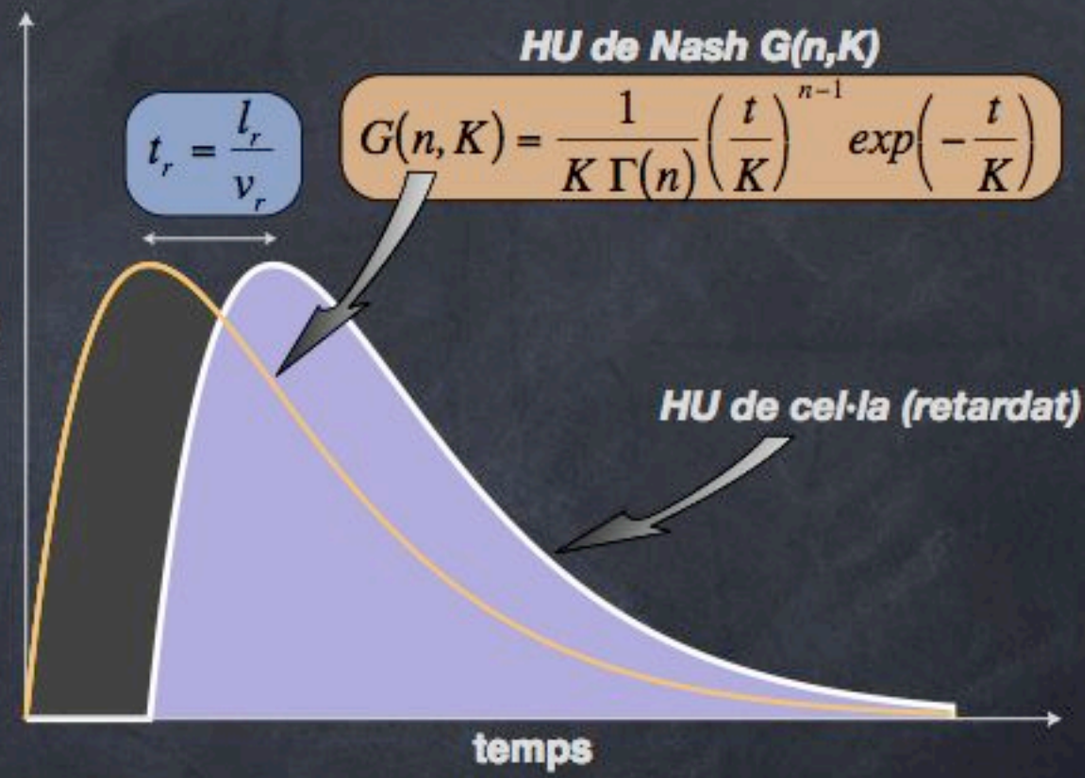


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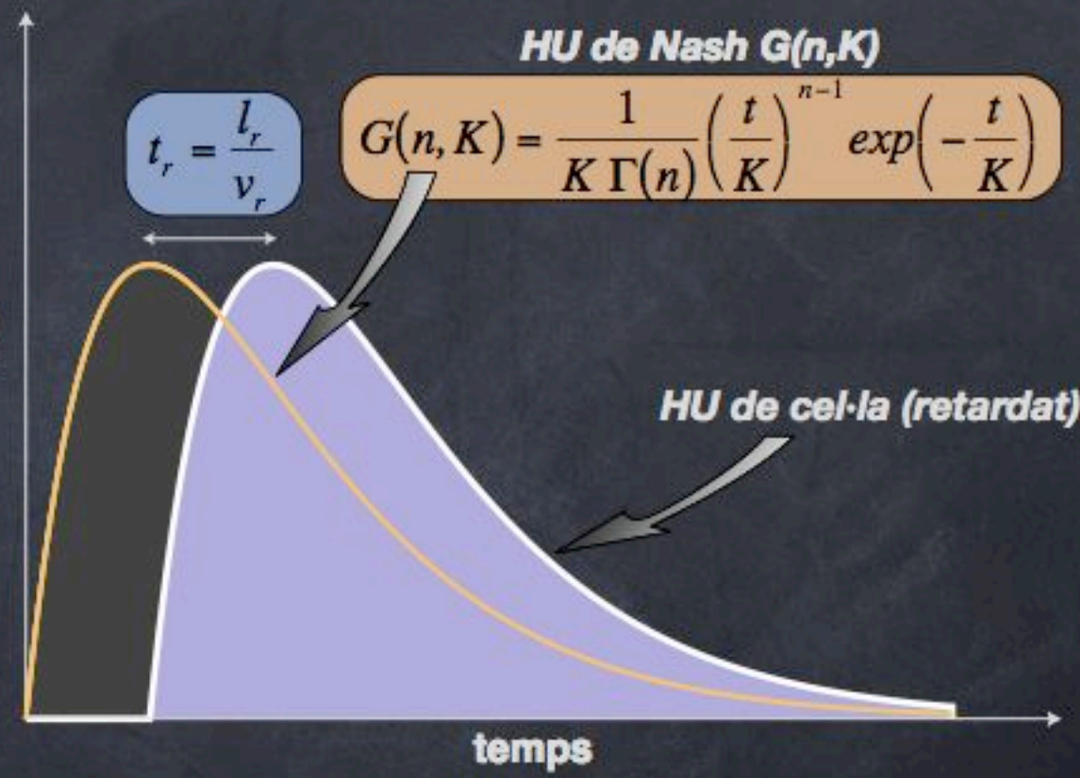


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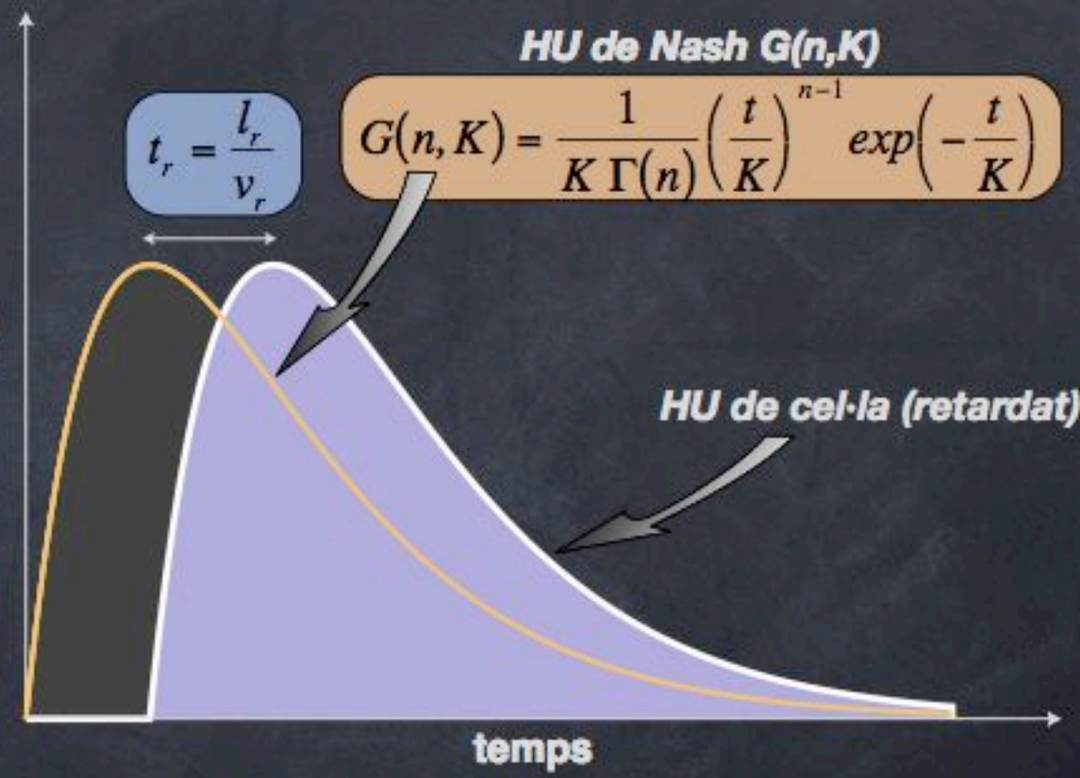


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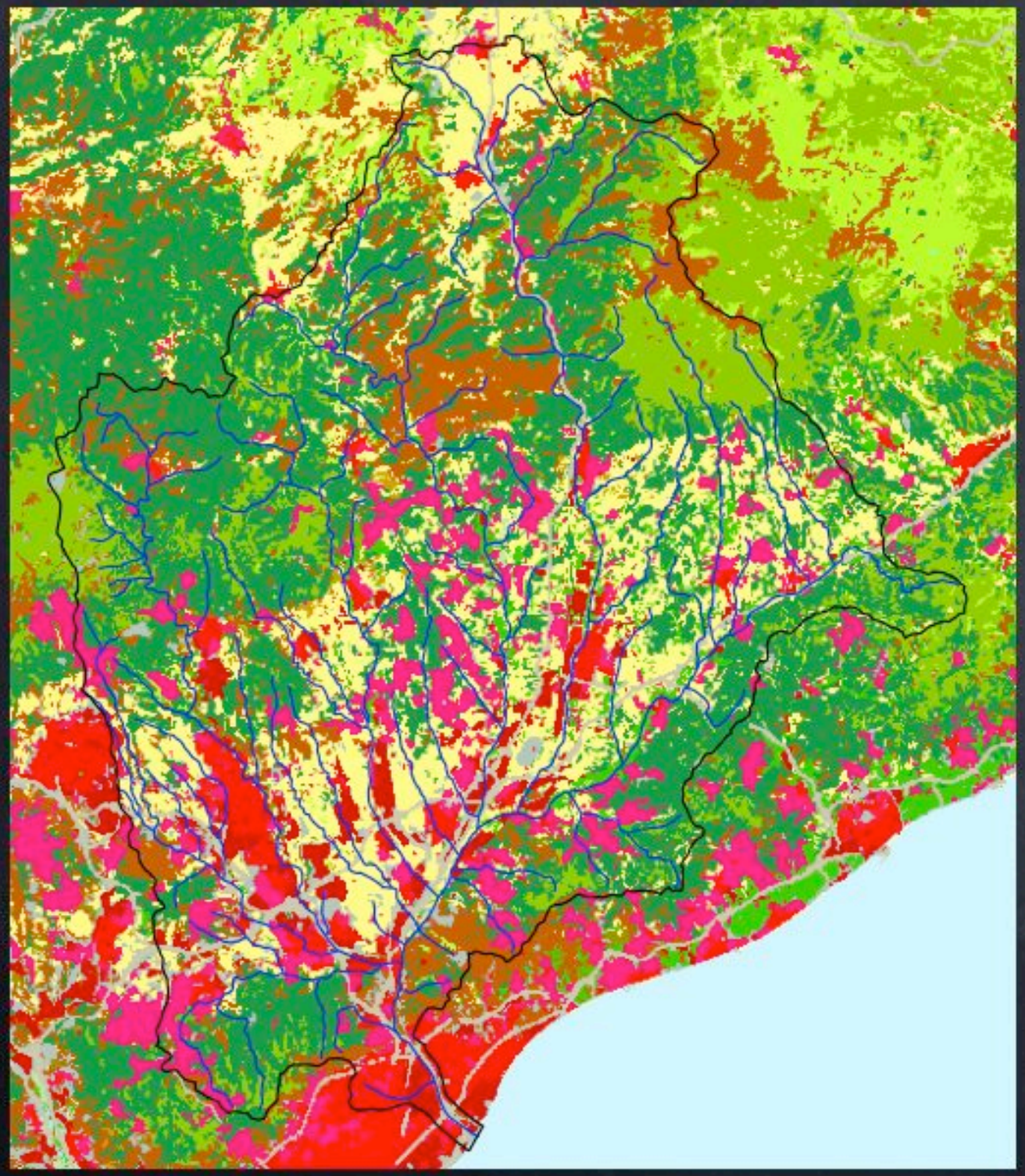




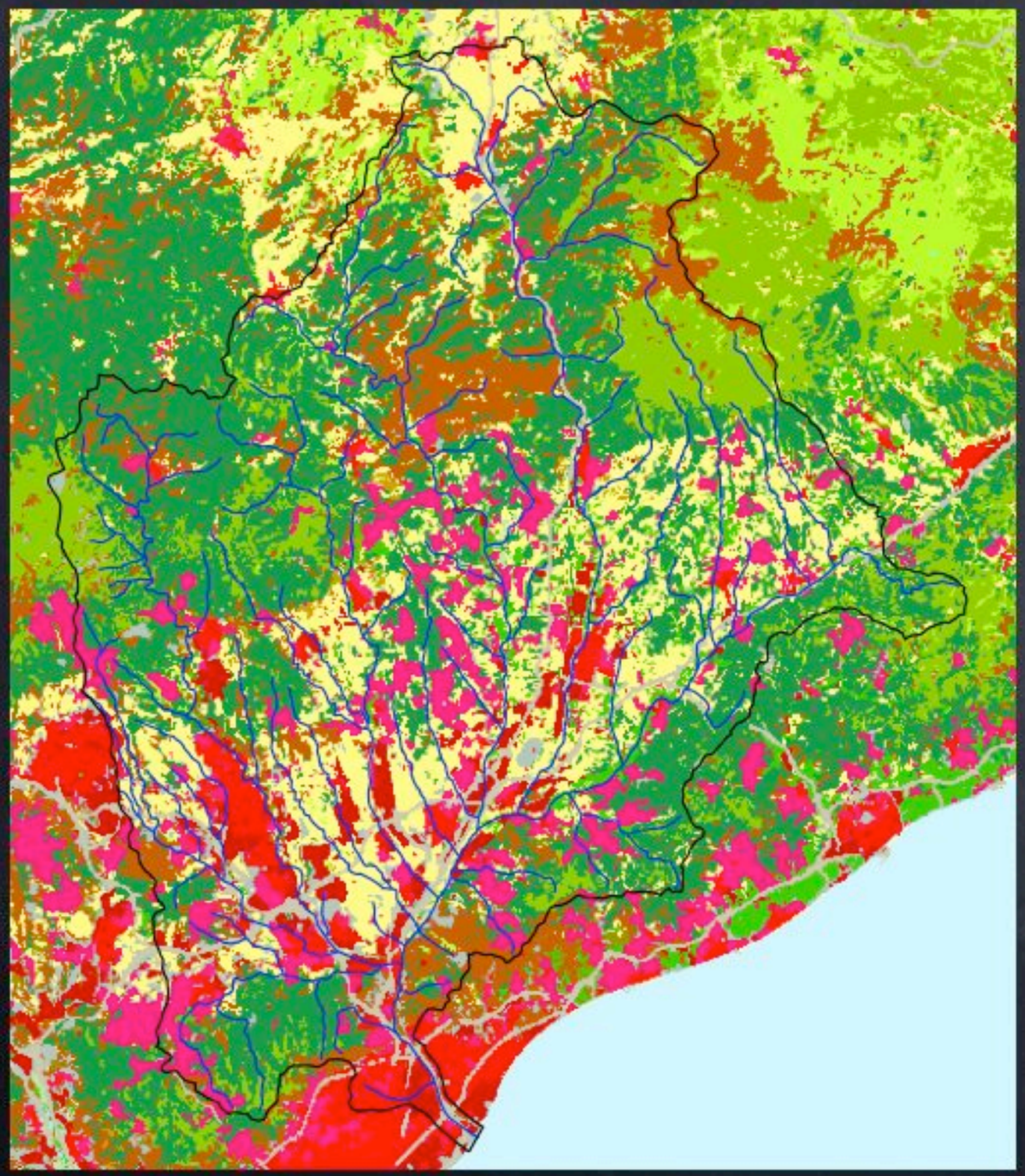
linealidad de la función de transporte

$$Q(t) = \sum_{i=1}^{N_c} A_i \int_0^t Q_{ci}(\tau)\, HU_i(t-\tau)\, d\tau$$

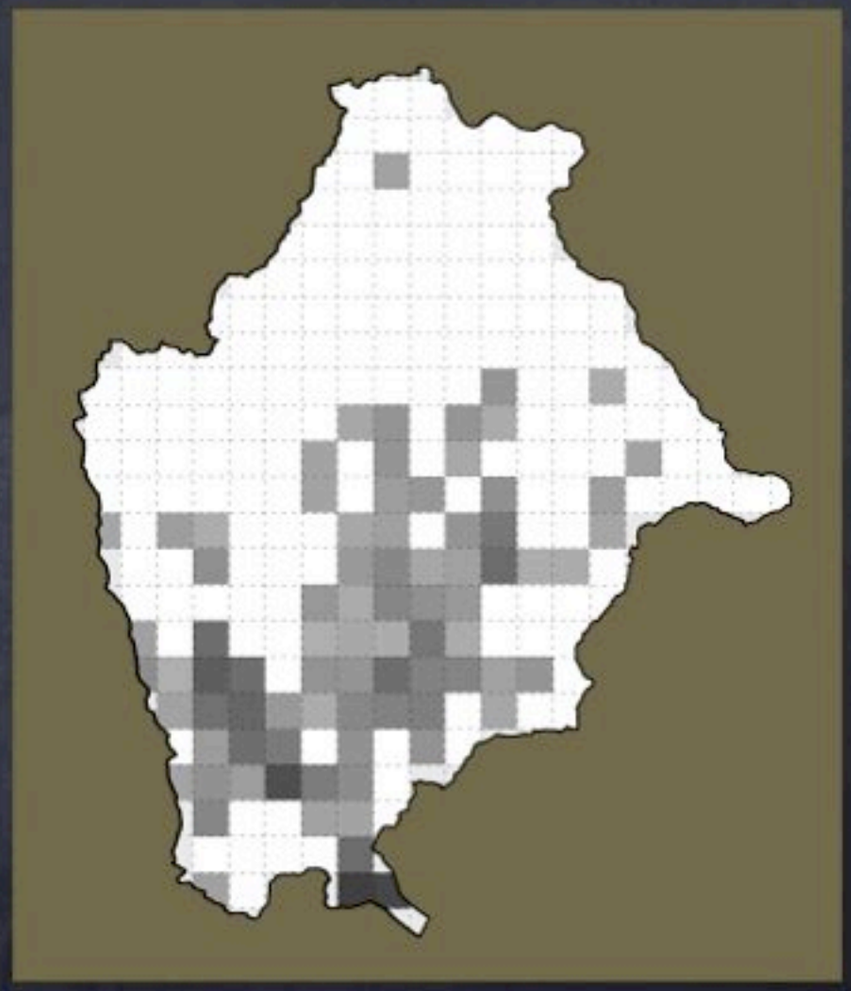
Celda urbana - Celda rural



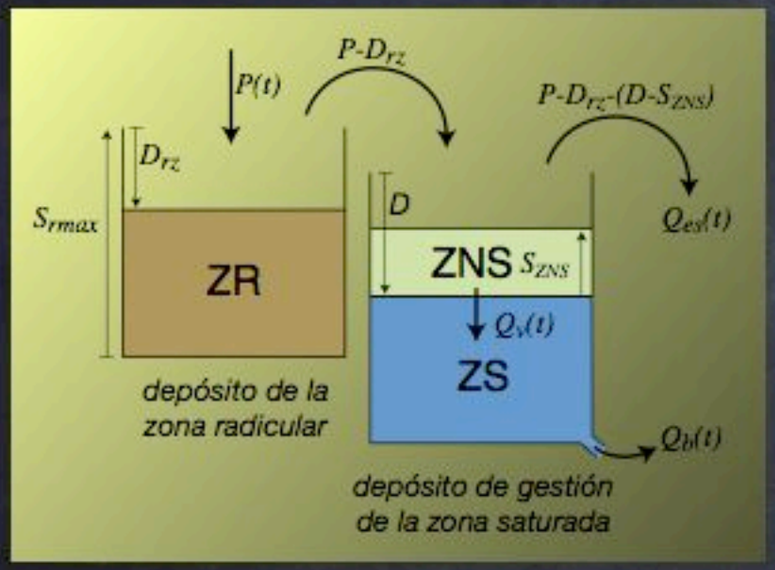
Celda urbana - Celda rural



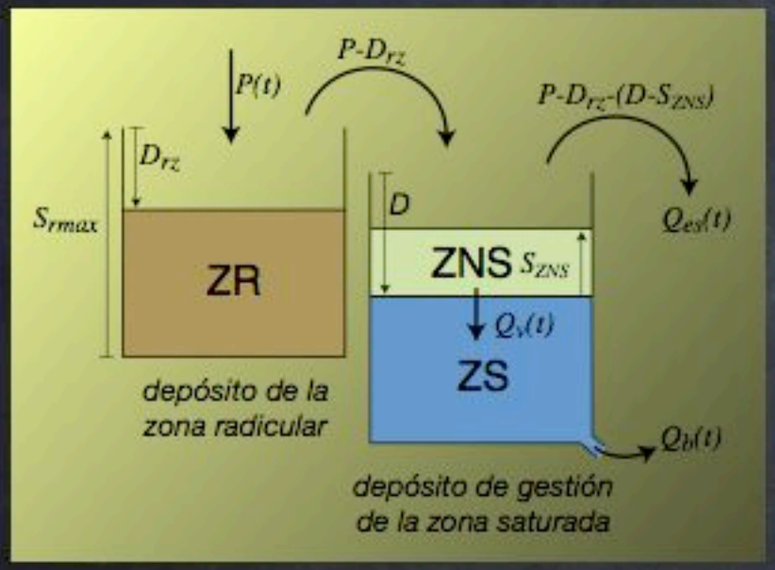
celda urbana:
urbanización > 25%

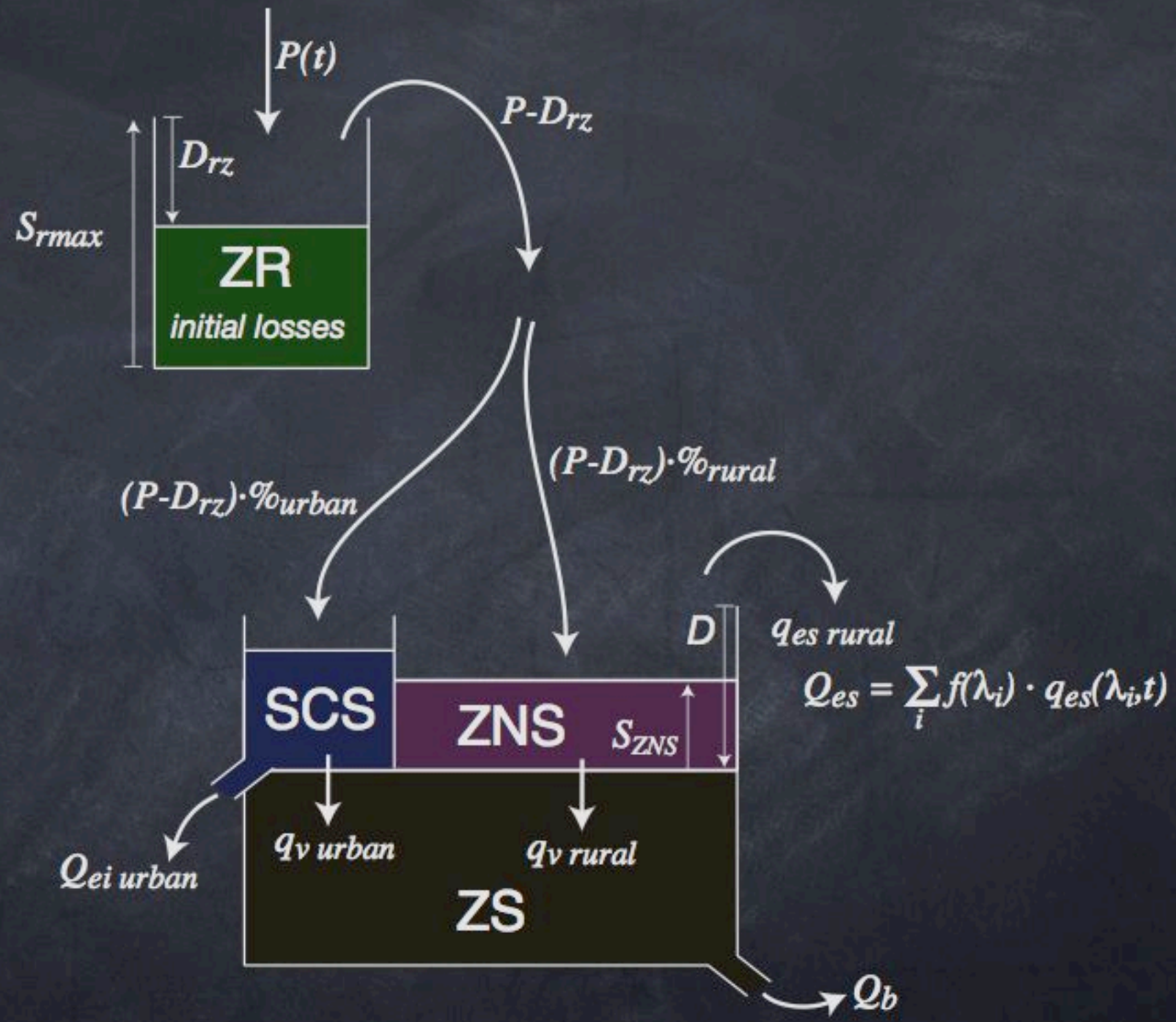


Celda urbana - Celda rural



Celda urbana - Celda rural





Calibración de los modelos hidrológicos

Calibración de los modelos hidrológicos

Optimización

Minimizar las diferencias entre las simulaciones y las medidas

Calibración de los modelos hidrológicos

Optimización

Minimizar las diferencias entre las simulaciones y las medidas

Qué se quiere optimizar?

Calibración de los modelos hidrológicos

Optimización

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Qué se quiere optimizar?

Cómo se optimiza?

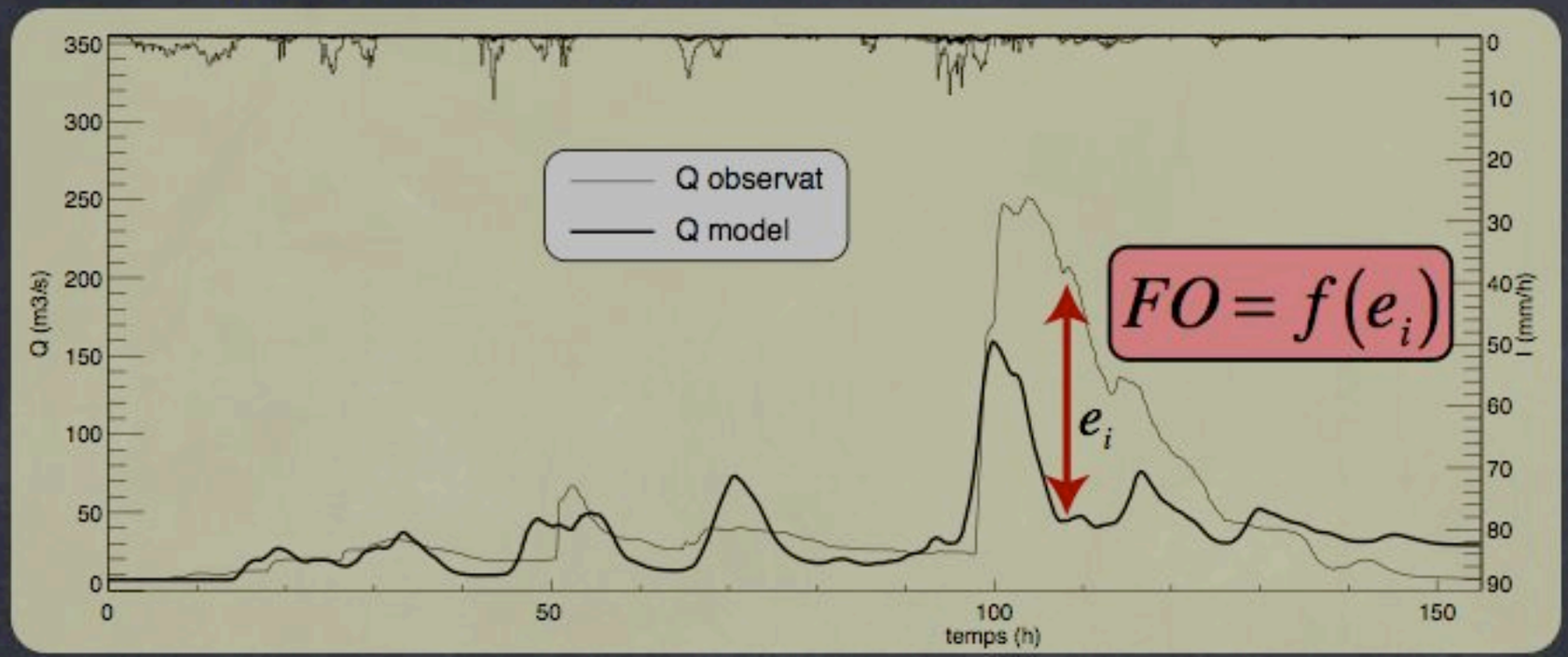
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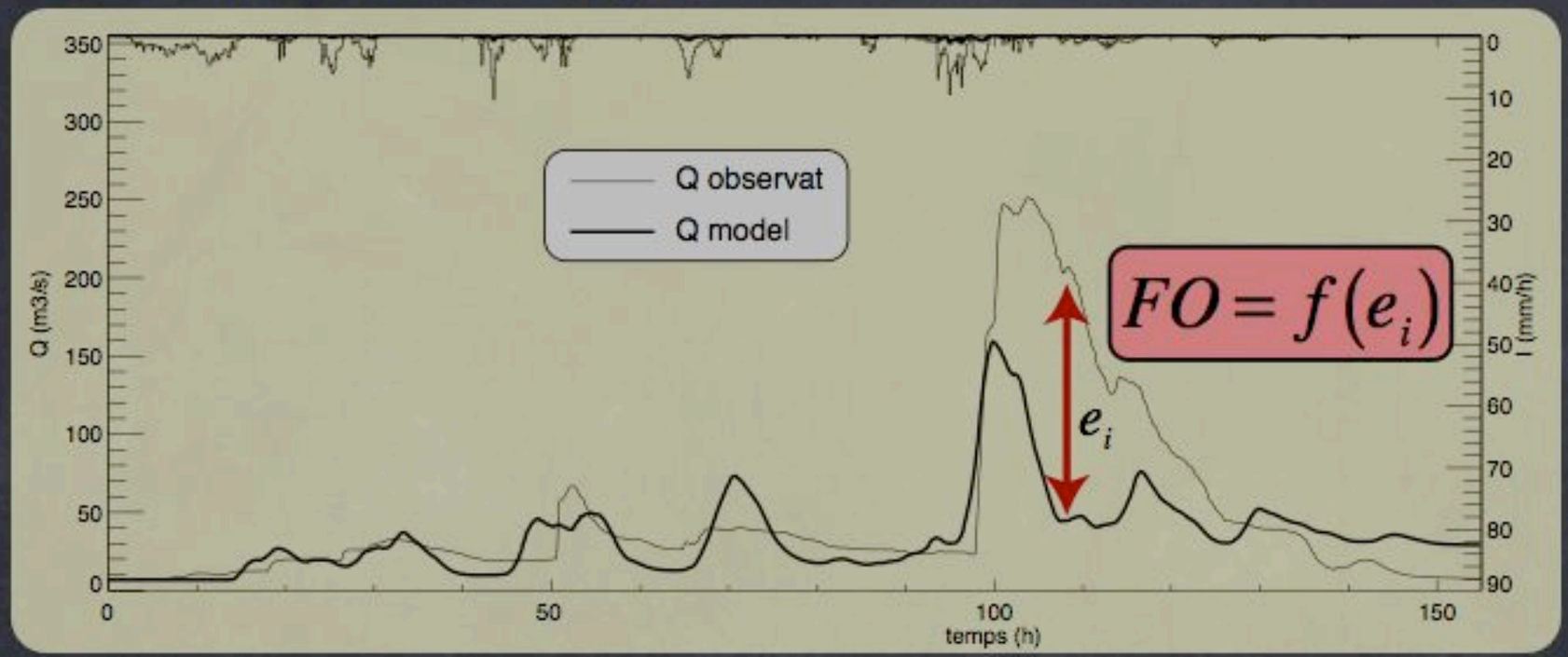
Definición de la función objetivo:



Calibración de los modelos hidrológicos

Qué se quiere optimizar?

Definición de la función objetivo:



$$AE = \sum_{i=1}^{n} \left| Q_{calc}(i) - Q_{obs}(i) \right|$$

Error absolu

$$NE = 1 - \frac{\sum_{i=1}^{n} \left(Q_{calc}(i) - Q_{obs}(i) \right)^2}{\sum_{i=1}^{n} \left(Q_{obs}(i) - \overline{Q}_{obs} \right)^2}$$

Eficiencia

Calibración de los modelos hidrológicos

Cómo se optimiza?

Calibración de los modelos hidrológicos

Cómo se optimiza?

Método de Metropolis-Montecarlo (1953):

Generar n conjuntos de parámetros θ, con una distribució de probabilidad dada

Calibración de los modelos hidrológicos

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SCE-UA (Suffled Complex Evolution): Duan et. al. (1992). Diferentes grupos que evolucionan al óptimo (con el Simplex). Los diferentes grupos són períodicamente barajados (se excluyen los peores θ). Al final, todos los grupos tienden al mejor θ.

Calibración de los modelos hidrológicos

Problemes:

Cada funció objectiu prioritza certs elements per sobre d'uns altres que poden resultar a la llarga més importants.

D'alguna manera s'admet que els paràmetres no tenen relació amb la física del sistema.

Els hidrogrames resultants poden no agradar una vegada visualitzats.

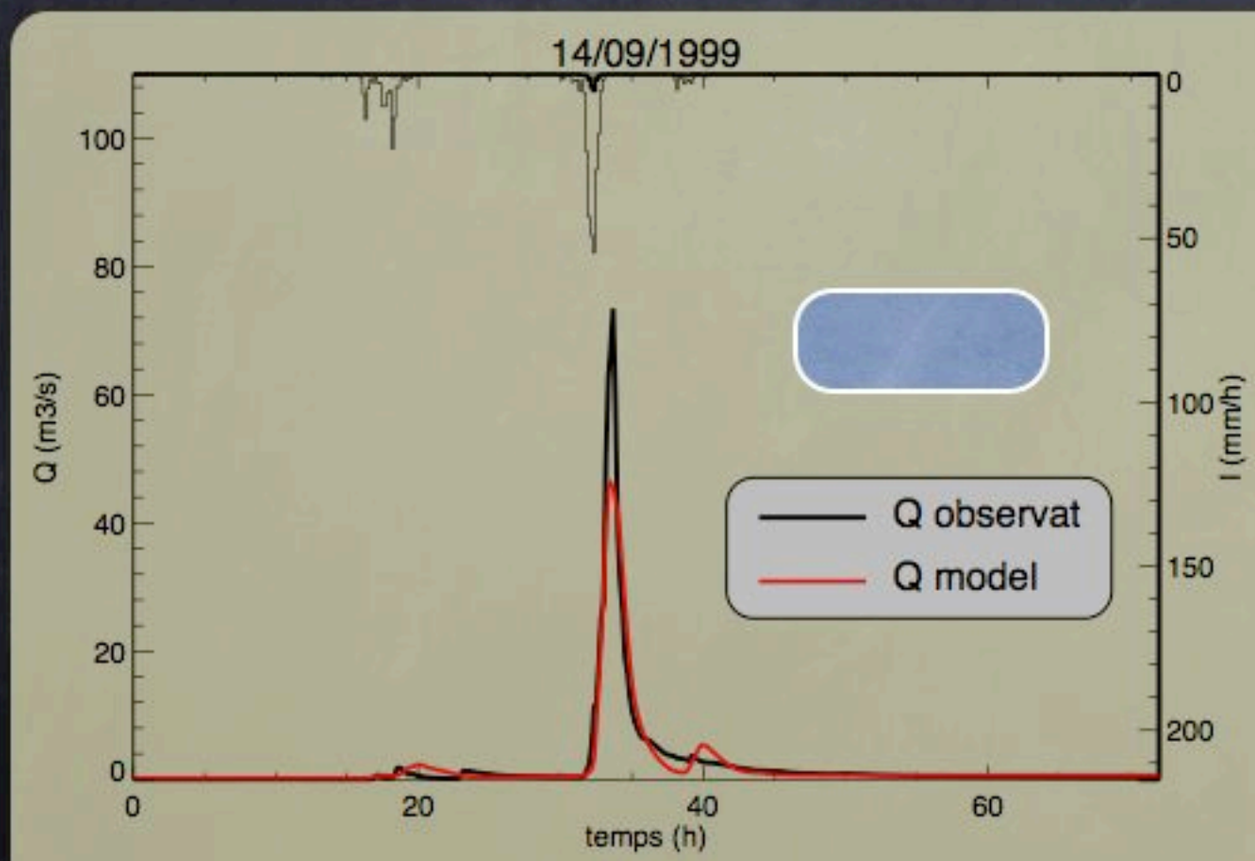
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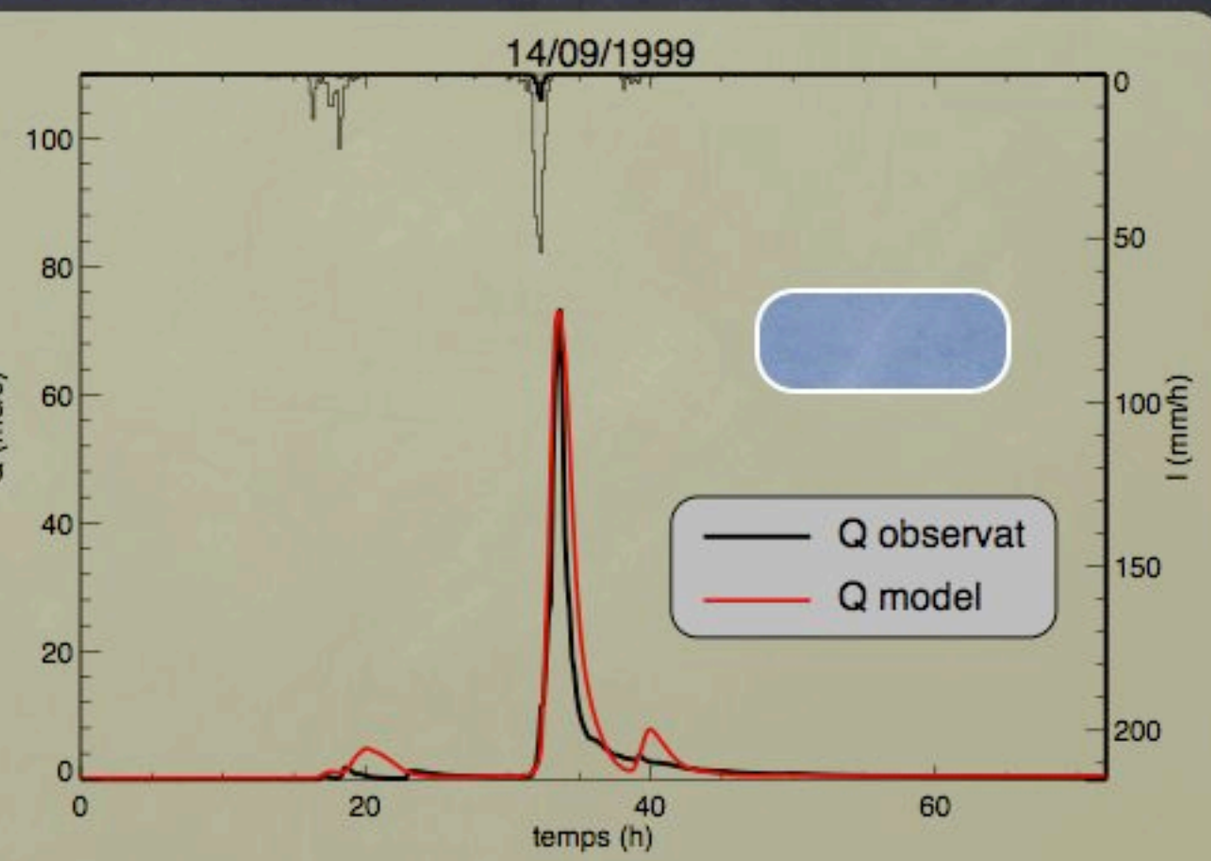
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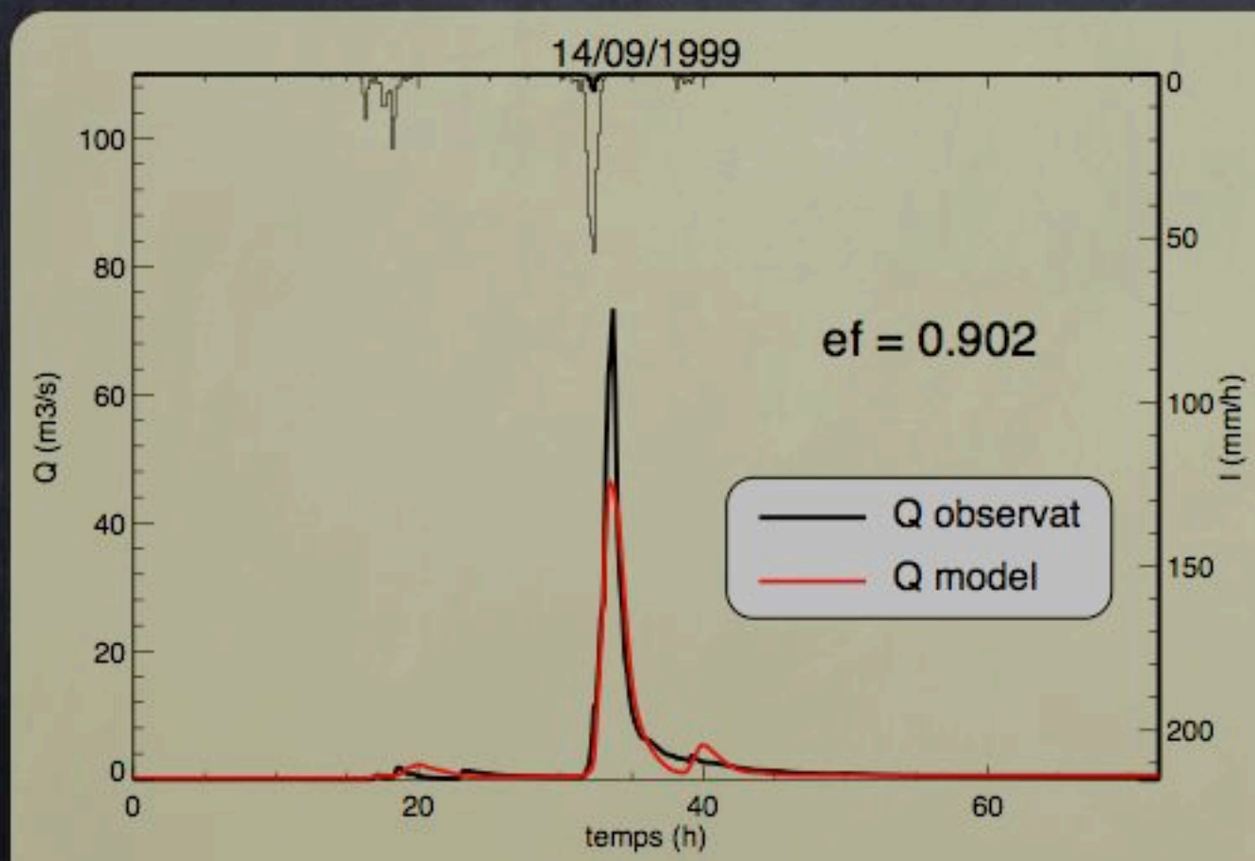
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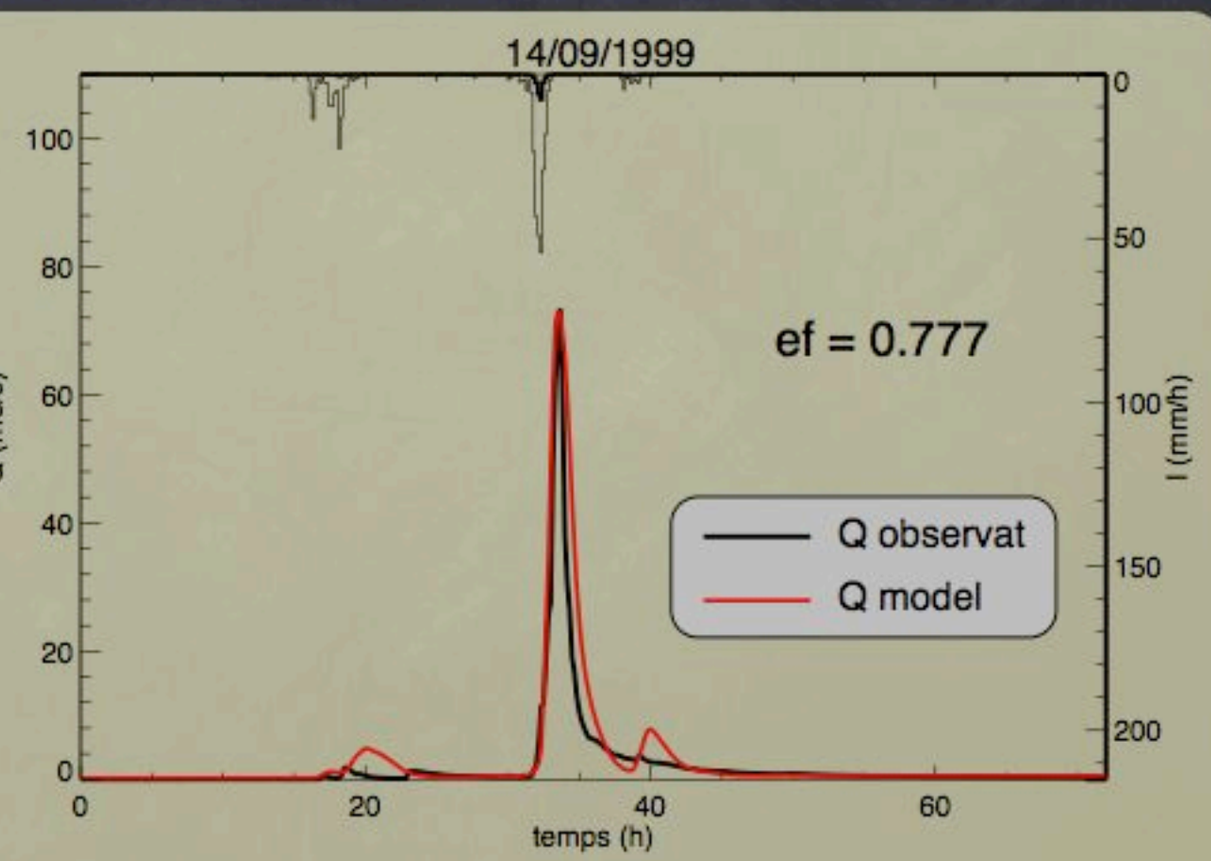
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determinación de los pesos (lógica difusa?)

Calibración de los modelos hidrológicos

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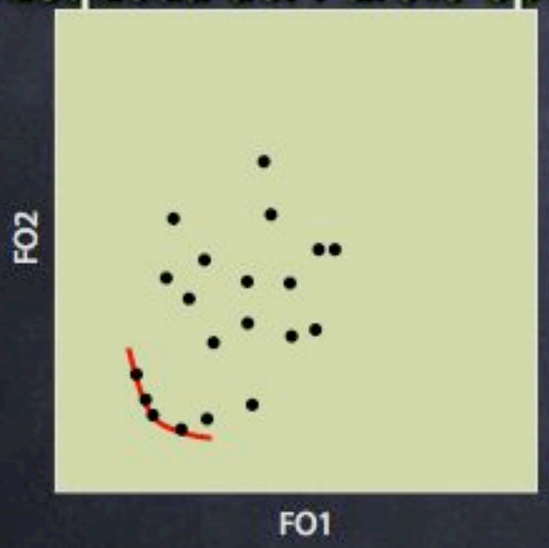
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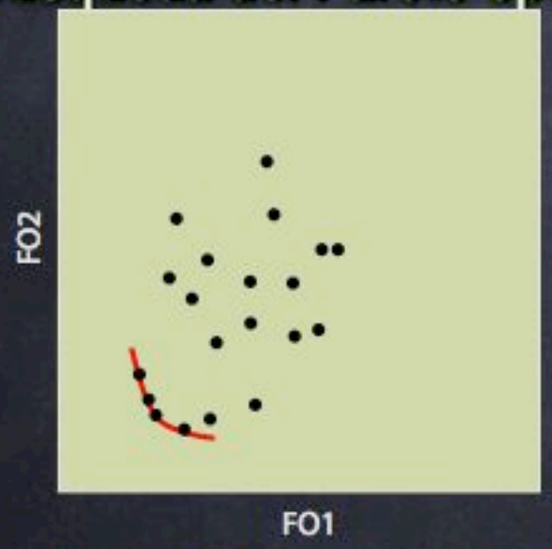
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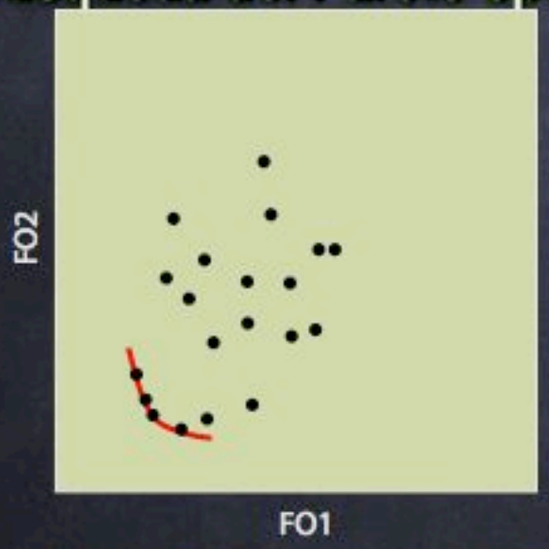
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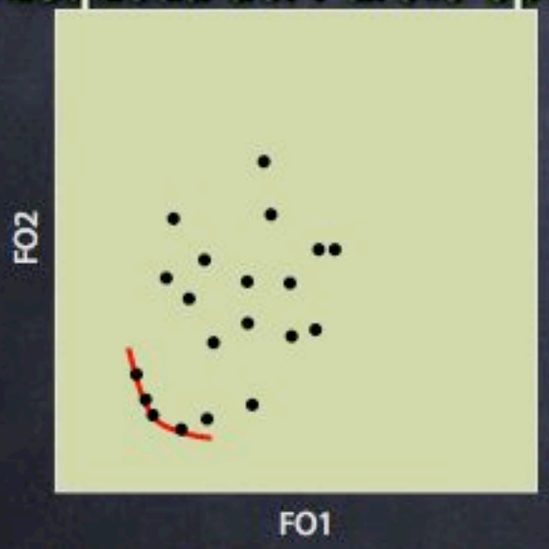
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Estructura del error que se espera (función gausiana, sin errores sistemáticos, etc)

Calibración de los modelos hidrológicos

Nos creemos los paràmetros óptimos?

Calibración de los modelos hidrológicos

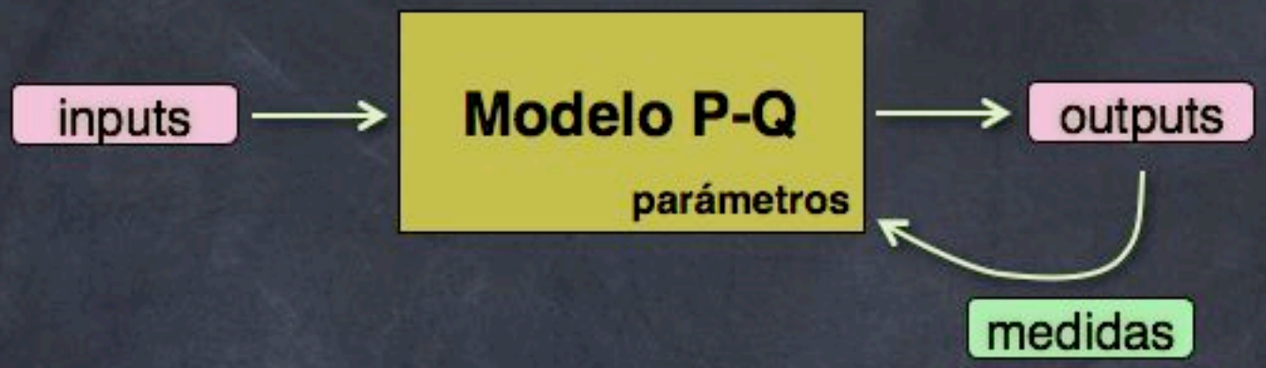
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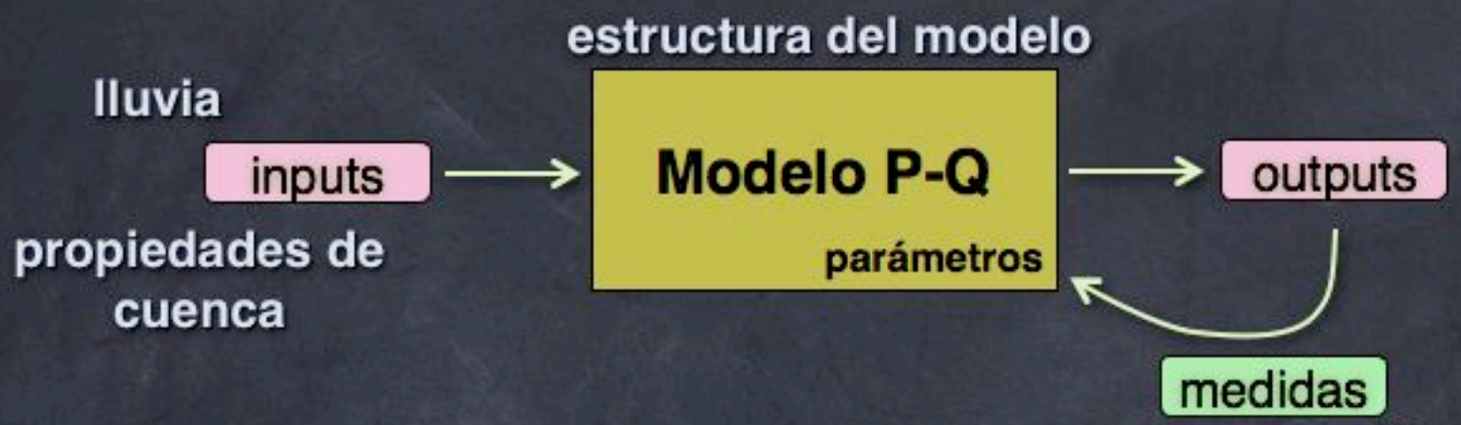
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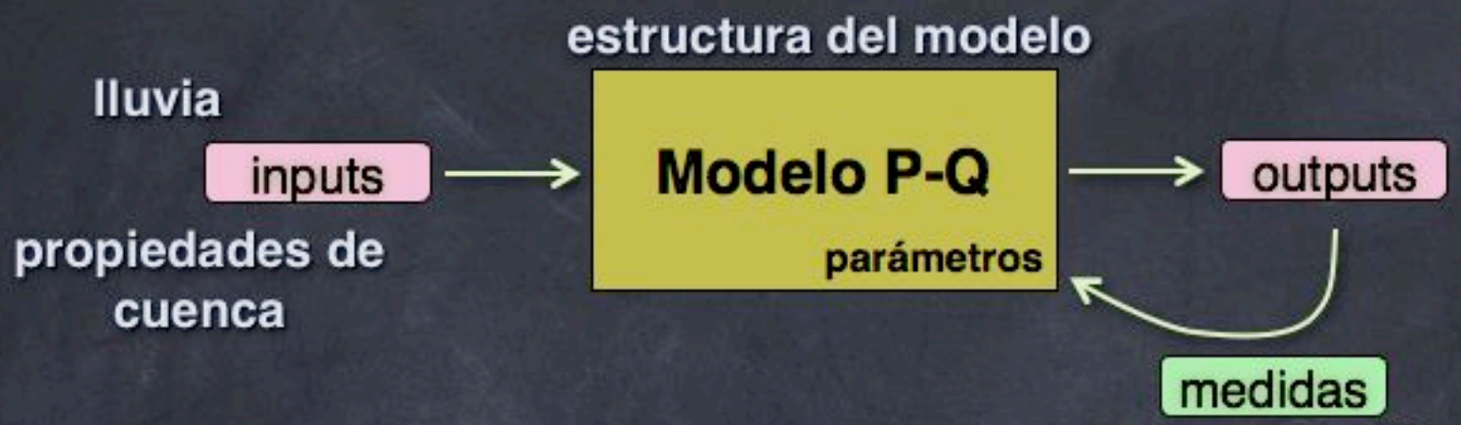
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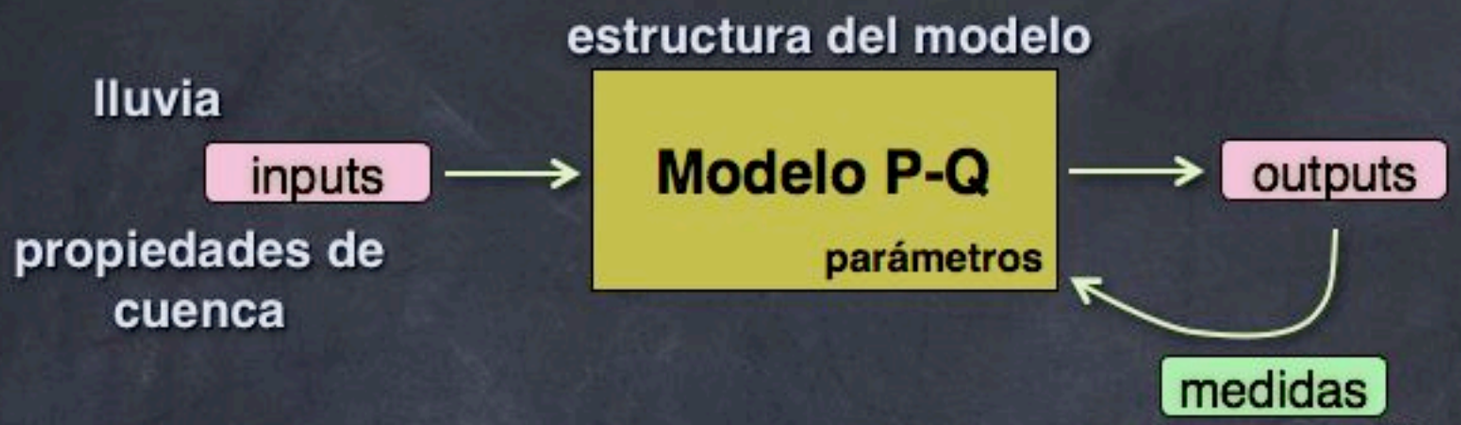


GLUE: Generalized Likelihood Uncertainty Estimation

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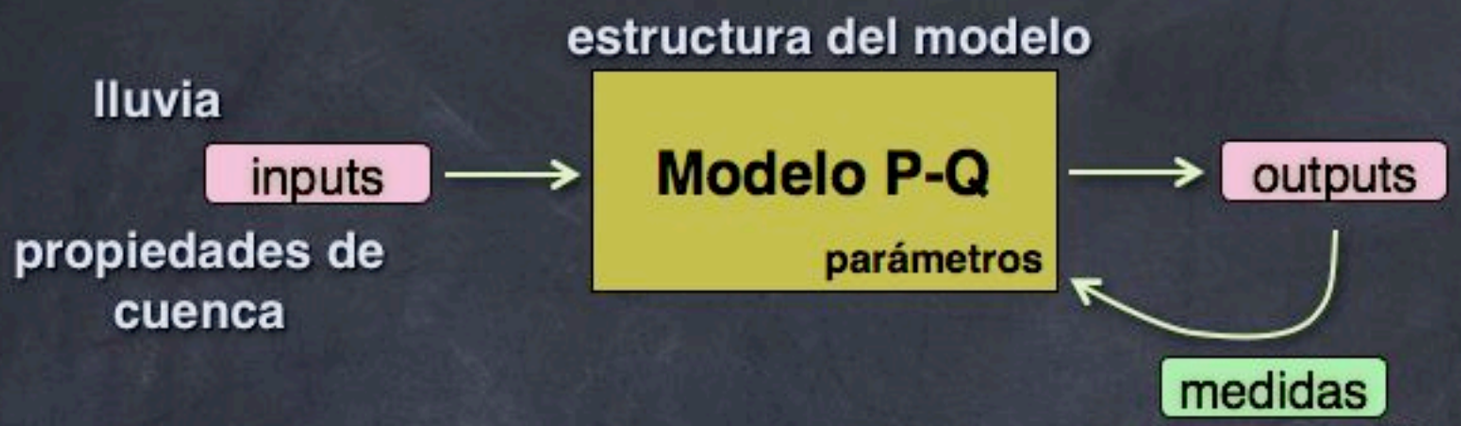
GLUE: Generalized Likelihood Uncertainty Estimation

Concentrar la incertidumbre en los parámetros θ

Calibración de los modelos hidrológicos

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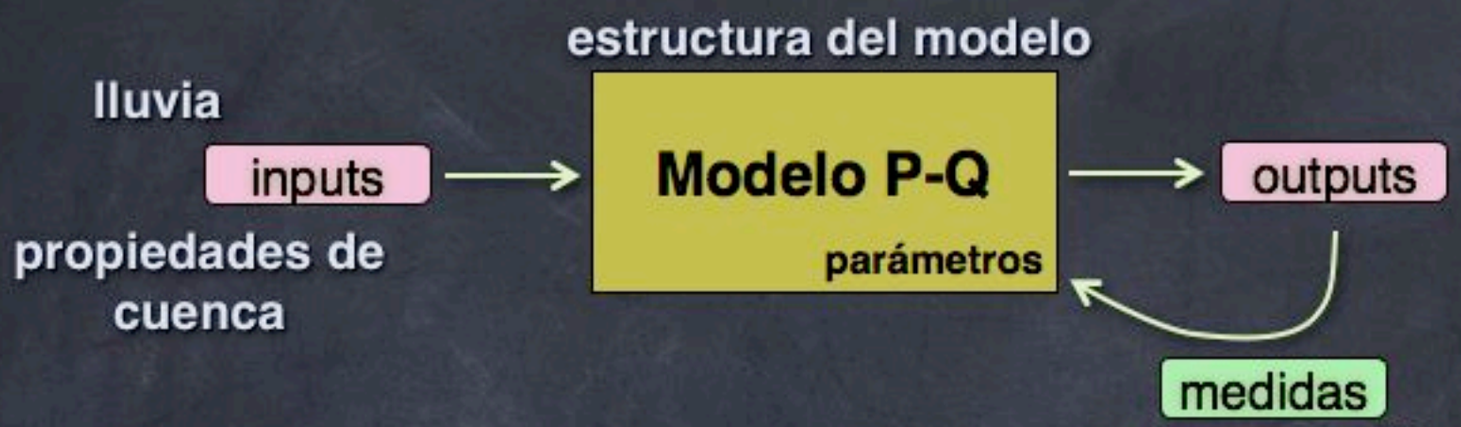
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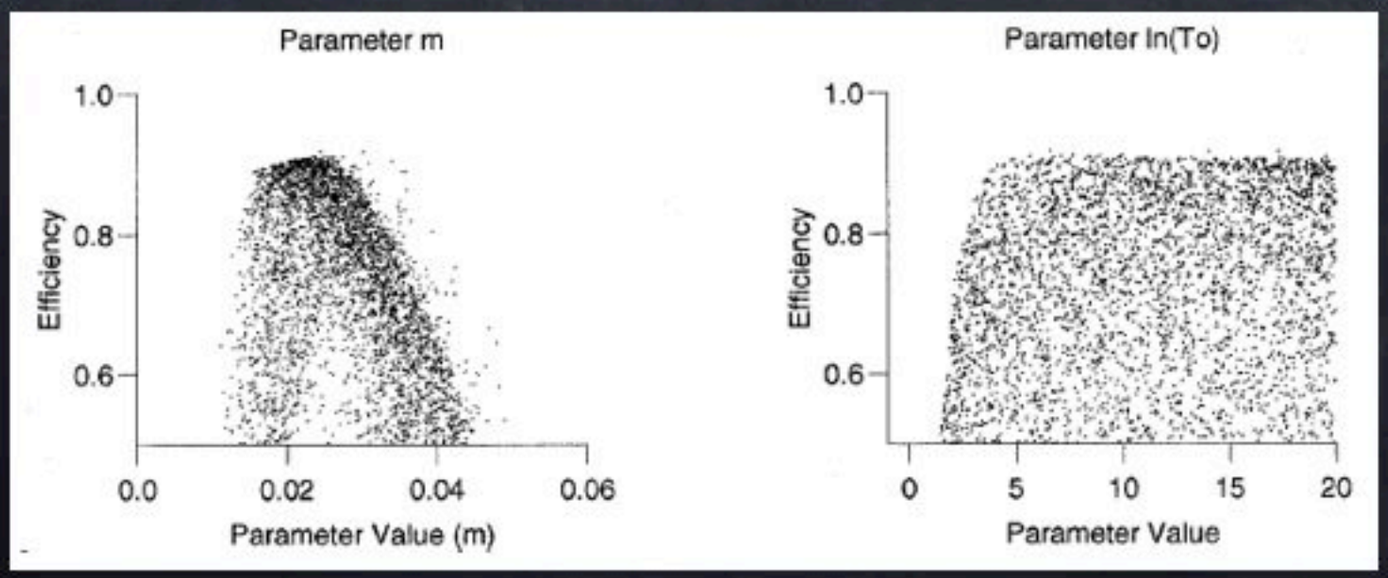
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extraido de "Topmodel: a critique", Beven (1997)

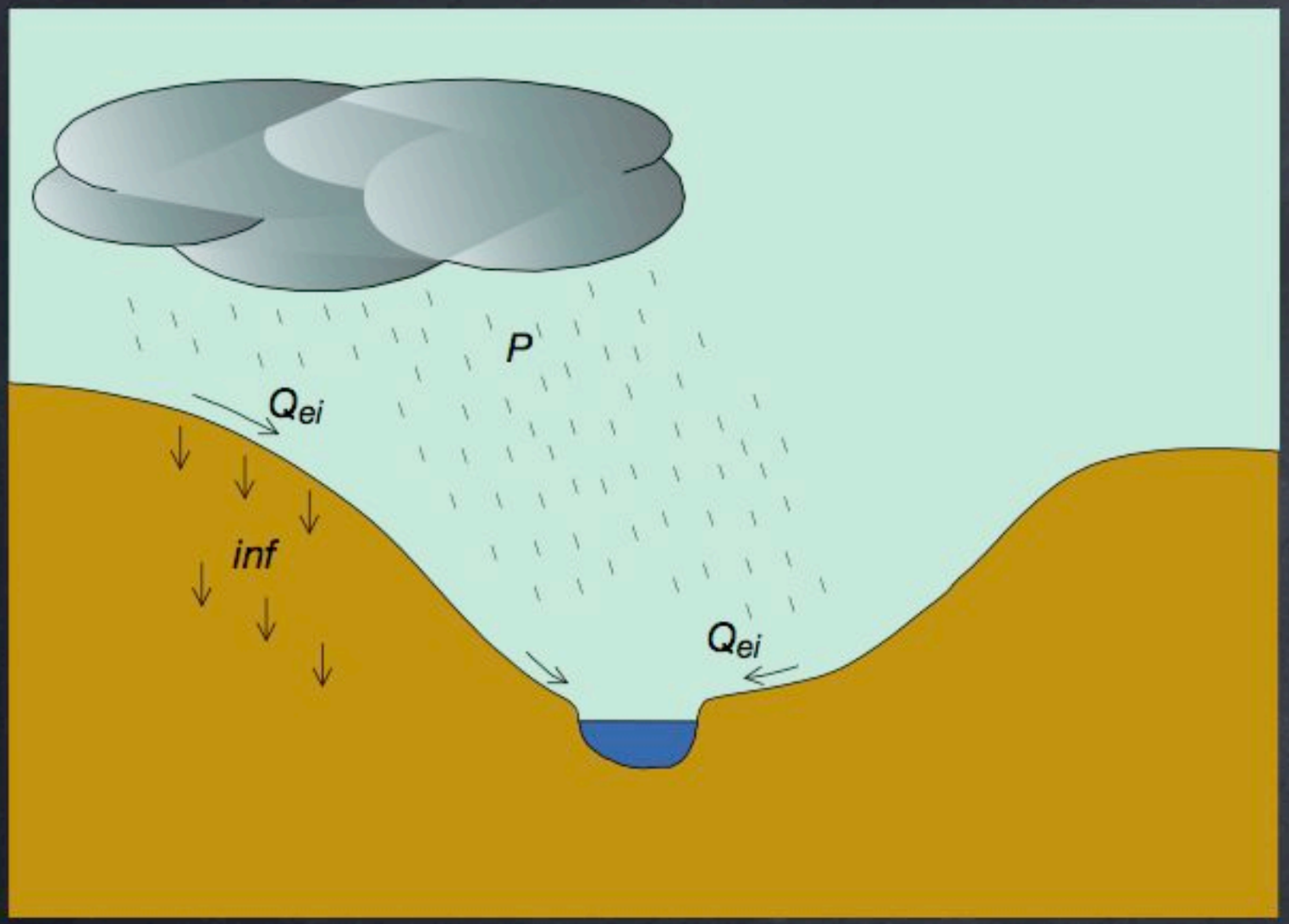
Modelos Hidrológicos

Introducción a Topmodel

Beven, K., Kirkby, M.J. (1979). A physically-based variable-contributing area model of basin hydrology. Hydrologic Science Bulletin, 24, p:27-53

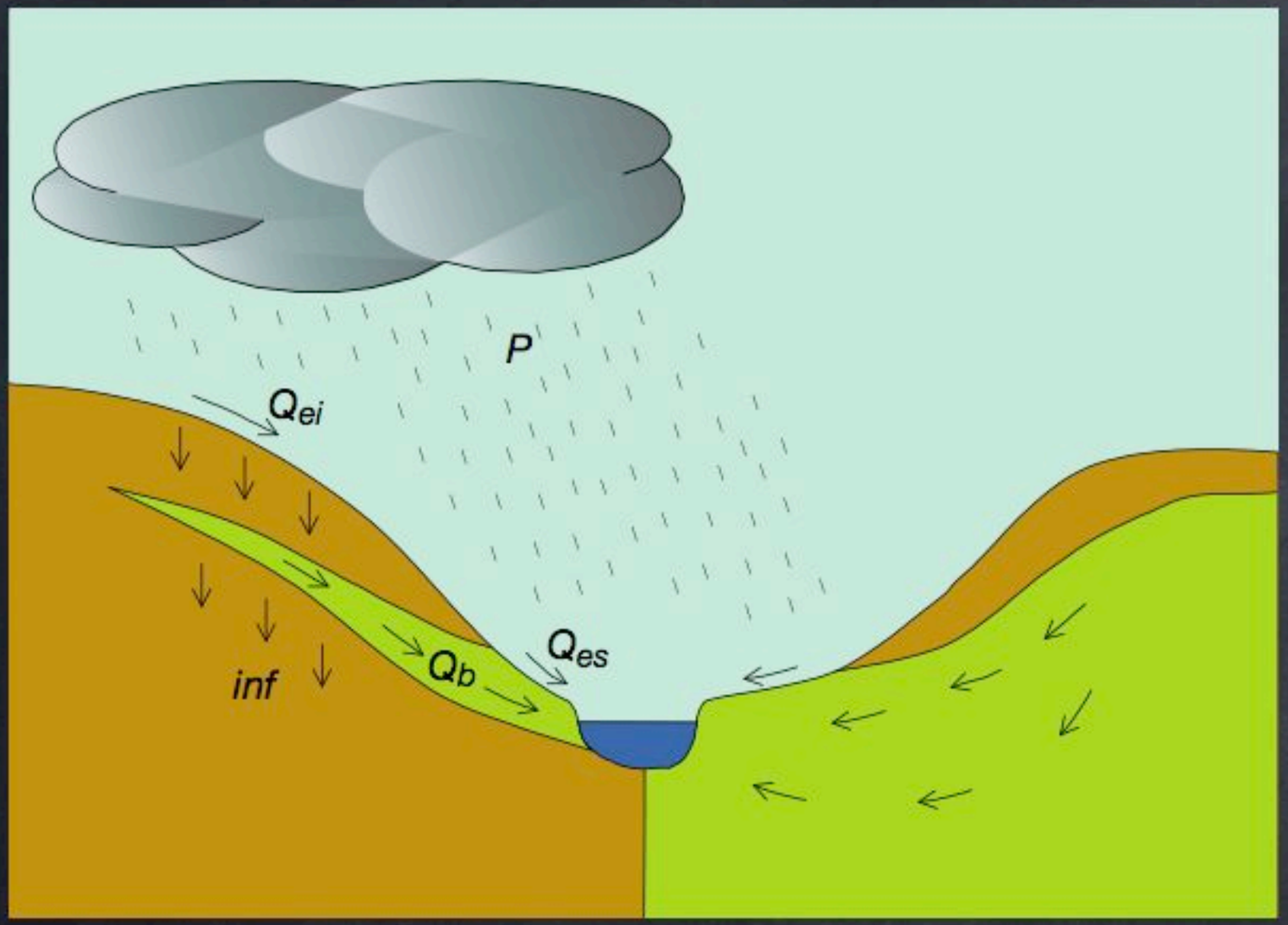
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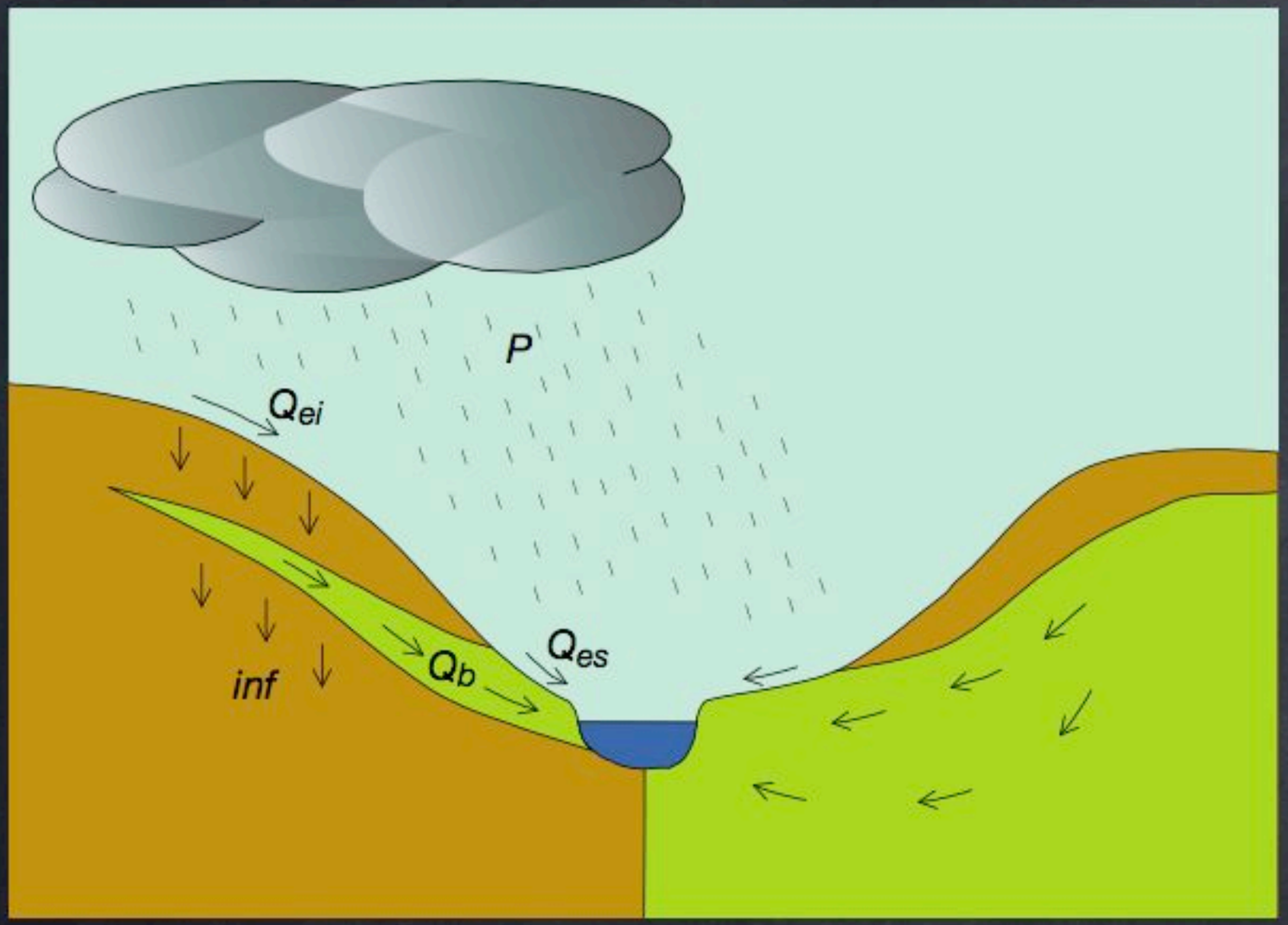
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Introducción a Topmodel

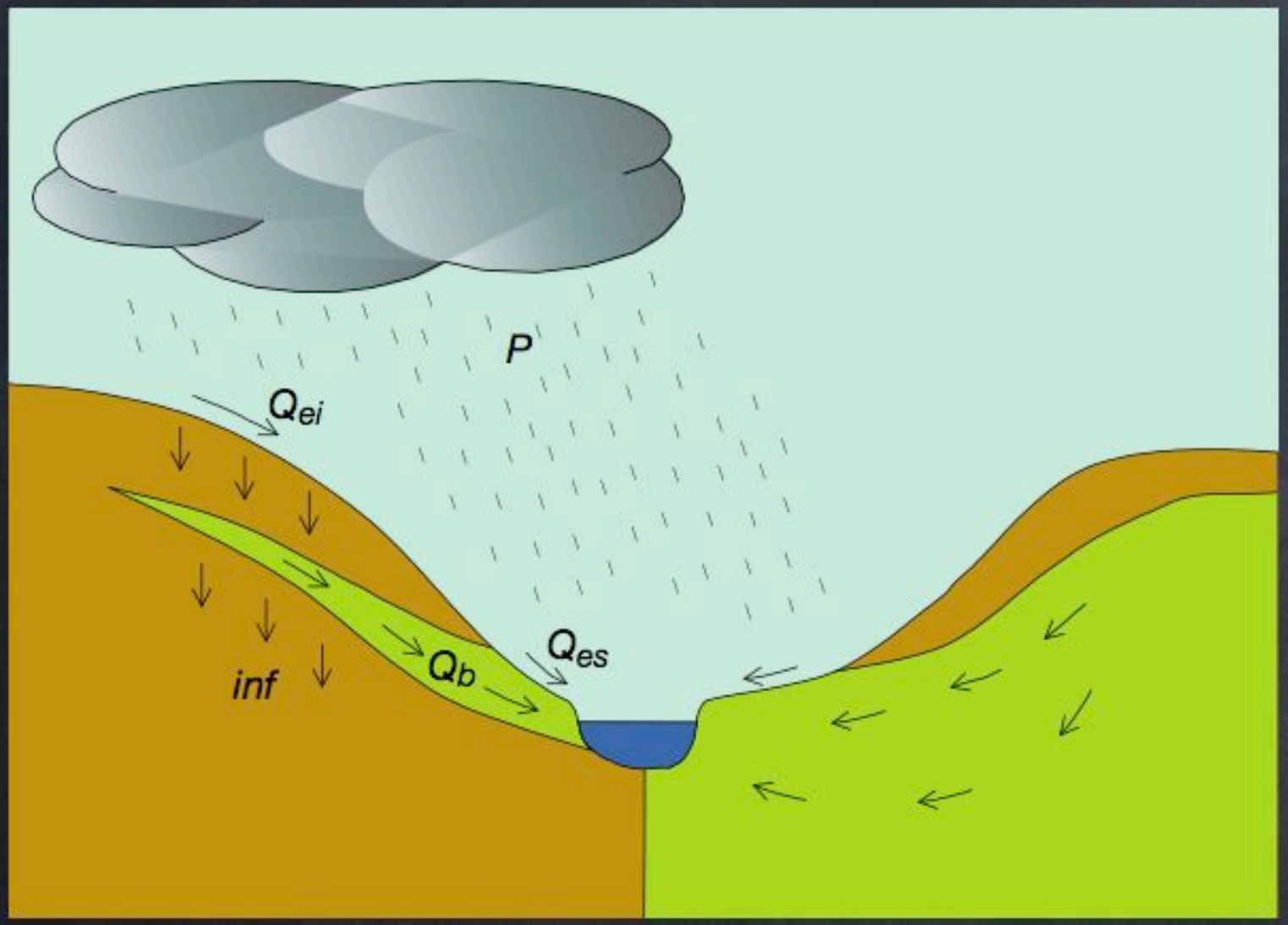
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Tipos de flujo:

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Tipos de flujo:

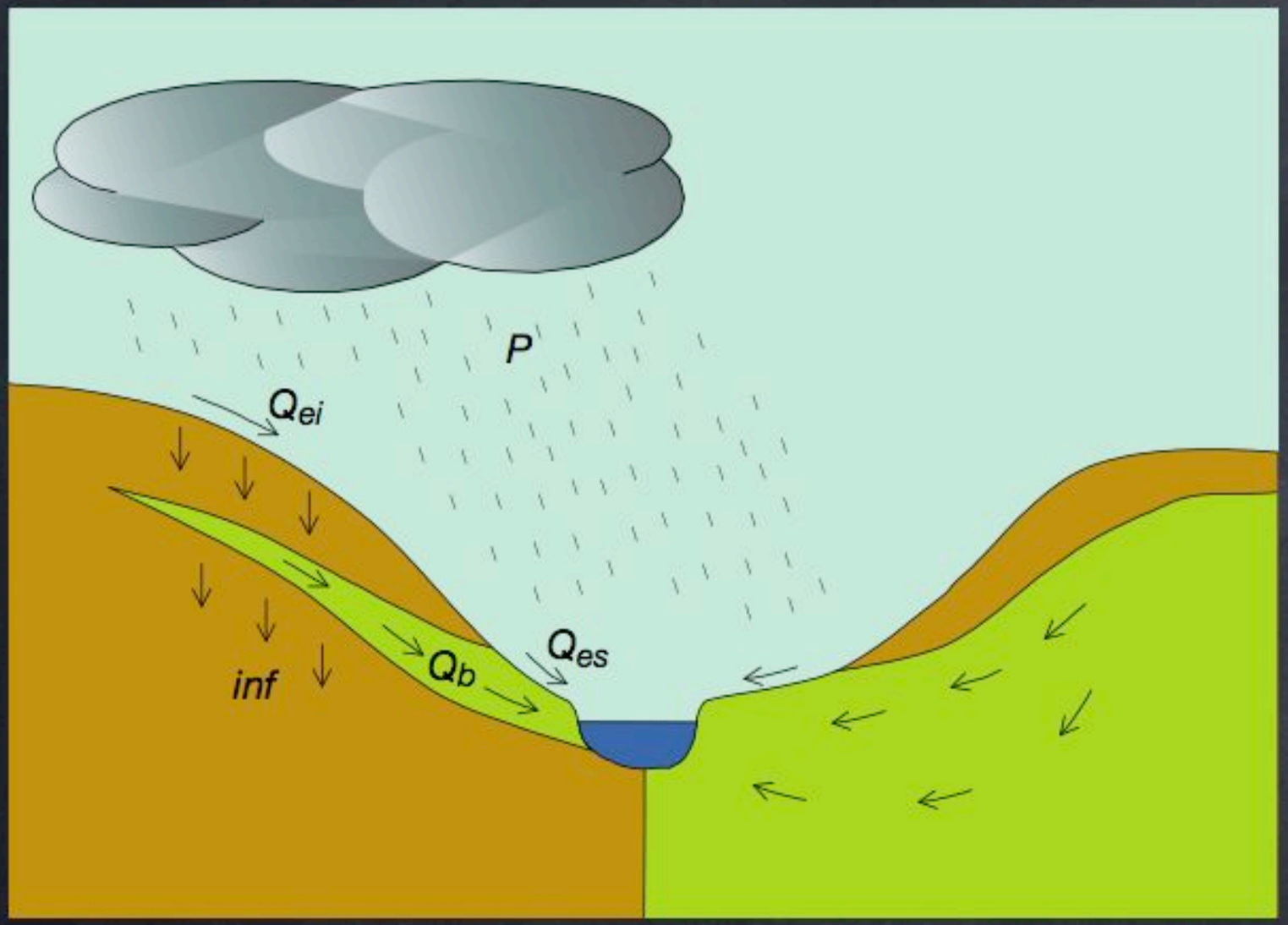
Flujo superficial (overland flow)

Qei: Exceso de infiltración o de Horton

Qes: Exceso de saturación o de Dunne

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Tipos de flujo:

Flujo superficial (overland flow)

Qei: Exceso de infiltración o de Horton

Qes: Exceso de saturación o de Dunne

Flujo base (base flow, return flow)

Flujo subsuperficial (interflow)

Flujo subterráneo

Observations in rainfall-runoff modelling

HBV rainfall-runoff model (SMHI - Bergström and Forsman 1973)

ELSEVIER

Journal of Hydrology 201 (1997) 272–288

Journal of Hydrology

Development and test of the distributed HBV-96 hydrological model

Göran Lindström*, Barbro Johansson, Magnus Persson, Marie Gardelin, Sten Bergström

Swedish Meteorological and Hydrological Institute, S-601 76 Norrköping, Sweden

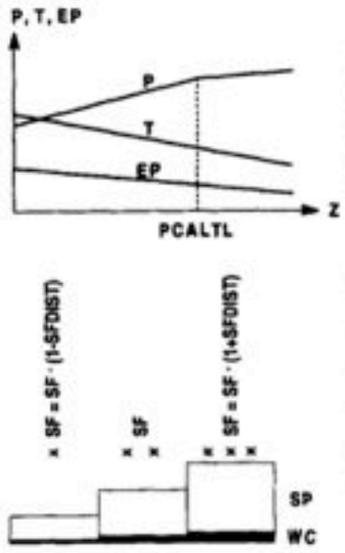
Received 11 October 1996; accepted 6 March 1997

Abstract

A comprehensive re-evaluation of the HBV hydrological model has been carried out. The objectives were to improve its potential for making use of spatially distributed data, to make it more physically sound and to improve the model performance. The new version, HBV-96, uses subbasin division with a typical resolution of 40 km^2, although any resolution can be used. In addition, each subbasin is divided into elevation bands, vegetation and snow classes. Automatic weighting of precipitation and temperature stations was introduced and a new automatic calibration scheme was developed. The modifications led to significant improvements in model performance. In seven test basins the average value of the efficiency criterion R^2 increased from 86 to 89%, with improvements in both the calibration and verification periods. © 1997 Elsevier Science B.V.

Observations in rainfall-runoff modelling

HBV rainfall-runoff model

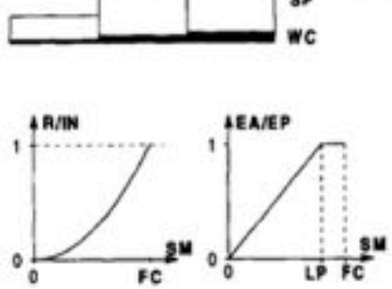


INPUT

$p = \Sigma\ w_i \cdot P_i$
$t = \Sigma\ w_i \cdot T_i$
$ep = \Sigma\ w_i \cdot EP_i$
$PC(z) = PCALT$ if $z \le PCALTL$
$PC(z) = PCALTUP$ if $z > PCALTL$
$P = p \cdot (1 + PC(z) \cdot (z - z_{vst}))$
$T = t - TCALT \cdot (z - z_{vst})$
$EP = ep \cdot (1 - ECALT \cdot (z - z_{vst}))$
$RF = RFCF \cdot P$ if $T \ge TT + TTI/2$
$SF = SFCF \cdot P$ if $T \le TT - TTI/2$
$EP = ECORR \cdot EP$

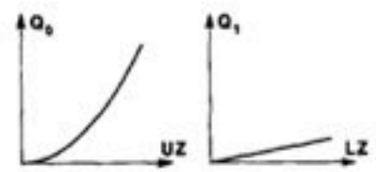
SNOW

$MELT = CFMAX \cdot (T - TTM)$ if $T > TTM$ $(MELT \le SP)$
$REFR = CFR \cdot CFMAX \cdot (T - TTM)$ if $T < TTM$ $(REFR \le WC)$
$WC = WC + MELT + RF$ if $WC < WHC \cdot SP$
$IN = MELT + RF$ if $WC \ge WHC \cdot SP$



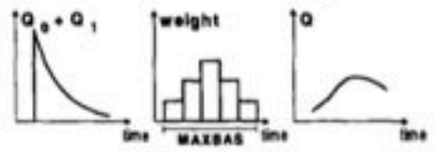
SOIL AND EVAPOTRANSPIRATION

$R/IN = (SM/FC)^{BETA}$
$EP = EP \cdot (1 + ETF \cdot (T - T_M)/T_M)$
$EA/EP = SM/LP$ if $SM < LP$
$EA/EP = 1$ if $SM \ge LP$
$CF = CFLUX \cdot (1 - SM/FC)$ $(CF \le UZ)$
$EL = CEVPL \cdot EP(-LAG)$



RESPONSE

$Q_0 = K \cdot UZ^{(1 + ALFA)}$
$Q_1 = K_1 \cdot LZ$



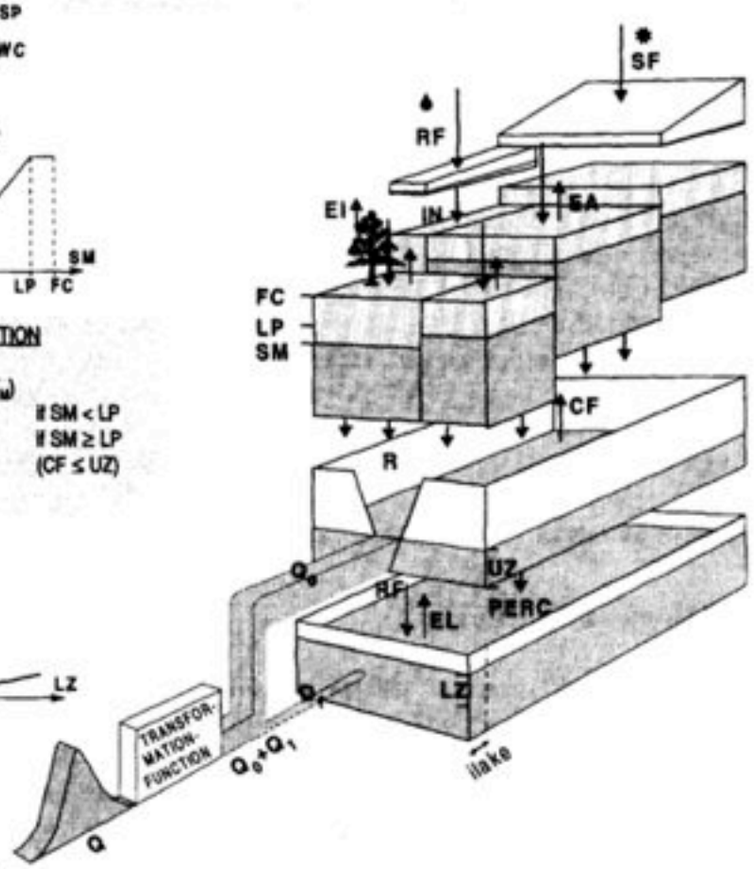


Fig. 3.

INPUT

Variables:

p	=	Weighted mean precipitation
t	=	Weighted mean temperature
ep	=	Weighted mean evaporation
P_i	=	Precipitation at station i
T_i	=	Temperature at station i
EP_i	=	Potential evaporation at station i (long-term mean values)
P	=	Zone precipitation
T	=	Zone temperature
EP	=	Zone potential evapotranspiration
RF	=	Zone rainfall
SF	=	Zone snowfall

Parameters and constants:

PC(z)	=	Elevation correction factor
TCALT	=	Elevation correction factor
ECALT	=	Elevation correction factor
z	=	Zone elevation
z_{vst}	=	Reference level
TT	=	Temperature limit for snow/rain
TTI	=	Temperature interval with a mixture of snow and rain
RFCF	=	Rainfall correction factor
SFCF	=	Snowfall correction factor
ECORR	=	Evaporation correction factor

SNOW

Variables:

SP	=	Frozen part of snowpack
WC	=	Liquid water in snow
MELT	=	Snowmelt
REFR	=	Refreezing of liquid water
IN	=	Infiltration to soil

Parameters and constants:

SFDIST	=	Distribution factor for snowfall
WHC	=	Water holding capacity
CFMAX	=	Degree day factor
TTM	=	Temperature limit for melting
CFR	=	Refreezing factor

SOIL AND EVAPOTRANSPIRATION

Variables:

SM	=	Soil moisture
R	=	Runoff from soil
EA	=	Actual evapotranspiration
EI	=	Interception evaporation
CF	=	Capillary flow
EL	=	Lake evaporation
T_M	=	Subbasin mean temperature (long-term daily means)

Parameters and constants:

FC	=	Maximum soil moisture content
LP	=	Limit for potential evapotranspiration
BETA	=	Parameter in soil routine
CFLUX	=	Maximum value of CF
CEVPL	=	Lake evaporation correction factor
LAG	=	Time lag for lake evaporation
ETF	=	Temperature correction factor

RESPONSE

Variables:

UZ	=	Storage in upper response box
Q_0	=	Outflow from upper response box
LZ	=	Storage in lower response box
Q_1	=	Outflow from lower response box
Q	=	Outflow from transformation function

Parameters and constants:

K	=	Recession coefficient
ALFA	=	Response box parameter
PERC	=	Percolation from upper to lower response box
K_1	=	Recession coefficient
MAXBAS	=	Transformation function parameter
ilake	=	Internal lake zone

Fig. 3. (*continued*) Schematic structure of one subbasin in the HBV-96 model, with routines for snow (top), soil (middle) and response (bottom). Bold letters indicate that the parameter is normally calibrated.

Hydrometeorological processes and its interaction with the terrain

Observations in rainfall-runoff modelling

HBV rainfall-runoff model

- Subbasin division.
- Snowmelt based on the degree-day approach (air temperature).
- Evapotranspiration: potential evapotranspiration based on Penman, with an altitude correction factor.
- Interception storage.
- Response function:

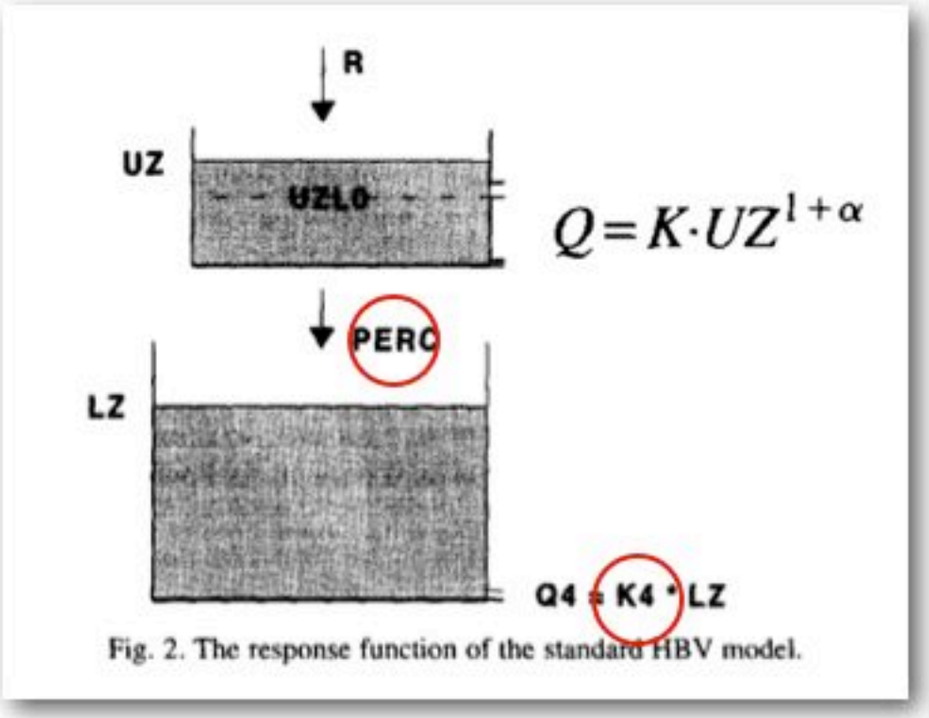
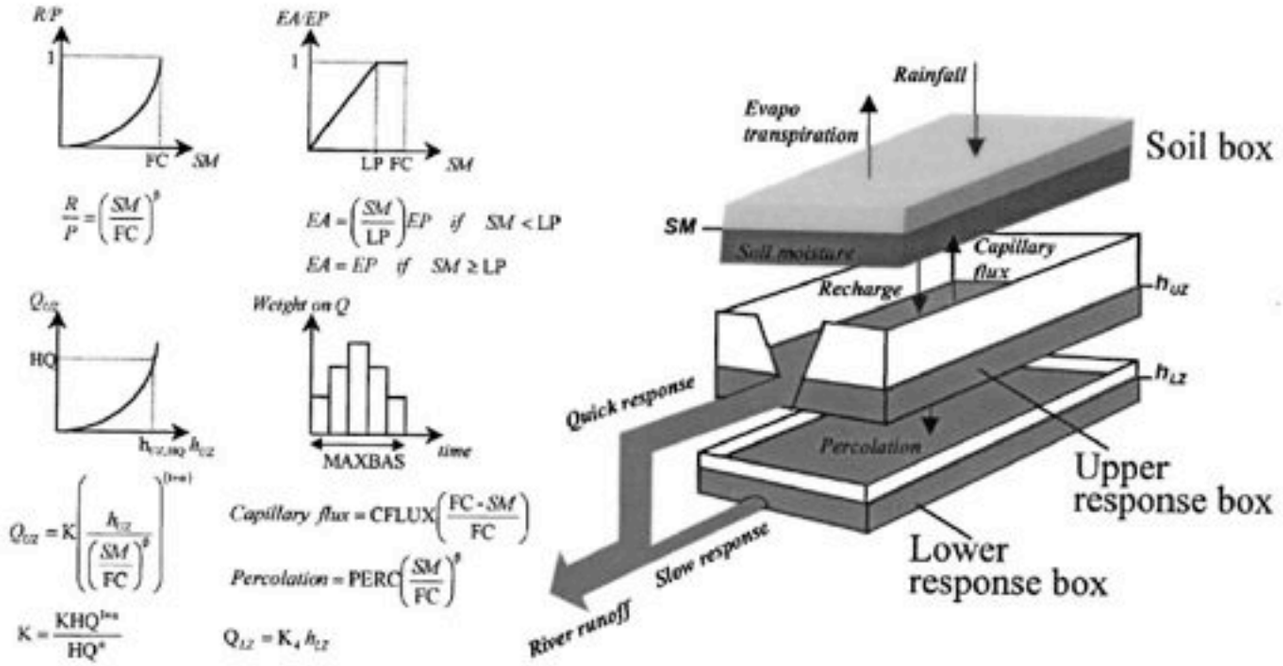


Fig. 2. The response function of the standard HBV model.

- Land use (open areas, forests, lakes and glaciers).
- Routing (Muskingum method).

The HBV-96 Rainfall-Runoff Model



VARIABLES

R	Recharge
P	Rainfall
SM	Soil moisture storage
EP	Potential evapotranspiration
EA	Actual evapotranspiration
h_{UZ}	Storage in upper response box
h_{LZ}	Storage in lower response box
Q_{UZ}	Runoff from upper response box
Q_{LZ}	Runoff from lower response box
Q	River runoff

PARAMETERS

FC	Maximum soil moisture storage
LP	Limit for potential evapotranspiration
β	Soil routine parameter
KHQ	Recession at HQ
HQ	Half of mean annual flood
α,K_4	Recession parameters
$h_{UZ,HQ}$	h_{UZ} level at HQ
PERC	Percolation rate
CFLUX	Capillary flux rate
MAXBAS	Routing parameter

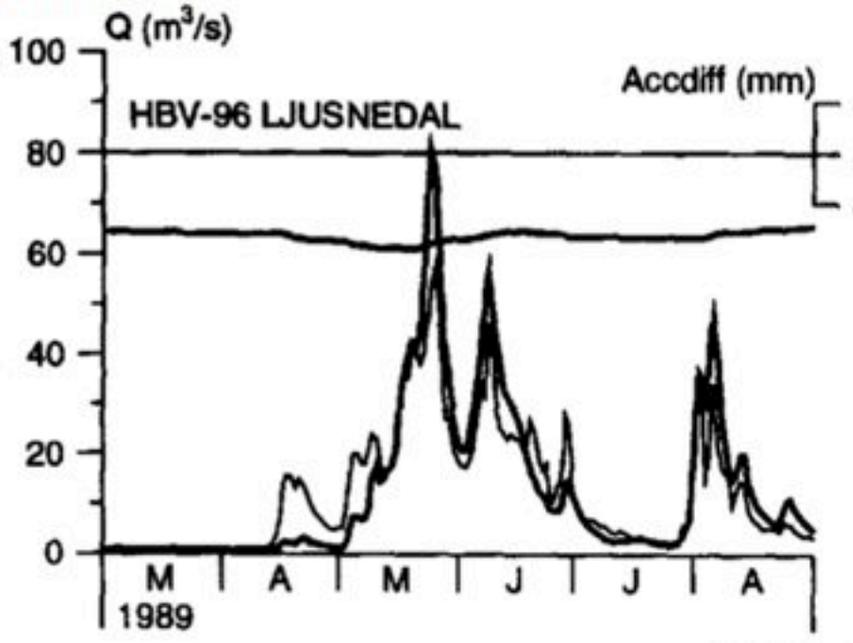
Fig. 1. The principal structure and parameters of the HBV-96 model when applied on catchments without snow as described by Lindström et al. (1997) including the recent modifications of the response routine by Bergström et al. (1997).

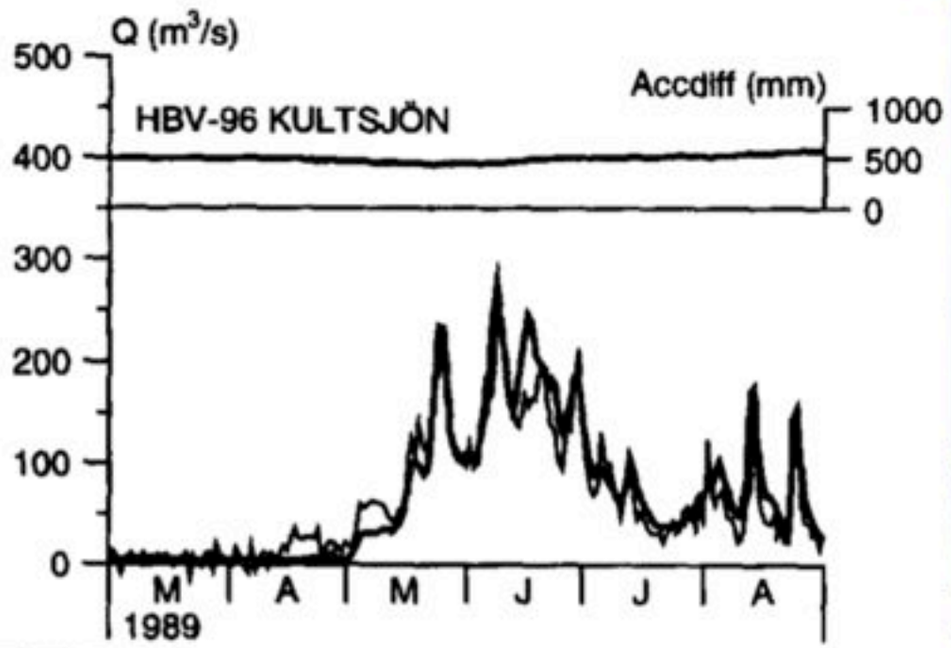
Hydrometeorological processes and its interaction with the terrain

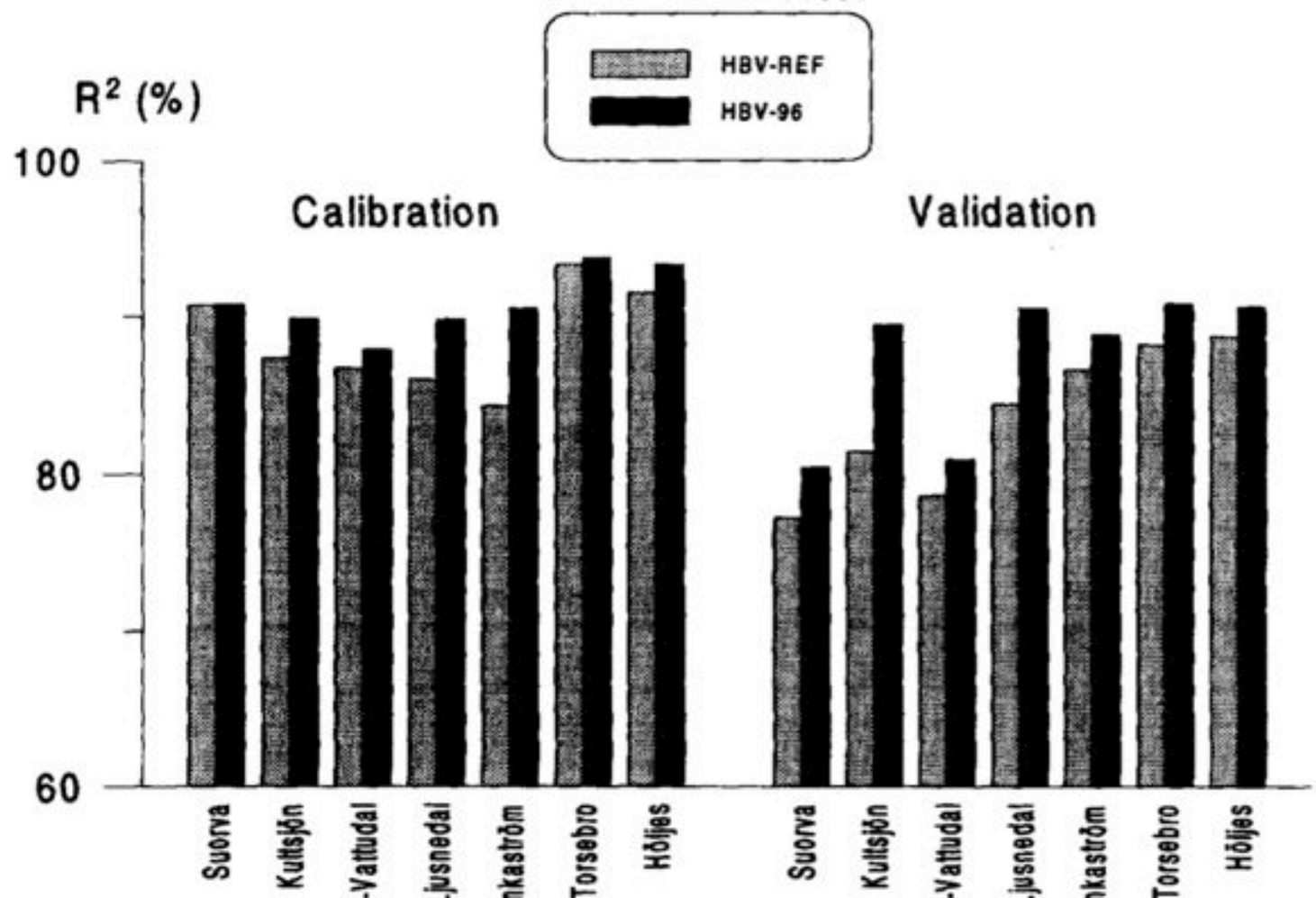
Observations in rainfall-runoff modelling

HBV rainfall-runoff model

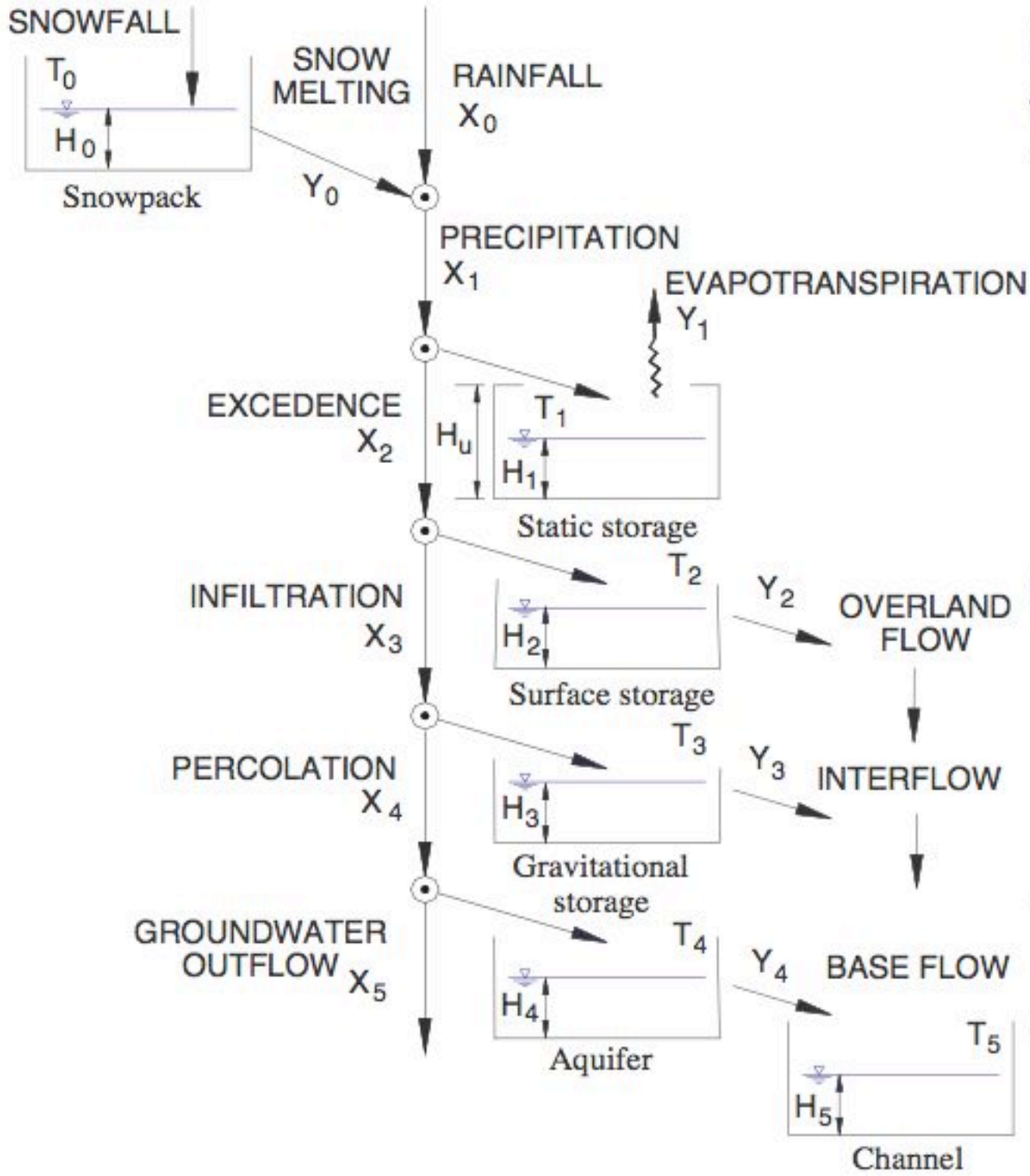








Hydrometeorological processes and its interaction with the terrain



Source: Vélez et al. (HESS2009).

Topmodel

Hipótesis

Topmodel

Hipótesis

- ***Estacionariedad: la dinámica de los procesos se puede representar por una cadena de procesos estacionarios ⇨ $S(t+1) = S(t) + \Delta S$***

Topmodel

Hipótesis

- ***Estacionariedad: la dinámica de los procesos se puede representar por una cadena de procesos estacionarios ⇨ S(t+1) = S(t) + ΔS***
- ***Uniformidad: la recarga a la zona saturada se puede considerar uniforme***

Topmodel

Hipótesis

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- ***El gradiente hidráulico de la zona saturada se puede aproximar por la pendiente del terreno***

Topmodel

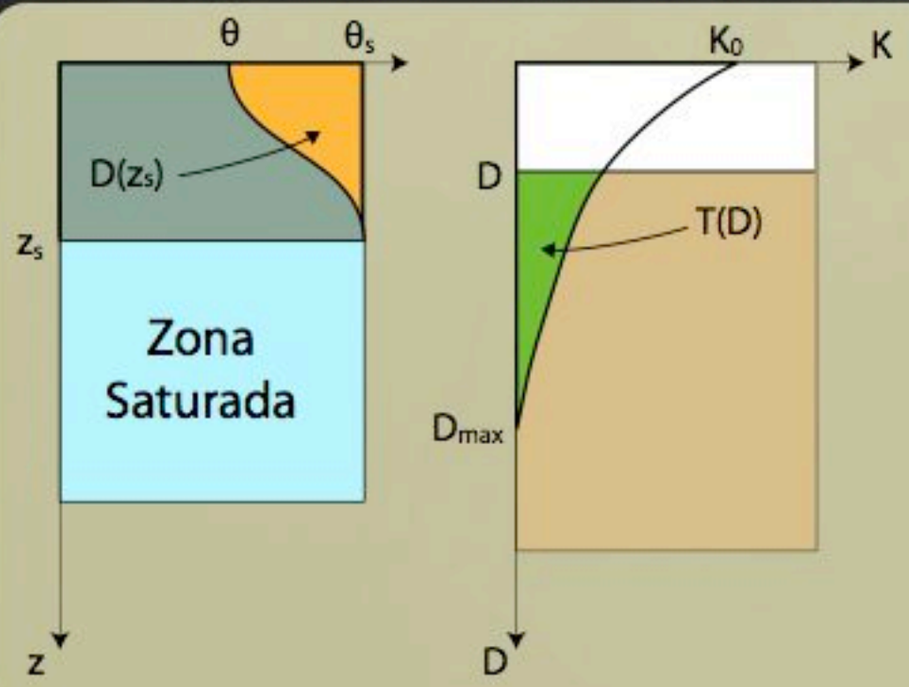
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- ***Función de la conductividad hidráulica (horizontal) con la profundidad (o el dèficit)***

Topmodel

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función exponencial $K(D_i) = K_0 \cdot \exp\left(-\frac{D_i}{m}\right)$

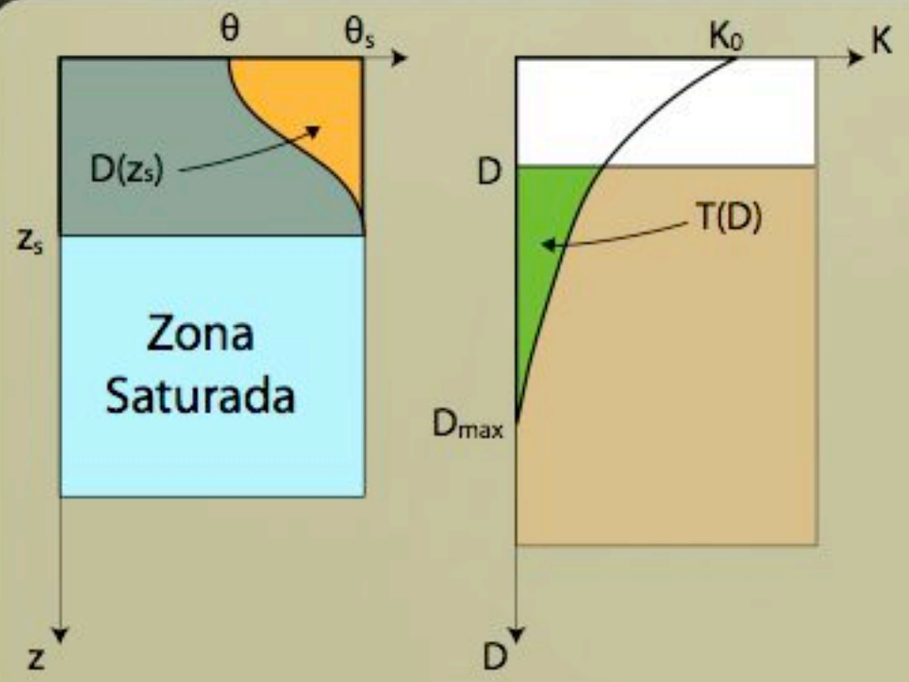
Déficit D :: profundidad efectiva de la zona saturada

Topmodel

Hipótesis

- ***Estacionariedad: la dinámica de los procesos se puede representar por una cadena de procesos estacionarios ⇨ $S(t+1) = S(t) + \Delta S$***
- ***Uniformidad: la recarga a la zona saturada se puede considerar uniforme***
- ***El gradiente hidráulico de la zona saturada se puede aproximar por la pendiente del terreno***

- ***Función de la conductividad hidráulica (horizontal) con la profundidad (o el dèficit)***

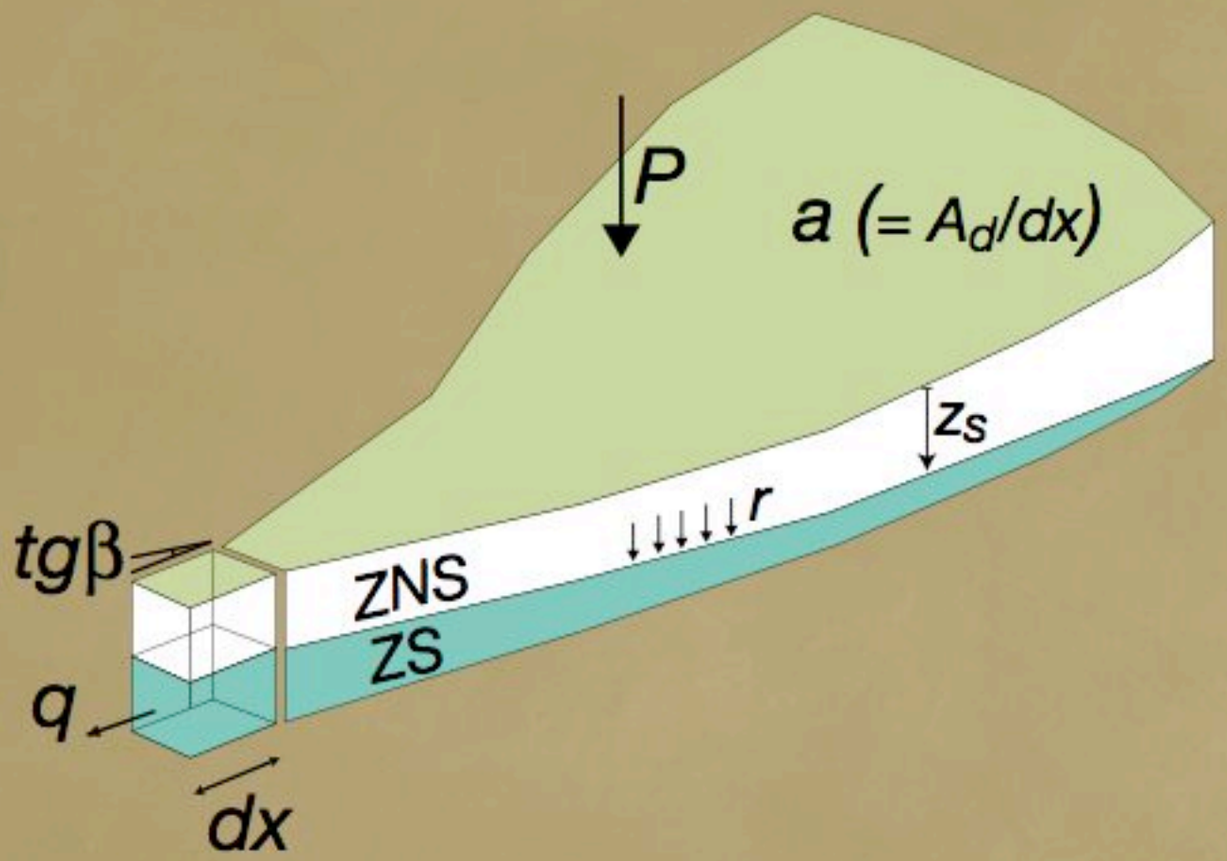


función exponencial $K(D_i) = K_0 \cdot \exp\left(-\frac{D_i}{m}\right)$

Déficit D :: profundidad efectiva de la zona saturada

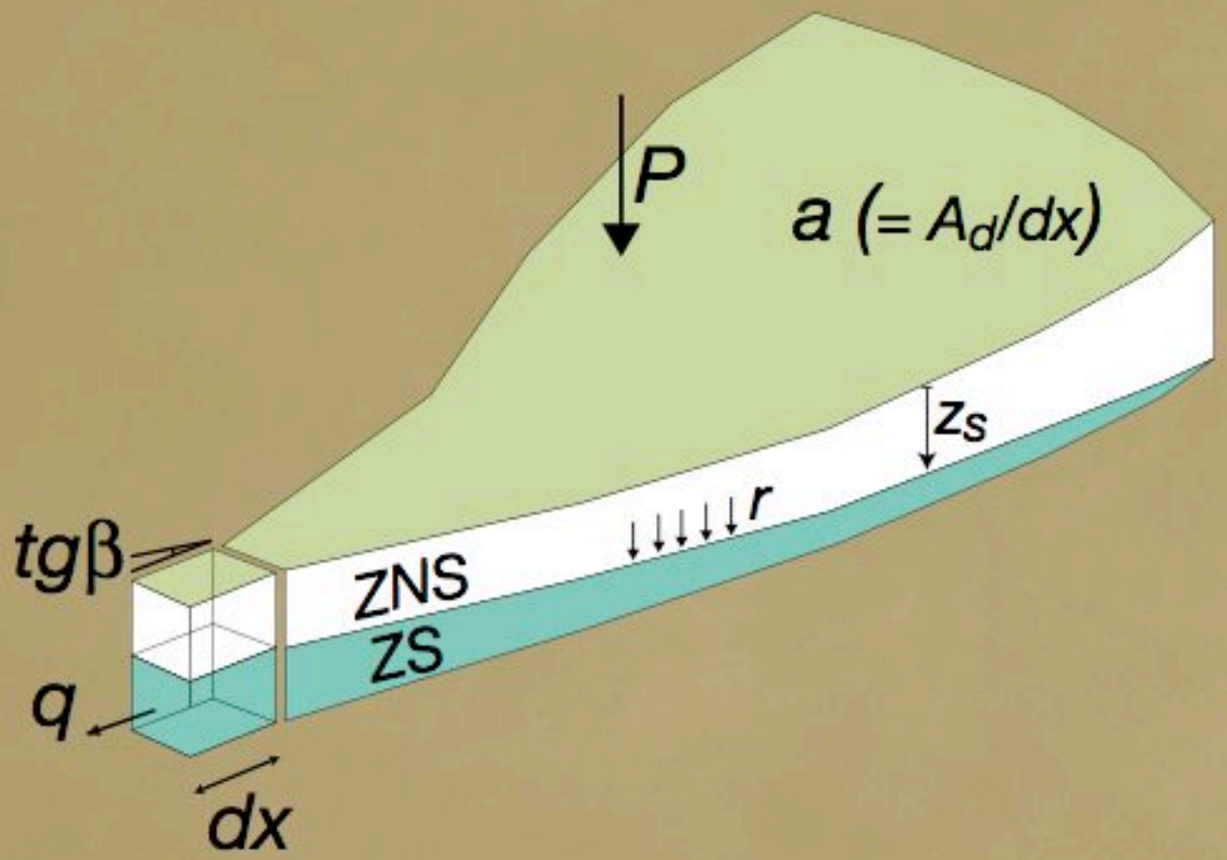
$$T(D_i) = \int_{\infty}^{D_i} K_0 \cdot \exp(-D_i/m) = \underbrace{m \cdot K_0}_{T_0} \cdot \exp(-D_i/m)$$

Topmodel



Darcy's law

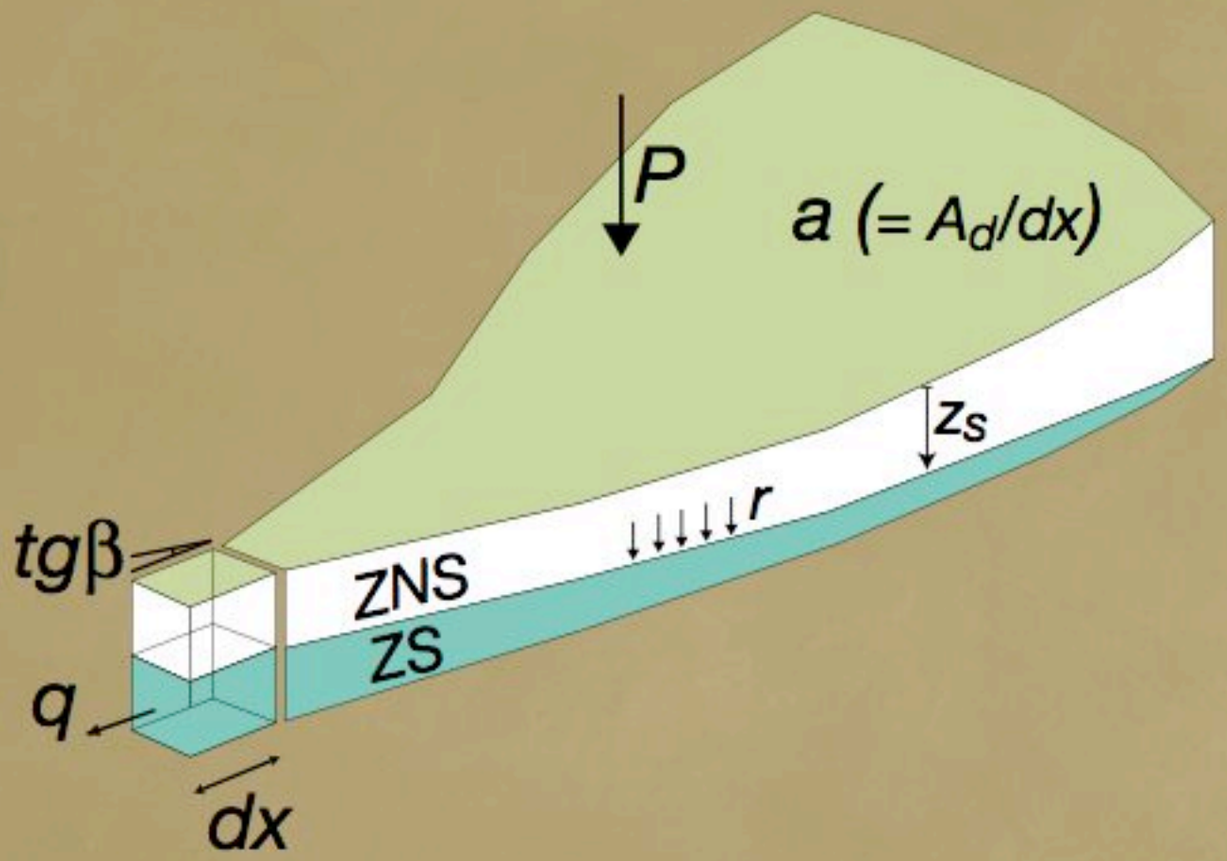
Topmodel



Darcy's law

$$q_i = \underbrace{T_0 \cdot \exp\left(-\frac{D_i}{m}\right)}_{T_i} \cdot \underbrace{Tg\beta_i}_{\nabla H_i} = r_i \cdot a_i$$

Topmodel

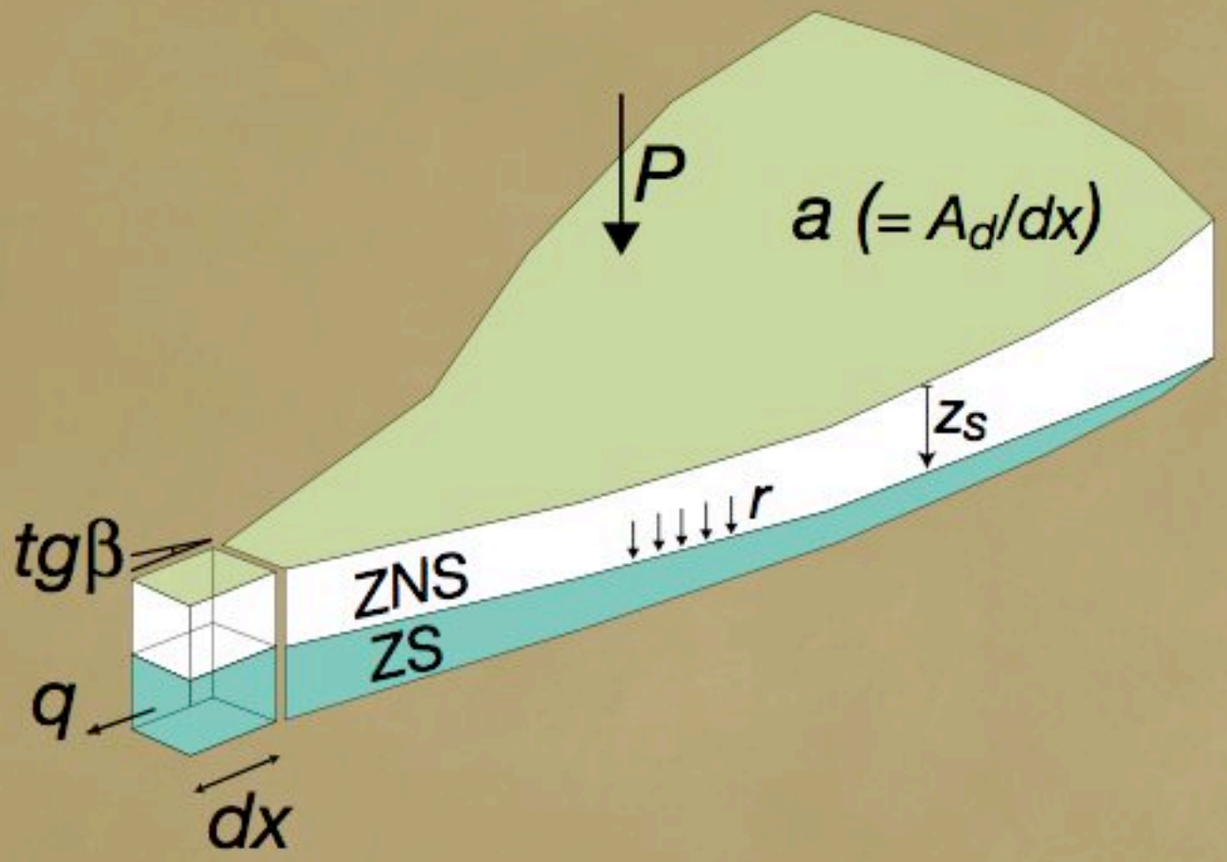


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$$\frac{D_i}{m} = -\ln(r) + \ln T_0 - \underbrace{\ln\left(\frac{a_i}{Tg\beta_i}\right)}_{\lambda_i}$$

Topmodel



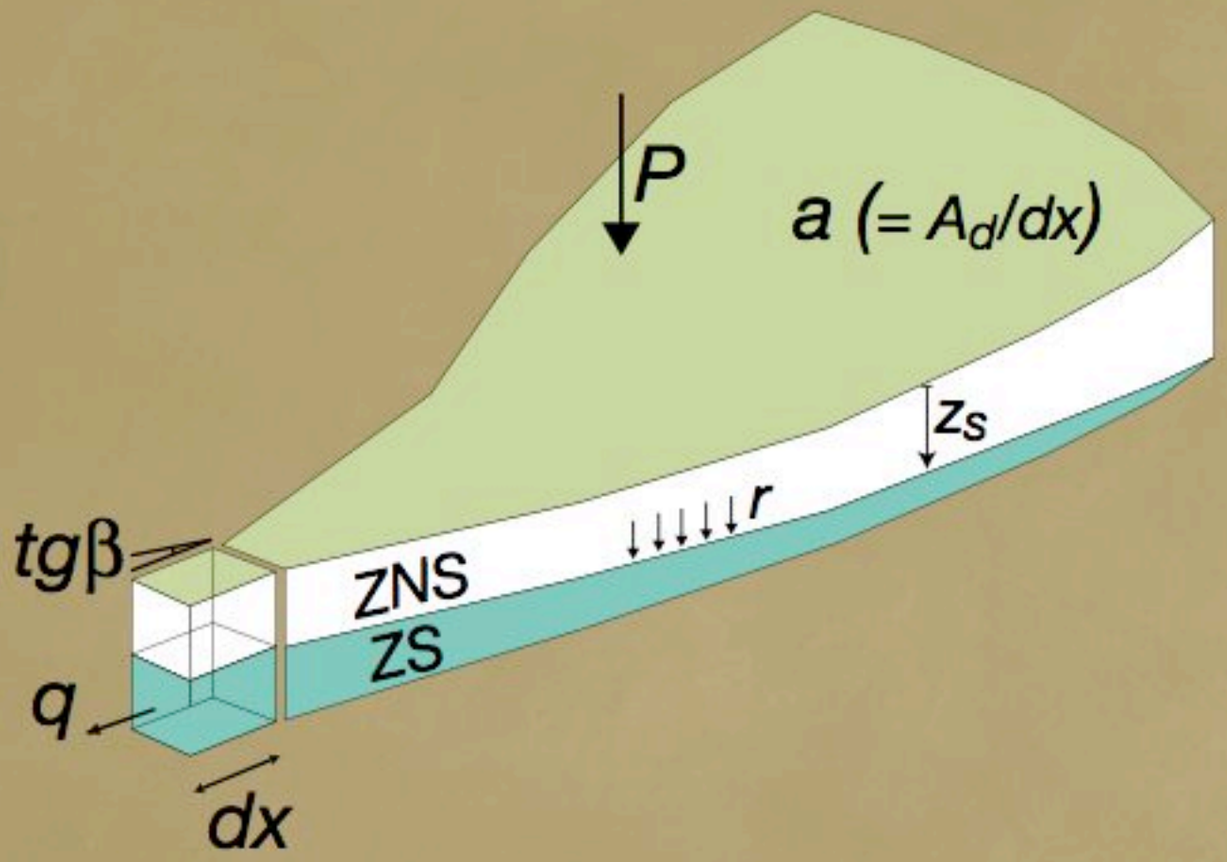
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$$\frac{D_i}{m} = -\ln(r) + \ln T_0 - \underbrace{\ln\left(\frac{a_i}{Tg\beta_i}\right)}_{\lambda_i}$$

$$\frac{D}{m} = \frac{1}{n}\sum\frac{D_i}{m} = -\ln(r) + \ln T_0 - \underbrace{\frac{1}{n}\sum\ln\left(\frac{a_i}{Tg\beta_i}\right)}_{\lambda}$$

Topmodel



Darcy's law

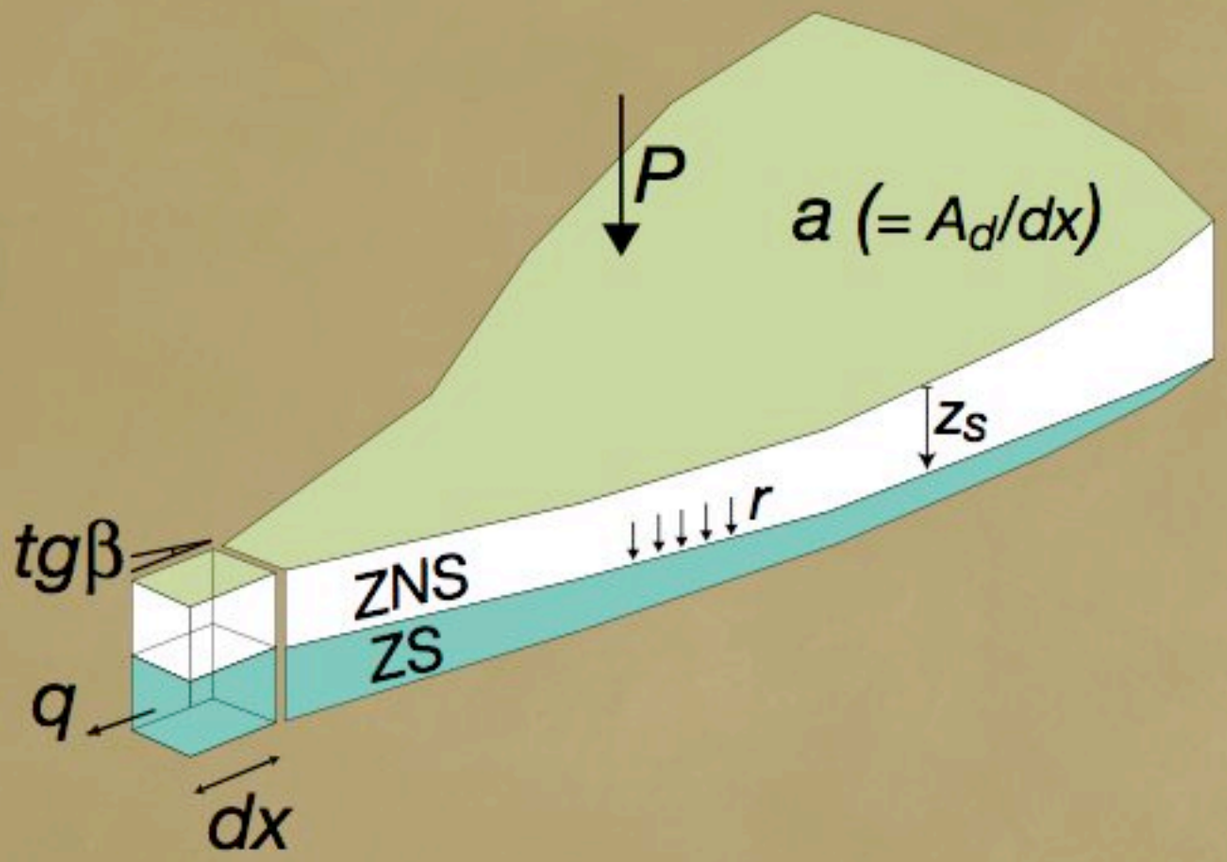
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$$D - D_i = -m \cdot (\lambda - \lambda_i)$$

Topmodel



Darcy's law

$$q_i = \underbrace{T_0 \cdot \exp\left(-\frac{D_i}{m}\right)}_{T_i} \cdot \underbrace{Tg\beta_i}_{\nabla H_i} = r_i \cdot a_i$$

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$$D - D_i = -m \cdot (\lambda - \lambda_i)$$

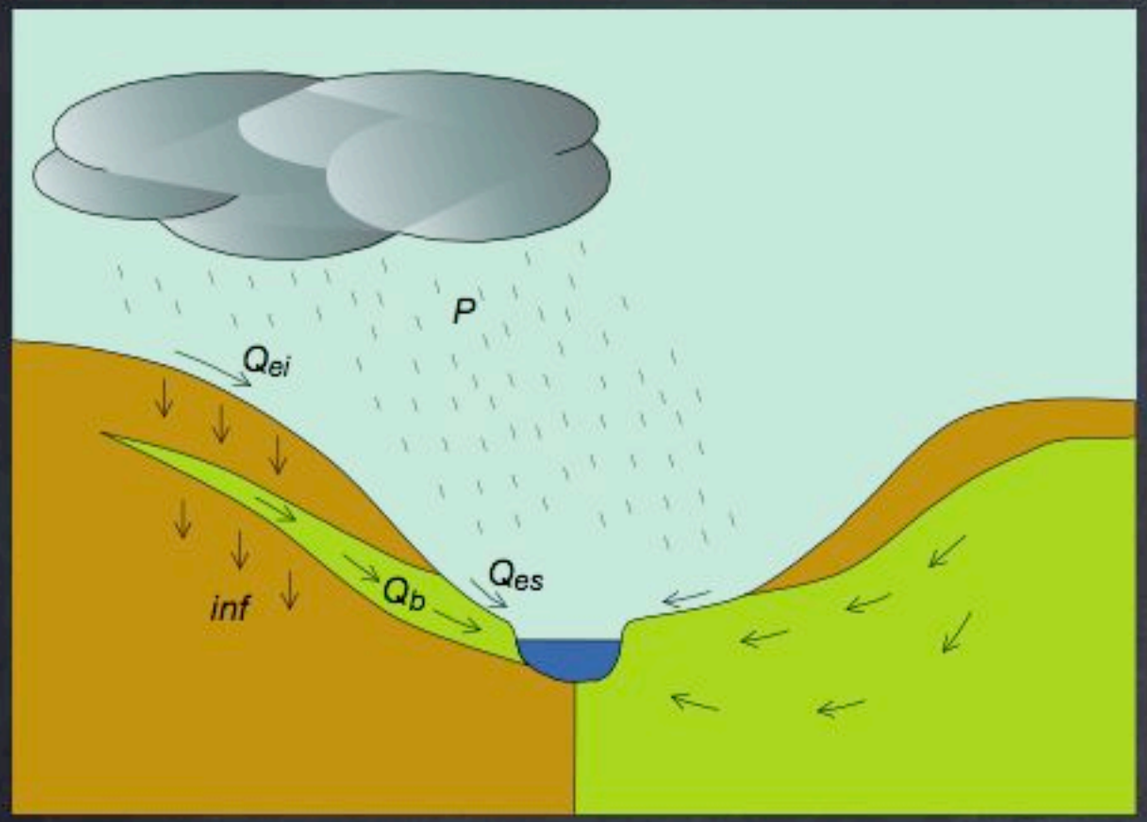
$$D_i = D + m \cdot (\lambda - \lambda_i)$$

Topmodel

Caudal base

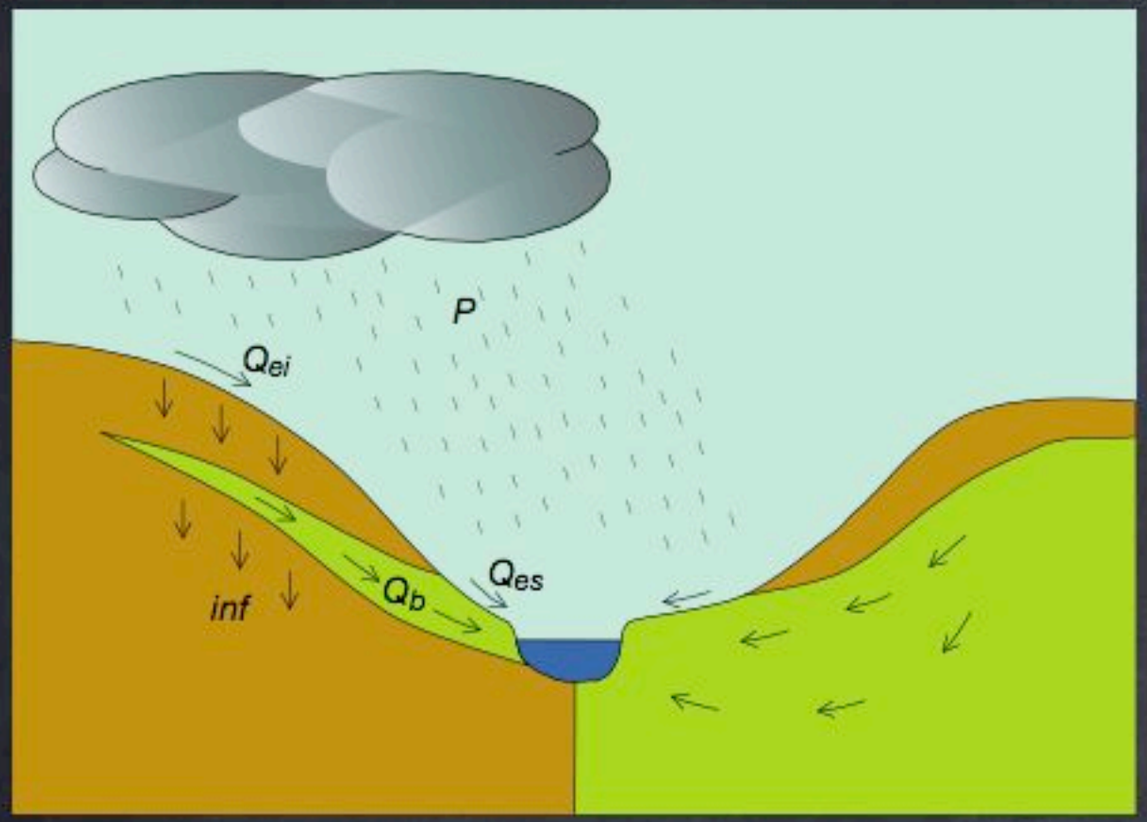
Topmodel

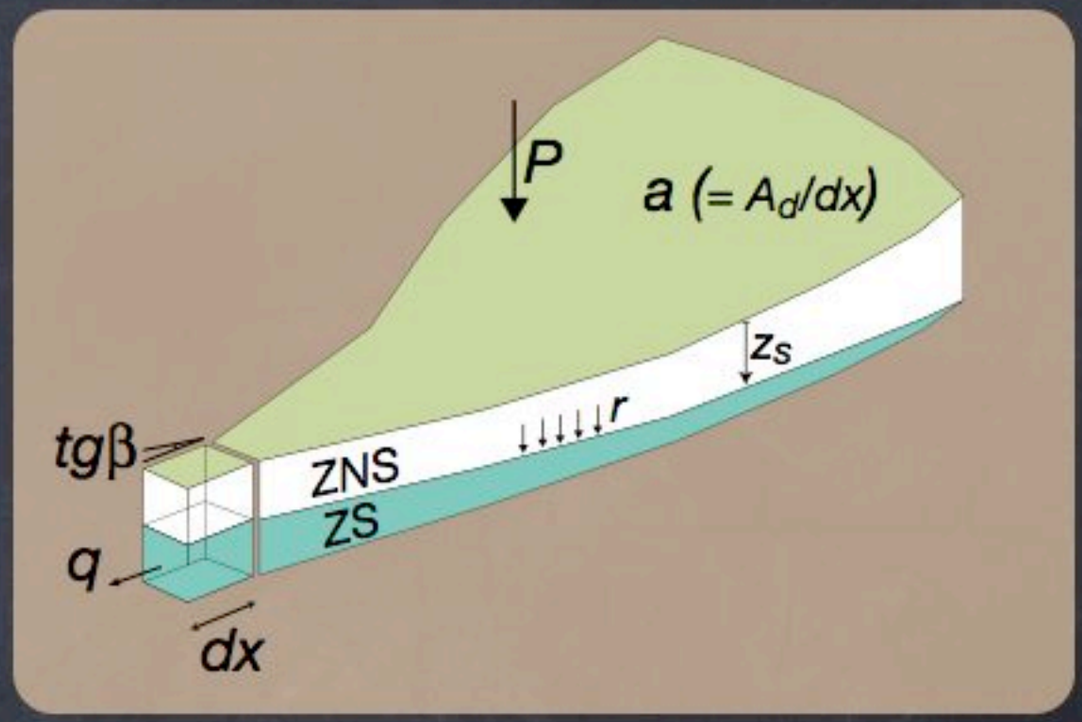
Caudal base



Topmodel

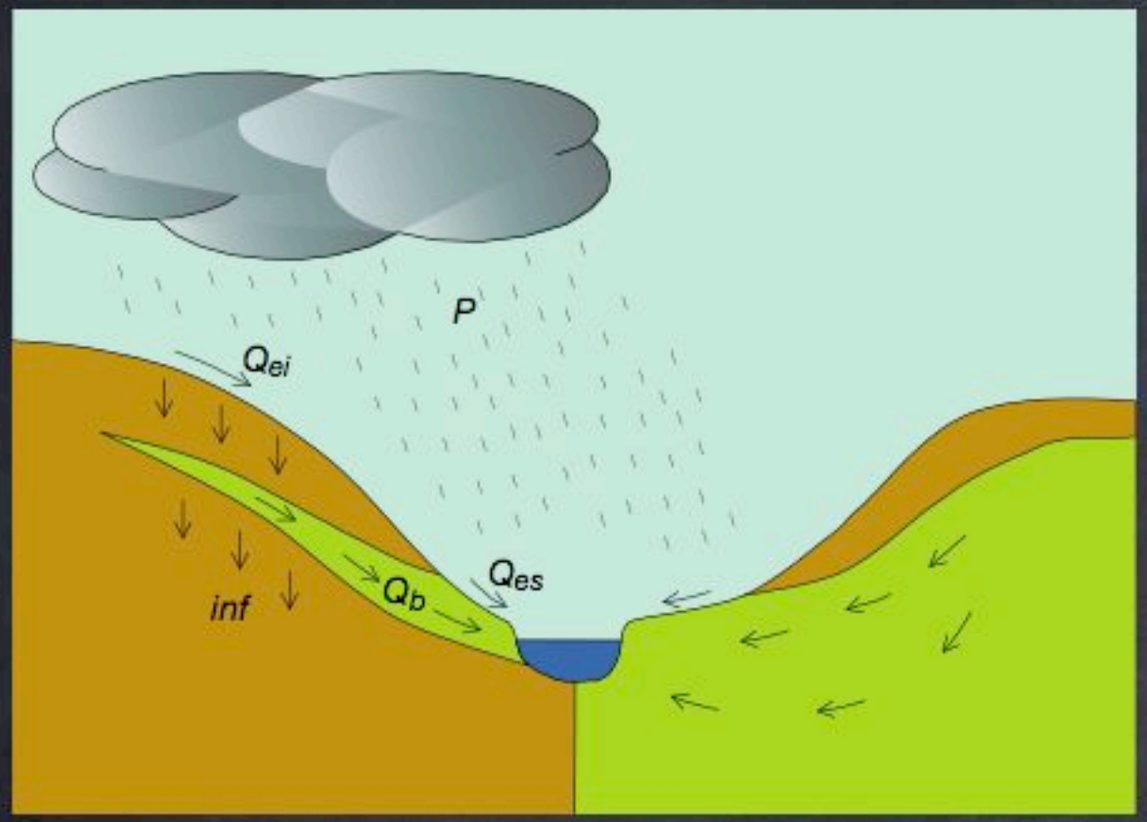
Caudal base

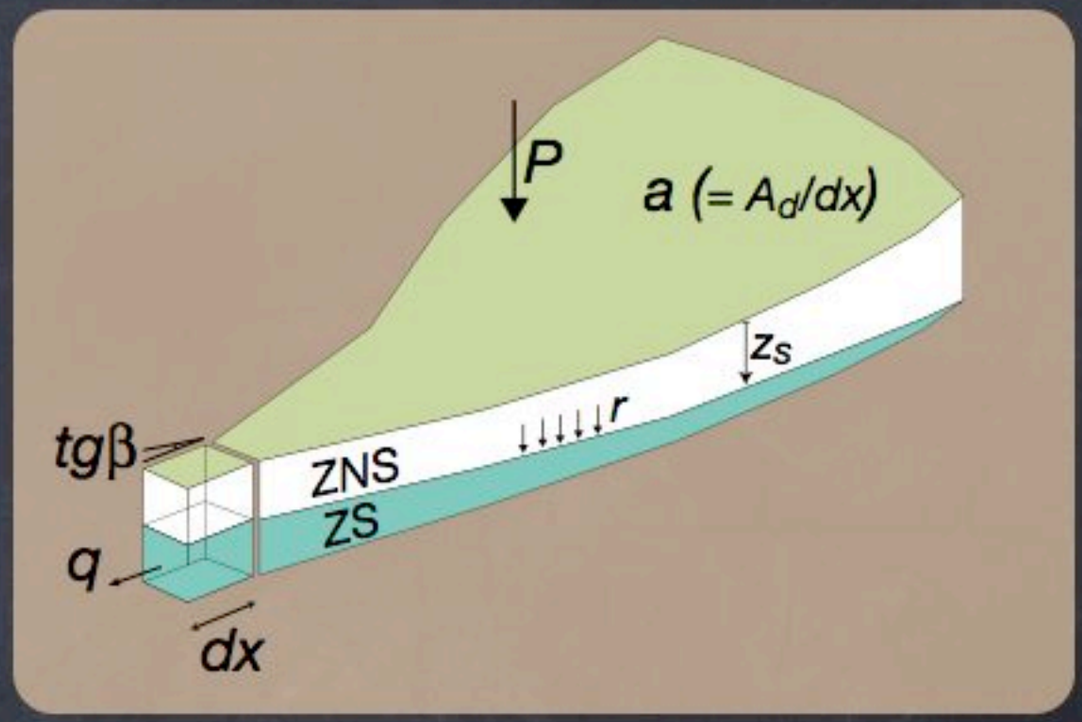




Topmodel

Caudal base



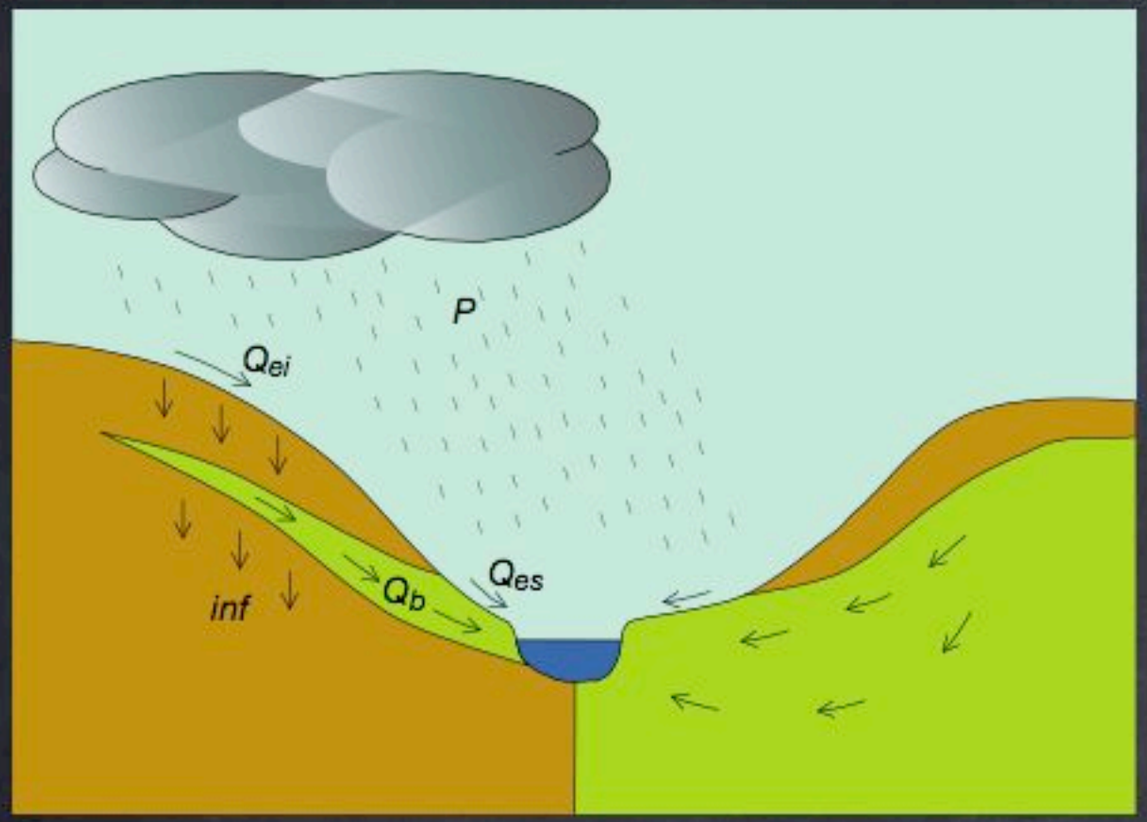


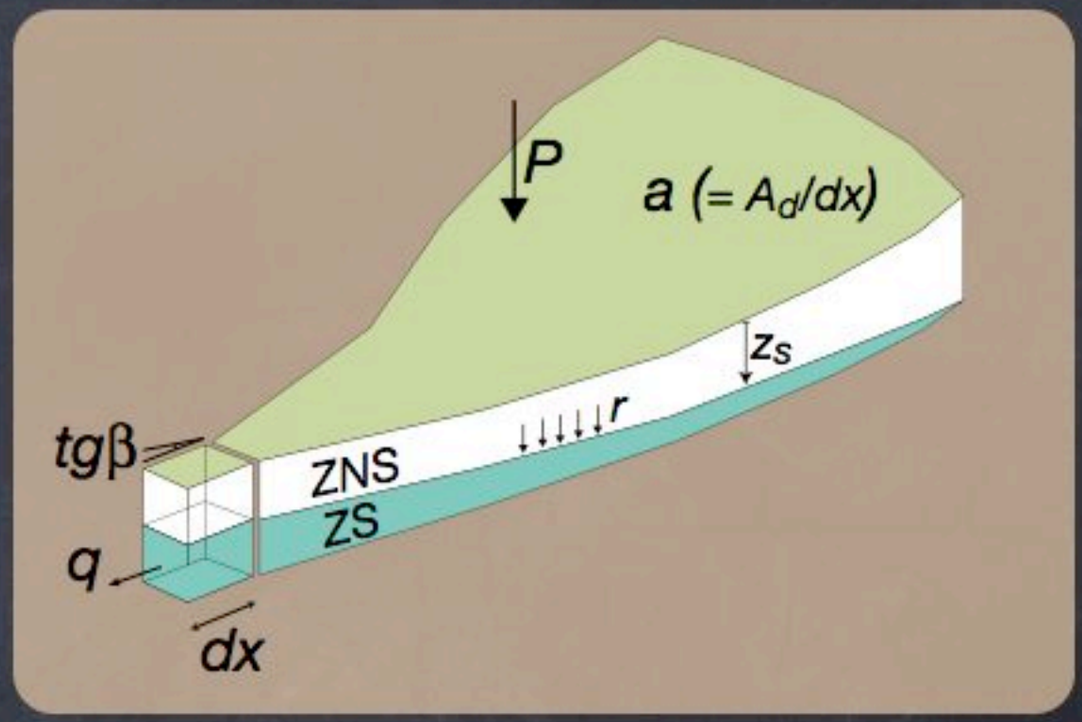
caudal base

$$Q_b(t) = \sum_{dx \in L} q_i(t) = \sum_{dx \in L} T_0 \cdot \exp\left(-\frac{D_i(t)}{m}\right) \cdot Tg\beta_i \cdot dx$$

Topmodel

Caudal base





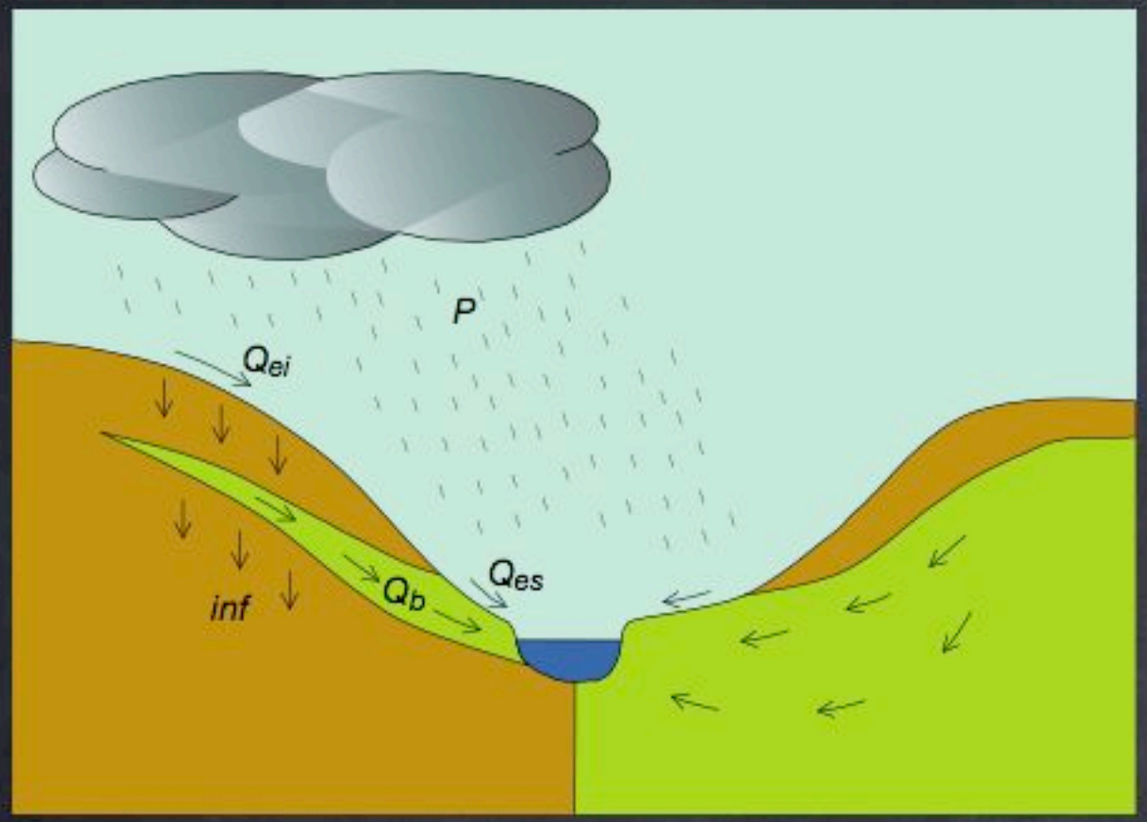
caudal base

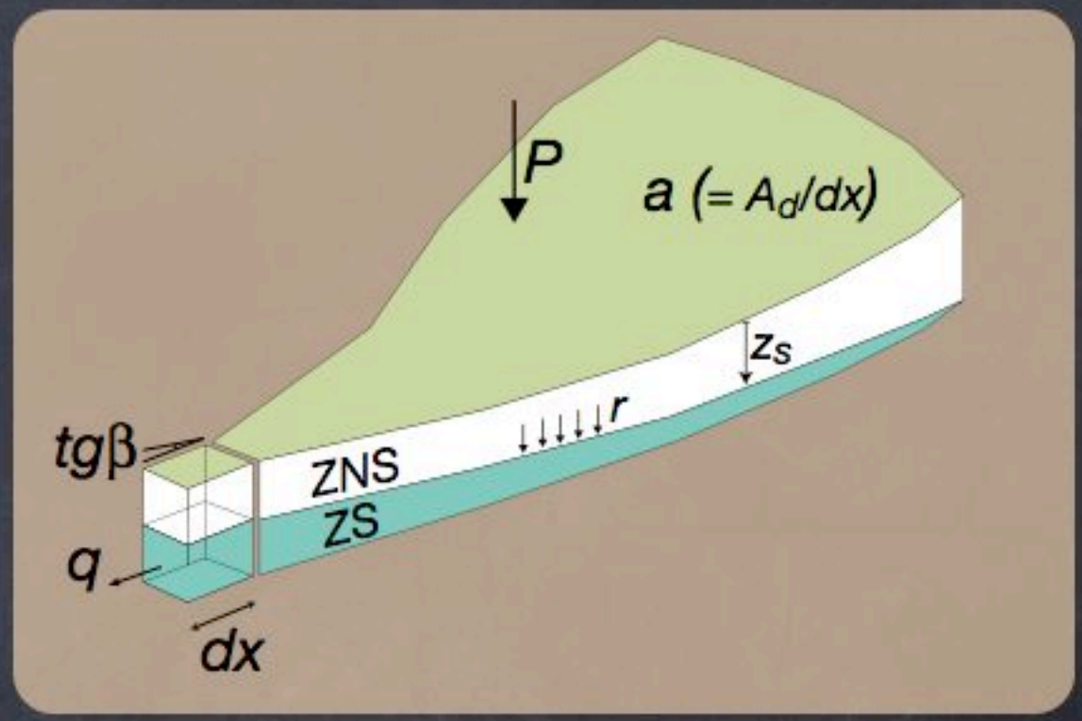
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L: celdas de río saturadas

Topmodel

Caudal base





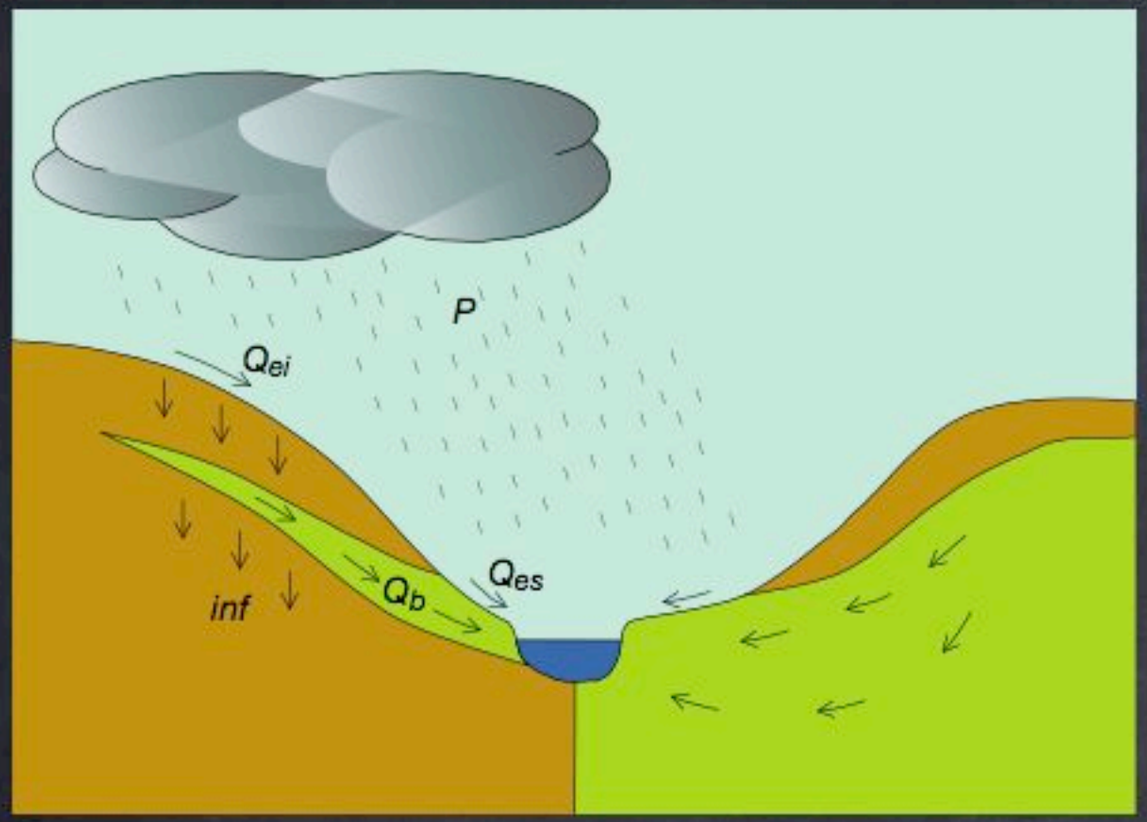
caudal base

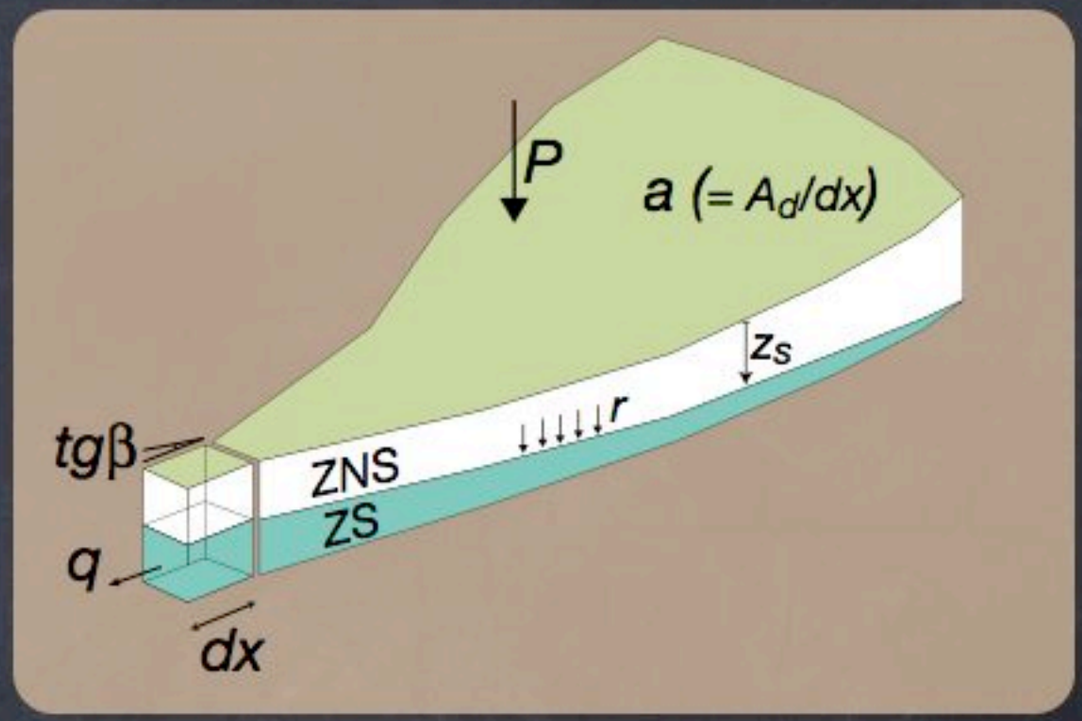
$$Q_b(t) = \sum_{dx \in L} q_i(t) = \sum_{dx \in L} T_0 \cdot \exp\underbrace{\left(-\frac{D_i(t)}{m}\right)}_{-\frac{D(t)}{m} - \lambda + \lambda_i} \cdot Tg\beta_i \cdot dx$$

L: celdas de río saturadas

Topmodel

Caudal base





caudal base

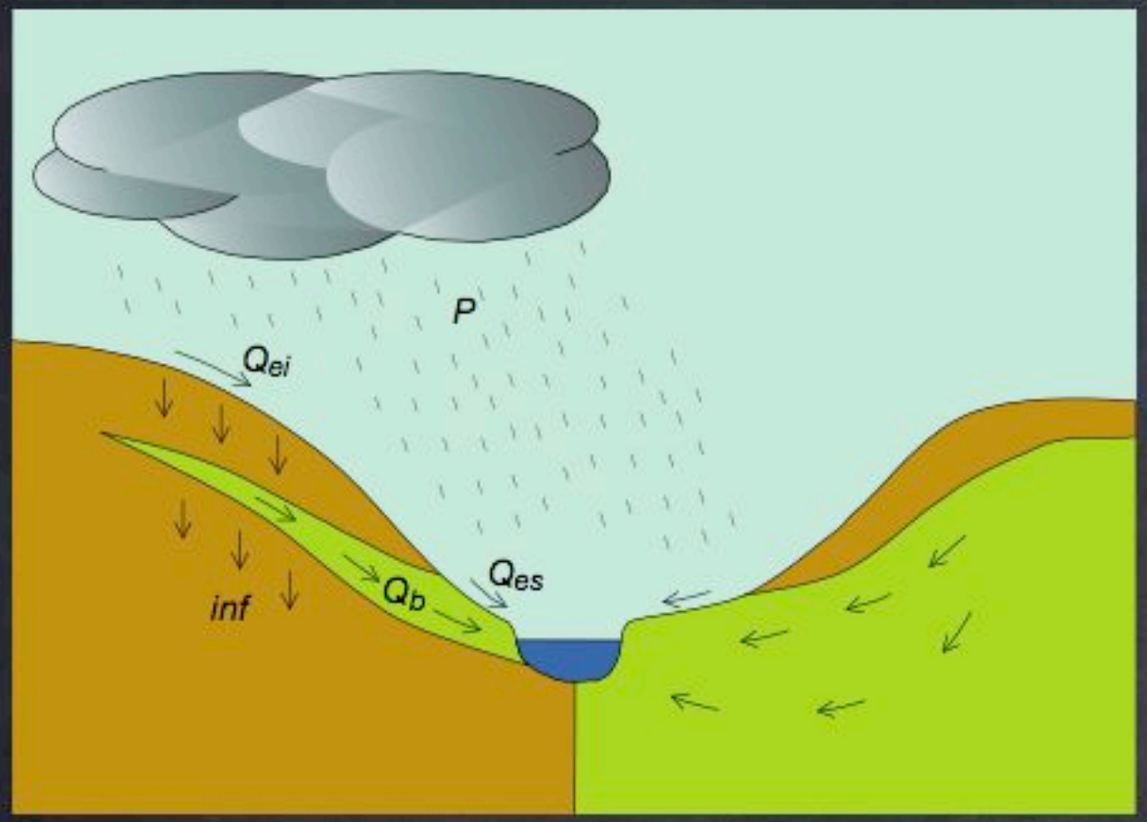
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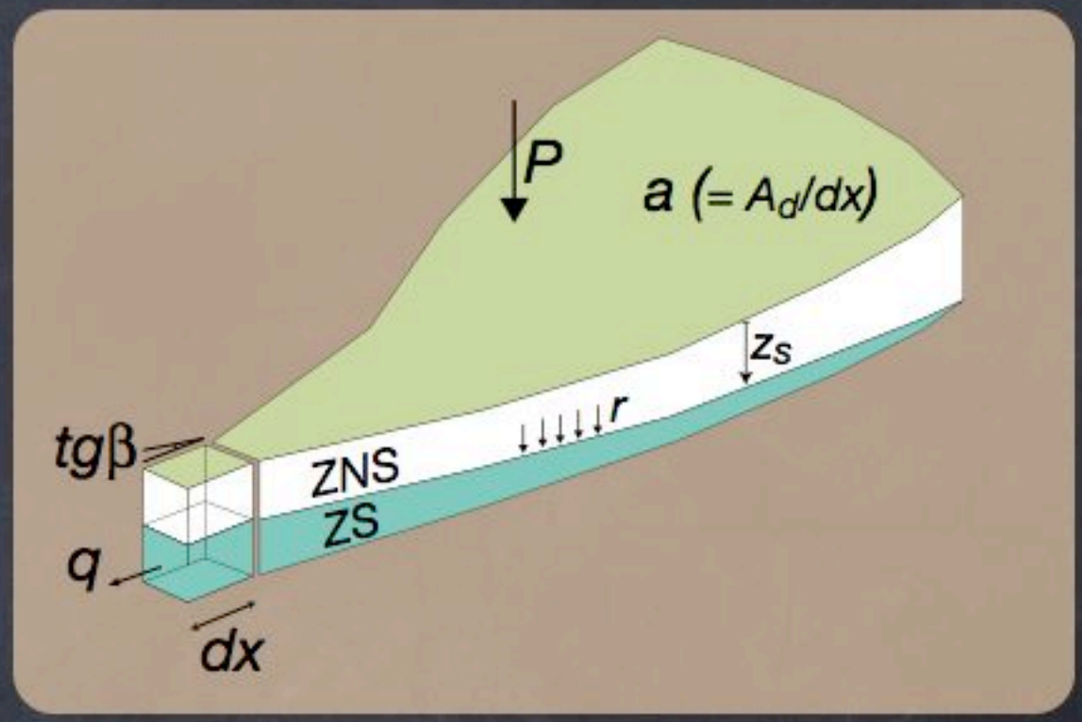
L: celdas de río saturadas

$$-\frac{D(t)}{m} - \lambda + \lambda_i \qquad \lambda_i = \ln\left(\frac{a_i}{tg\beta_i}\right)$$

Topmodel

Caudal base





caudal base

$$Q_b(t) = \sum_{dx \in L} q_i(t) = \sum_{dx \in L} T_0 \cdot \exp\left(-\frac{D_i(t)}{m}\right) \cdot Tg\beta_i \cdot dx$$

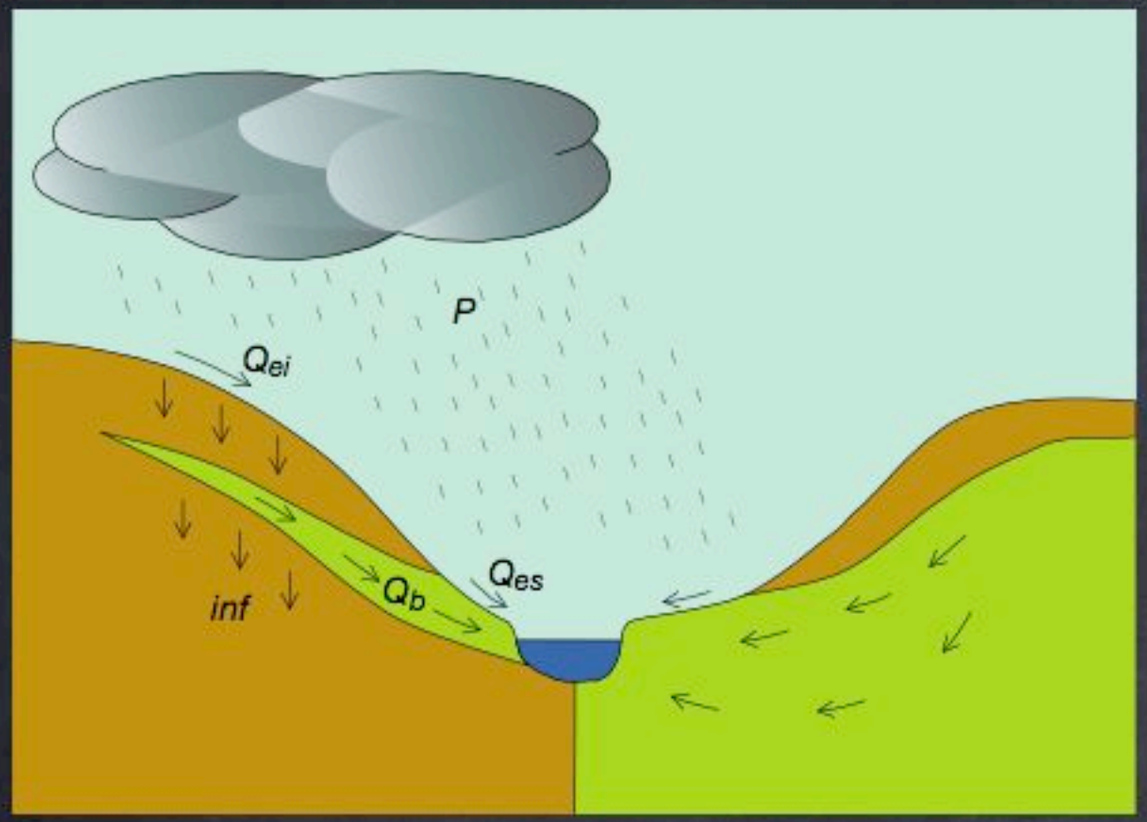
L: celdas de río saturadas

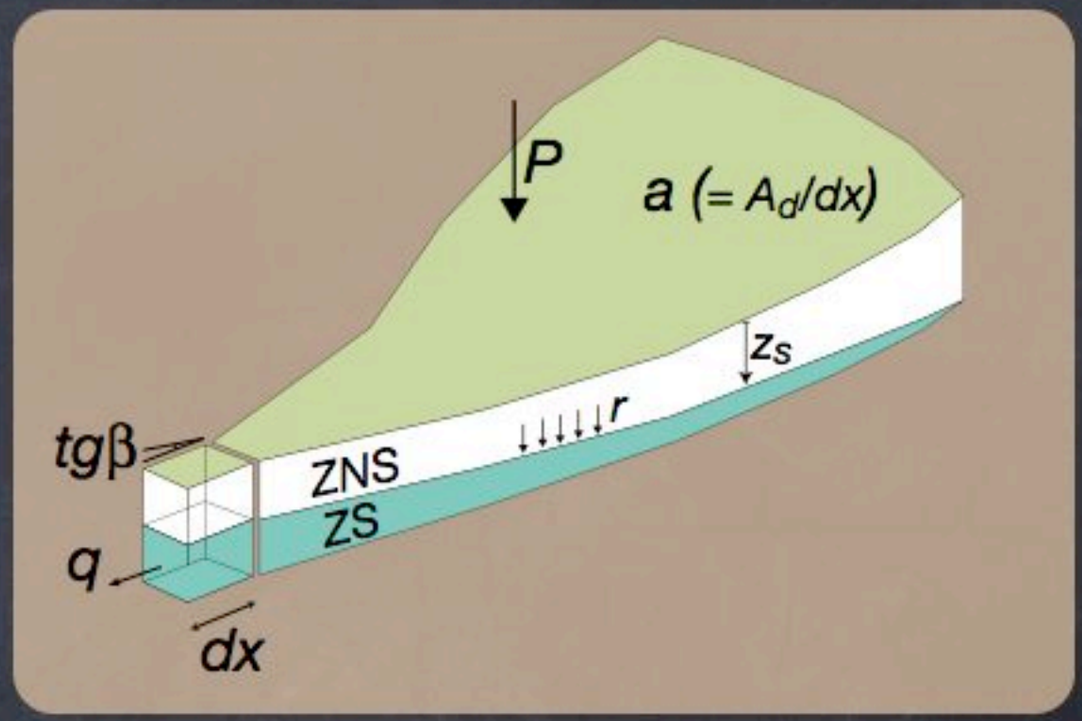
$$-\frac{D(t)}{m} - \lambda + \lambda_i \qquad \lambda_i = \ln\left(\frac{a_i}{tg\beta_i}\right)$$

$$Q_b(t) = T_0 \cdot \exp\left(-\frac{D(t)}{m} - \lambda\right) \cdot \sum_{dx \in L} a_i \cdot dx$$

Topmodel

Caudal base





caudal base

$$Q_b(t) = \sum_{dx \in L} q_i(t) = \sum_{dx \in L} T_0 \cdot \exp\left(-\frac{D_i(t)}{m}\right) \cdot Tg\beta_i \cdot dx$$

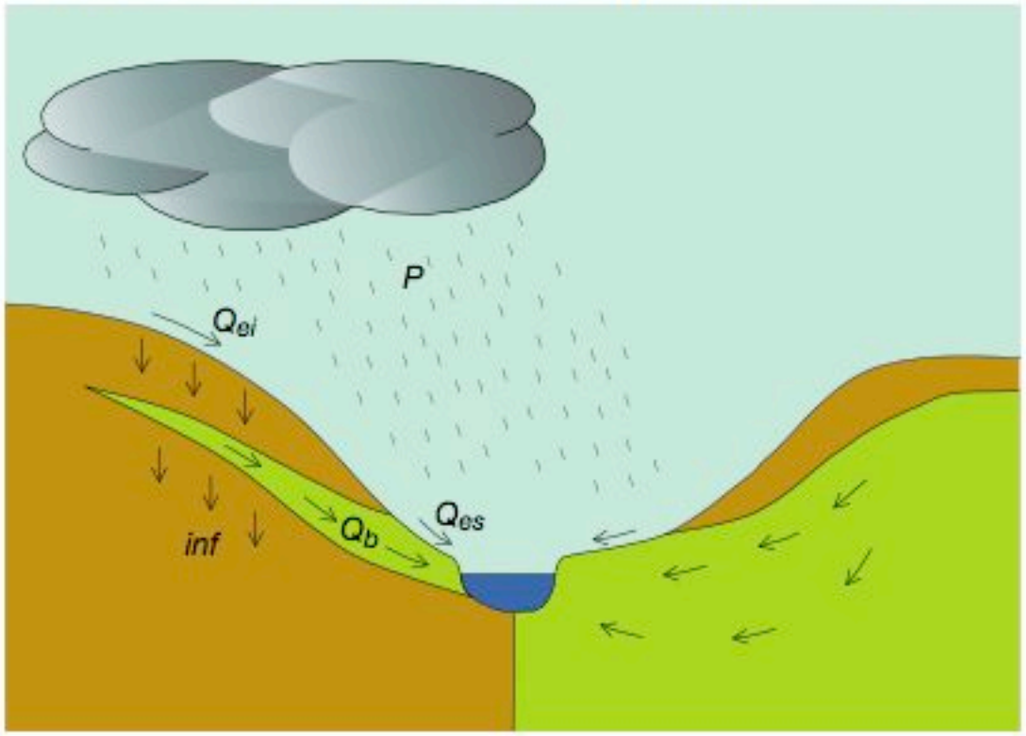
L: celdas de río saturadas

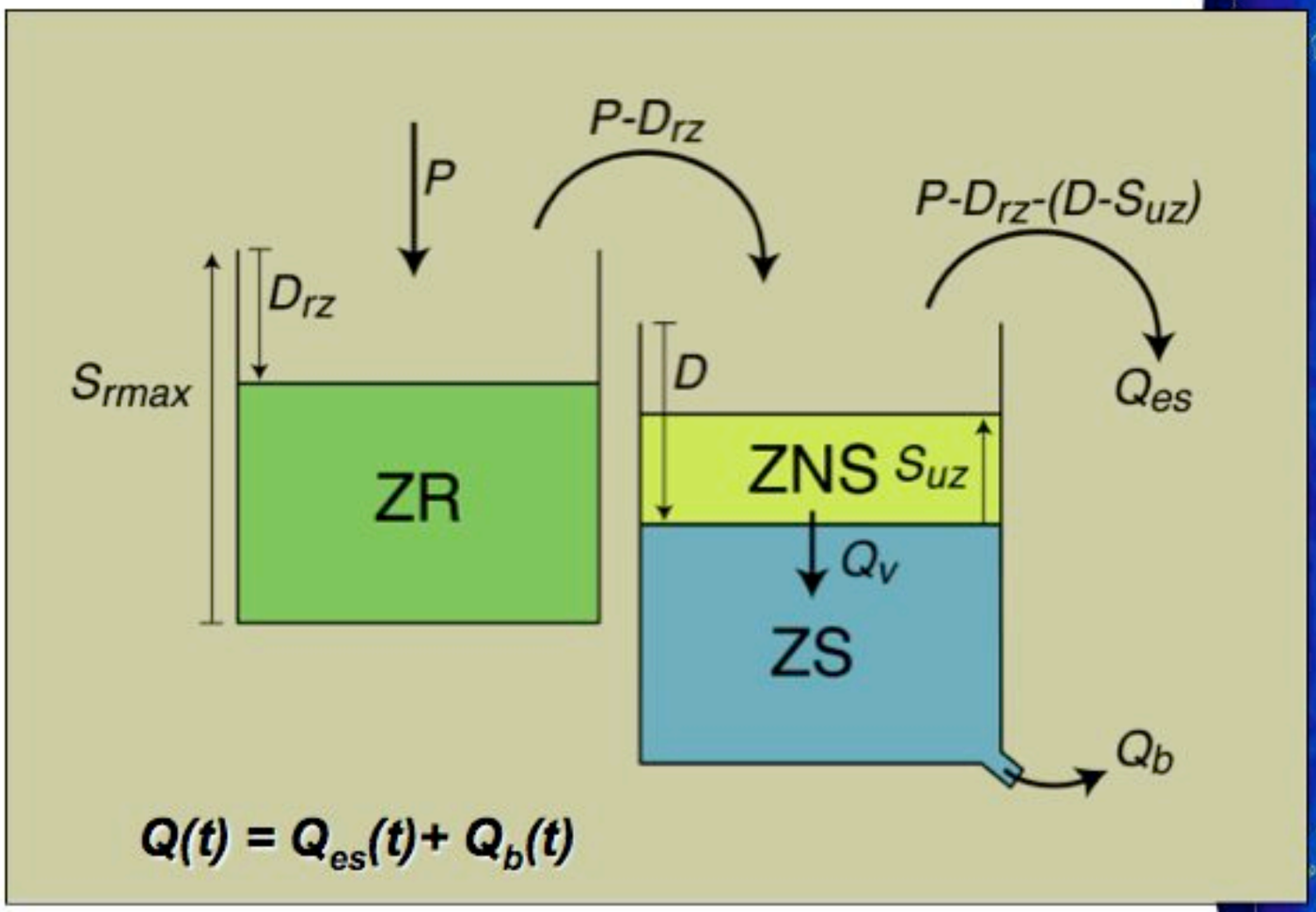
$$-\frac{D(t)}{m} - \lambda + \lambda_i \qquad \lambda_i = \ln\left(\frac{a_i}{tg\beta_i}\right)$$

$$Q_b(t) = T_0 \cdot \exp\left(-\frac{D(t)}{m} - \lambda\right) \cdot \underbrace{\sum_{dx \in L} a_i \cdot dx}_{A}$$

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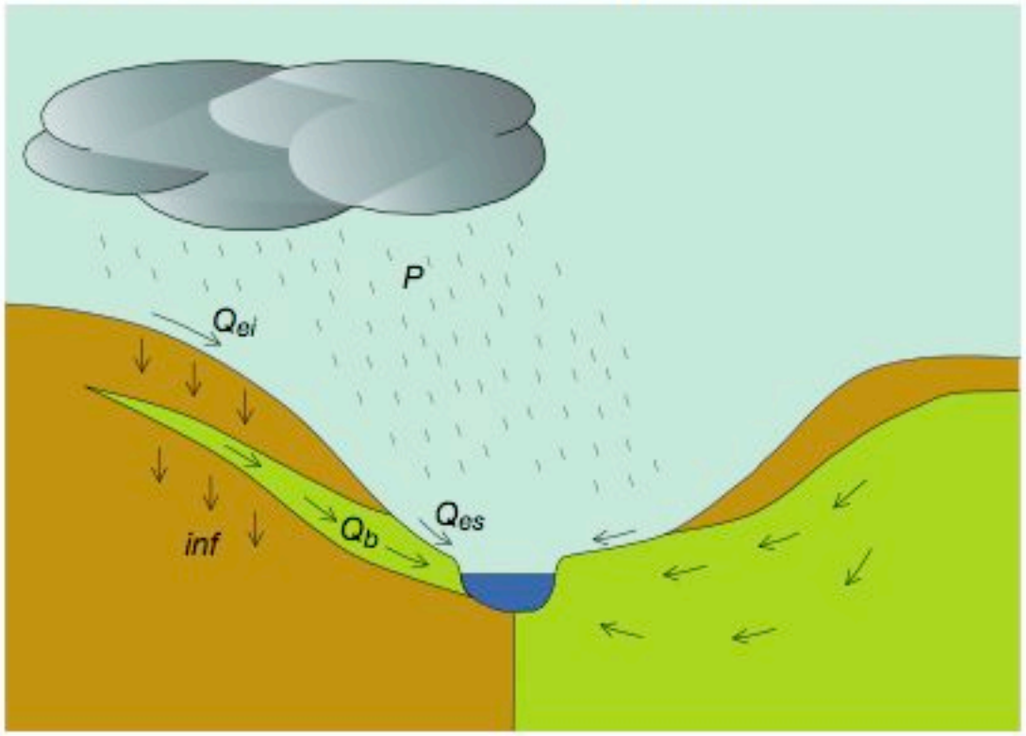
$$q_v(\lambda_i) = \frac{T_0}{m} exp\left(-\frac{D(\lambda_i)}{m}\right)$$

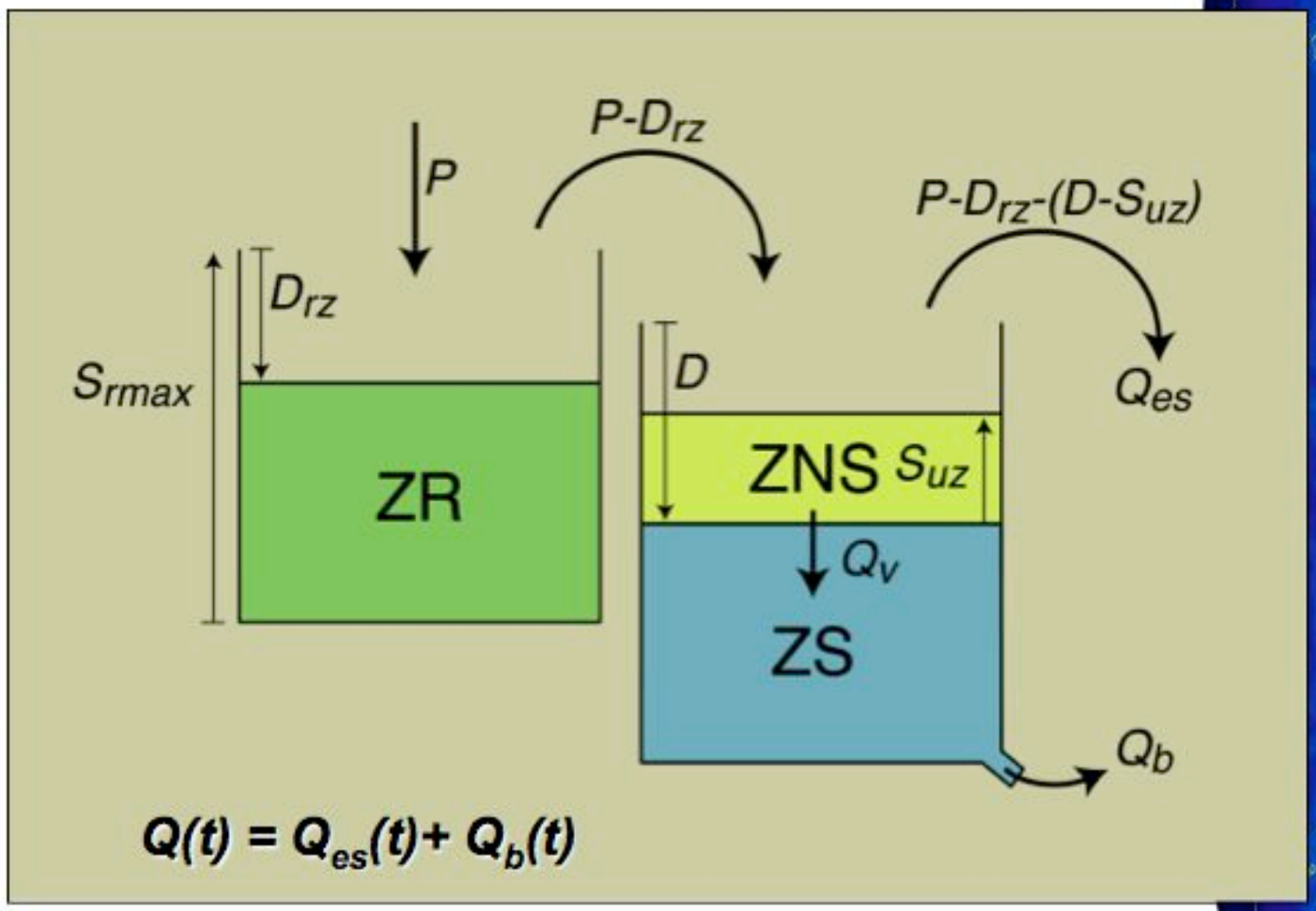
$$Q_b = A \; T_0 \; exp\left(-\bar{\lambda}\right) \; exp\left(-\frac{\overline{D}}{m}\right)$$

Hydrometeorological processes and its interaction with the terrain

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Flow types:

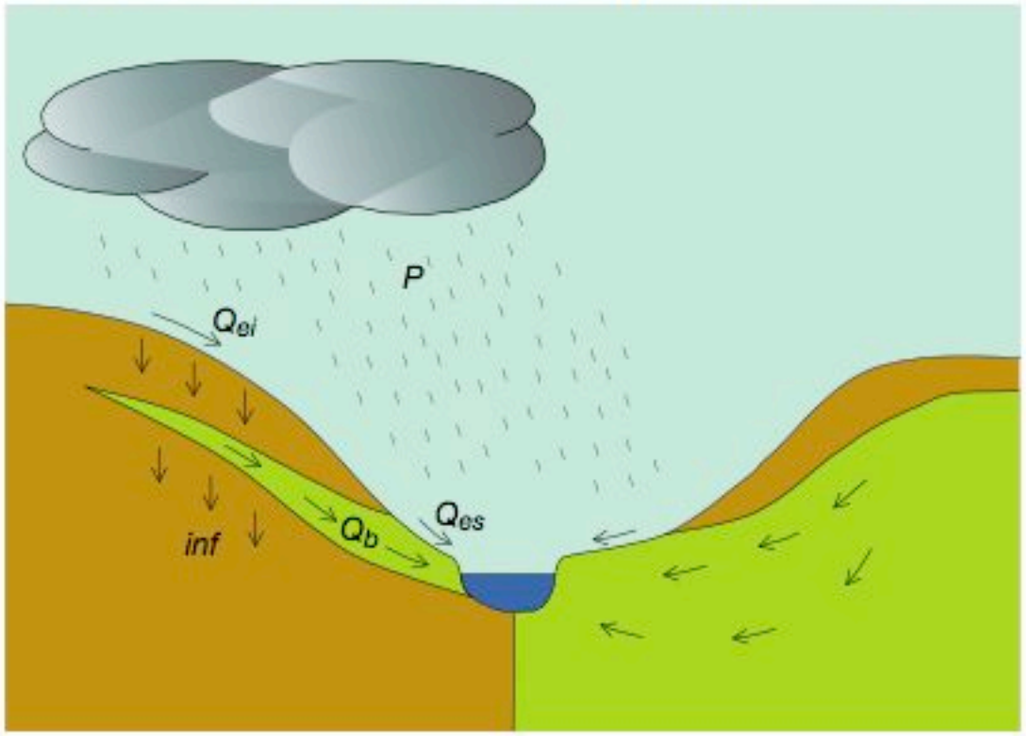
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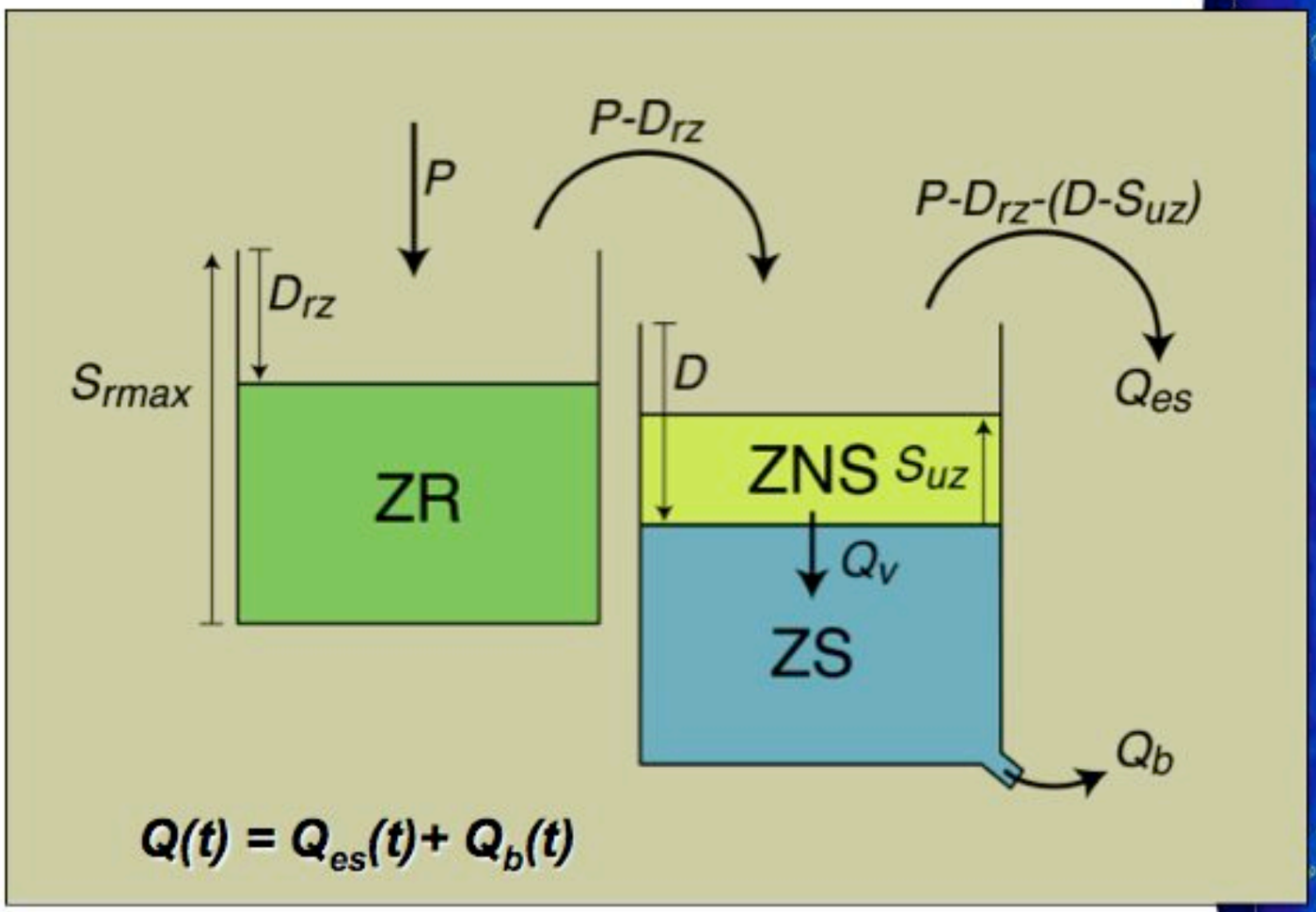
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Flow types:

Overland flow:

Qei: Infiltration excess (Horton mechanism).

Qes: Saturation excess (Dunne mechanism).

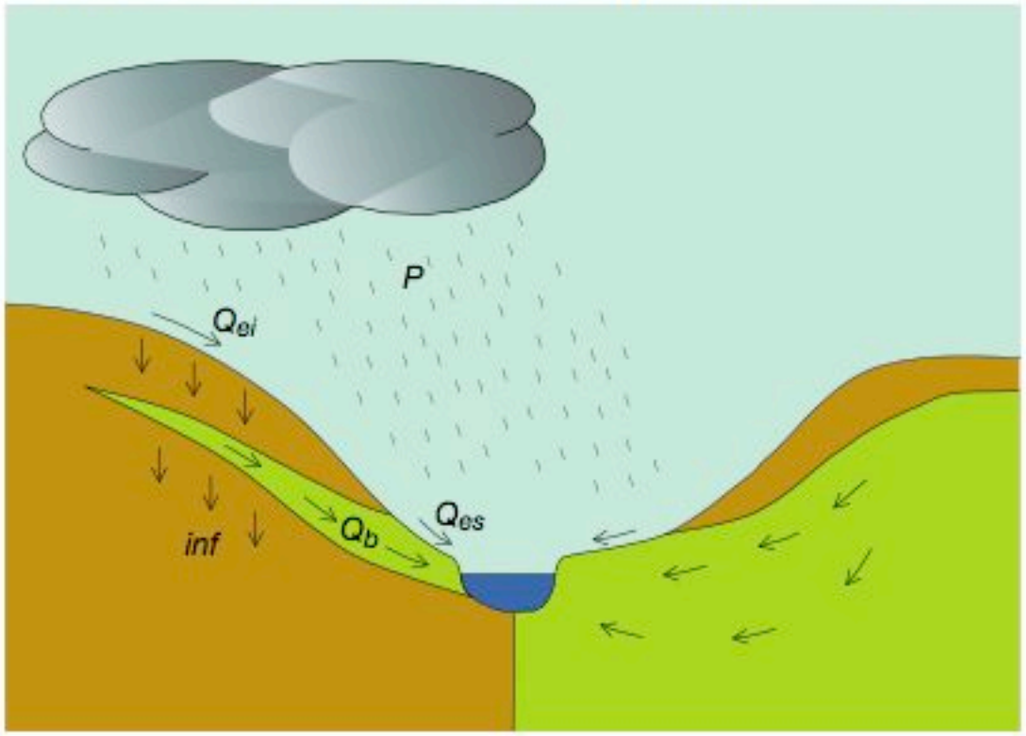
$$q_v(\lambda_i) = \frac{T_0}{m} exp\left(-\frac{D(\lambda_i)}{m}\right)$$

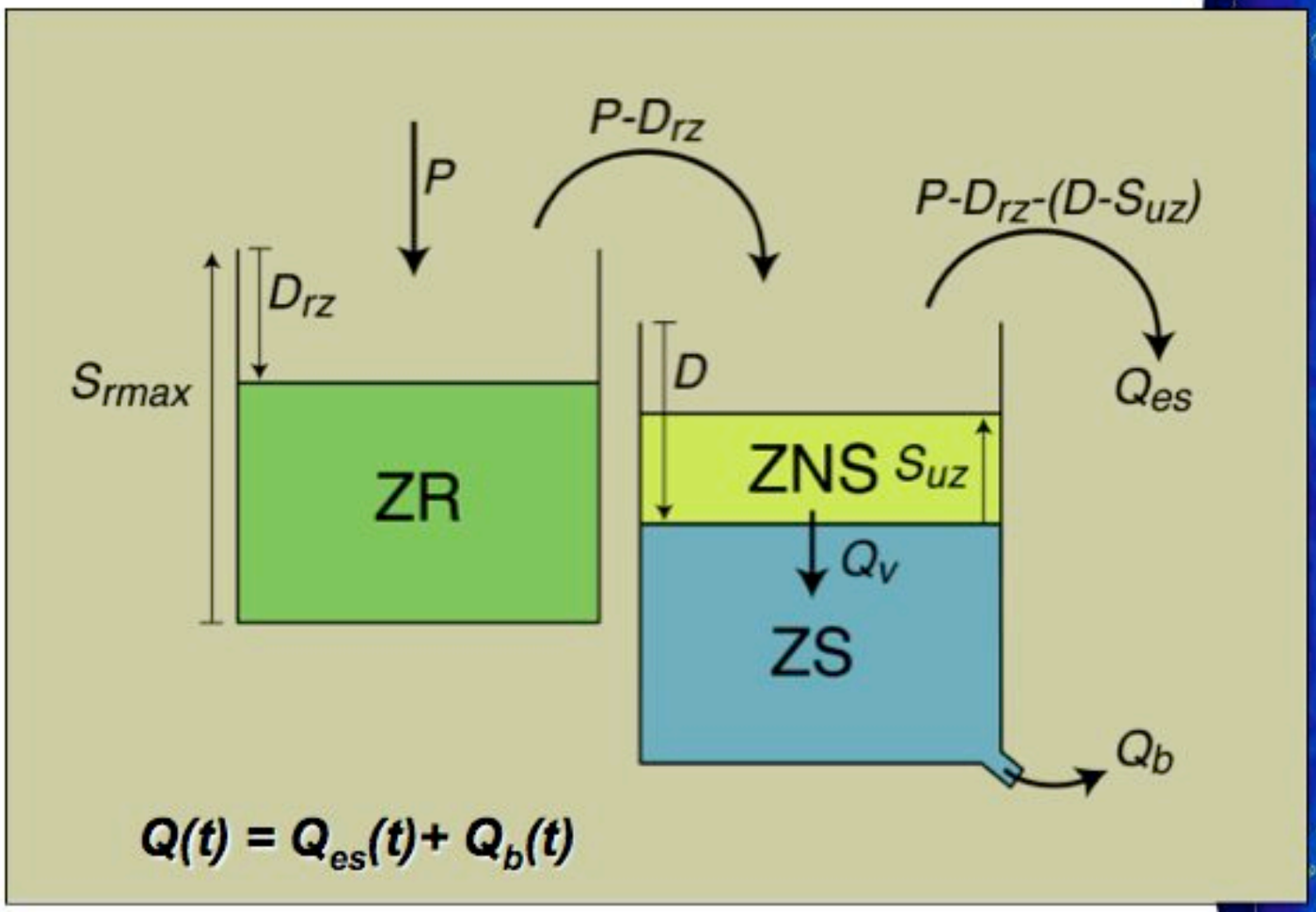
$$Q_b = A\ T_0\ exp\left(-\bar{\lambda}\right)\ exp\left(-\frac{\overline{D}}{m}\right)$$

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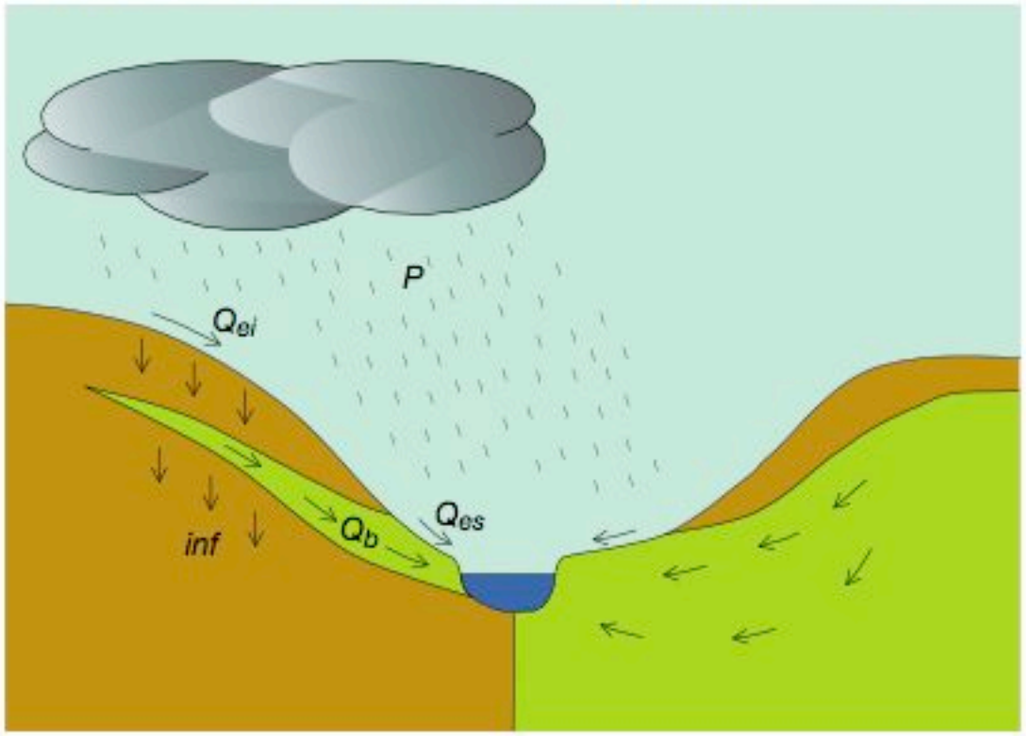
Base flow:

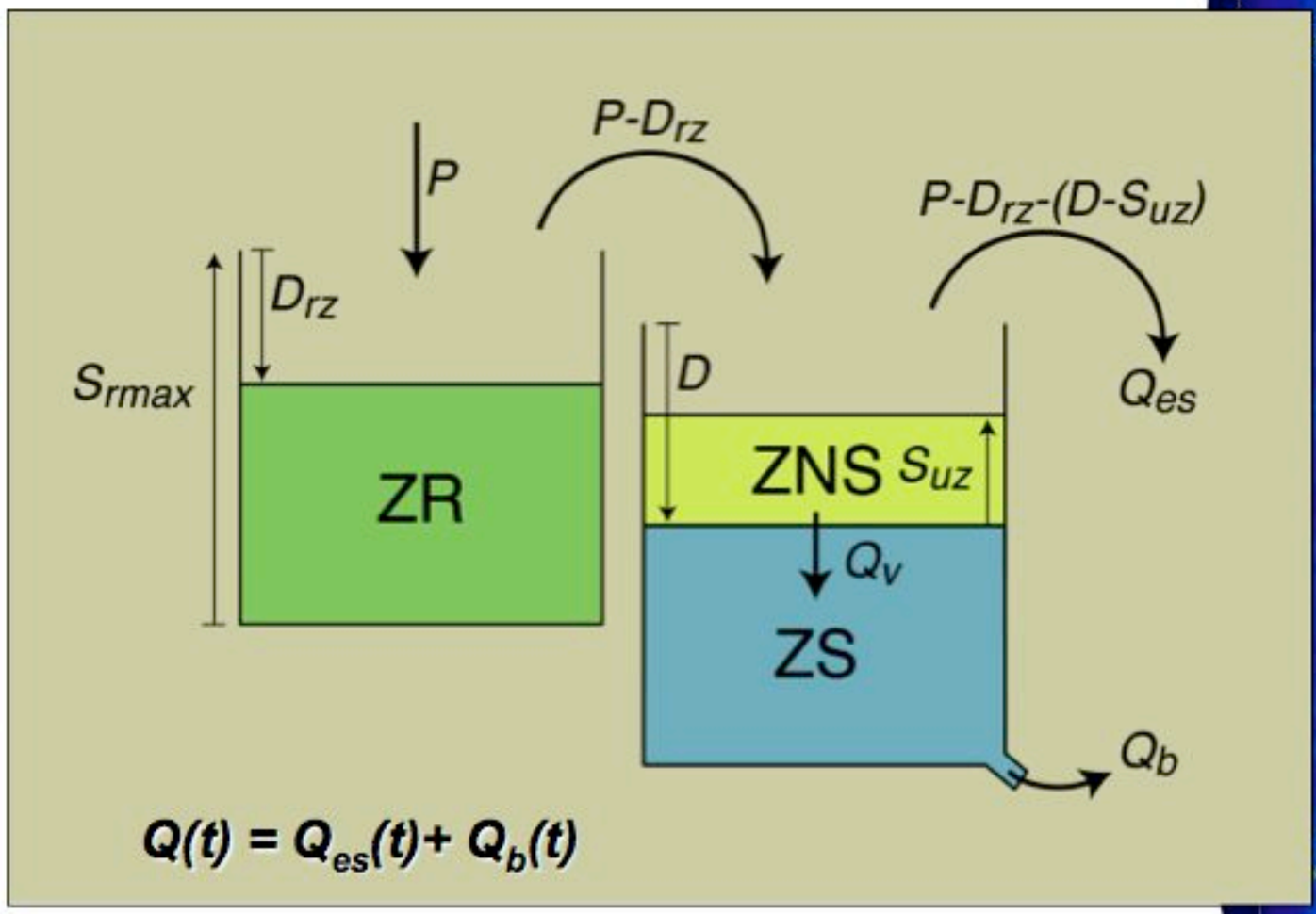
Percolation: $q_v(\lambda_i) = \frac{T_0}{m} exp\left(-\frac{D(\lambda_i)}{m}\right)$ **Base flow:** $Q_b = A\ T_0\ exp\left(-\bar{\lambda}\right)\ exp\left(-\frac{\overline{D}}{m}\right)$

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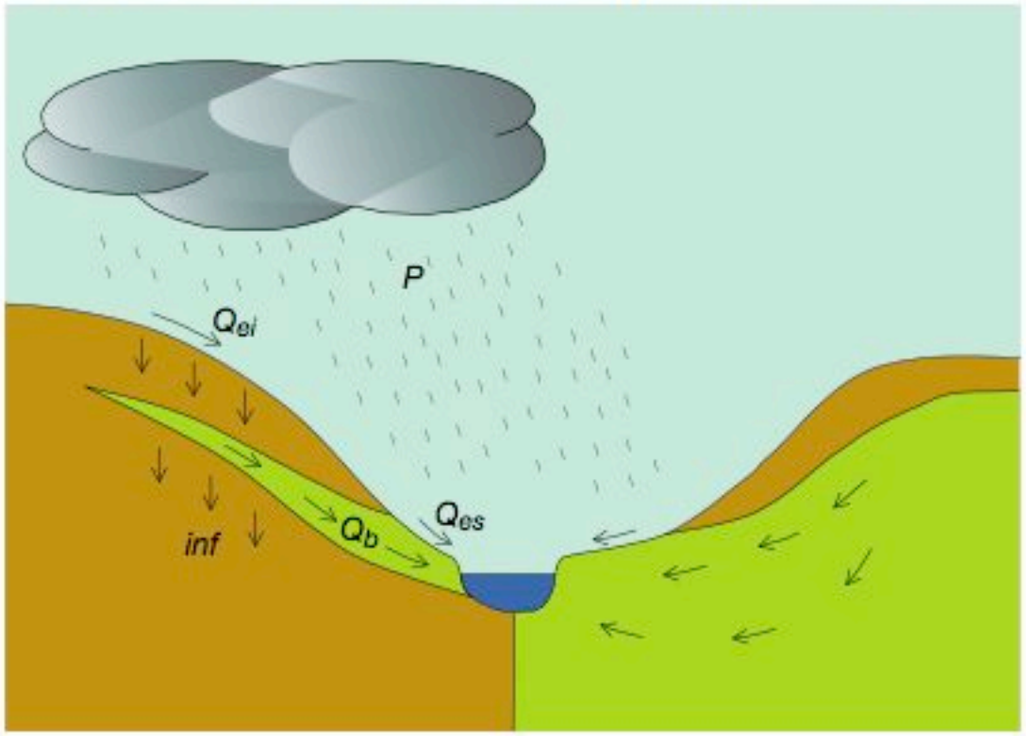
$$D_i = D + m \cdot (\lambda - \lambda_i)$$

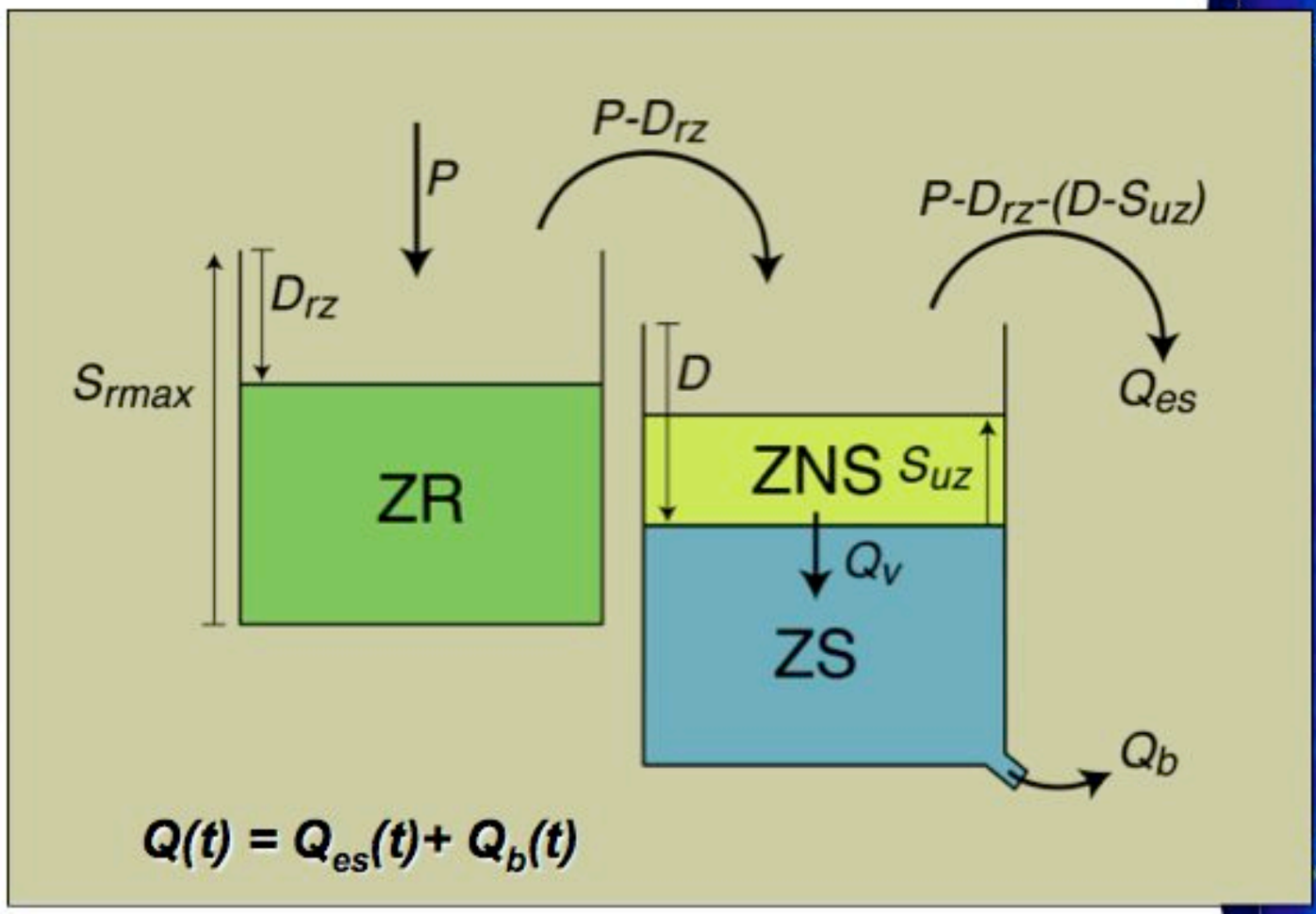
$$D(t+1) = D(t) + \Delta D \qquad \Delta D = P(t+1) - D_{rz}(t+1) - \overline{Q_v}(t+1)$$

Hydrometeorological processes and its interaction with the terrain

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Spatial variability of Di

$$D_i = D + m \cdot (\lambda - \lambda_i)$$

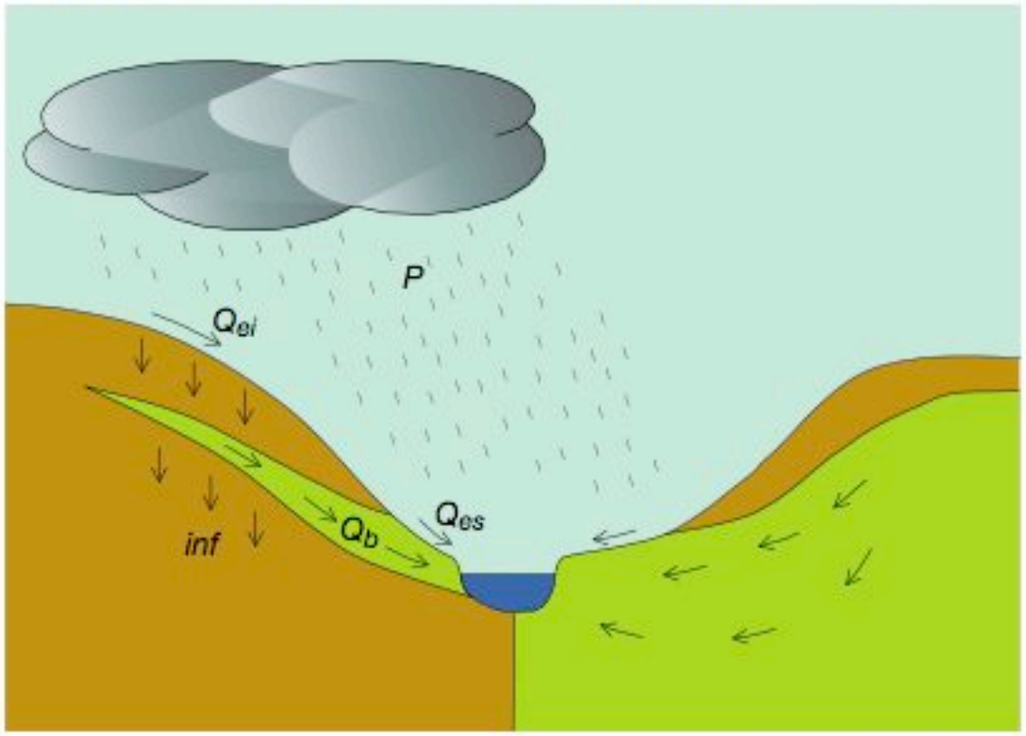
$$D(t+1) = D(t) + \Delta D$$

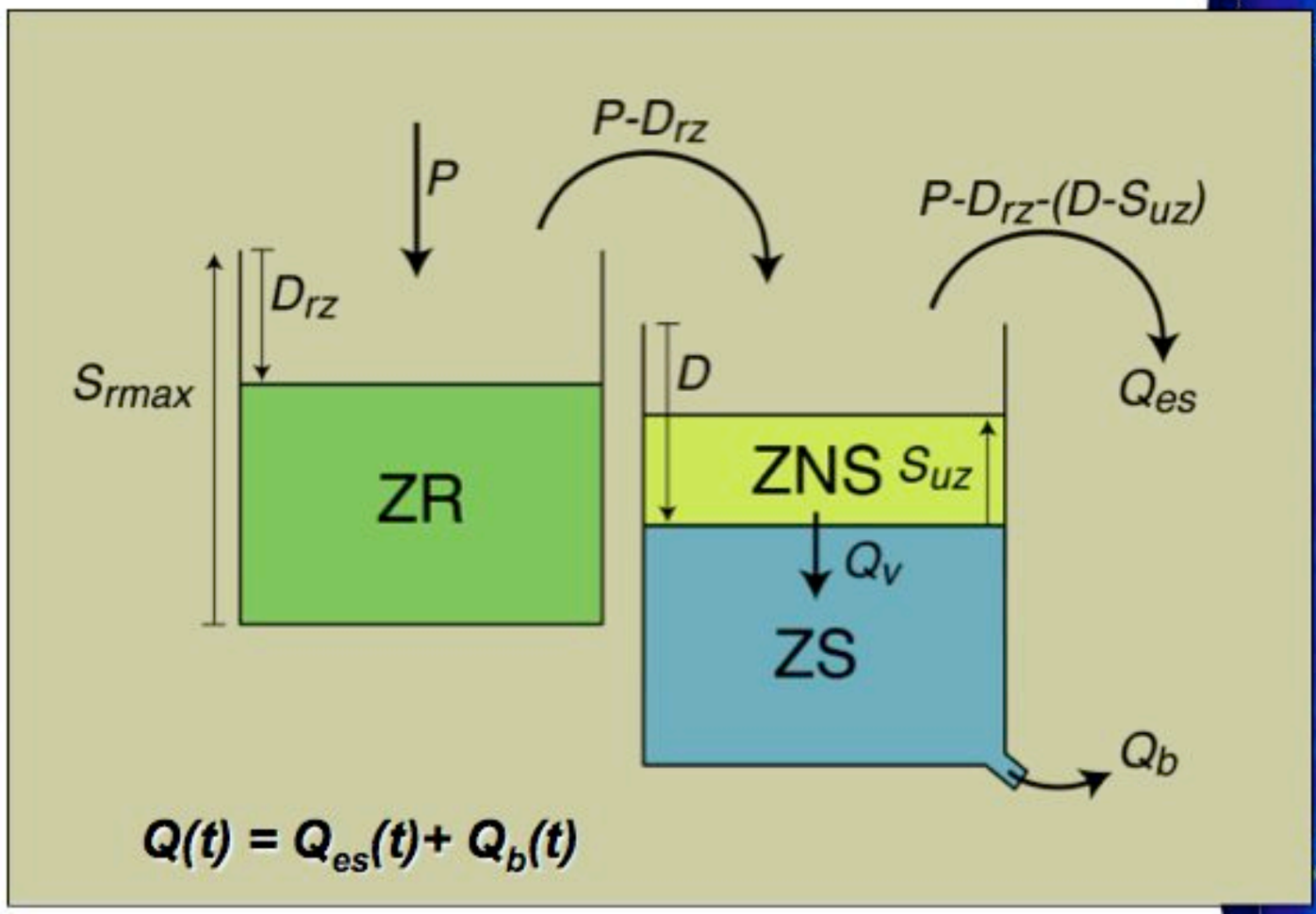
$$\Delta D = P(t+1) - D_{rz}(t+1) - \overline{Q_v}(t+1)$$

Hydrometeorological processes and its interaction with the terrain

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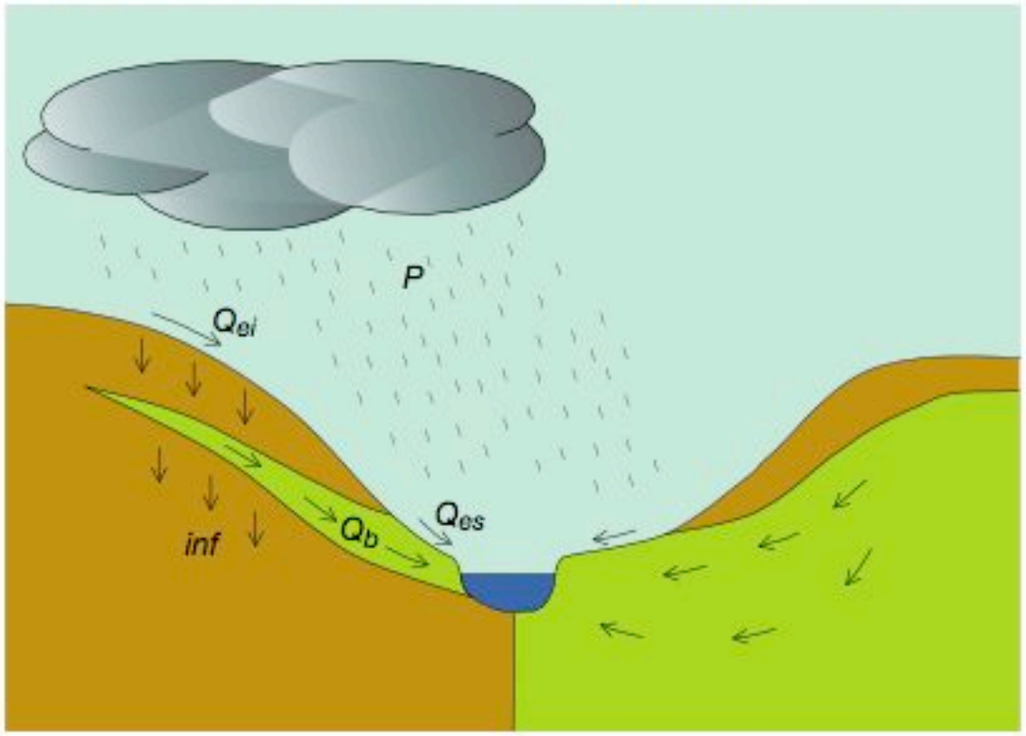
Time update

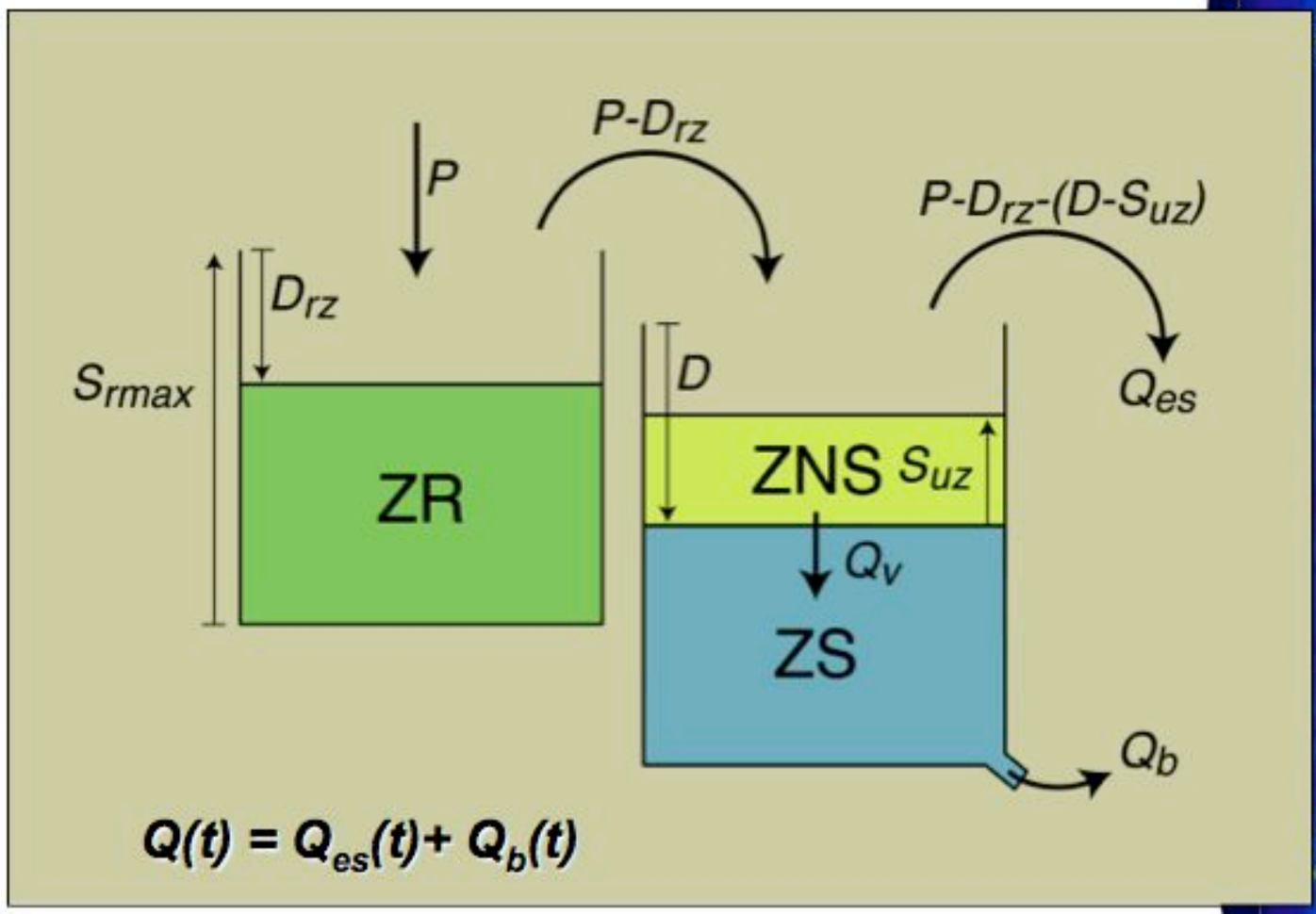
$$D(t+1) = D(t) + \Delta D \qquad \Delta D = P(t+1) - D_{rz}(t+1) - \overline{Q_v}(t+1)$$

Hydrometeorological processes and its interaction with the terrain

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Spatial variability of Di

$$D_i = D + m \cdot (\lambda - \lambda_i)$$

Time update

$$D(t+1) = D(t) + \Delta D \qquad \text{where} \quad \Delta D = P(t+1) - D_{rz}(t+1) - \overline{Q_v}(t+1)$$

Hydrometeorological processes and its interaction with the terrain

Topmodel

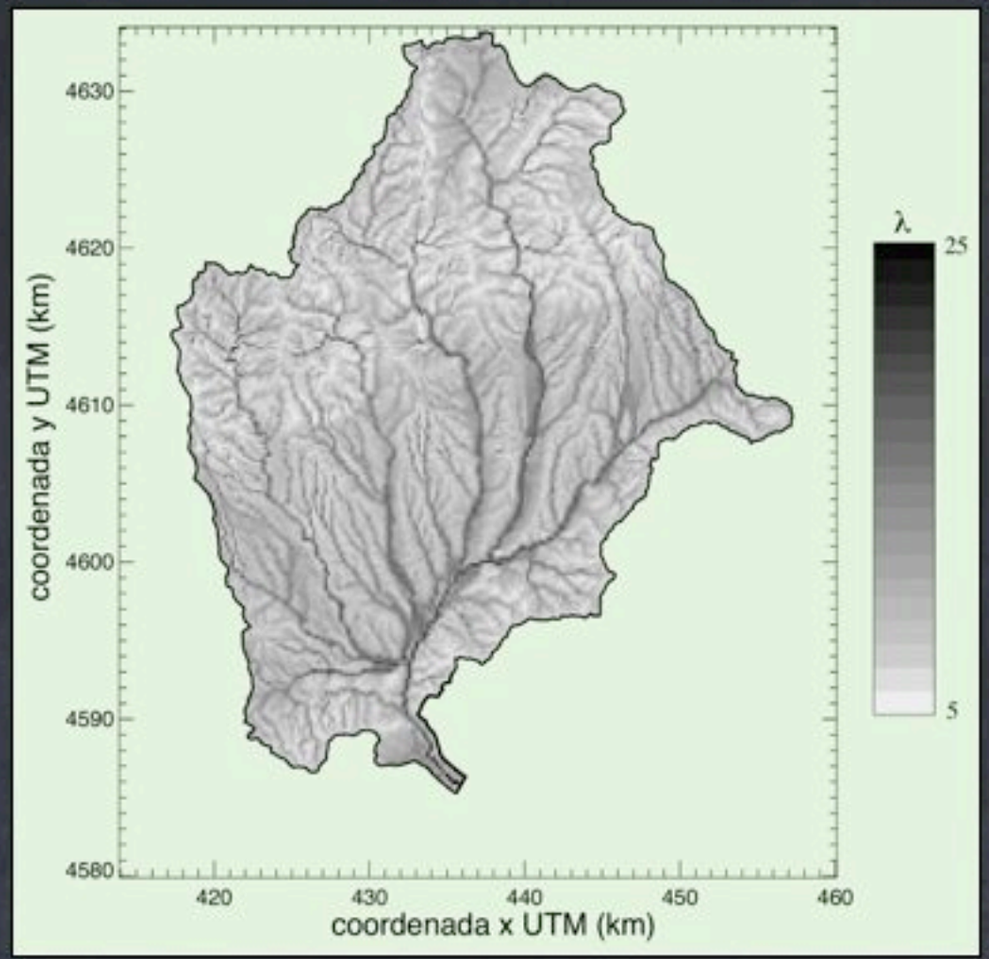
Índice Topográfico

$$\lambda_i = \ln\left(\frac{a_i}{tg\beta_i}\right)$$

Topmodel

Índice Topográfico

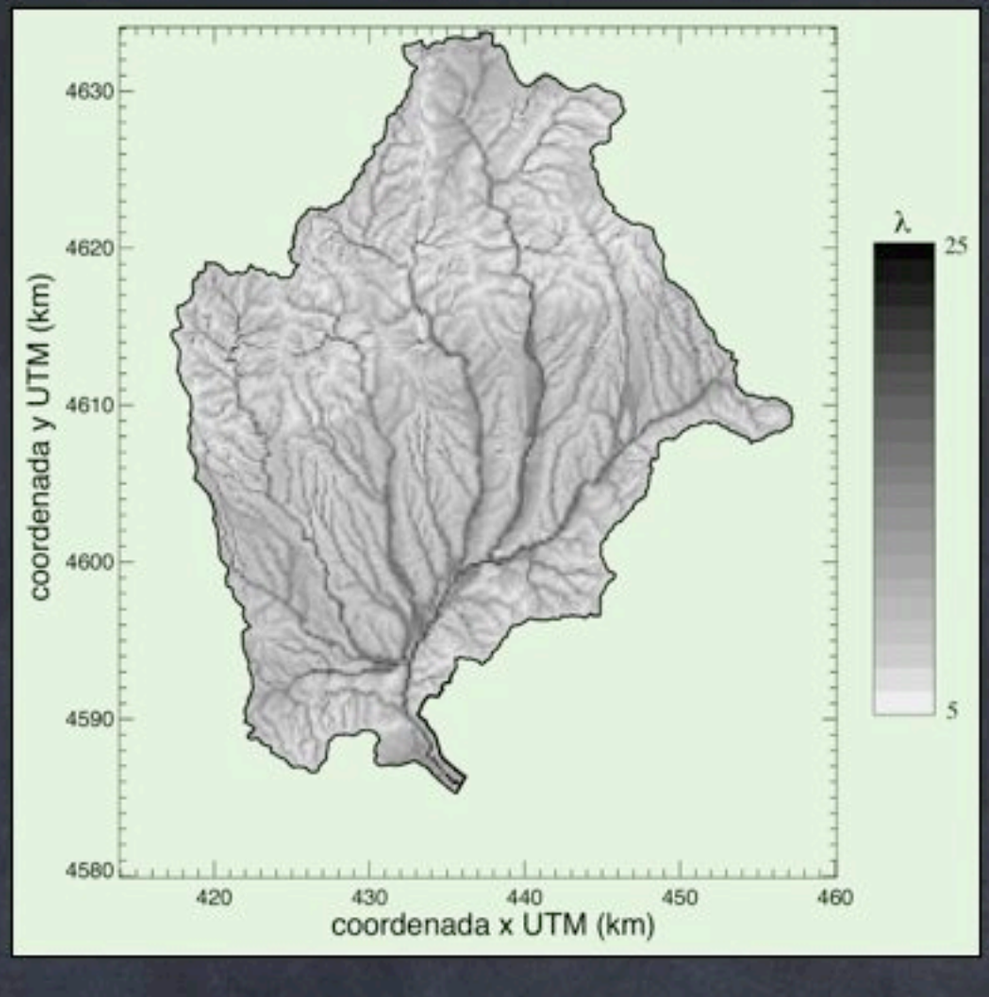
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Topmodel

Índice Topográfico

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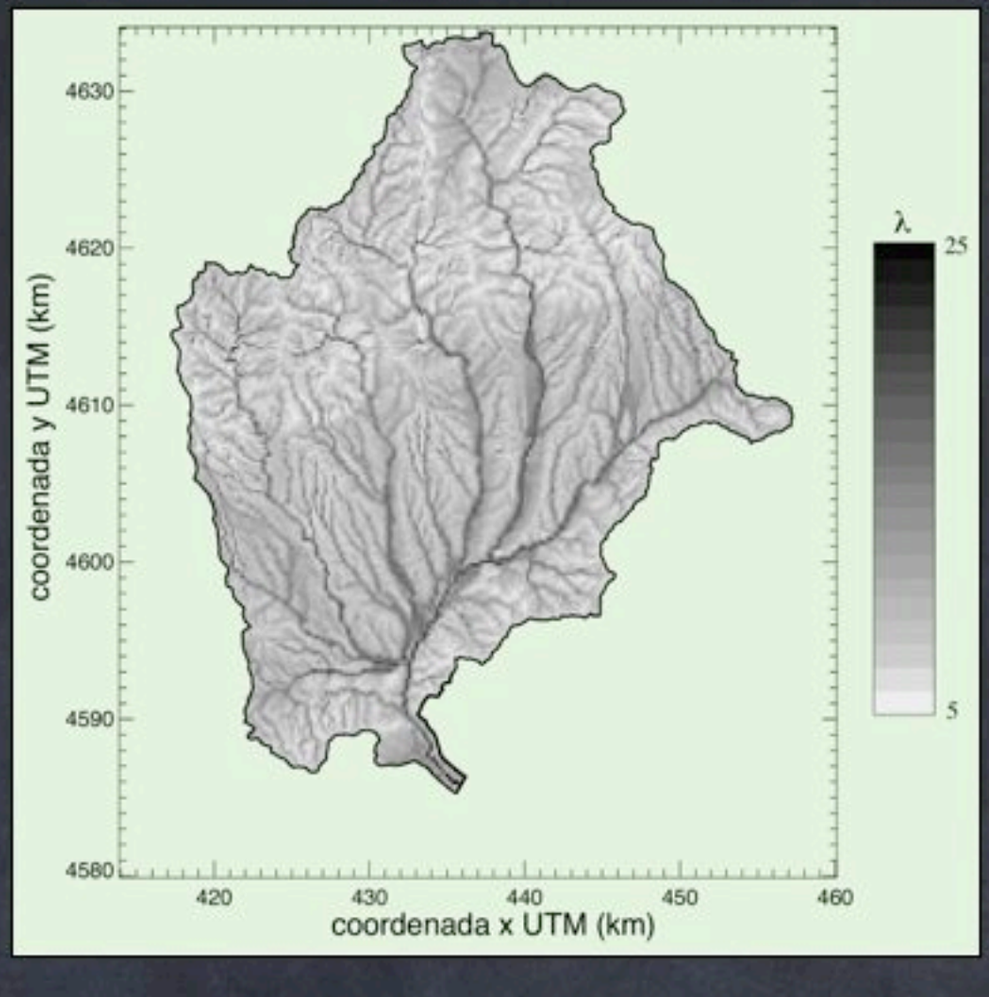


Índice de similaridad hidrológica

Topmodel

Índice Topográfico

$$\lambda_i = \ln\left(\frac{a_i}{tg\beta_i}\right)$$



Índice de similaridad hidrológica

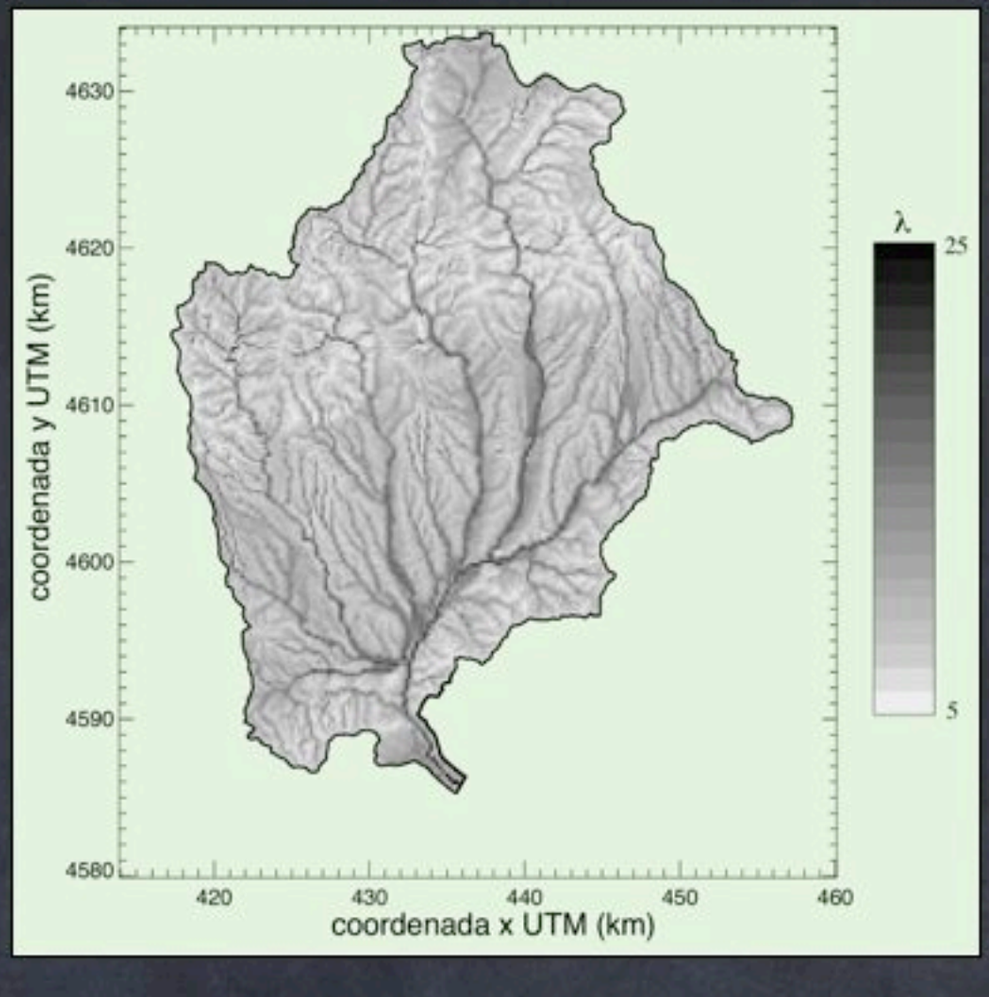
ecuación fundamental de topmodel

$$D_i = D + m \cdot (\lambda - \lambda_i)$$

Topmodel

Índice Topográfico

$$\lambda_i = \ln\left(\frac{a_i}{tg\beta_i}\right)$$



Índice de similaridad hidrológica

ecuación fundamental de topmodel

$$D_i = D + m \cdot (\lambda - \lambda_i)$$

celdas saturadas

$$D_i \leq 0 \Rightarrow \lambda_i \geq \lambda_s(t) = \lambda + \frac{D(t)}{m}$$

Topmodel

celdas saturadas

$$D_i \leq 0 \Rightarrow \lambda_i \geq \lambda_s(t) = \lambda + \frac{D(t)}{m}$$

Topmodel

celdas saturadas

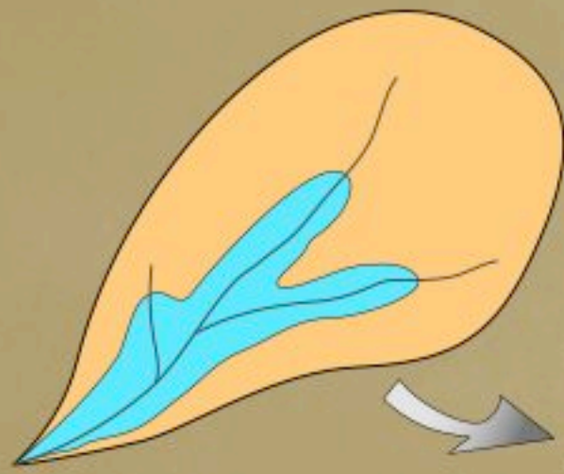
$$D_i \leq 0 \Rightarrow \lambda_i \geq \lambda_s(t) = \lambda + \frac{D(t)}{m}$$

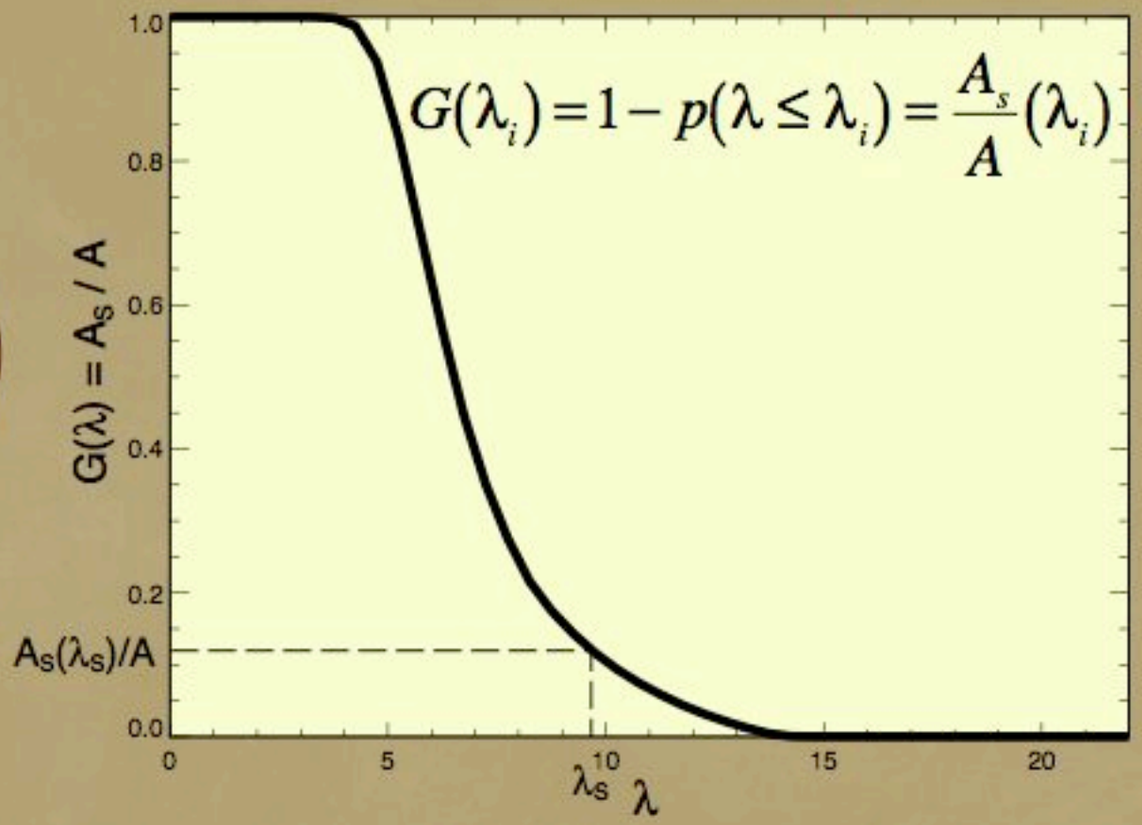
$$G(\lambda_i) = 1 - p(\lambda \leq \lambda_i) = \frac{A_s}{A}(\lambda_i)$$

Topmodel

celdas saturadas

$$D_i \leq 0 \Rightarrow \lambda_i \geq \lambda_s(t) = \lambda + \frac{D(t)}{m}$$

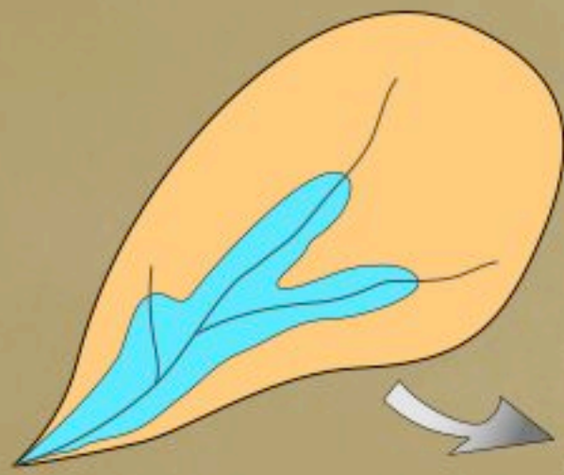


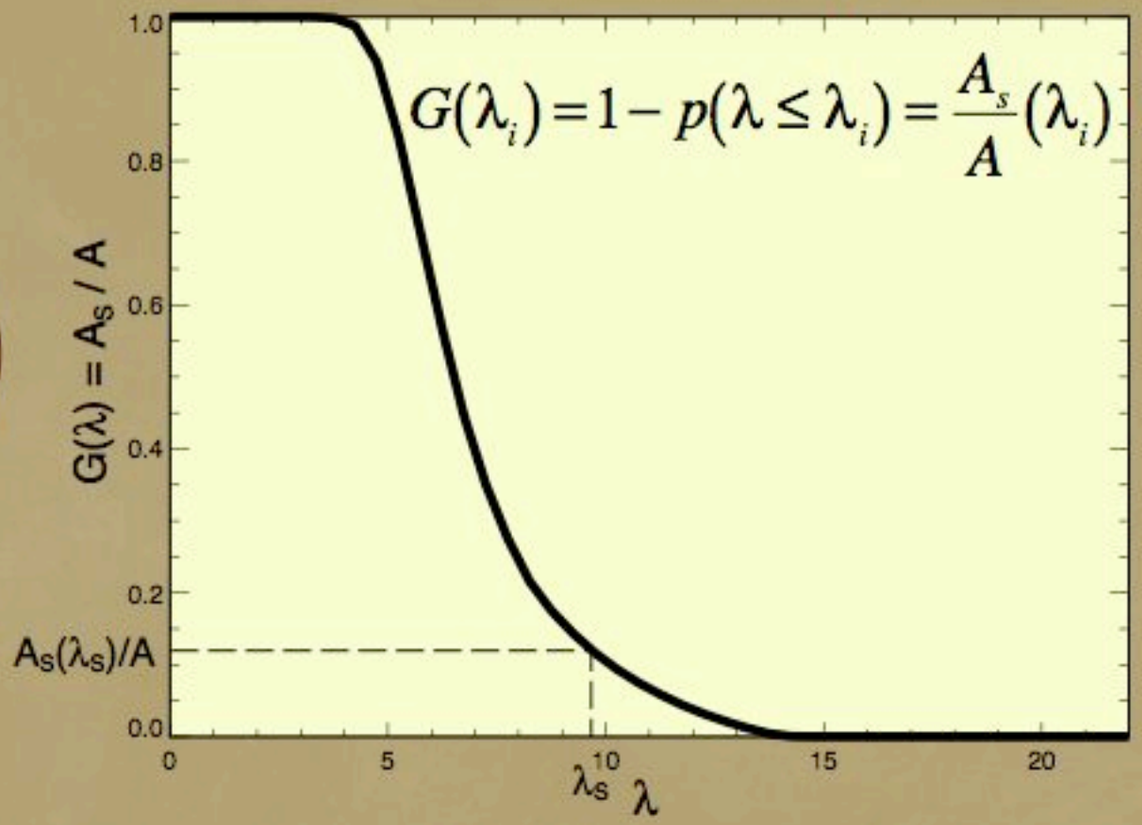


Topmodel

celdas saturadas

$$D_i \le 0 \Rightarrow \lambda_i \ge \lambda_s(t) = \lambda + \frac{D(t)}{m}$$

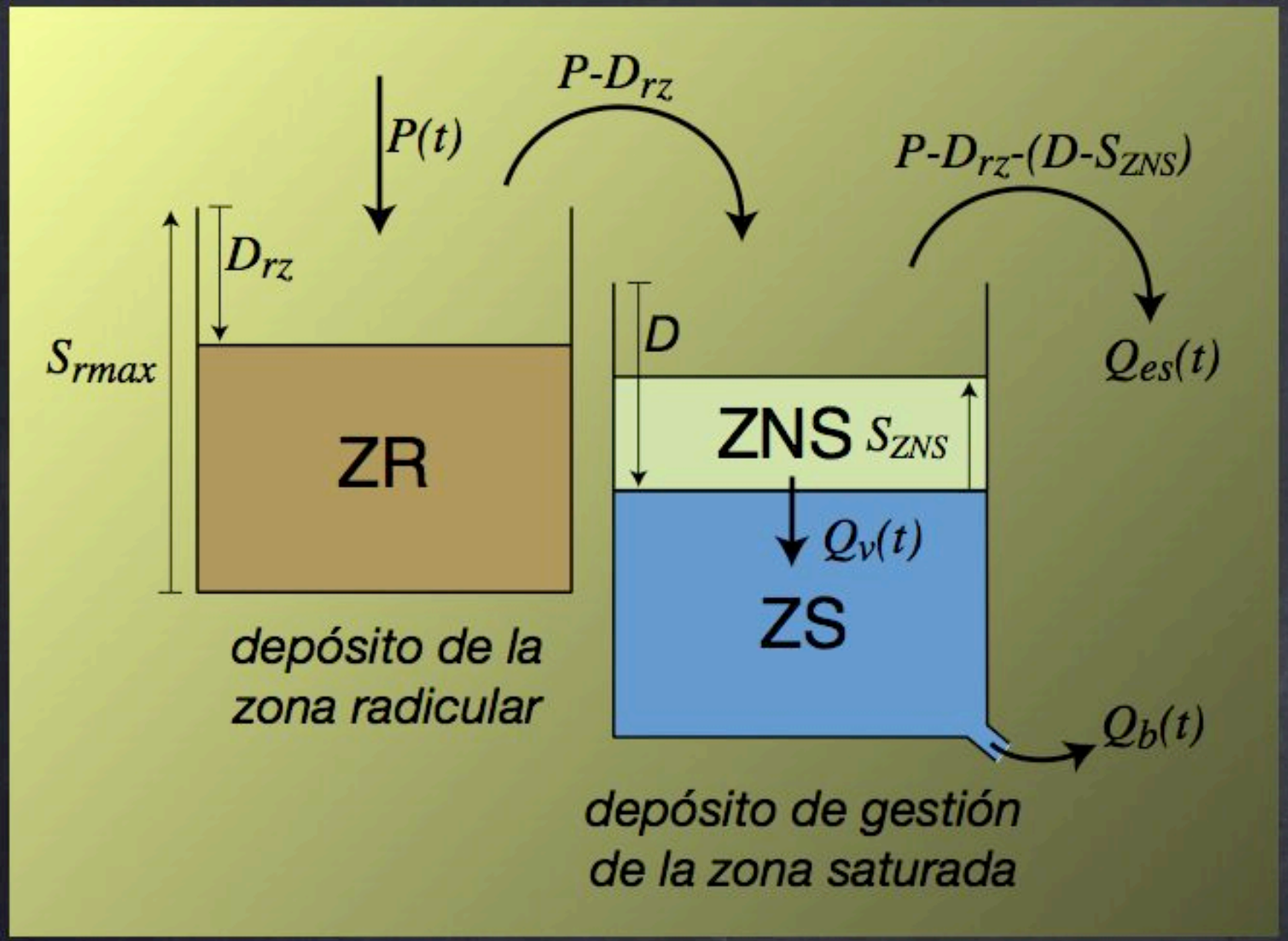




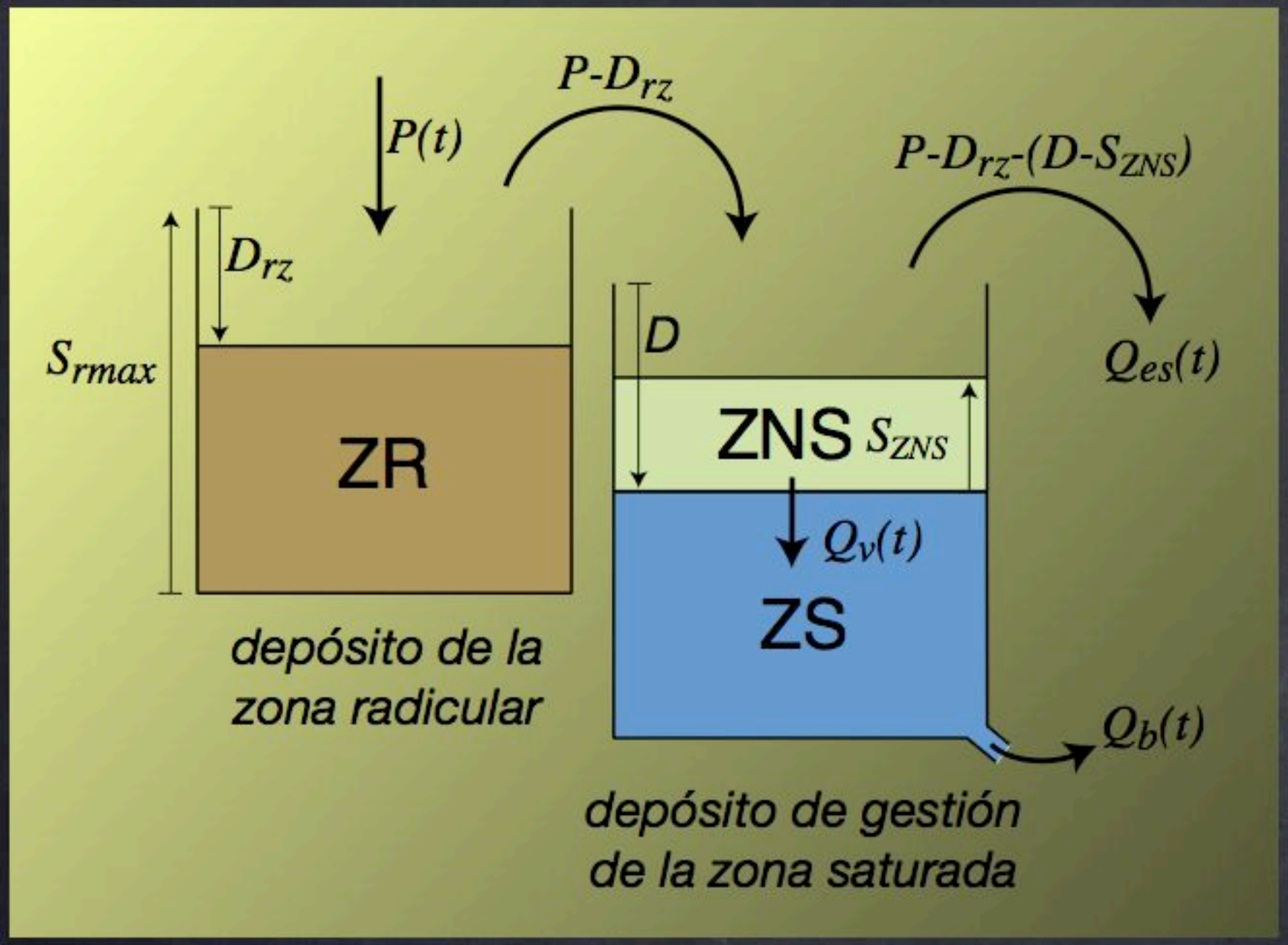
caudal por exceso de saturación

$$Q_{es}(t) = P(t) \cdot A_s(t) = P(t) \cdot A \cdot G(\lambda_s(t))$$

Topmodel


P(t)
P-Drz
P-Drz-(D-SZNS)
Drz
Srmax
ZR
D
ZNS SZNS
Qv(t)
ZS
Qes(t)
Qb(t)
depósito de la
zona radicular
depósito de gestión
de la zona saturada

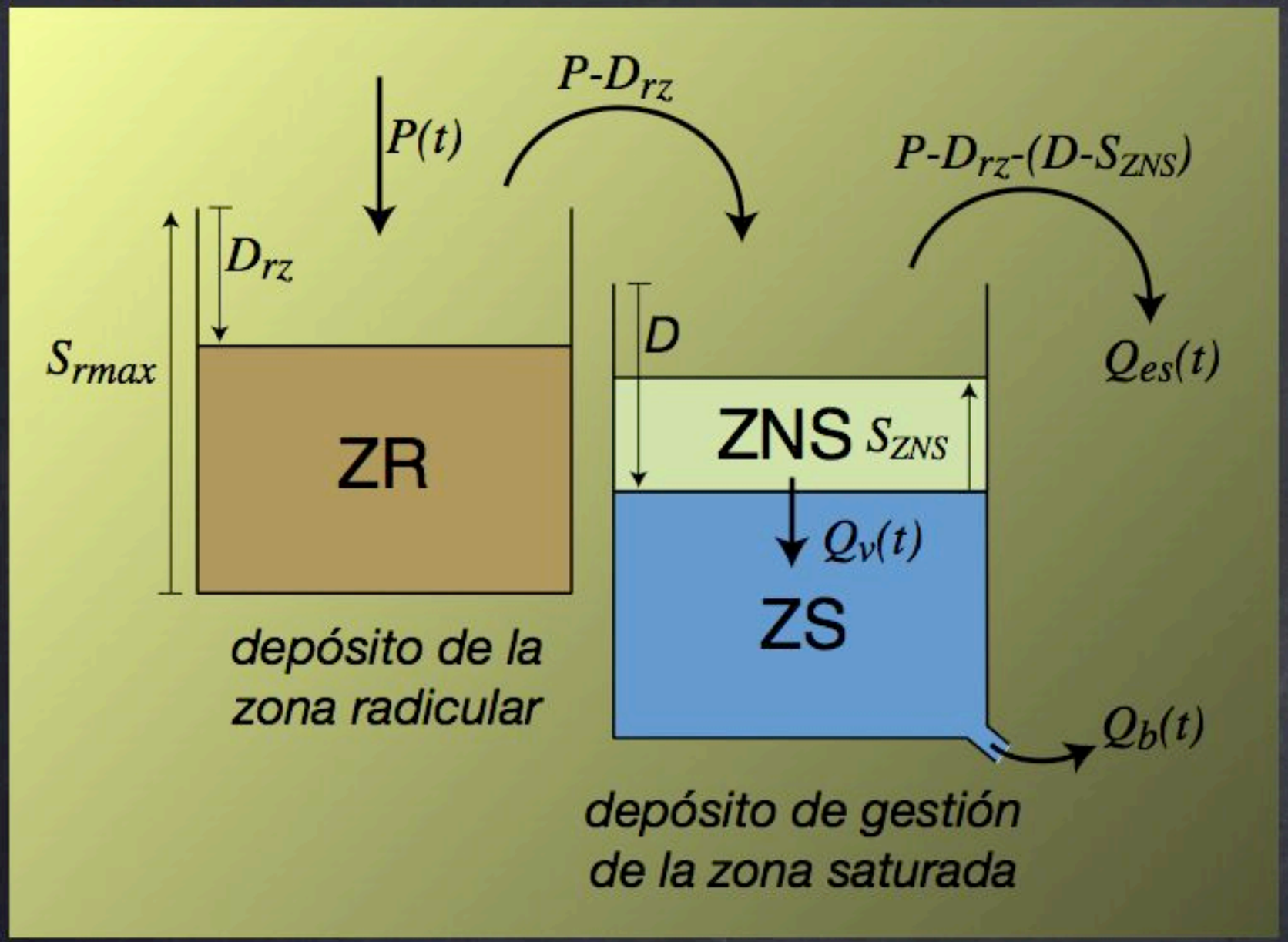
Topmodel



$$Q_{es}(t) = P(t) \cdot A \cdot G\left(\lambda_s(t)\right)$$

$$Q_b(t) = A \cdot T_0 \cdot \exp\underbrace{\left(-\lambda_s(t)\right)}_{\lambda + \frac{D(t)}{m}}$$

Topmodel

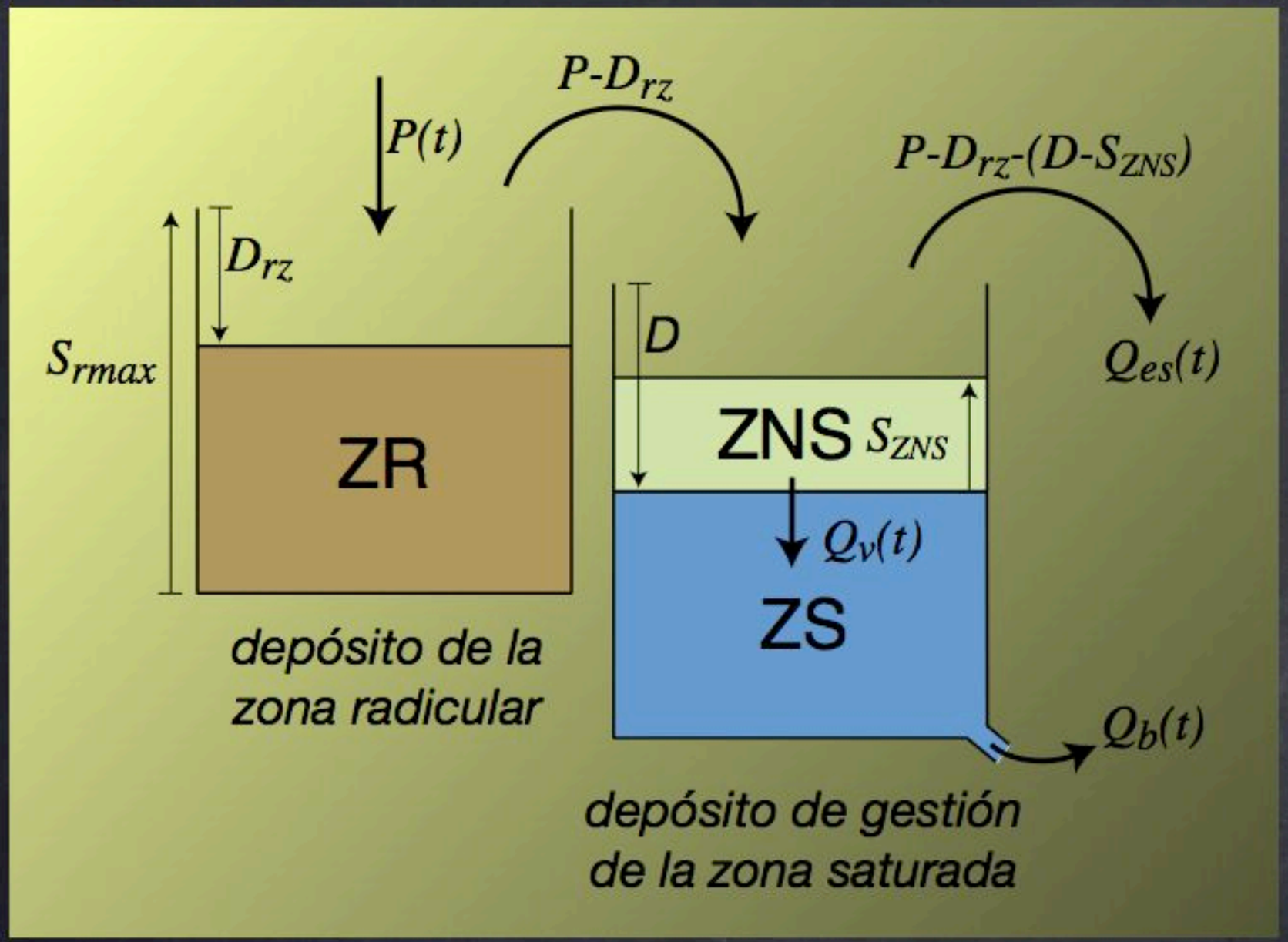


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$$D(t+1) = D(t) + \Delta D \Rightarrow \lambda_s(t+1)$$

Topmodel



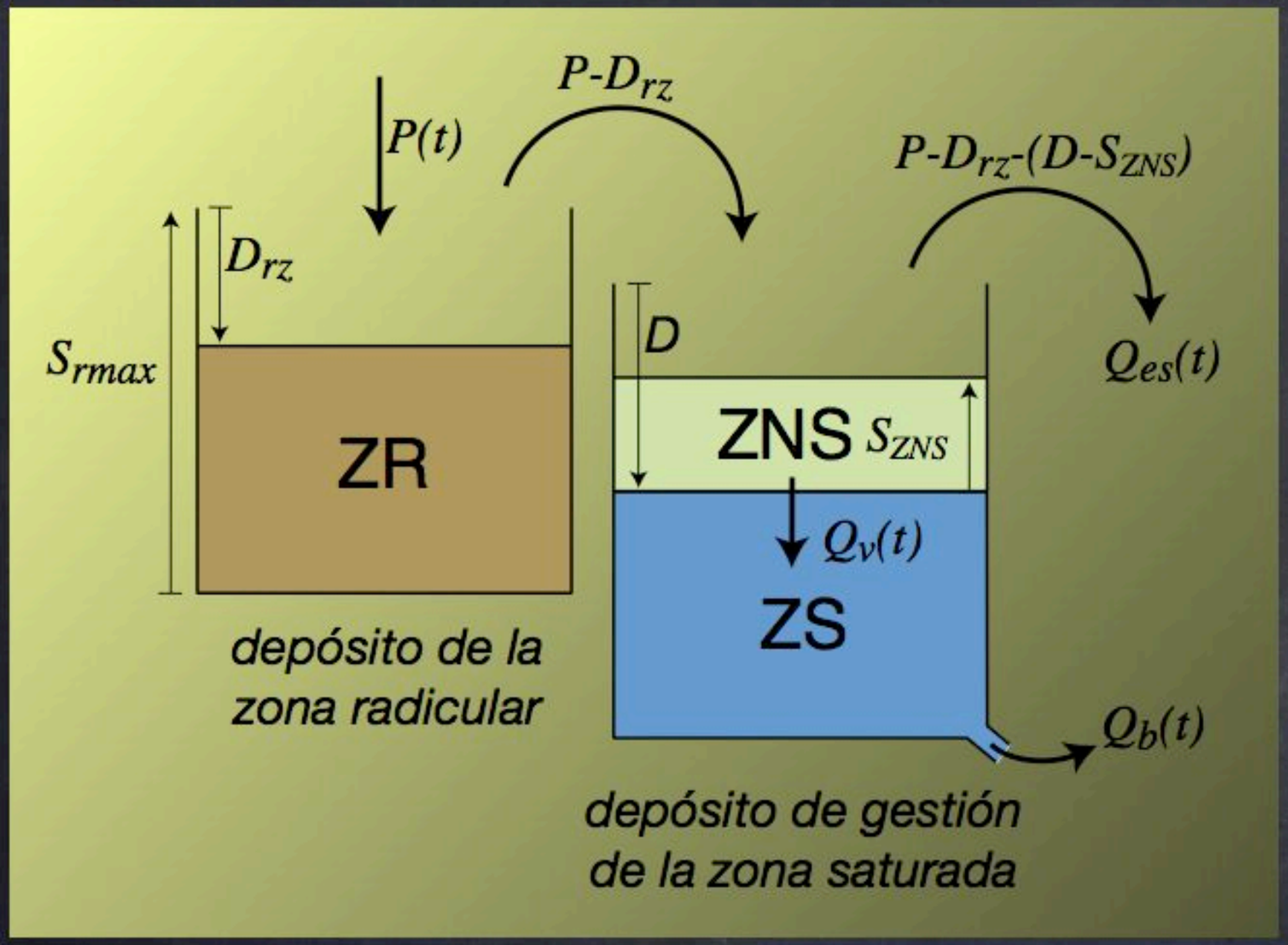
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$$Q_b(t) = A \cdot T_0 \cdot \exp\underbrace{(-\lambda_s(t))}_{\lambda + \frac{D(t)}{m}}$$

$$D(t+1) = D(t) + \Delta D \Rightarrow \lambda_s(t+1)$$

2 propuestas para Qv(t):

Topmodel



$$Q_{es}(t) = P(t) \cdot A \cdot G(\lambda_s(t))$$

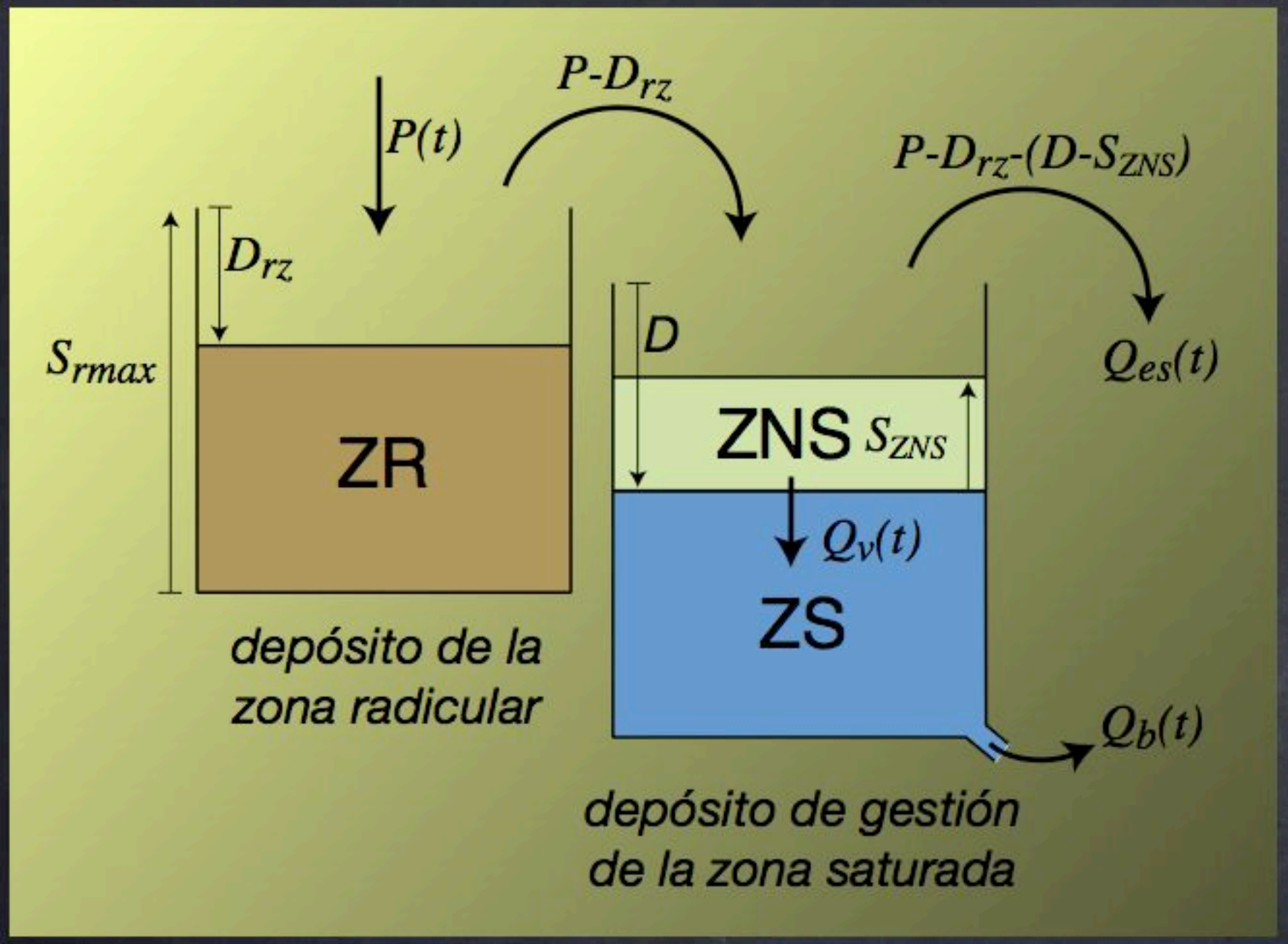
$$Q_b(t) = A \cdot T_0 \cdot \exp\underbrace{(-\lambda_s(t))}_{\lambda + \frac{D(t)}{m}}$$

$$D(t+1) = D(t) + \Delta D \Rightarrow \lambda_s(t+1)$$

2 propuestas para Qv(t):

$$q_v(\lambda_i, t) = \frac{T_0}{m} \cdot \exp\left(-\frac{D(\lambda_i, t)}{m}\right) \leq S_{ZNS}(\lambda_i)$$

Topmodel



$$Q_{es}(t) = P(t) \cdot A \cdot G\left(\lambda_s(t)\right)$$

$$Q_b(t) = A \cdot T_0 \cdot \exp\left(-\underbrace{\lambda_s(t)}_{\lambda + \frac{D(t)}{m}}\right)$$

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$$q_v(\lambda_i, t) = S_{ZNS}(\lambda_i) \Big/ \left(D(\lambda_i, t) \cdot t_d\right) \leq S_{ZNS}(\lambda_i)$$

Topmodel

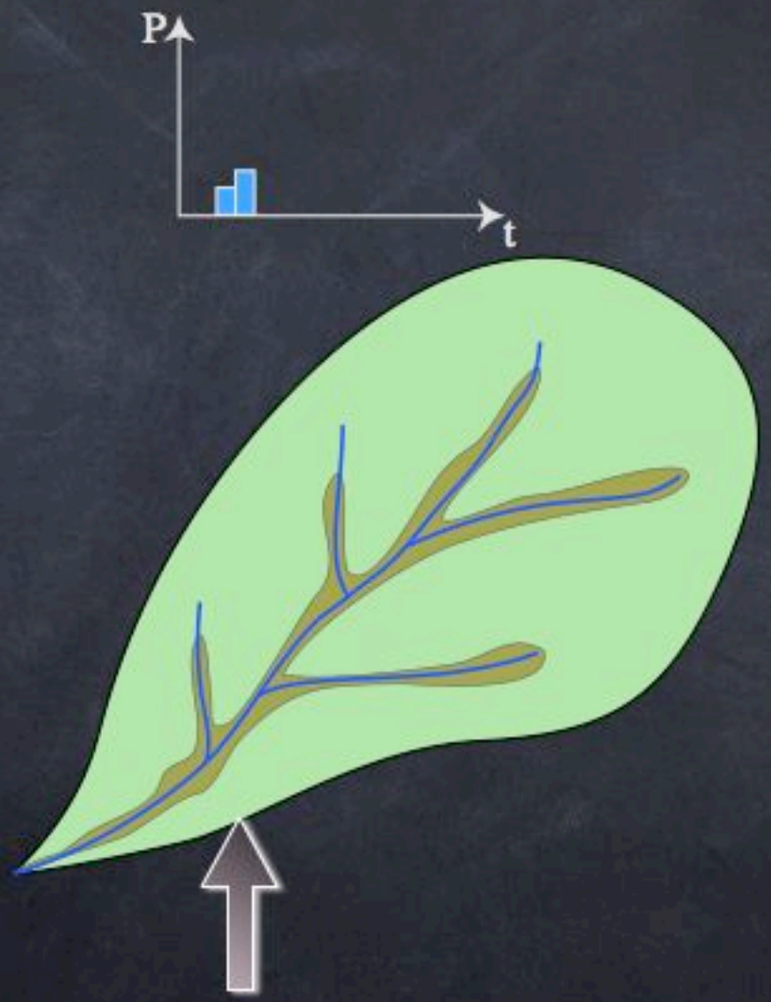
- *concepto de área contributiva variable (Cappus, 1960)*

Topmodel

- *concepto de área contributiva variable (Cappus, 1960)*
- *influencia de la topografía en la dinámica de las áreas saturadas*

Topmodel

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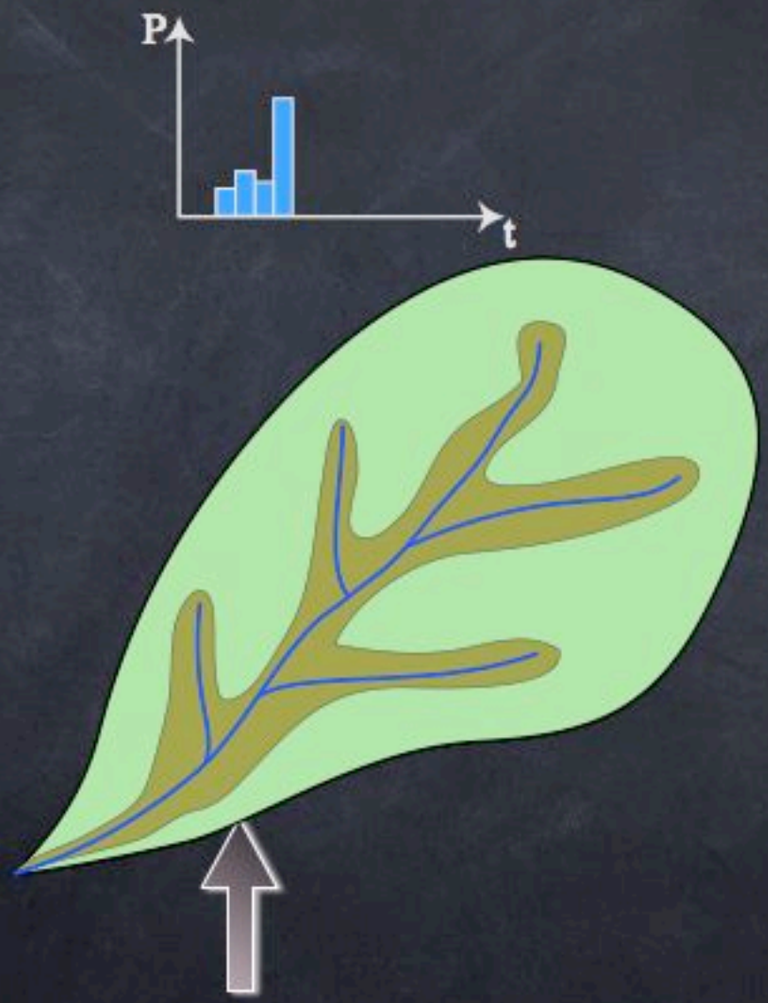


$$Qes(t) = P(t) \cdot As(t)$$

área saturada (As)

Topmodel

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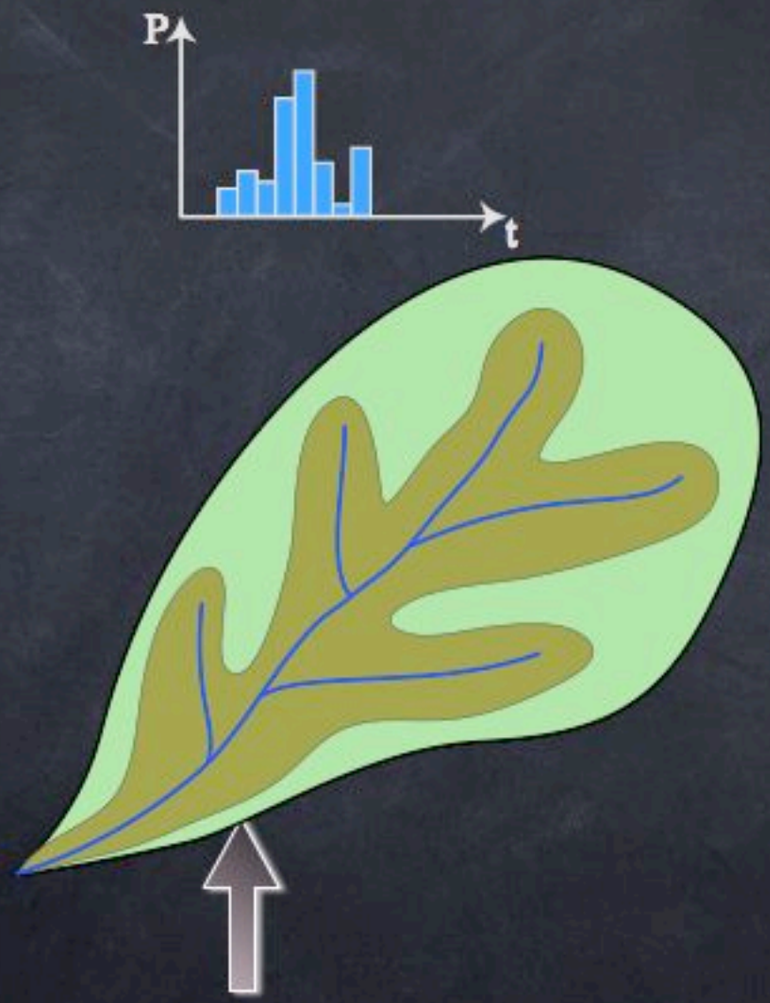


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Topmodel

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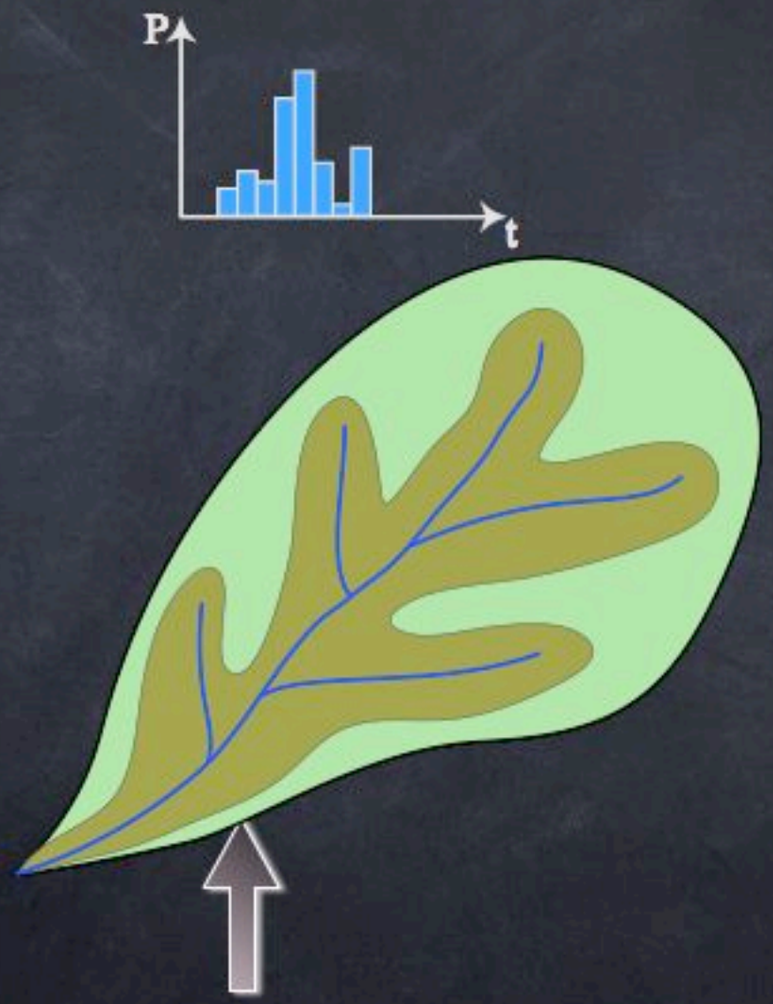
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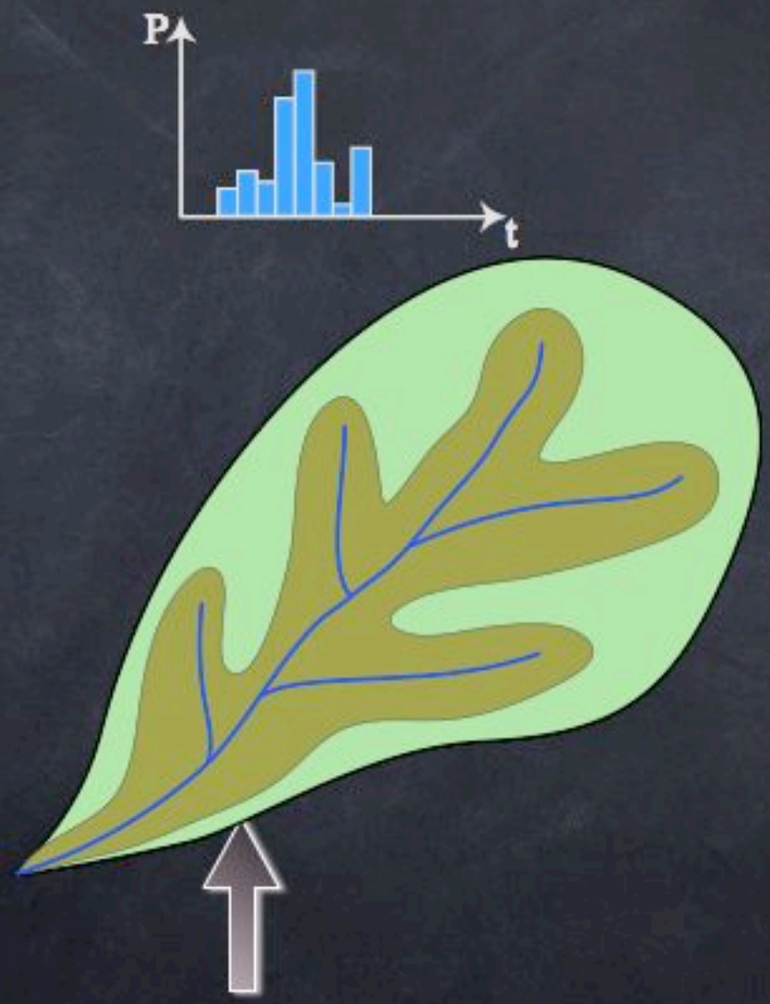


Concepto de lluvia efectiva

$$Q = PE \cdot A = (c \cdot P) \cdot A$$

Topmodel

- *concepto de área contributiva variable (Cappus, 1960)*
- *influencia de la topografía en la dinámica de las áreas saturadas*



$$Qes\,(t) = P(t) \cdot As(t)$$

área saturada (As)

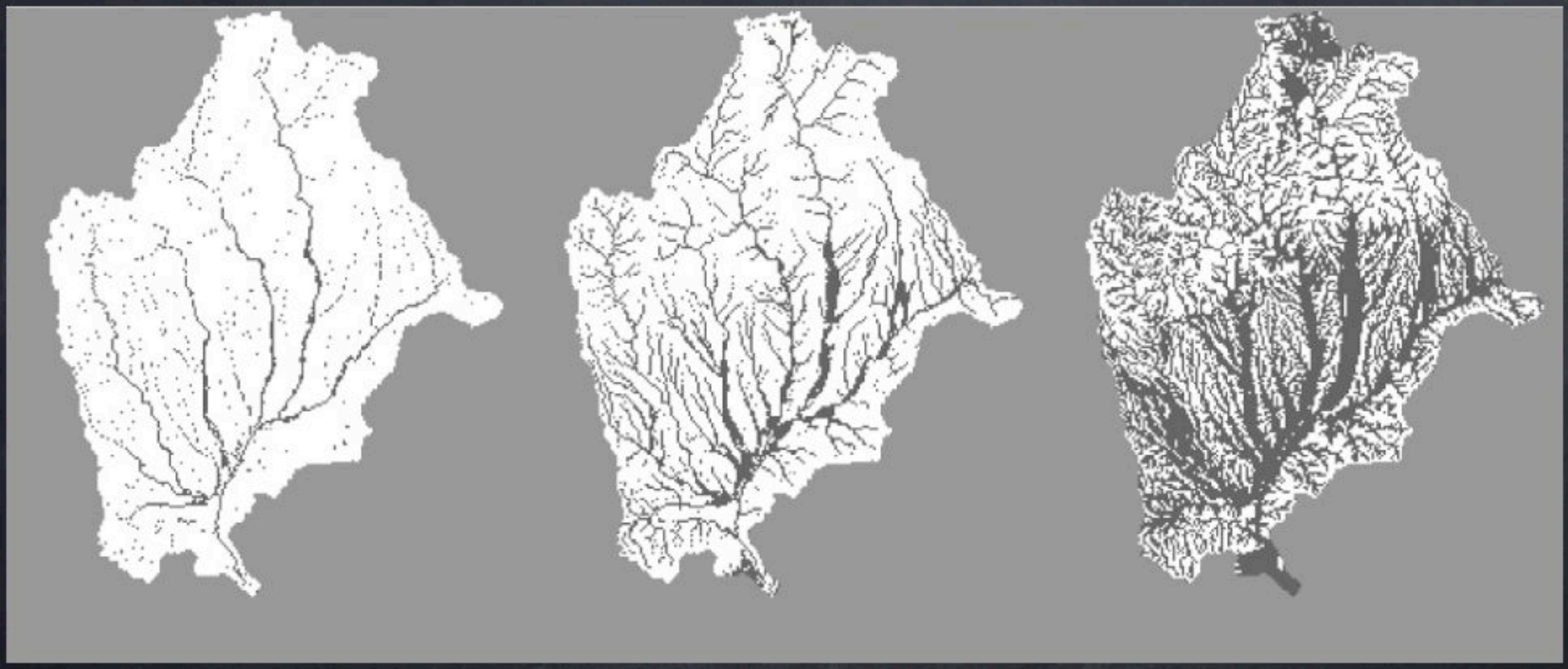
Concepto de lluvia efectiva

$$Q = PE \cdot A = (c \cdot P) \cdot A$$

$$Q = P \cdot A_s = (c \cdot A) \cdot P$$

Concepto de área contributiva variable

Topmodel



Topmodel

Estimación de paràmetros: inicialización Drz, D

Topmodel

Estimación de paràmetros: inicialización Drz, D

Drz(t=0) : a partir de lluvia antecedente, evapotranspiración (difícil)

Topmodel

Estimación de paràmetros: inicialización Drz, D

Drz(t=0) : a partir de lluvia antecedente, evapotranspiración (difícil)

D(t=0) : a partir del caudal observado

Topmodel

Estimación de paràmetros: inicialización Drz, D

Drz(t=0) : a partir de lluvia antecedente, evapotranspiración (difícil)

D(t=0) : a partir del caudal observado

$$Q_b(t) = A \cdot T_0 \cdot \exp\left(-\frac{D(t)}{m}\right) \cdot \exp(-\lambda)$$

Topmodel

Estimación de paràmetros: inicialización Drz, D

Drz(t=0) : a partir de lluvia antecedente, evapotranspiración (difícil)

D(t=0) : a partir del caudal observado

$$Q_b(t) = A \cdot T_0 \cdot \exp\left(-\frac{D(t)}{m}\right) \cdot \exp(-\lambda)$$

$$D(t=0) = m\left(\ln(T_0) - \lambda - \ln\left(\frac{Q_b(0)}{A}\right)\right)$$

Topmodel

Estimación de paràmetros: T_0, m

Topmodel

Estimación de paràmetros: T_0, m

- *Generalmente mediante calibración*
- *Seria deseable mediante otra información*

Topmodel

Estimación de paràmetros: T_0, m

- *Generalmente mediante calibración*
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- *m a partir de análisis de recesiones*

Topmodel

Estimación de paràmetros: T_0, m

Generalmente mediante calibración

Seria deseable mediante otra información

m a partir de análisis de recesiones

$$q(t) = \frac{Q_b(t)}{A} = T_0 \cdot \exp\left(-\frac{D(t)}{m}\right) \cdot \exp(-\lambda)$$

Topmodel

Estimación de paràmetros: T_0, m

Generalmente mediante calibración

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Topmodel

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$$q(t) = q_0 \cdot \left(1 + t\frac{q_0}{m}\right)^{-1}$$

Topmodel

Estimación de paràmetros: T_0, m

Generalmente mediante calibración

Seria deseable mediante otra información

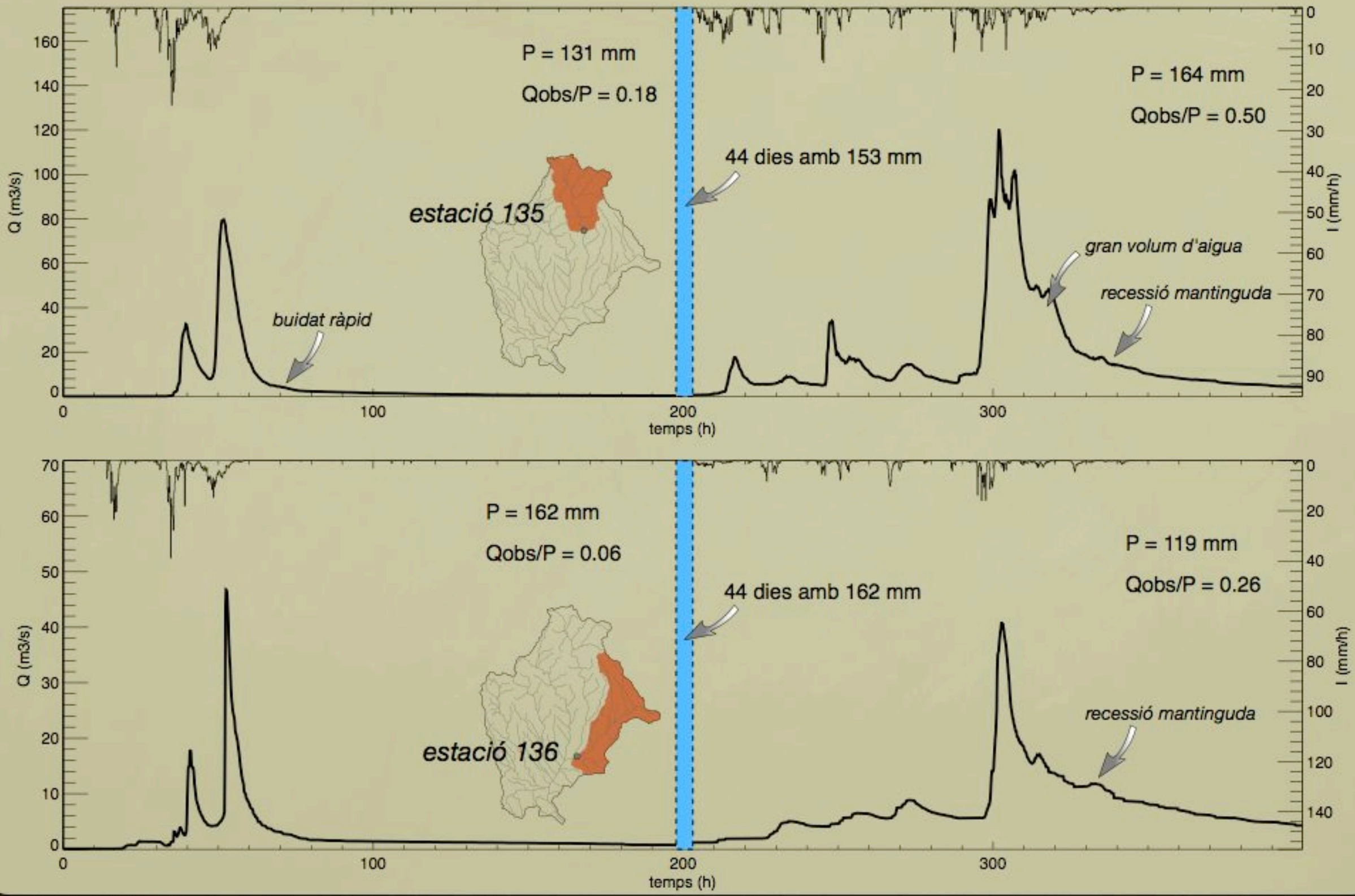
m a partir de análisis de recesiones

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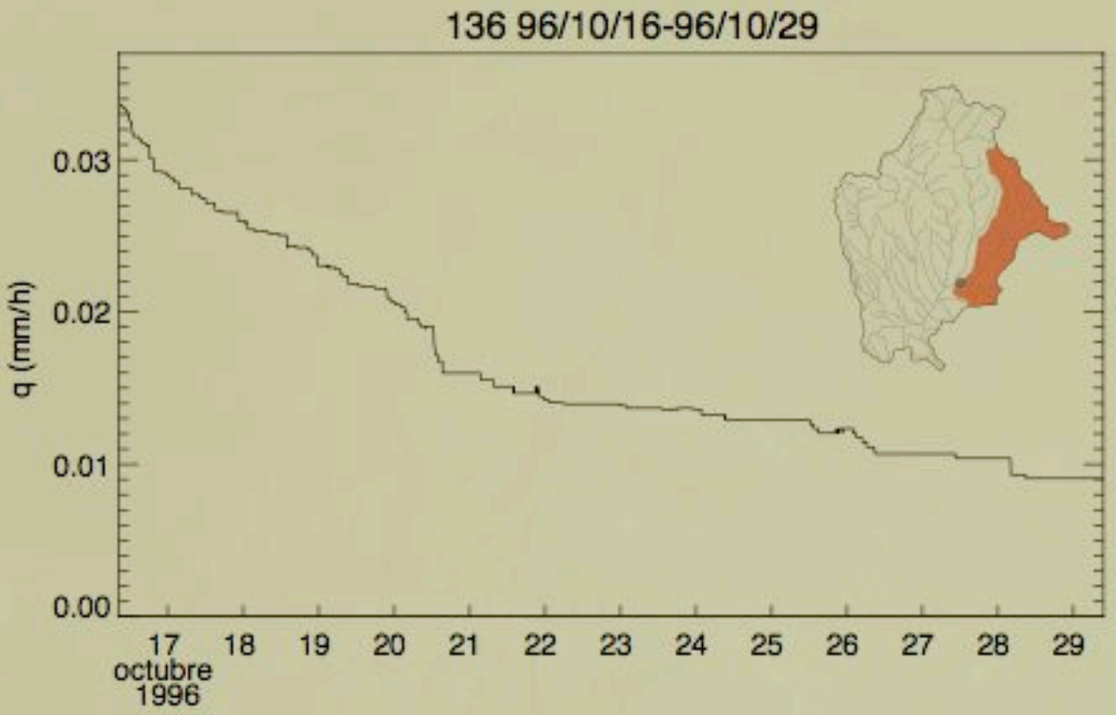
$$\frac{dq(t)}{dt} = \frac{-1}{m} \cdot \underbrace{\frac{dD(t)}{dt}}_{q(t)} \cdot q(t)$$

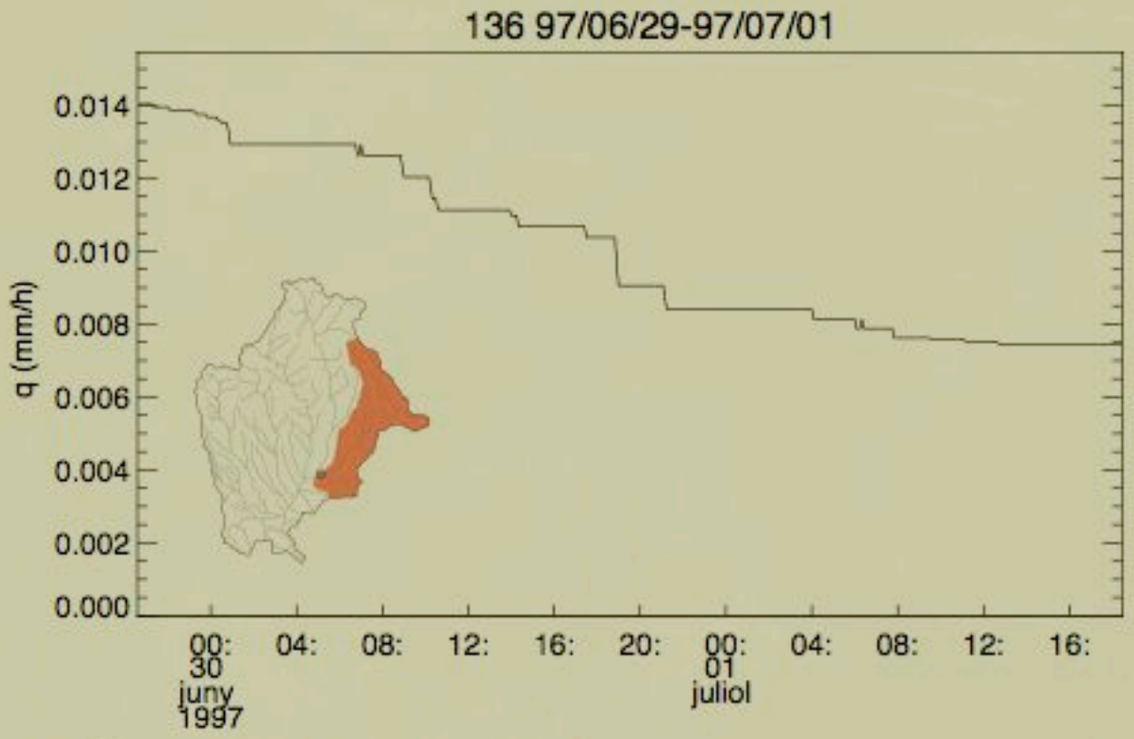
$$q(t) = q_0 \cdot \left(1 + t\frac{q_0}{m}\right)^{-1} \qquad \frac{1}{q(t)} - \frac{1}{q_0} = \frac{t}{m}$$

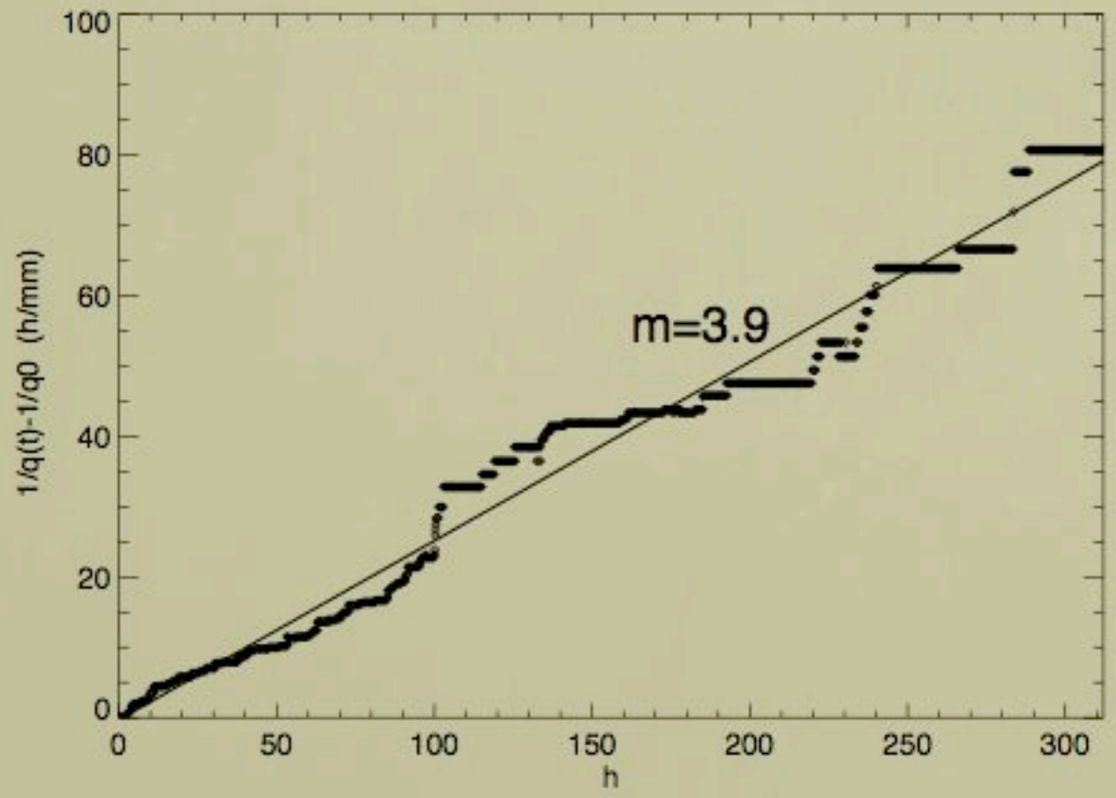
Análisis de recesiones de hidrogramas

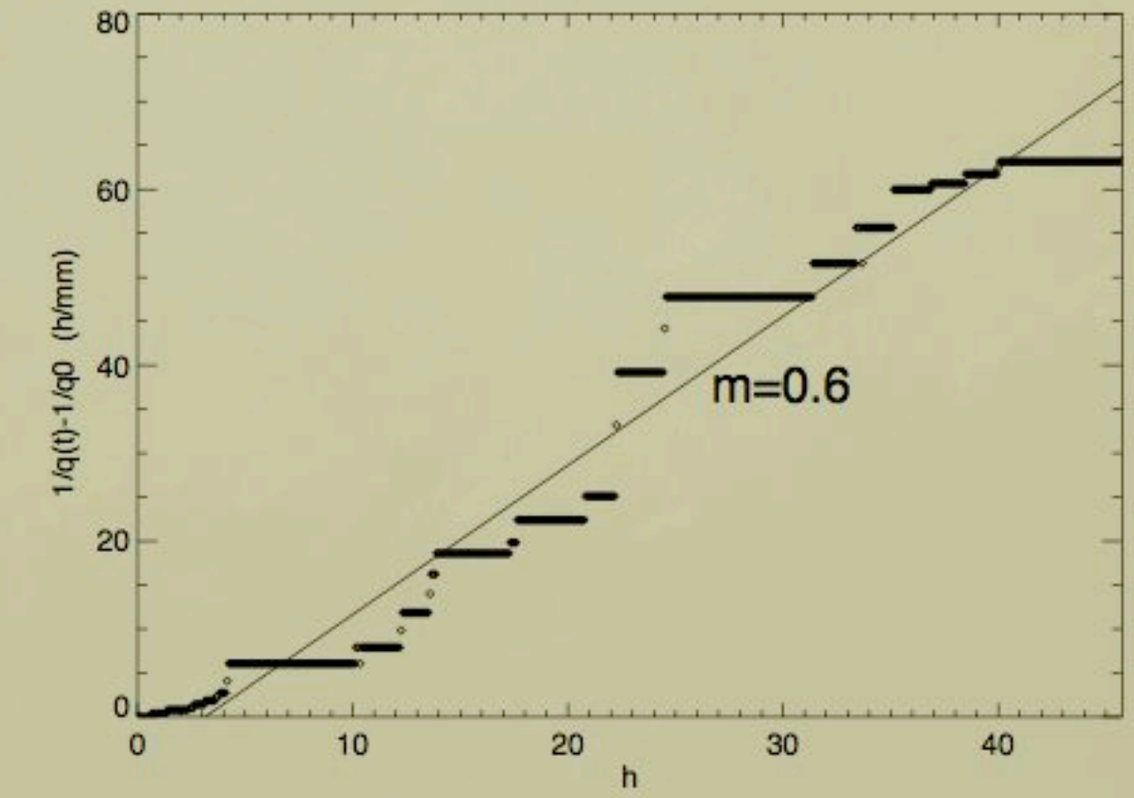


Análisis de recesiones de hidrogramas

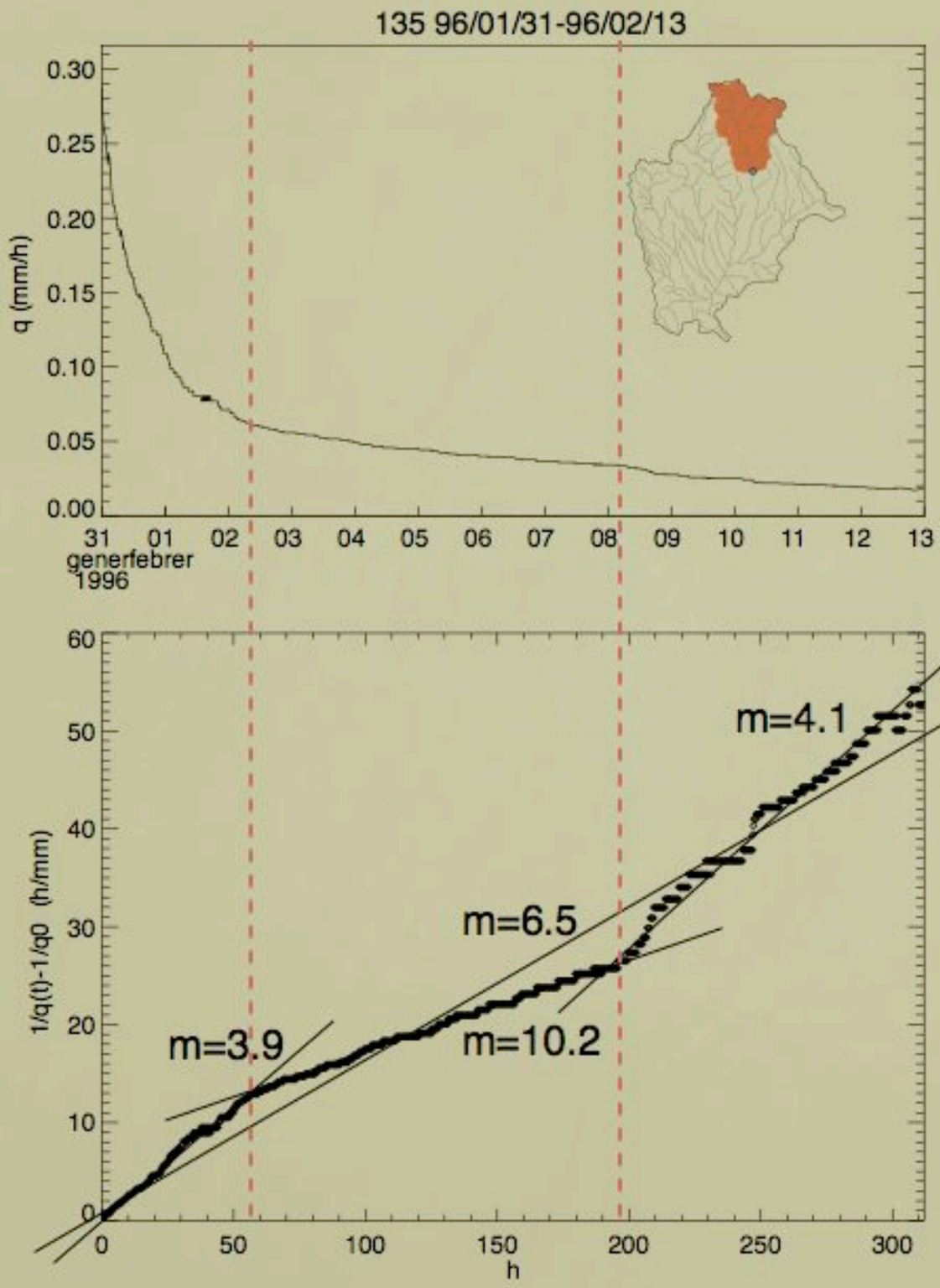


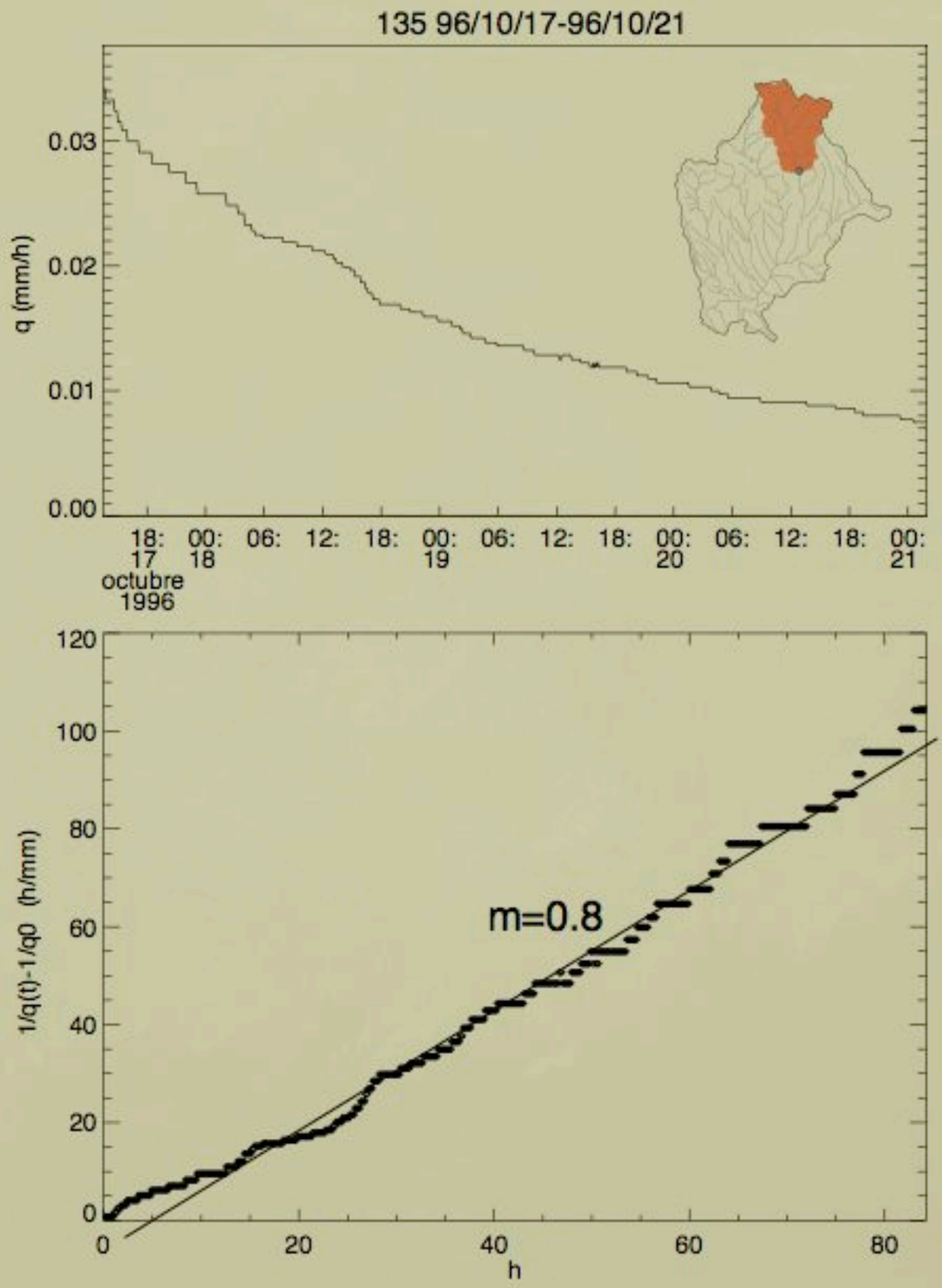






Análisis de recesiones de hidrogramas







Level 3:
Full Hydrological modeling

The rainfall-runoff model Dichitop (Corral, 2004)



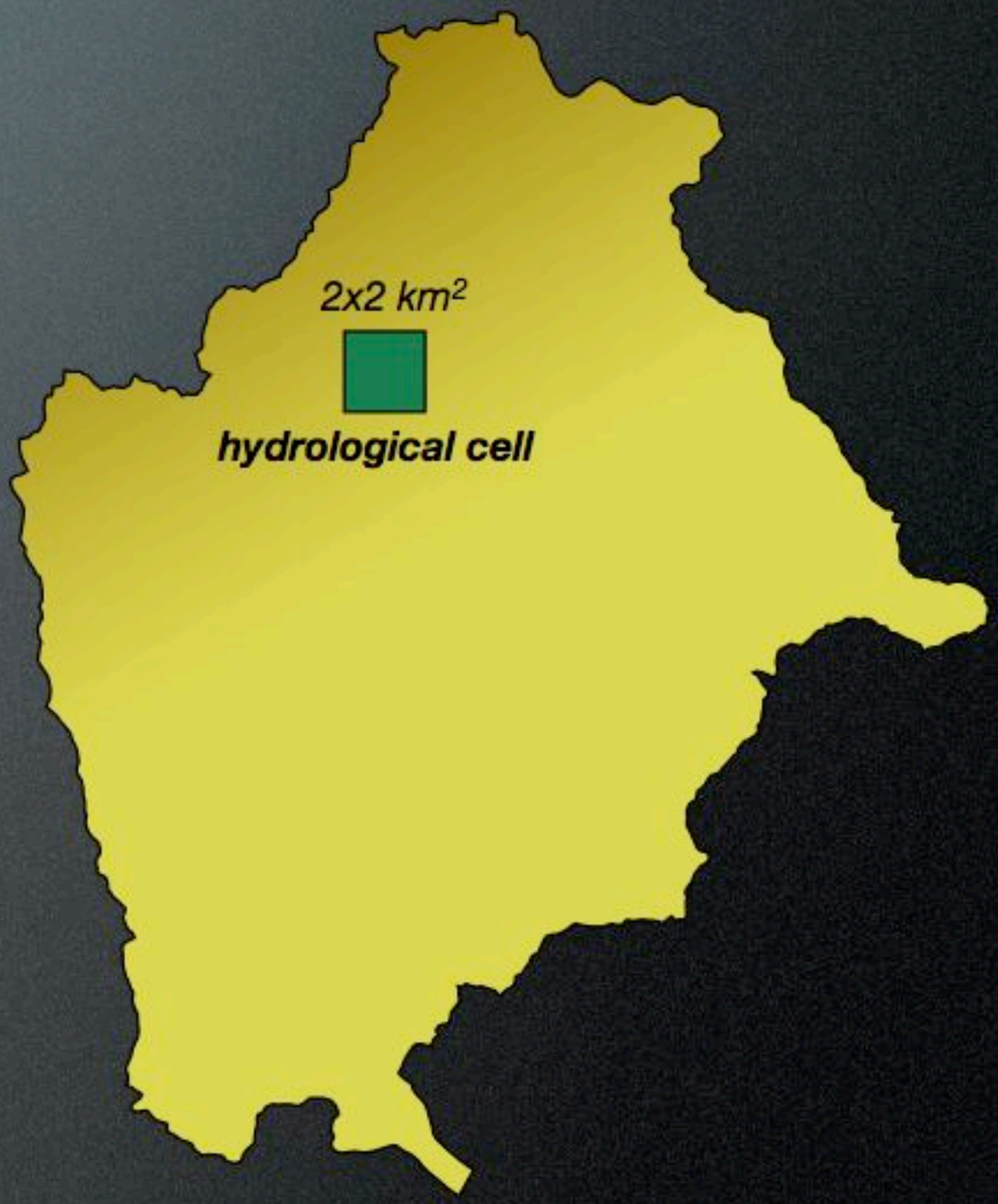
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CRAHI

UPC

The rainfall-runoff model Dichitop (Corral, 2004)

- **Distributed model** able to use distributed rainfall fields.



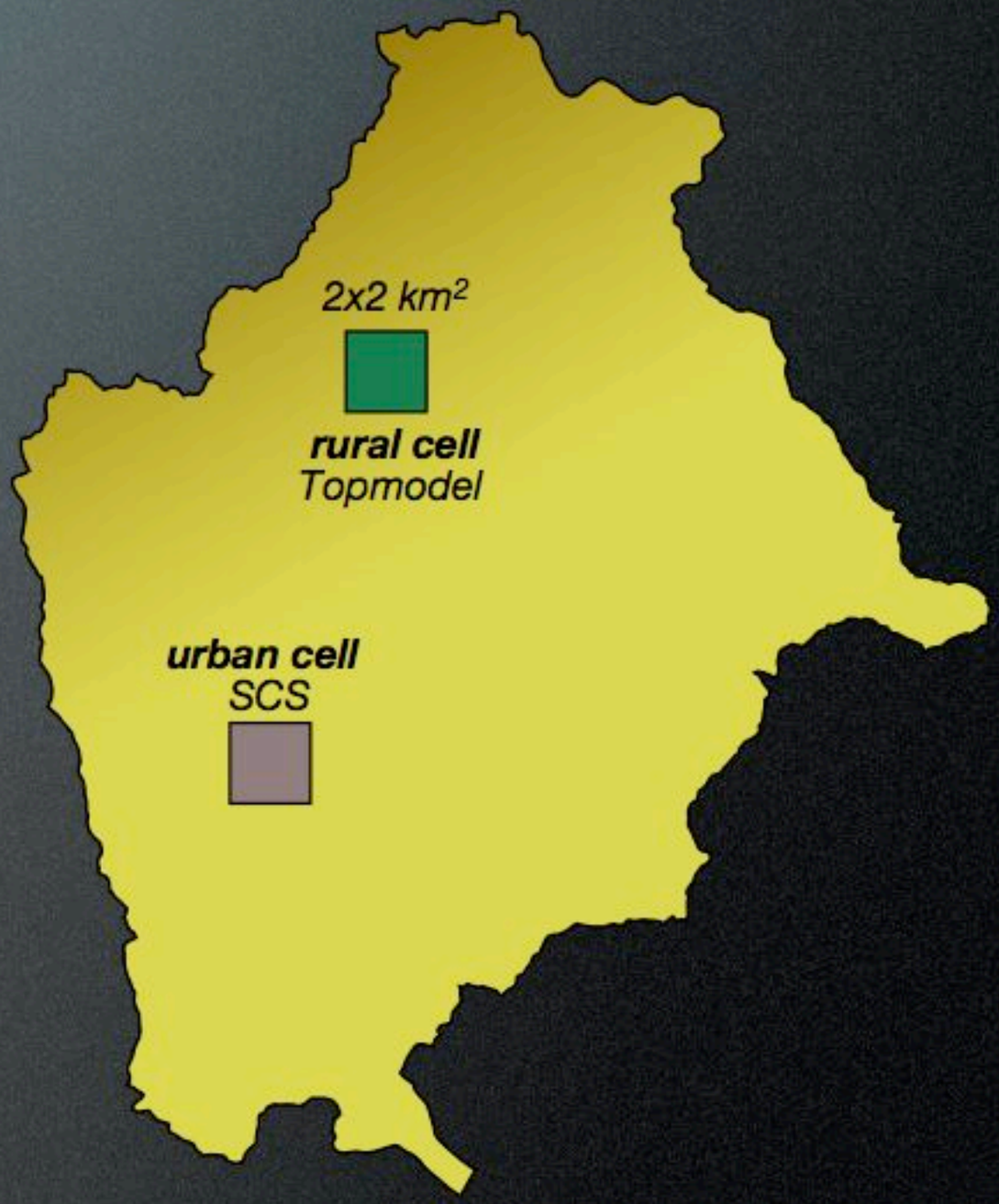
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The rainfall-runoff model Dichitop (Corral, 2004)

- **Grid-based model** able to use distributed rainfall fields.
- Able to produce runoff depending on the characteristics of the hydrological cells.



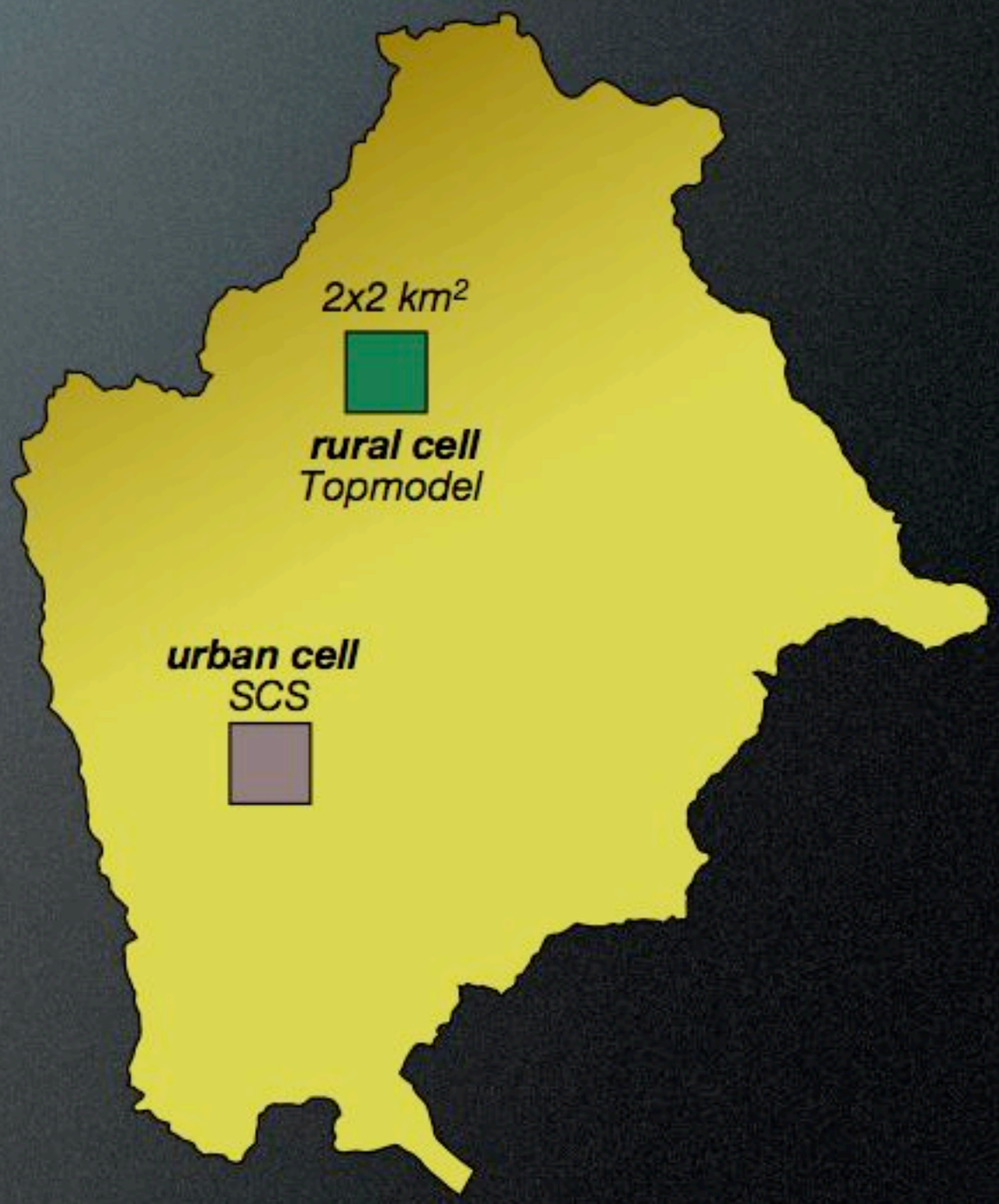
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The rainfall-runoff model Dichitop (Corral, 2004)

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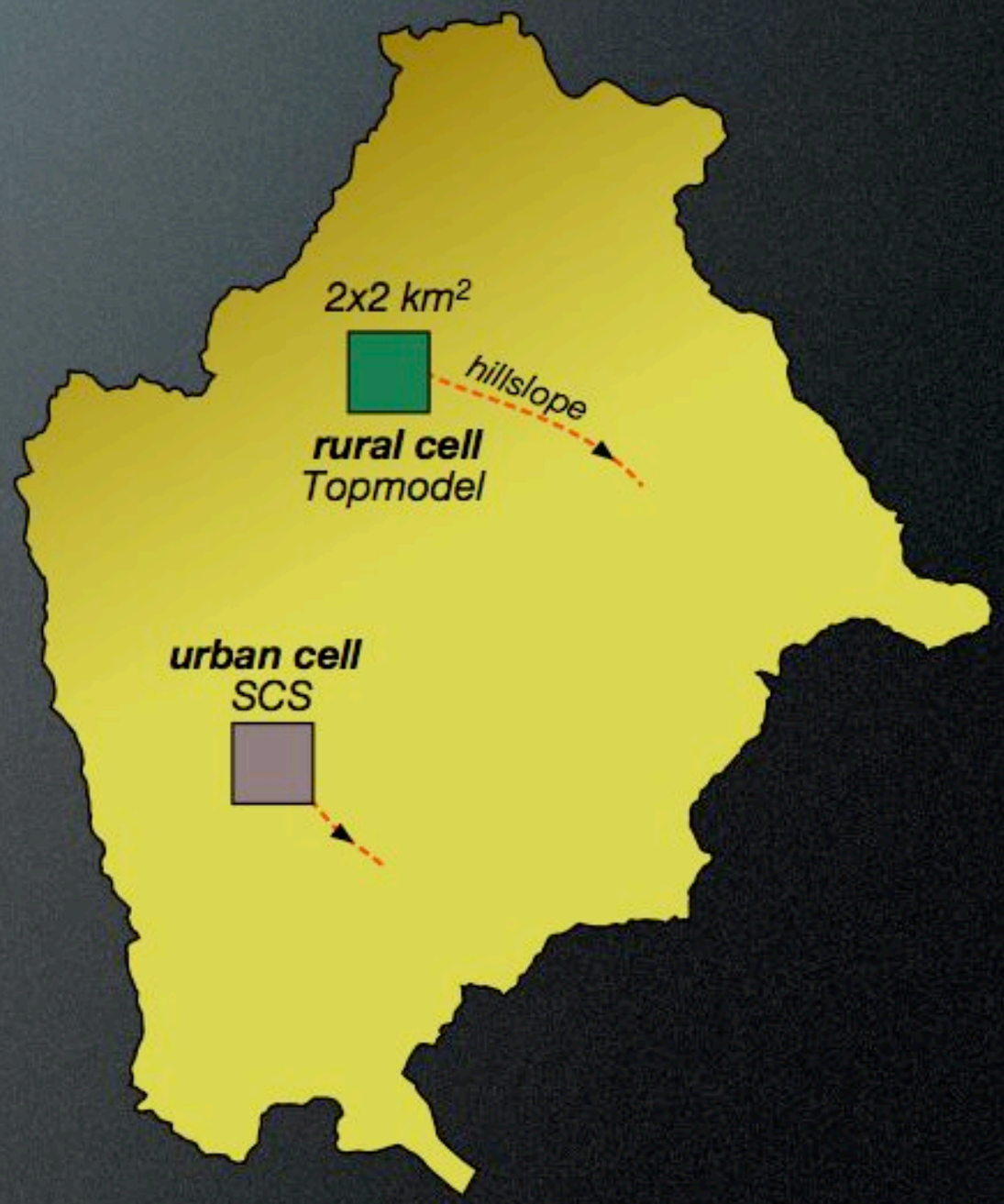
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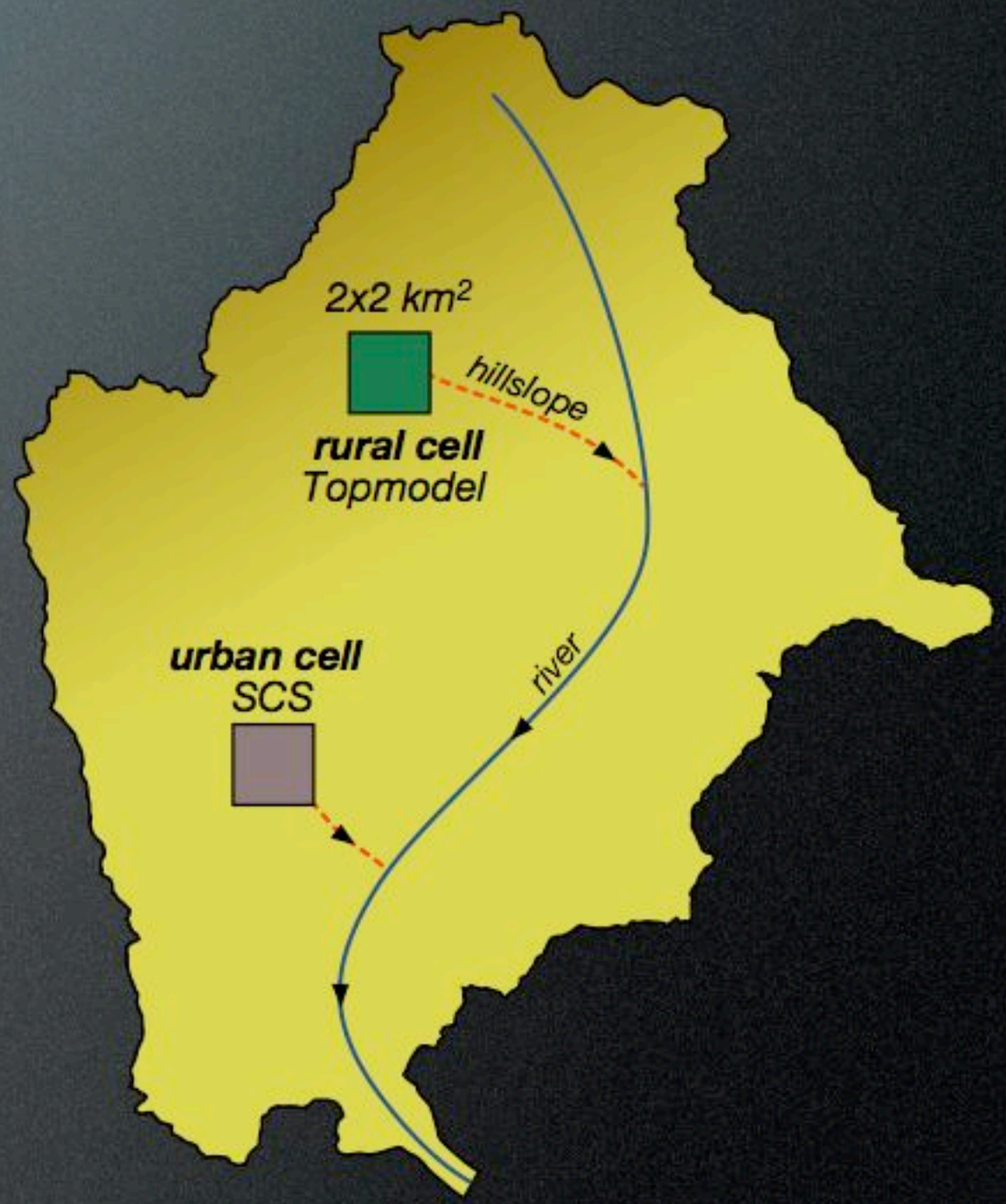
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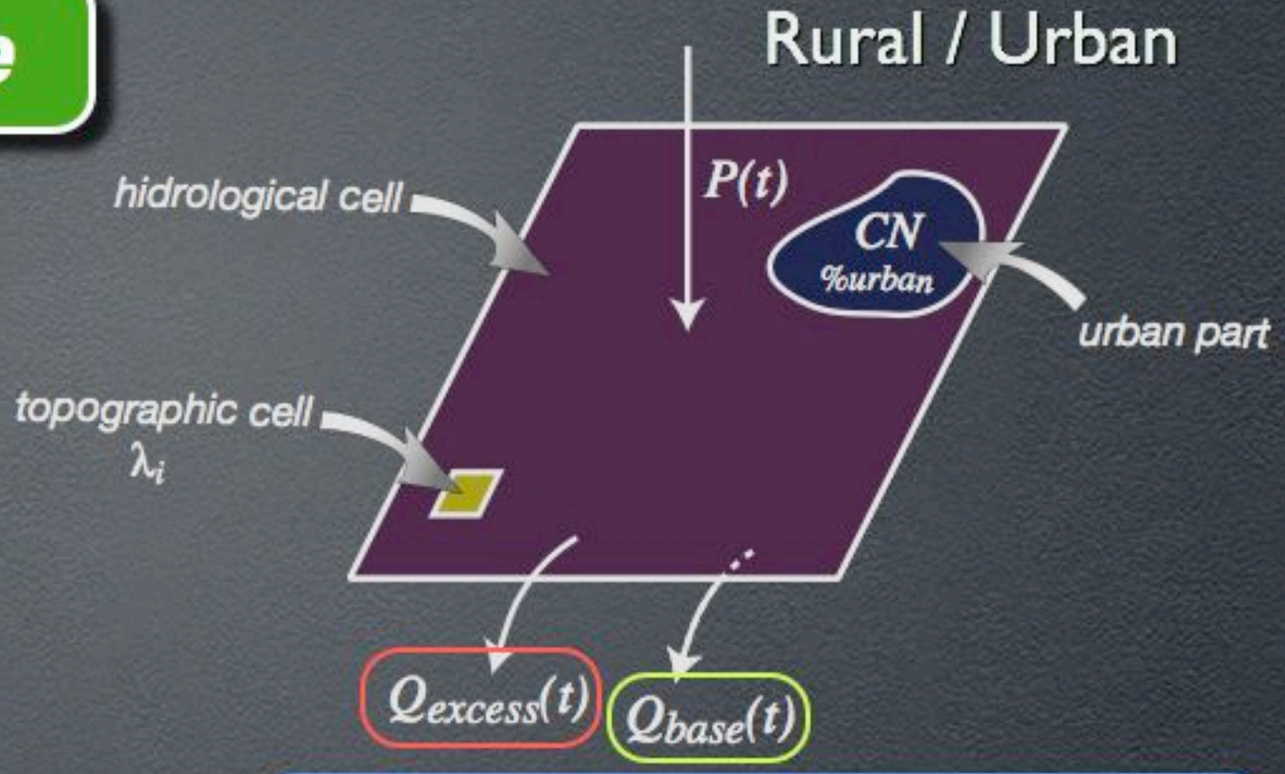
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Loss function at cell scale



Loss function at cell scale



Coupled loss function

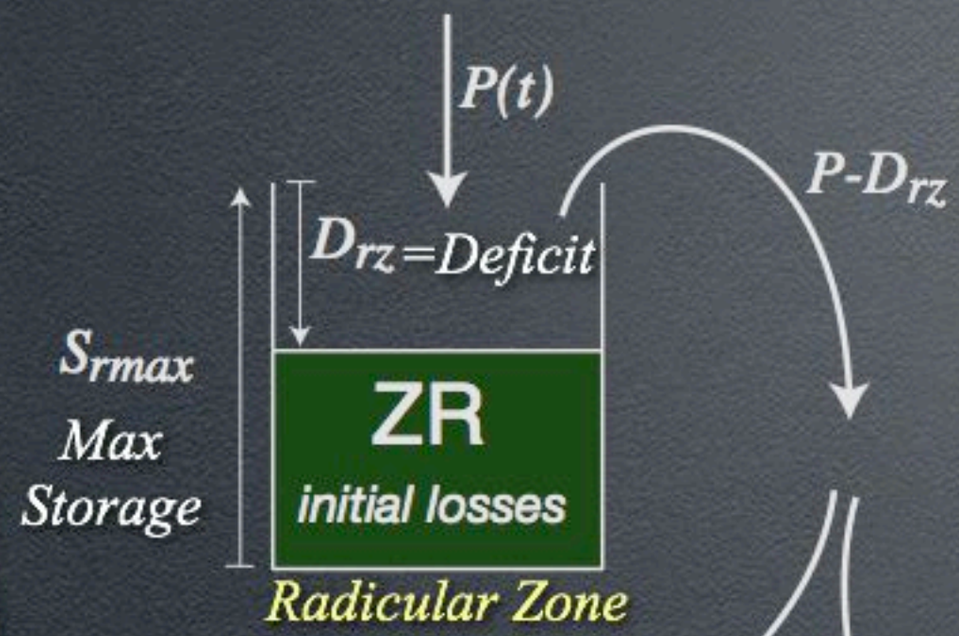
Topmodel (rural) + SCS (urban)

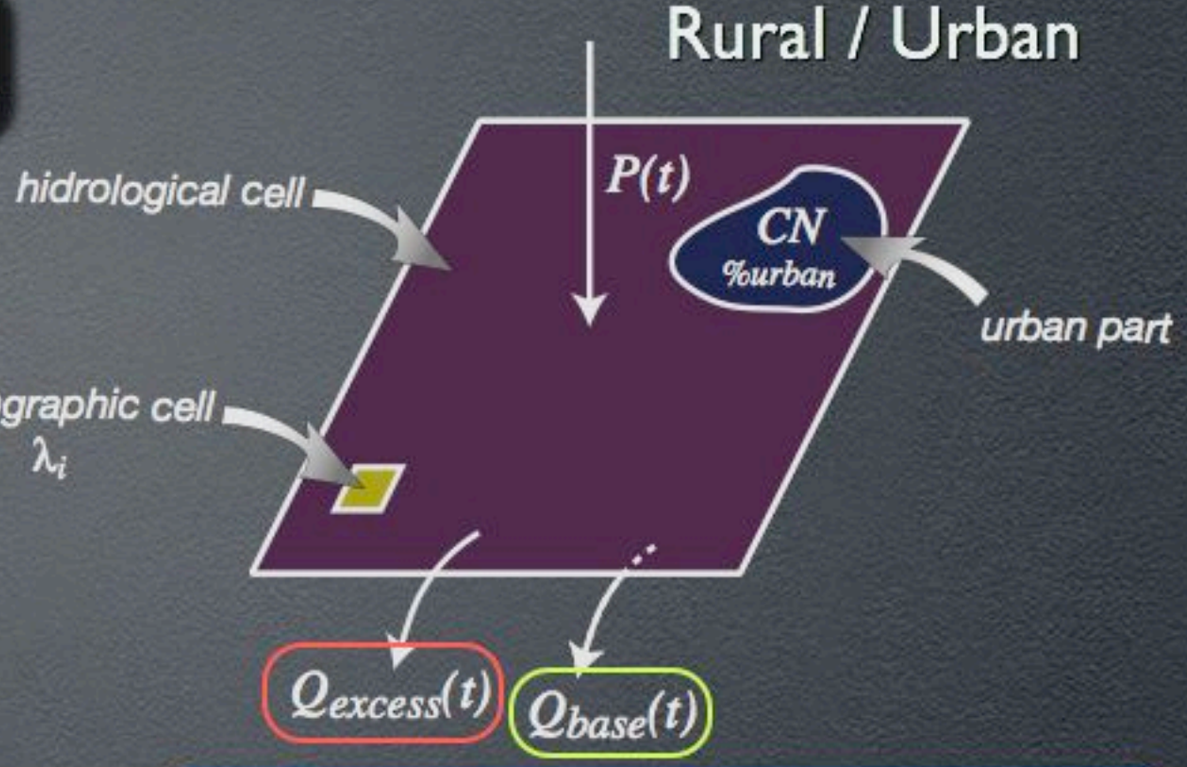
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Loss function at cell scale

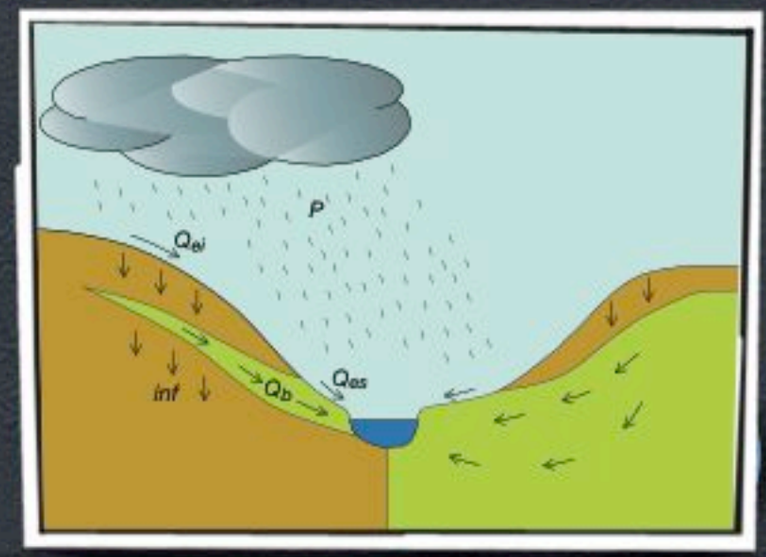




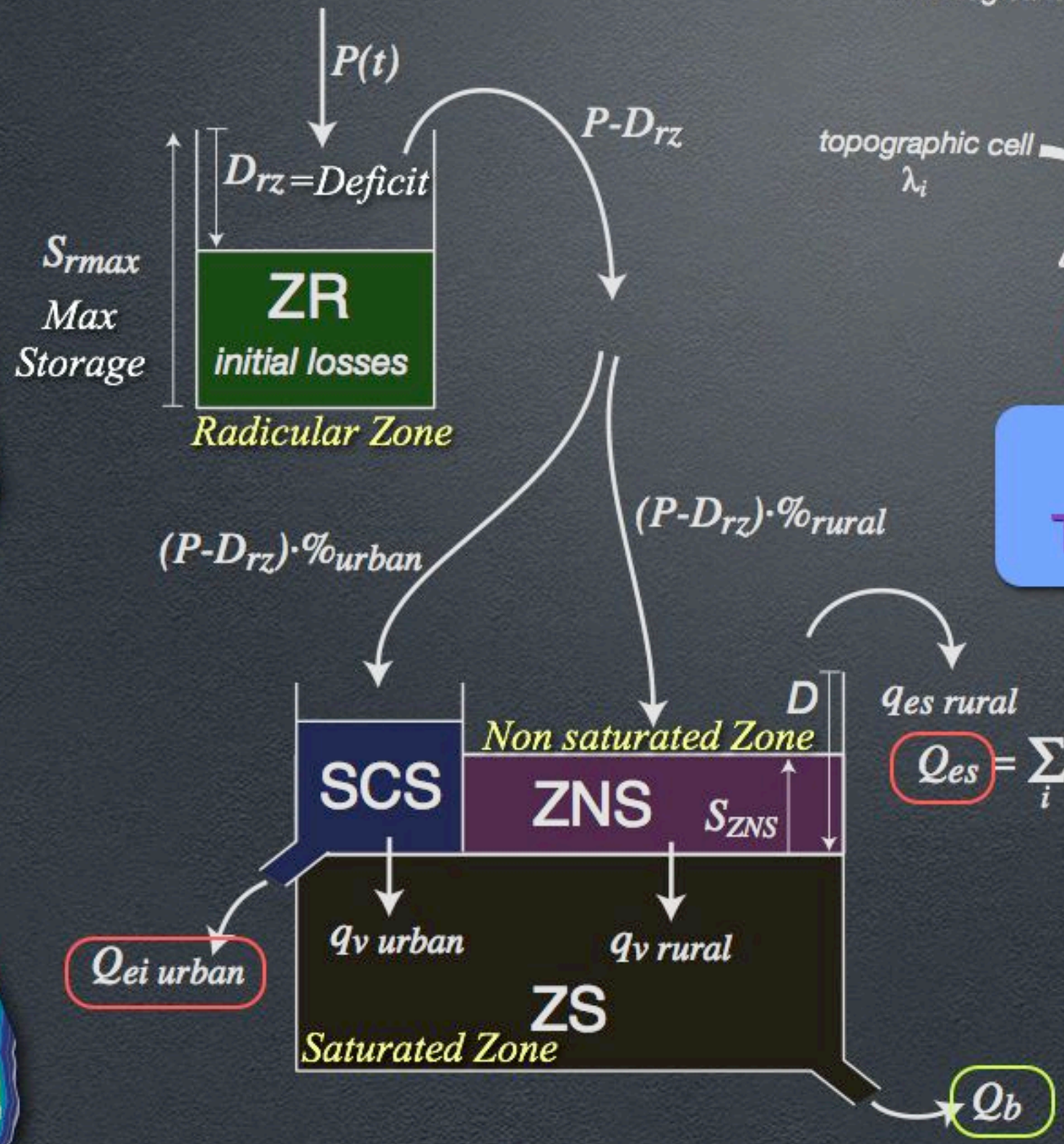
Coupled loss function

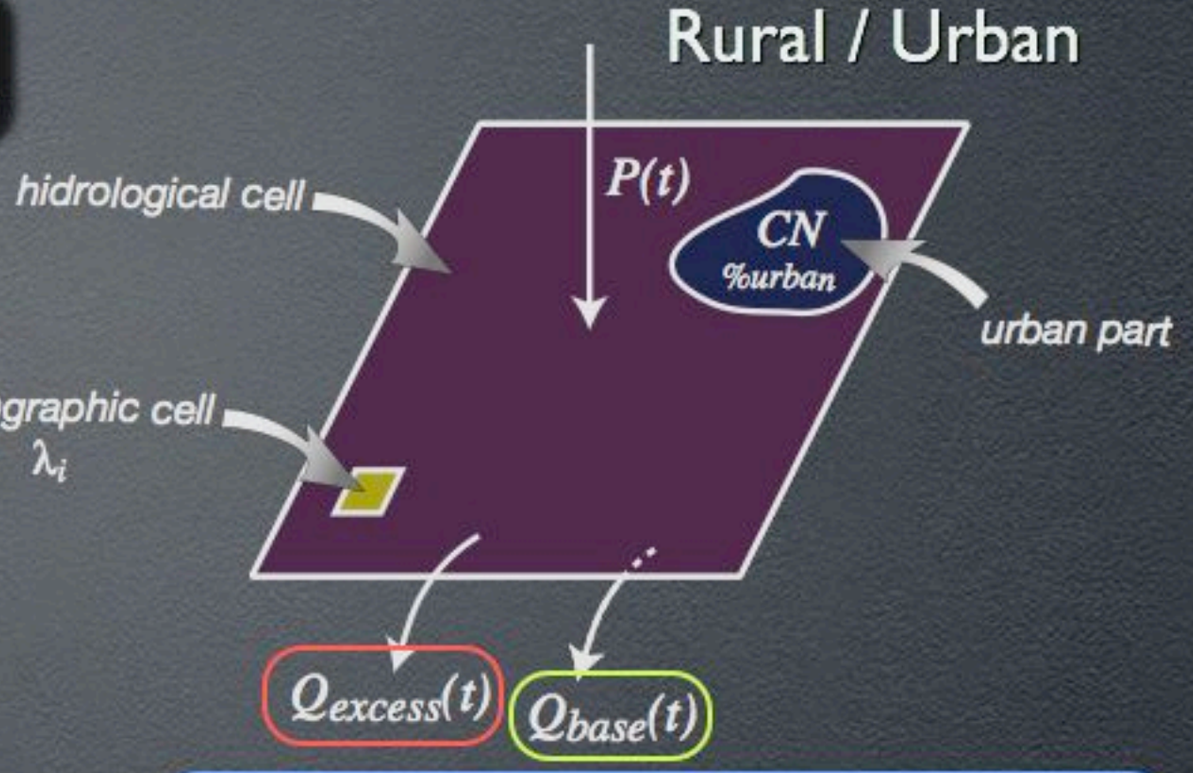
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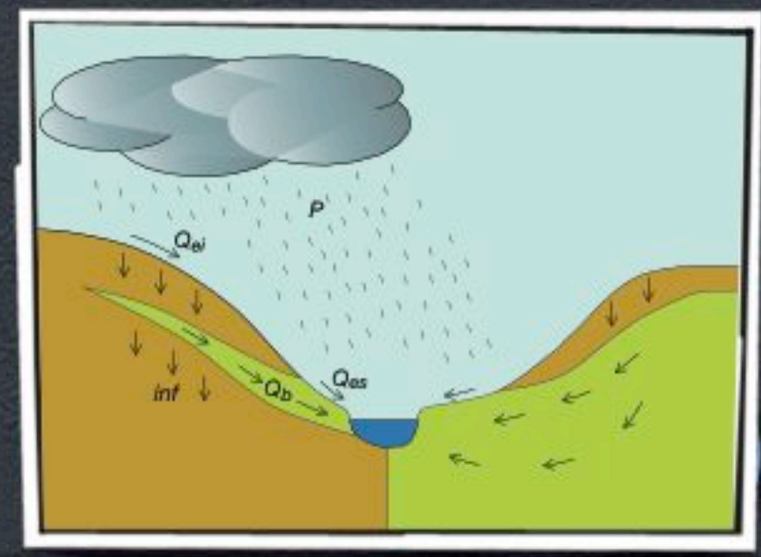
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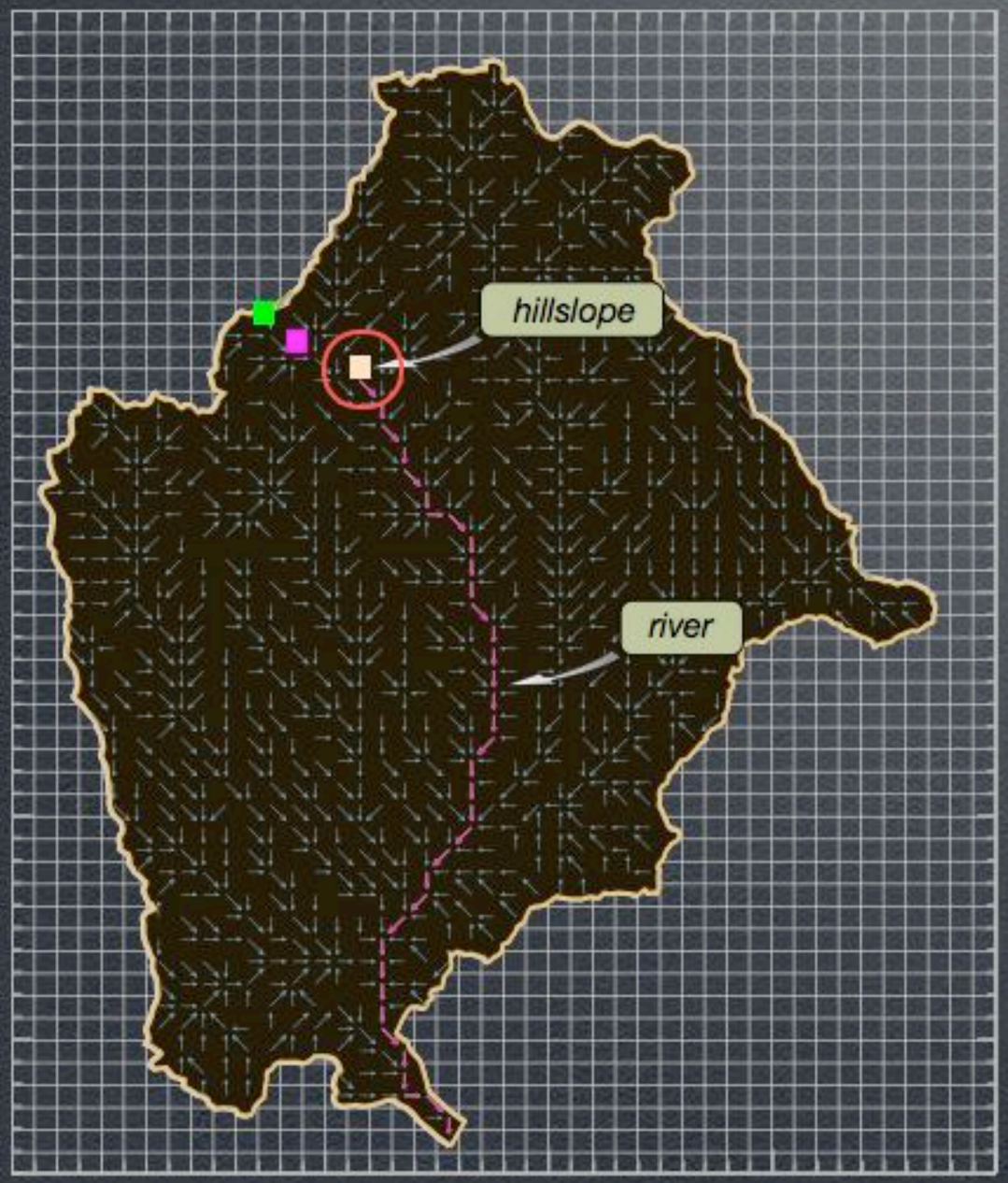


Coupled loss function

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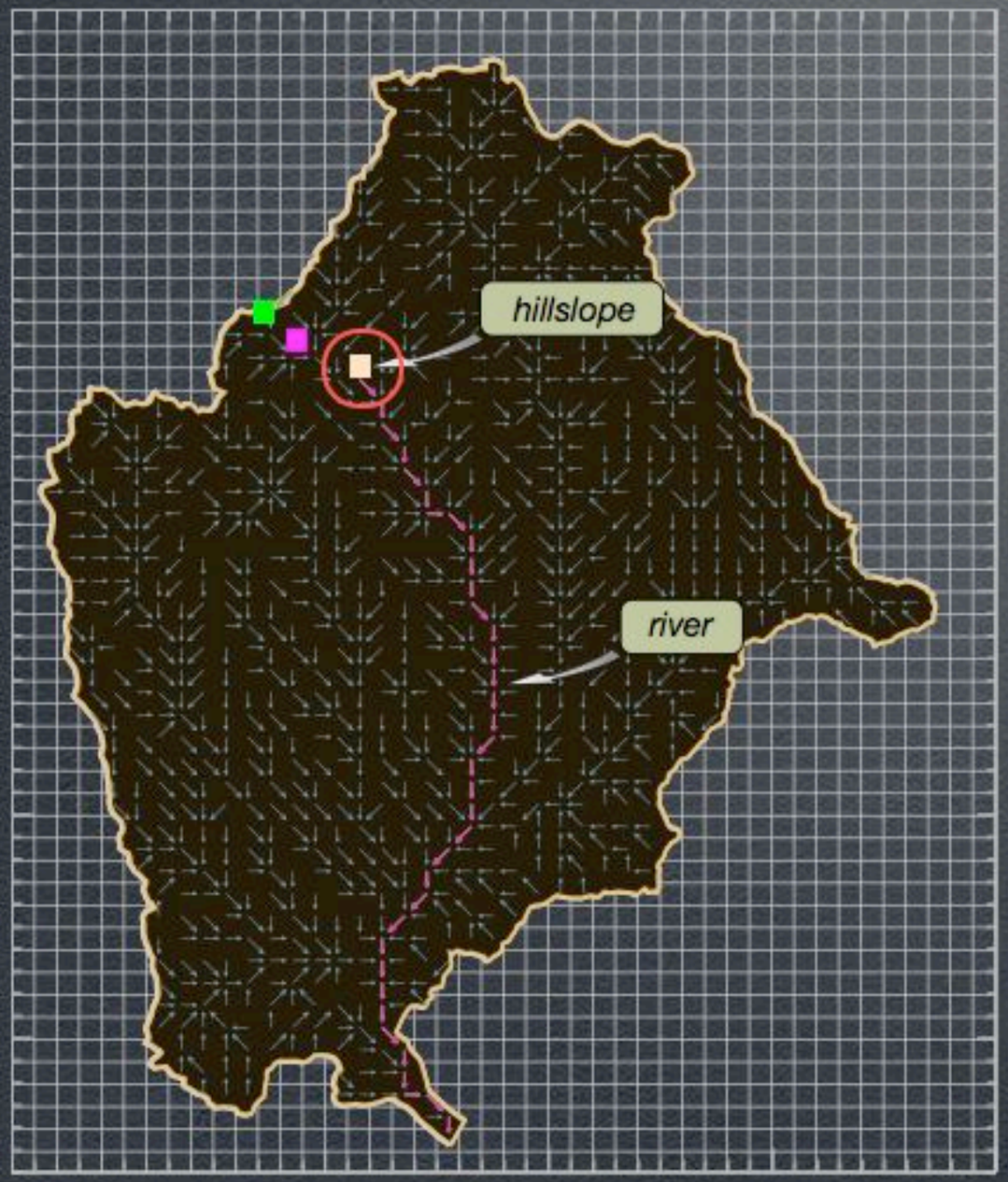


Routing in hillslope cell



hillslope cell - Upstream Area < 30 km2

Routing in hillslope cell

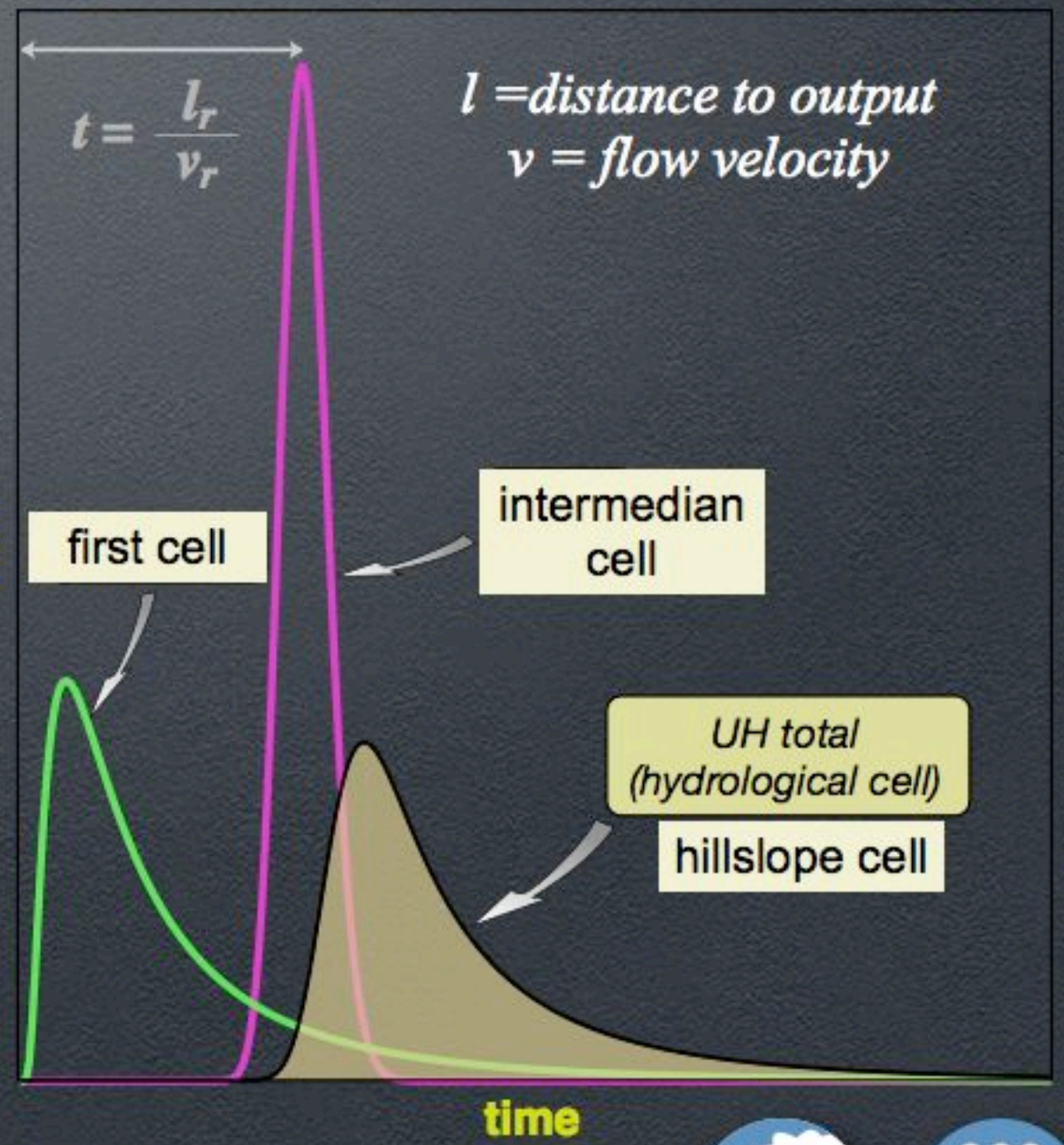


hillslope cell - Upstream Area < 30 km2

Difussive Wave Unit Hydrograph with Muskingum parameters

(Szymkievicz, JH 2002)

$$HUODM(t) = \frac{1}{\sqrt{2\pi(1-2X)}} \frac{N}{K} \left(\frac{K}{t}\right)^{3/2} \exp\left(-\frac{(t-NK)^2}{2(1-2X)Kt}\right)$$



$$Q(t) = \sum Q(t)_{cell\ i}$$

The rainfall-runoff model Dichitop (Corral, 2004)

- **Grid-based model** able to use distributed rainfall fields.
- Able to produce runoff depending on the characteristics of the hydrologicla cells.
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- A **simplified drainage network** is used to transfer cell hydrographs.
- **Basin hydrograph** is calculated as the linear combination of cell hydrographs.



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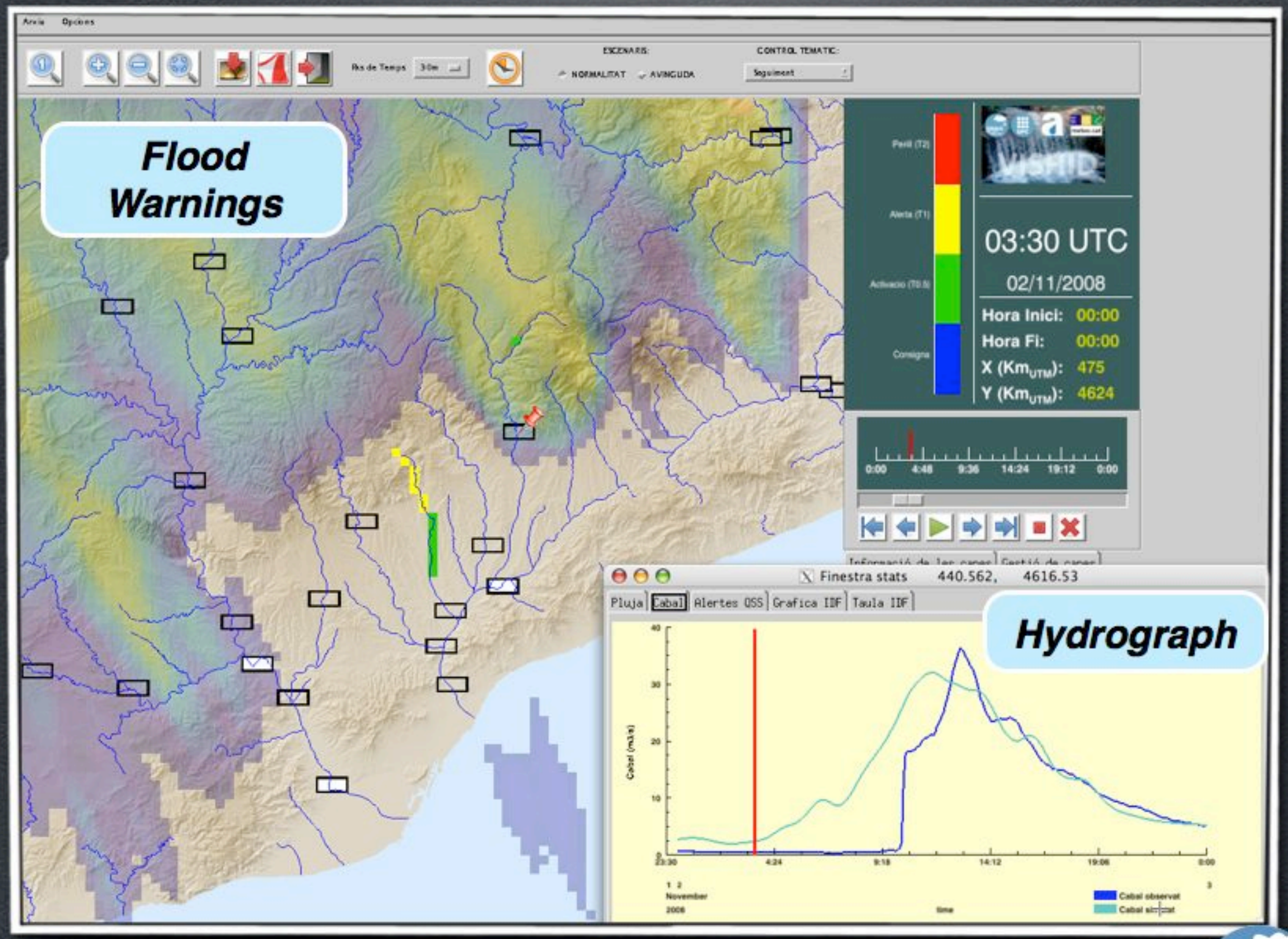


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Arxiu Opcions
Flood Warnings
ESCENARIS:
NORMALITAT
AVINGUDA
CONTROL TEMATIC:
Seguiment
Pas de Temps
Perill (T2)
Alerta (T1)
Activació (T0.5)
Consigna
03:30 UTC
02/11/2008
Hora Inici: 00:00
Hora Fi: 00:00
X (Km$_{UTM}$): 475
Y (Km$_{UTM}$): 4624
0:00 4:48 9:36 14:24 19:12 0:00
Finestra stats 440.562, 4616.53
Pluja Cabal Alertes QSS Grafica IDF Taula IDF
Hydrograph
Cabal (m3/s)
November
2008
time
Cabal observat
Cabal simulat

Simplified Hydrologic Models

- **Methodology**:

  Application of a simple hydrological rainfall-runoff models (Loss functions P-Q) in selected catchments.

  Lumped: the simulated Hydrogram Q(t) is forecasted at the output of each subbasin (node). Radar QPE is spatially averaged in the subbsins.

  Ungaged: Applied to catchments where no monitoring/ observation are available (no streamflow gages)

Required Data

Required Data

- ***RAINFALL: Radar QPE (+QPF)***

Required Data

RAINFALL: Radar QPE (+QPF)

CARTOGRAPHY: basin boundary, stream network, urban areas

Required Data

- **RAINFALL: Radar QPE (+QPF)**
- **CARTOGRAPHY: basin boundary, stream network, urban areas**
- **BASIN PROPERTIES: Geology, land use, slopes**

System Outputs

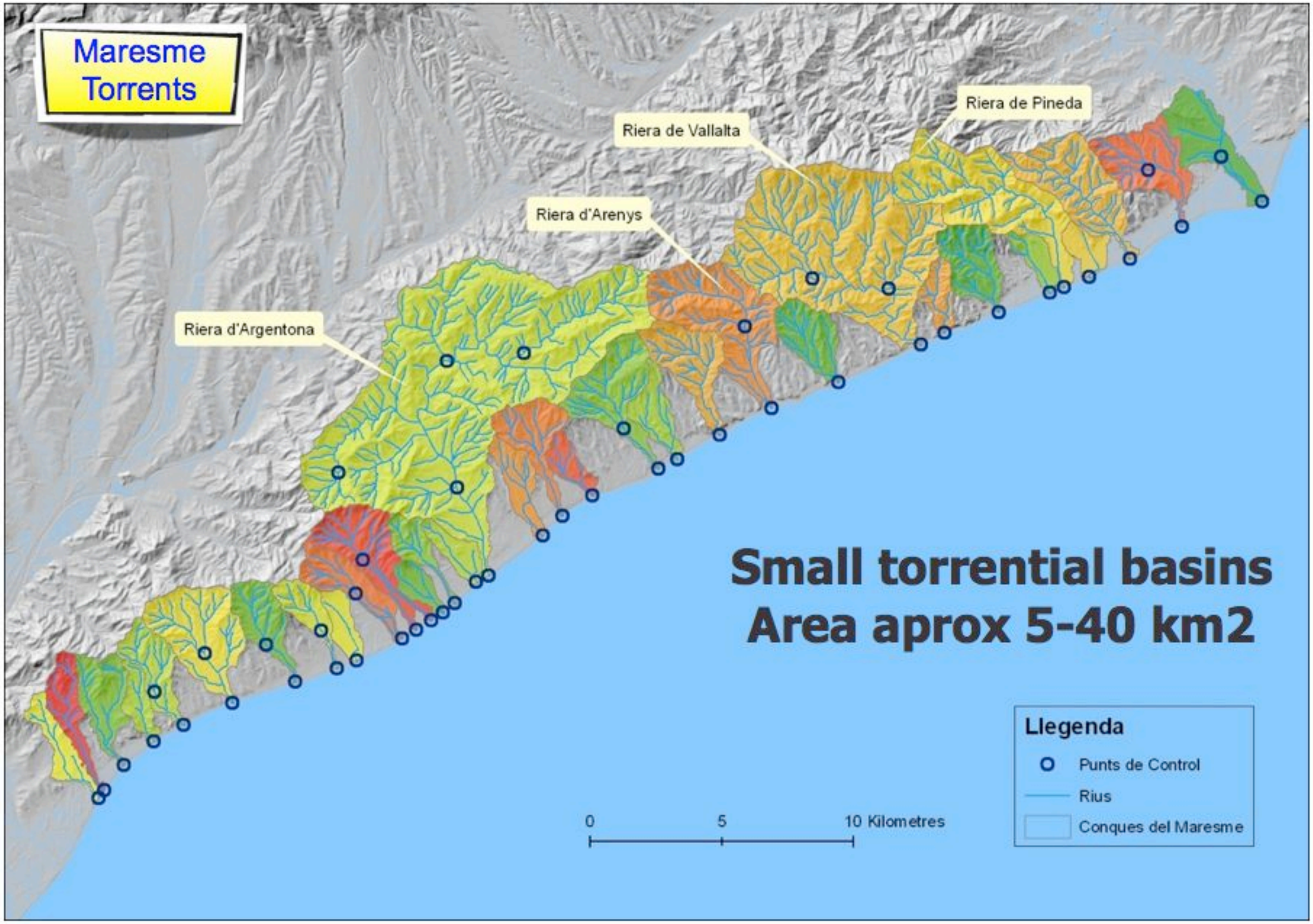
System Outputs

- **DISCHARGES: discharge forecast in the nodes**

System Outputs

DISCHARGES: discharge forecast in the nodes

FLOOD HAZARD WARNINGS:
Discharge thresholds at nodes


Maresme
Torrents
Riera de Pineda
Riera de Vallalta
Riera d'Arenys
Riera d'Argentona
Small torrential basins
Area aprox 5-40 km2
Llegenda
Punts de Control
Rius
Conques del Maresme
0
5
10 Kilometres

Coupling urban and rural (non urban) processes. Coupled simulation of urban run-off and non-urban run-off (rural areas)

Coupling urban and rural (non urban) processes. Coupled simulation of urban run-off and non-urban run-off (rural areas)

Urban

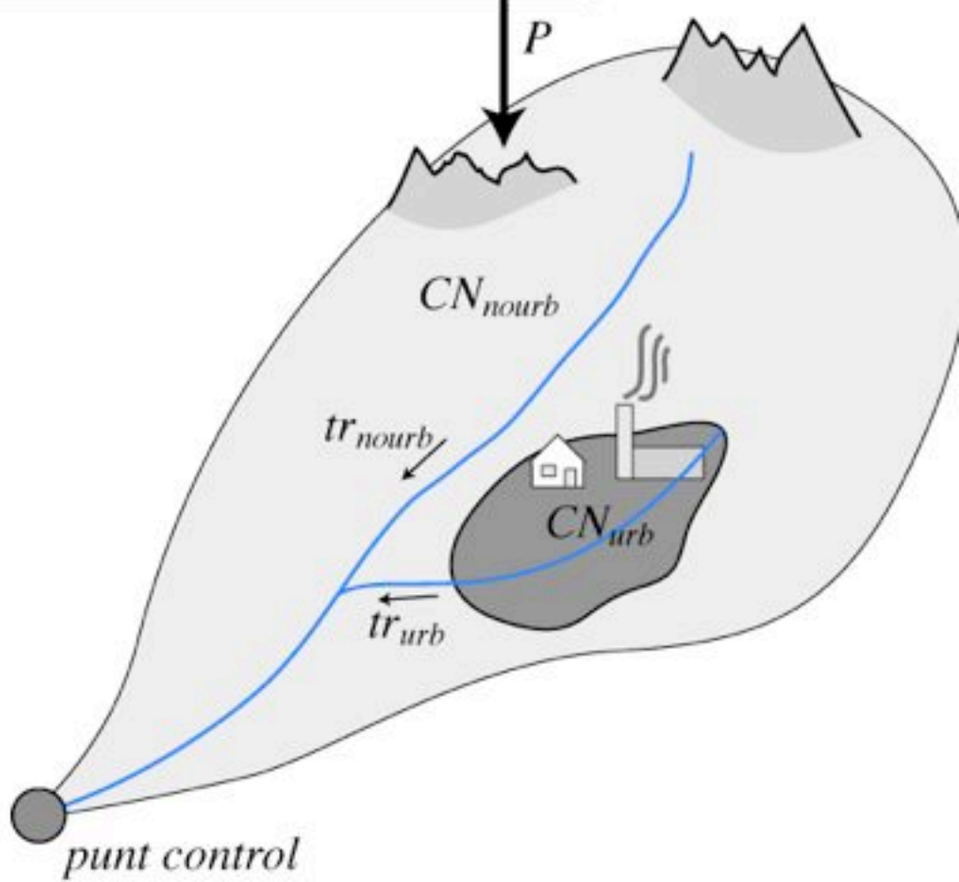
Loss function SCS (FP_{urb})

Unit Hydrogr. SCS (HU_{urb})

Non Urban

Loss function SCS (FP_{nourb})

Unit Hydrograph SCS (HU_{nourb})



Coupling urban and rural (non urban) processes. Coupled simulation of urban run-off and non-urban run-off (rural areas)

Urban

Loss function SCS (FP_{urb})

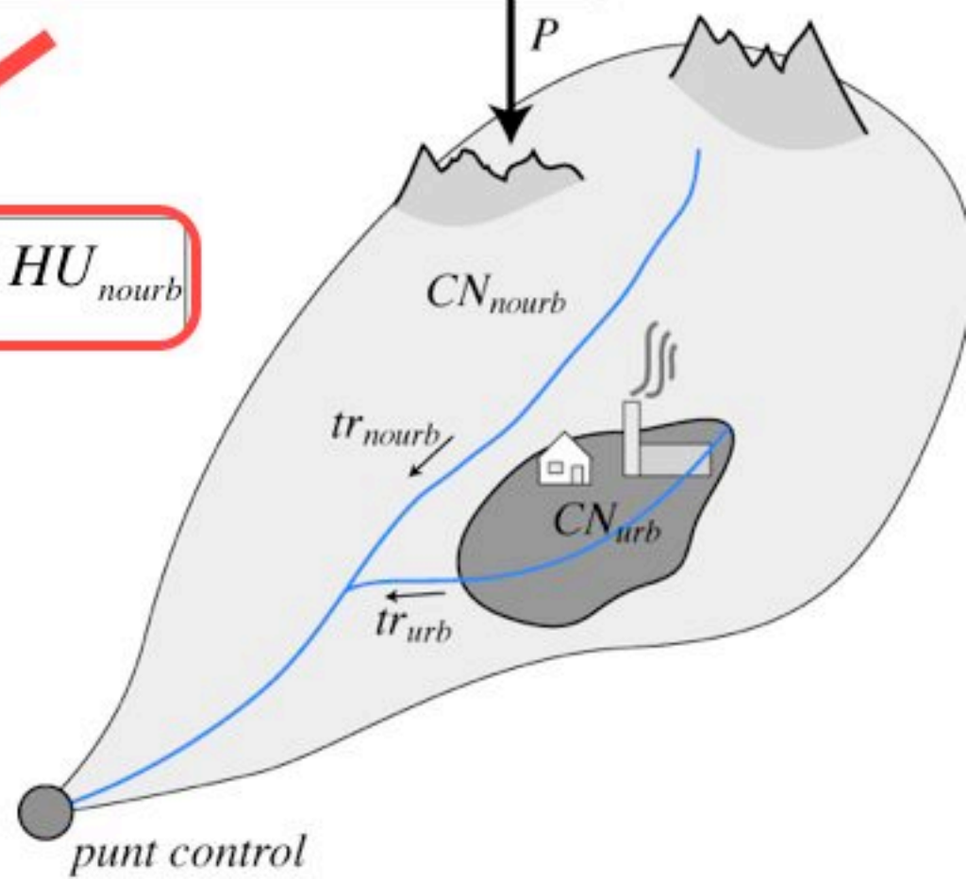
Unit Hydrogr. SCS (HU_{urb})

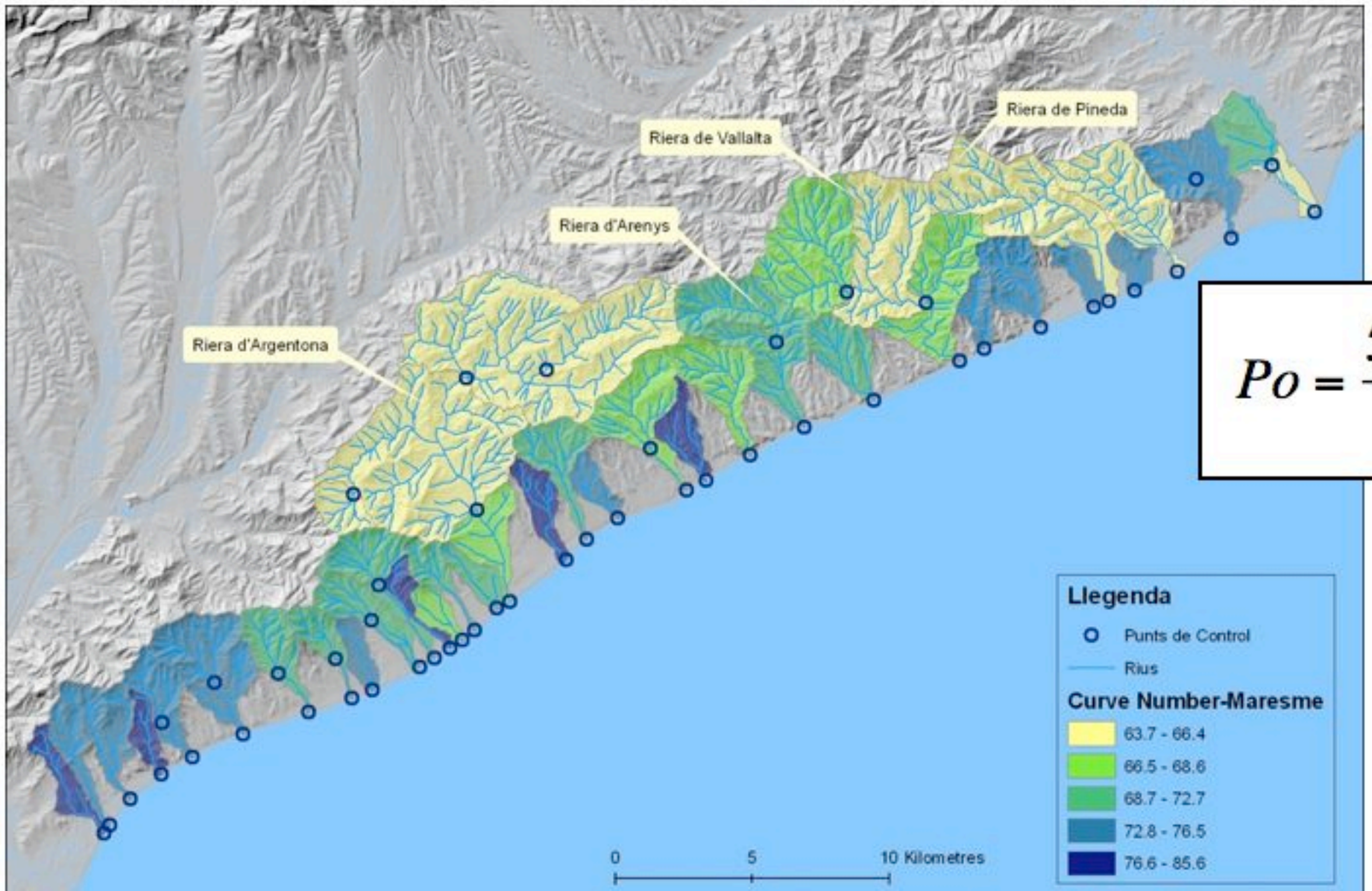
Non Urban

Loss function SCS (FP_{nourb})

Unit Hydrograph SCS (HU_{nourb})

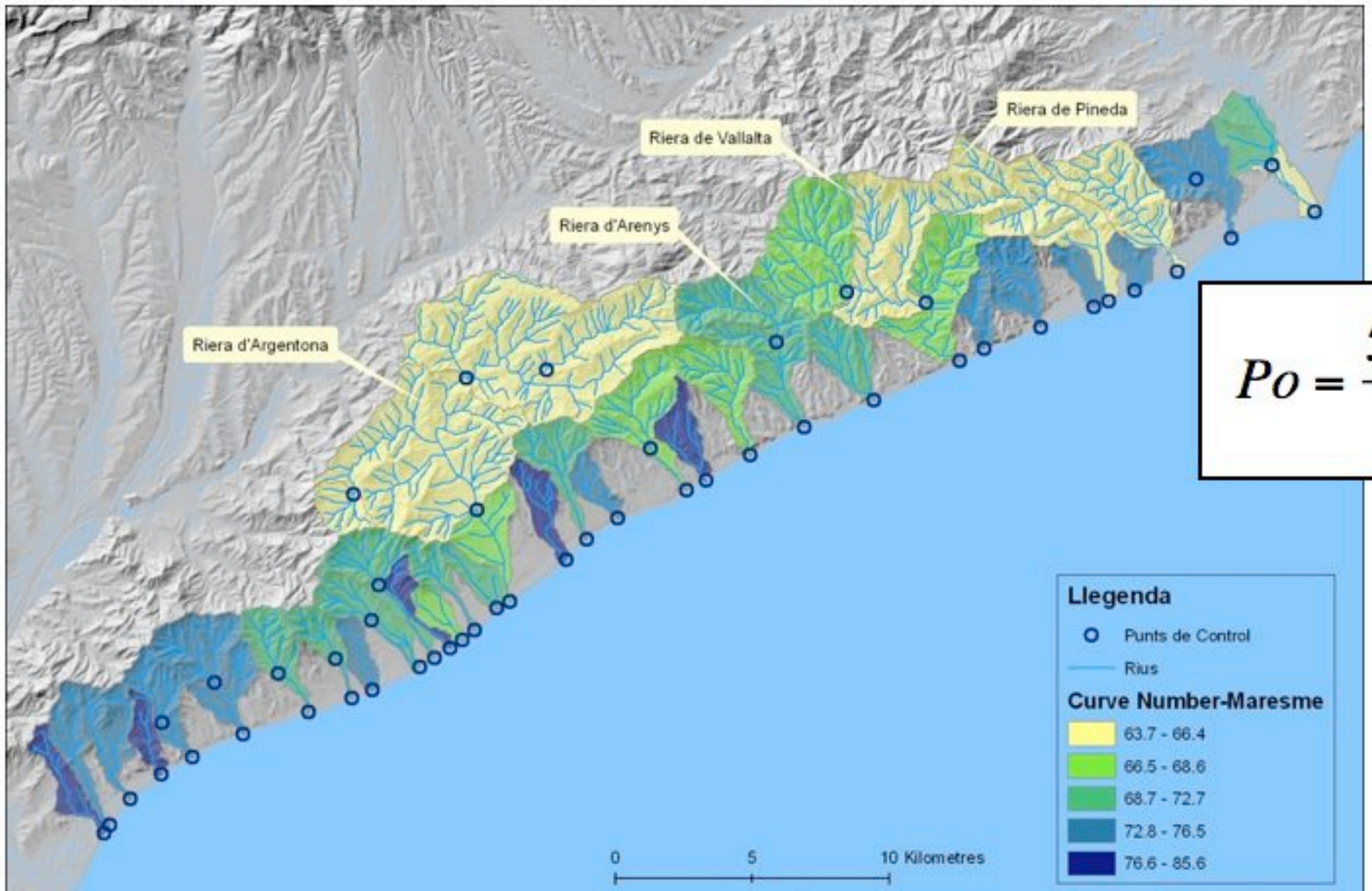
$$Q = A_{urb} \cdot FP_{urb}(P) \otimes HU_{urb} + A_{nourb} \cdot FP_{nourb}(P) \otimes HU_{nourb}$$





$$Po = \frac{5000}{CN} - 50 \text{ (mm)}$$

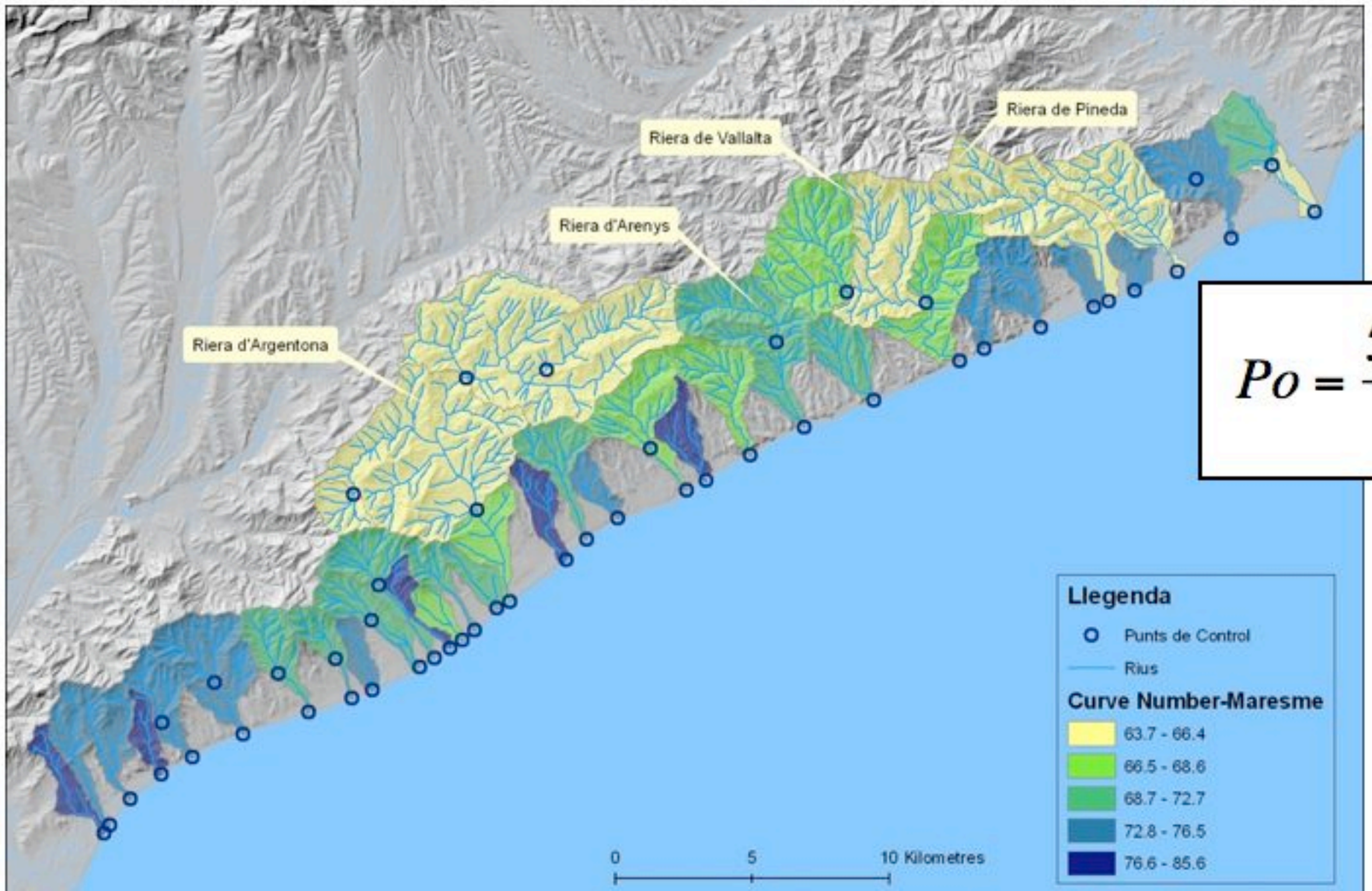
Loss Function - SCS method: Curve Number Method



$$Po = \frac{5000}{CN} - 50 \text{ (mm)}$$

- **Loss Function - SCS method: Curve Number Method**

  Estimation of the mean Curve Number CN for the urban area (CNurb) and the non-urban area (CNnourb)

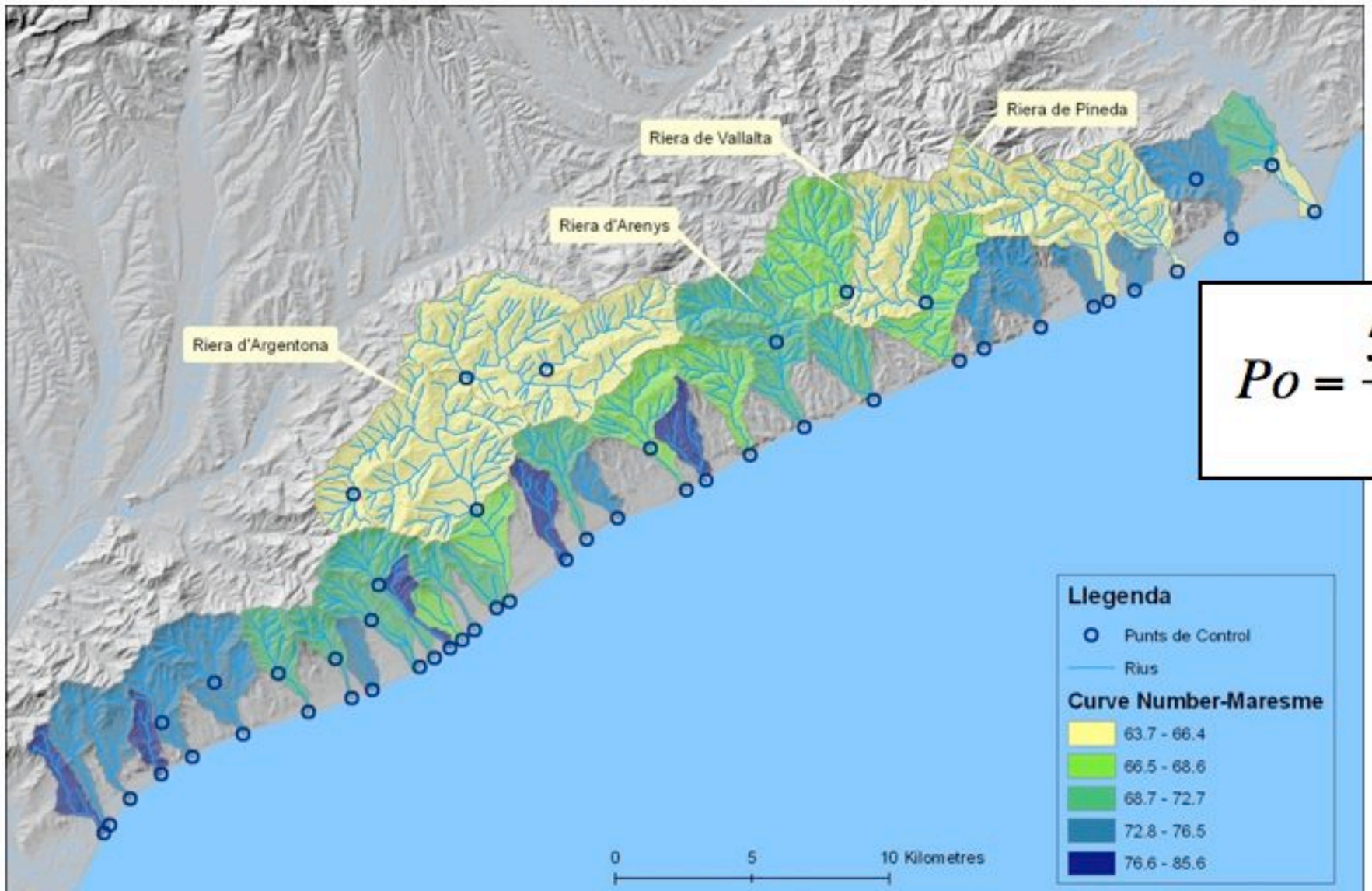


$$Po = \frac{5000}{CN} - 50 \text{ (mm)}$$

- **Loss Function - SCS method: Curve Number Method**

  Estimation of the mean Curve Number CN for the urban area (CNurb) and the non-urban area (CNnourb)

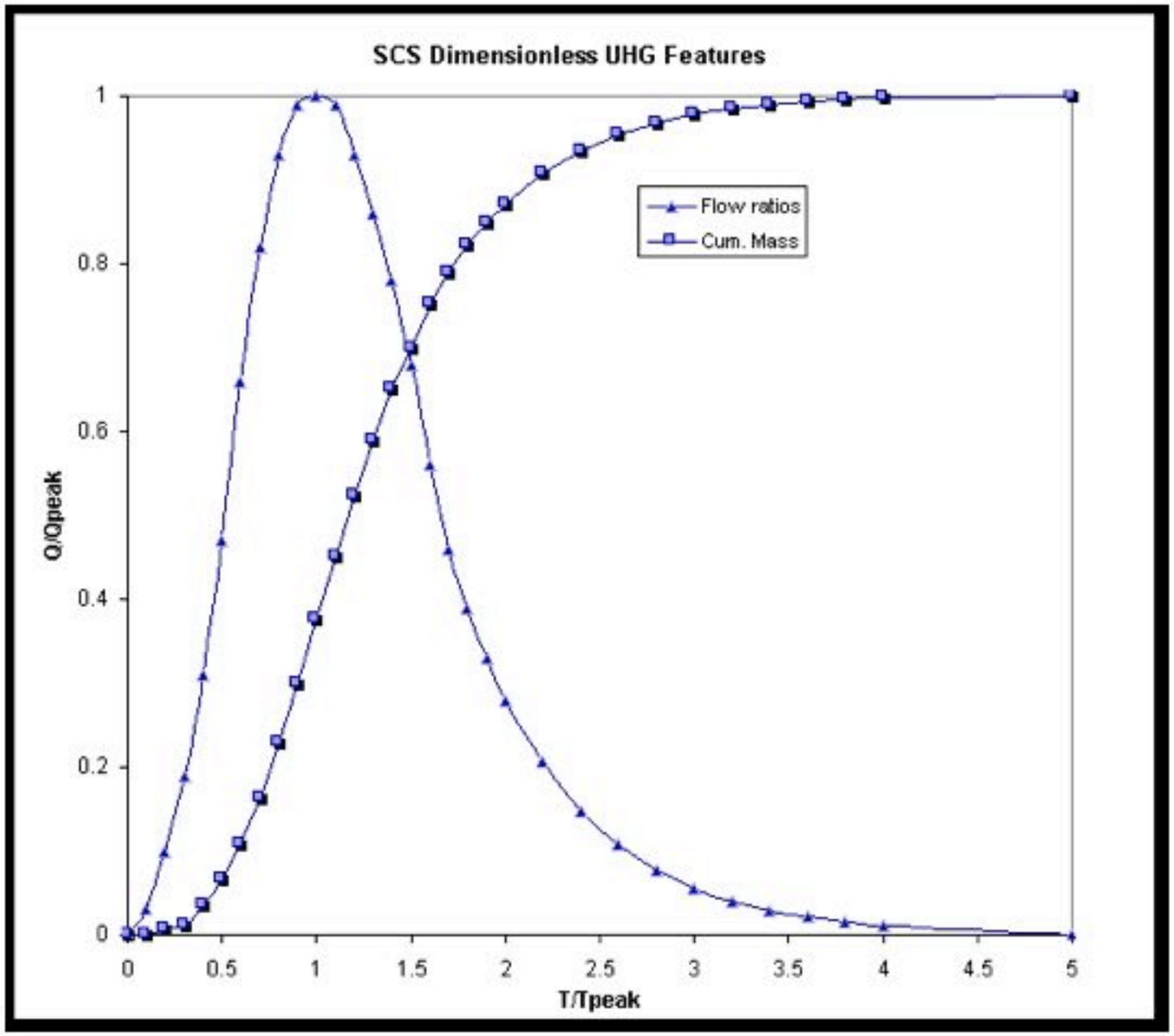
  The Loss function parameters (Po, initial abstraction) are estimated separately for the urban and non-urban area



$$Po = \frac{5000}{CN} - 50 \text{ (mm)}$$

- **SCS Unit Hydrograph:**
  - The SCS Unit Hydrograph is asociated to an adimensional hydrograph where time to peak (t_p) and Peak discharge (Q_p) are the governing parameters

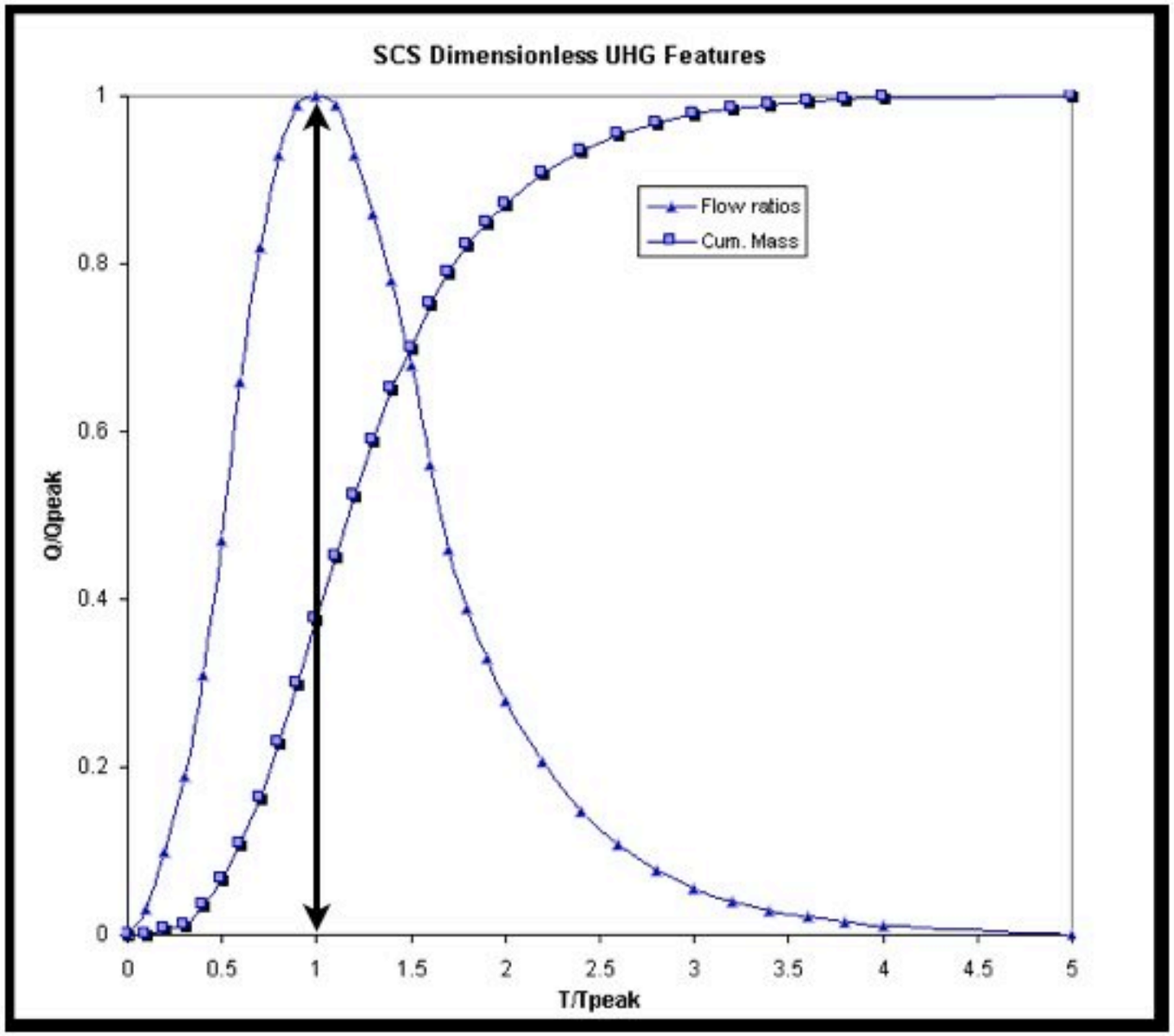
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- **SCS Unit Hydrograph:**
  - The SCS Unit Hydrograph is asociated to an adimensional hydrograph where time to peak (t_p) and Peak discharge (Q_p) are the governing parameters

Time to peak t_p is estimated as a function of the basin concentration time t_c:

$$tp = 0{,}35 \cdot tc$$



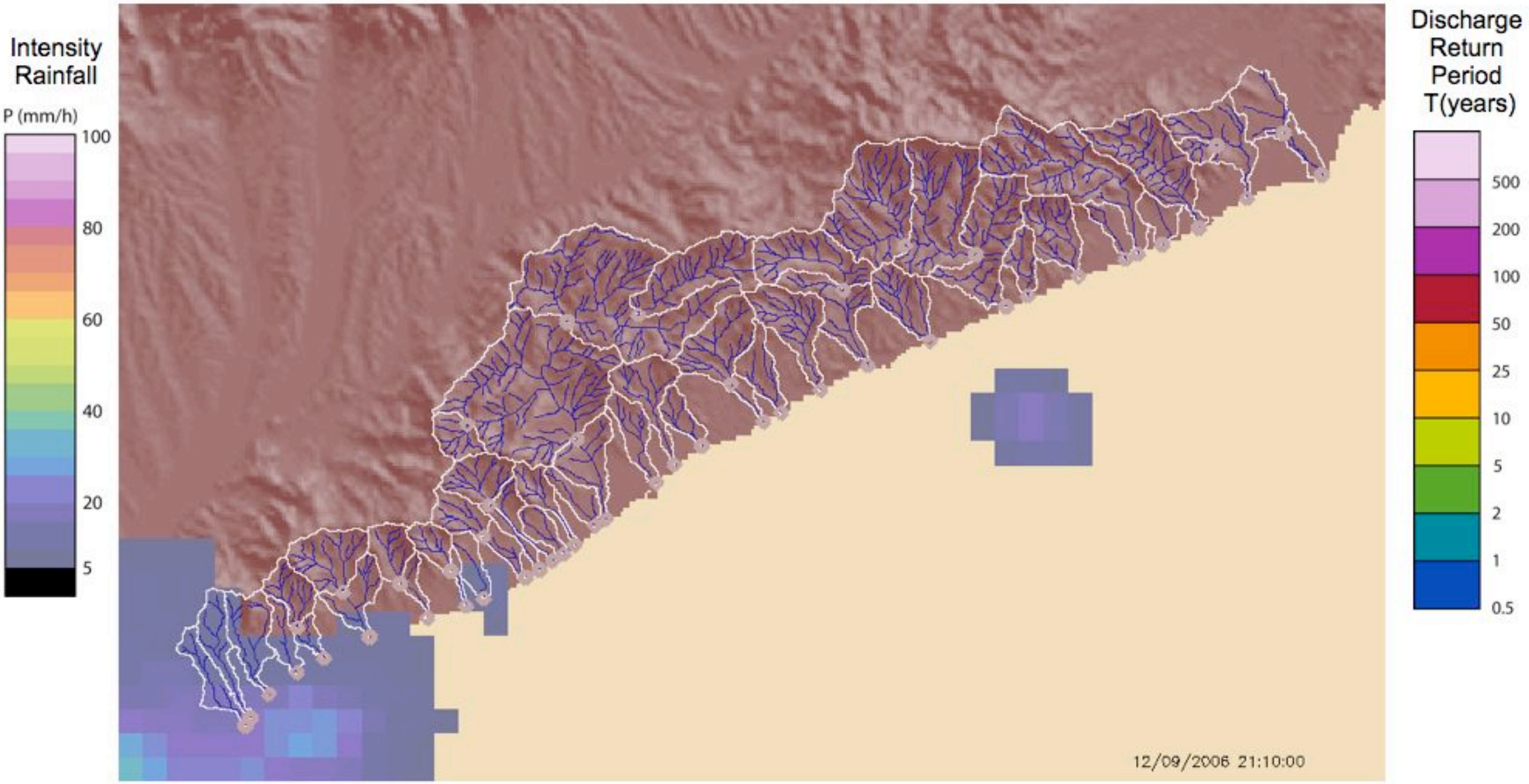
- **Reference Discharges:**

  Estimation of Discharge thresholds associated to Hazard (return periods)

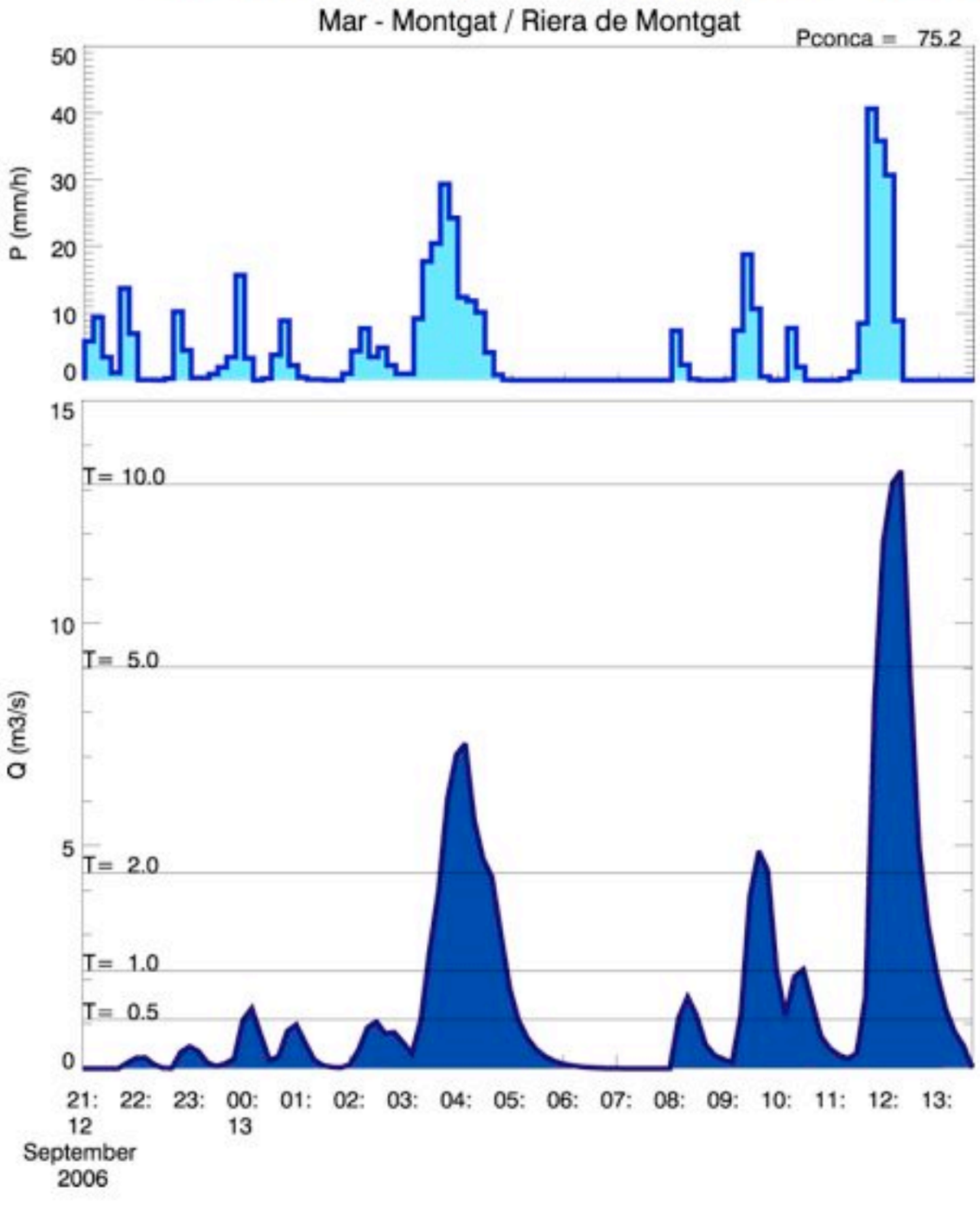
  Rational method (when Ungaged): Reference discharges associated to T=2 and 500 year Return Periods have been estimated using the classical Rational Method at every subbasin.

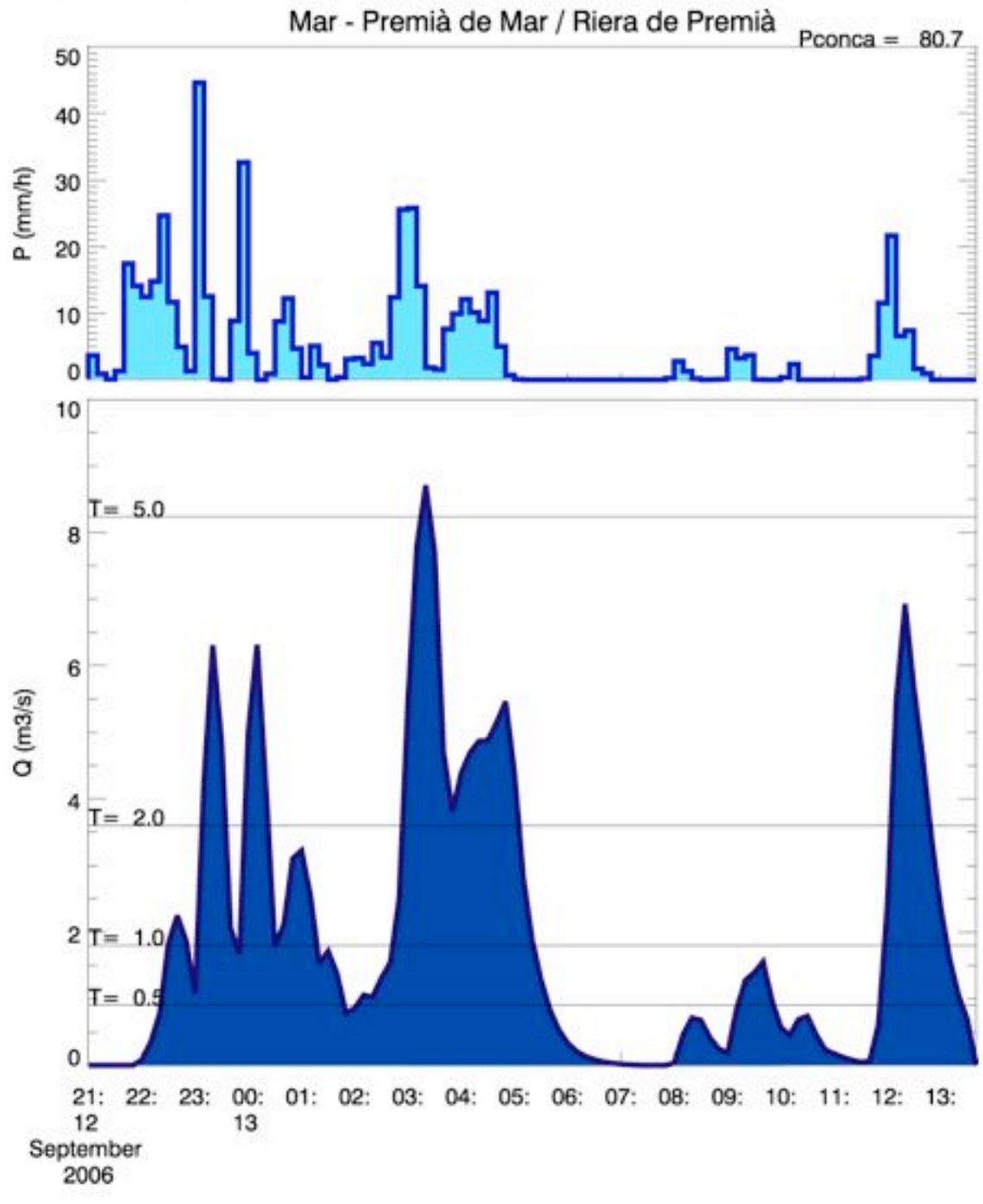
  Discharge frequency analysis (when Gaged): Applied to catchments where historical discharge series are available (streamflow gages).

A Flash Flood Basin case: Maresme, 12 Set 2006. Radar rainfields



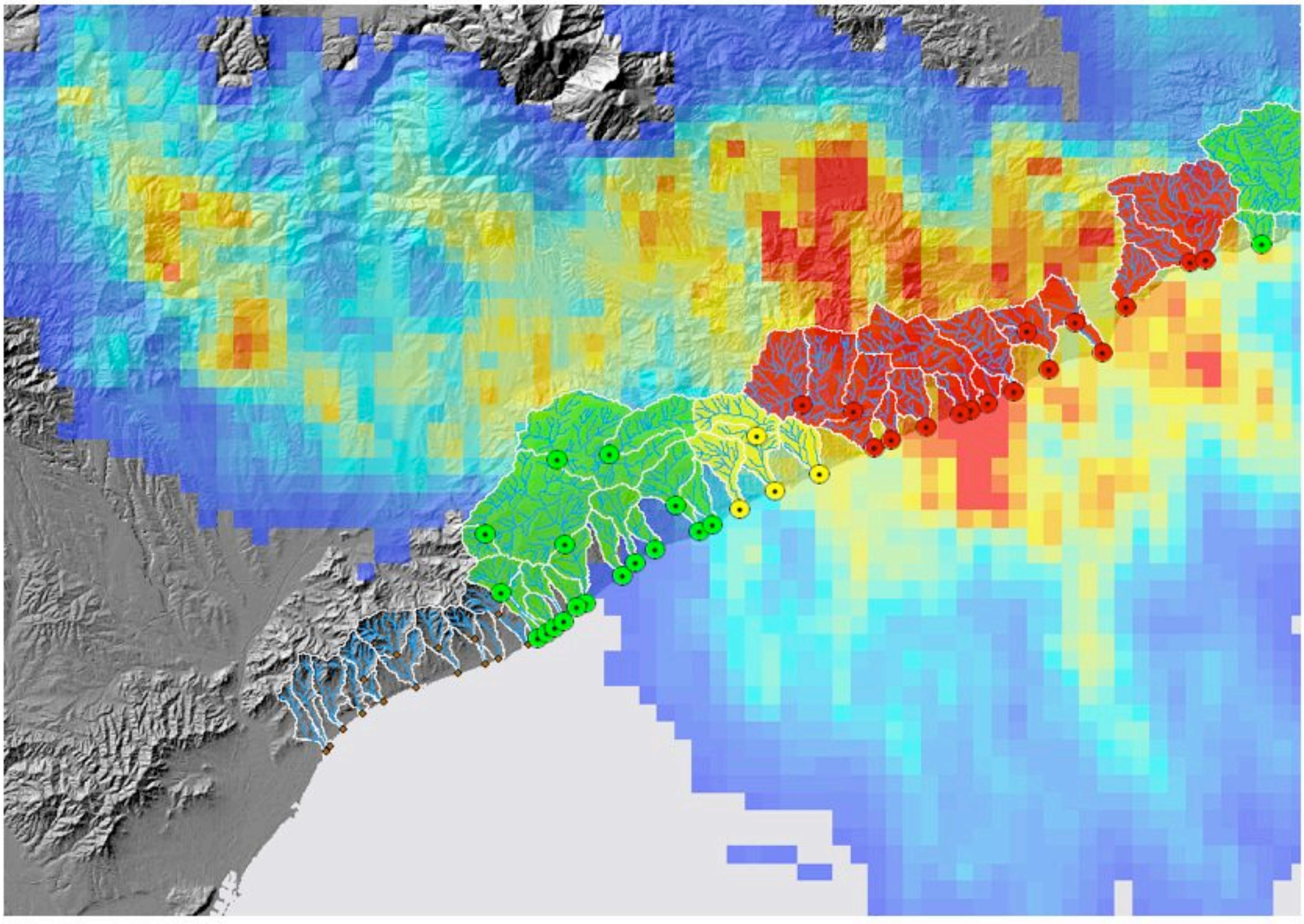
A Flash Flood Basin case: Maresme, 12 Set 2006. Radar rainfields





- Simulated Hydrographs

Pronóstico Hidrometeorológico



- Flash Flood Warning System in ungagged basins

PREVISIÓN PROBABILÍSTICA

Effect of the interaction of both sources of uncertainty on the hydrological modelling

A study of the uncertainty related to hydrological modelling

Monte Carlo simulation

Monte Carlo simulation

***n* parameter sets**

(n = 5000)

Monte Carlo simulation

***n* parameter sets**

(n = 5000)

↓

Run model

Monte Carlo simulation

***n* parameter sets**

(n = 5000)

↓

Run model

↓

***n* simulations**

Monte Carlo simulation

***n* parameter sets**

(n = 5000)

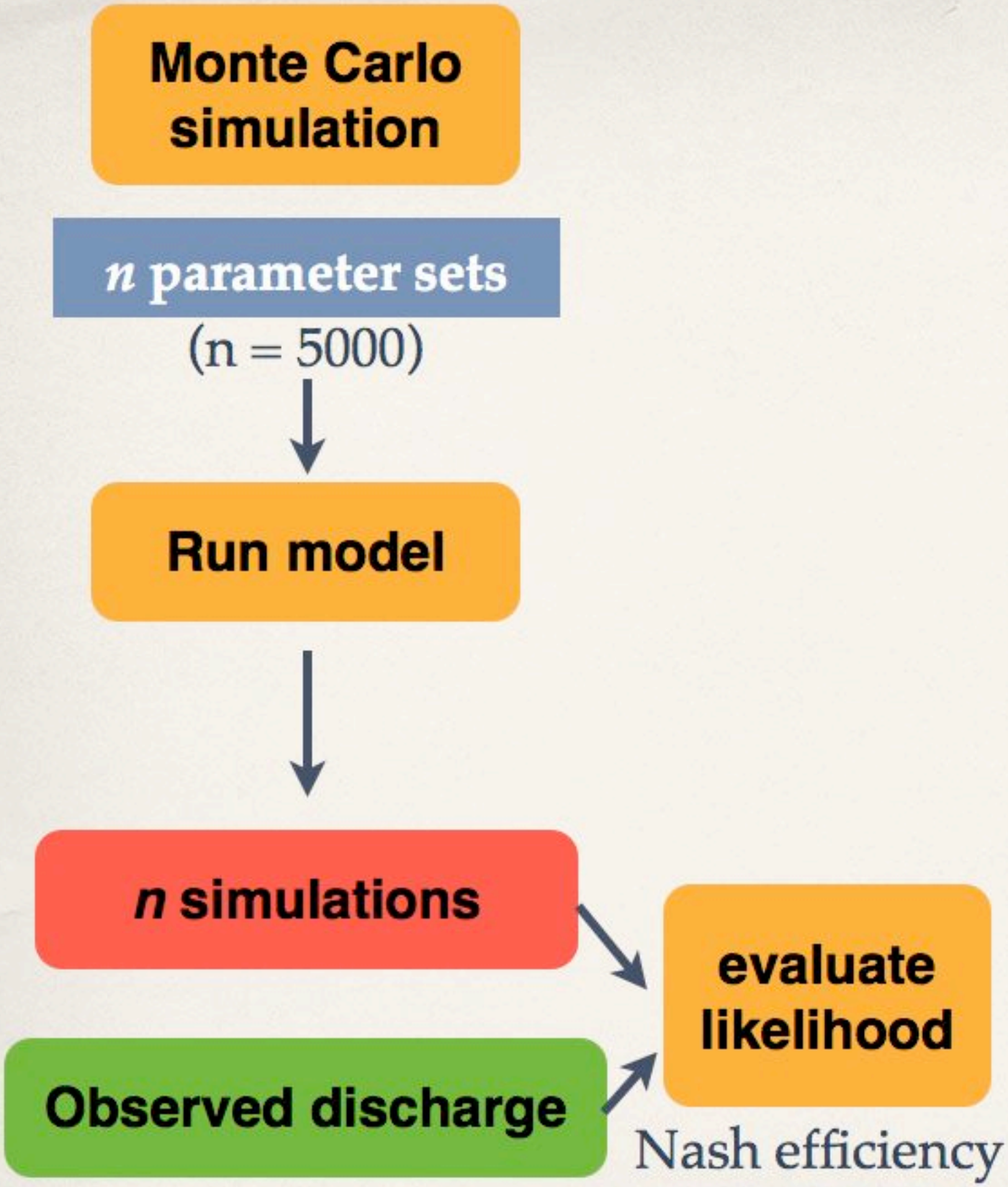
↓

Run model

↓

***n* simulations**

Observed discharge


Monte Carlo simulation
n parameter sets
(n = 5000)
Run model
n simulations
Observed discharge
evaluate likelihood
Nash efficiency

Monte Carlo simulation

***n* parameter sets**

(n = 5000)

Run model

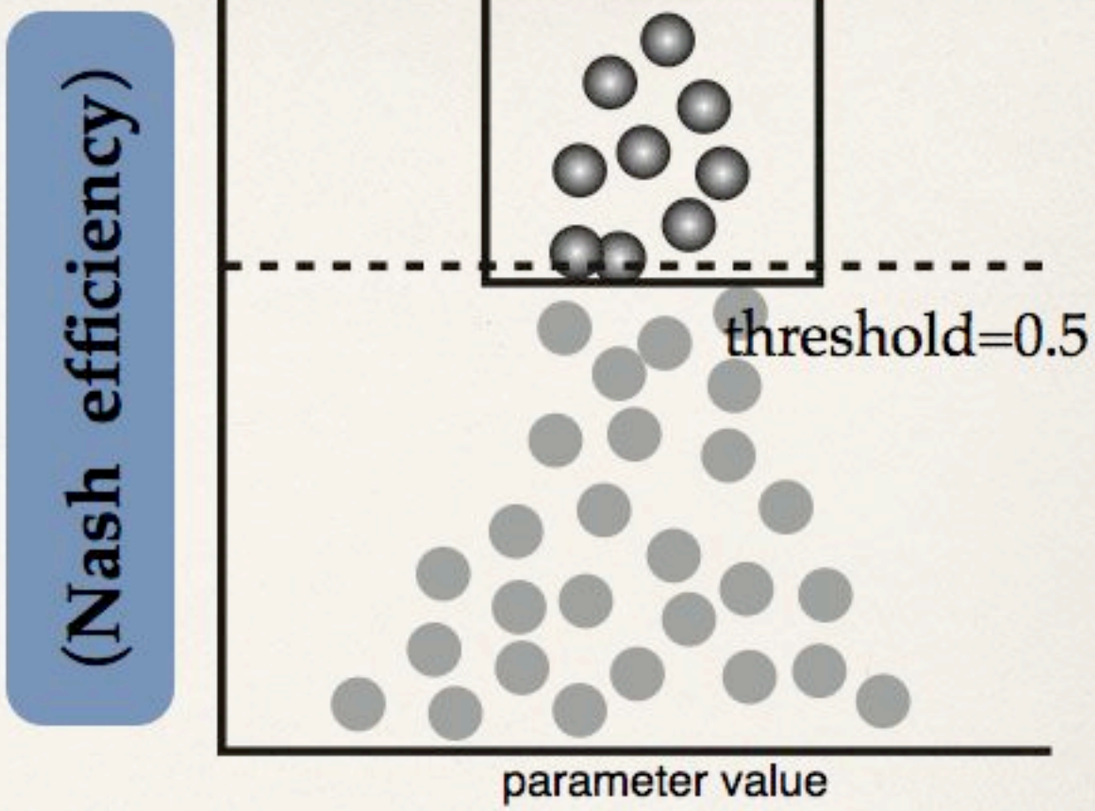
***n* simulations**

Observed discharge

evaluate likelihood

Nash efficiency

Acceptable parameter sets



Monte Carlo simulation

***n* parameter sets**

(n = 5000)

Run model

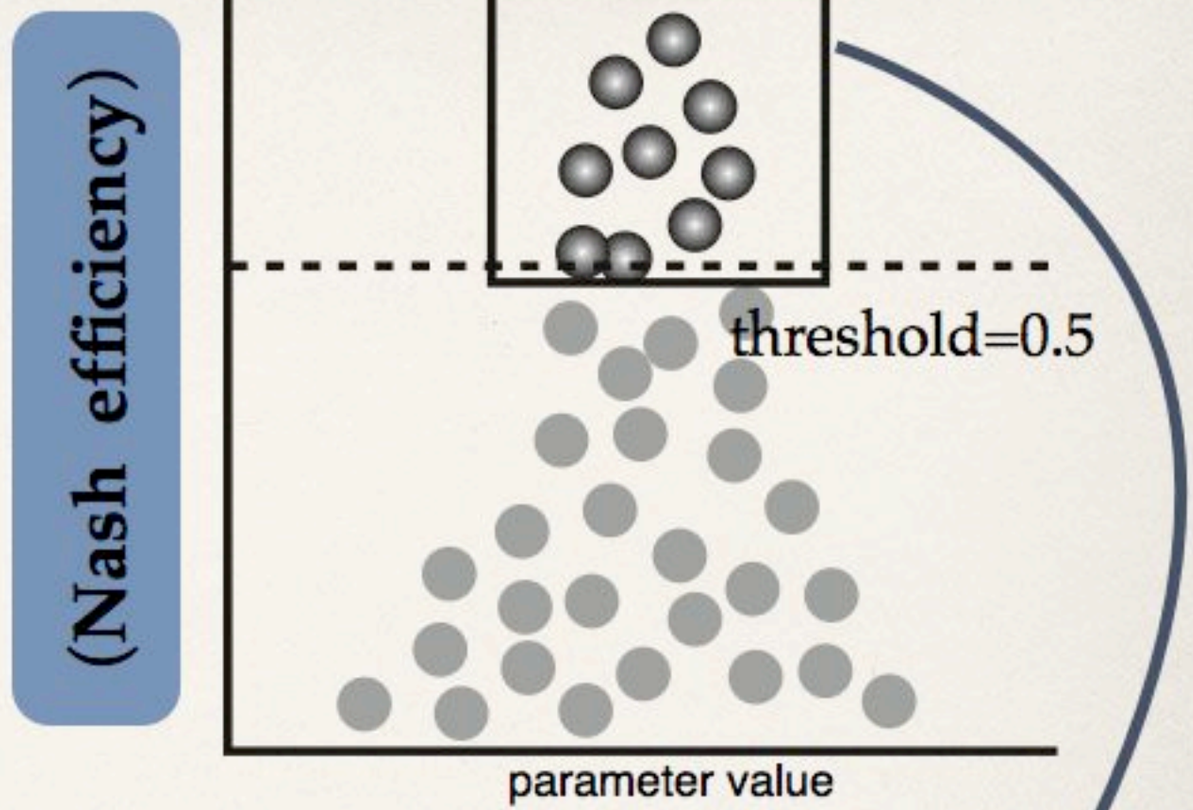
***n* simulations**

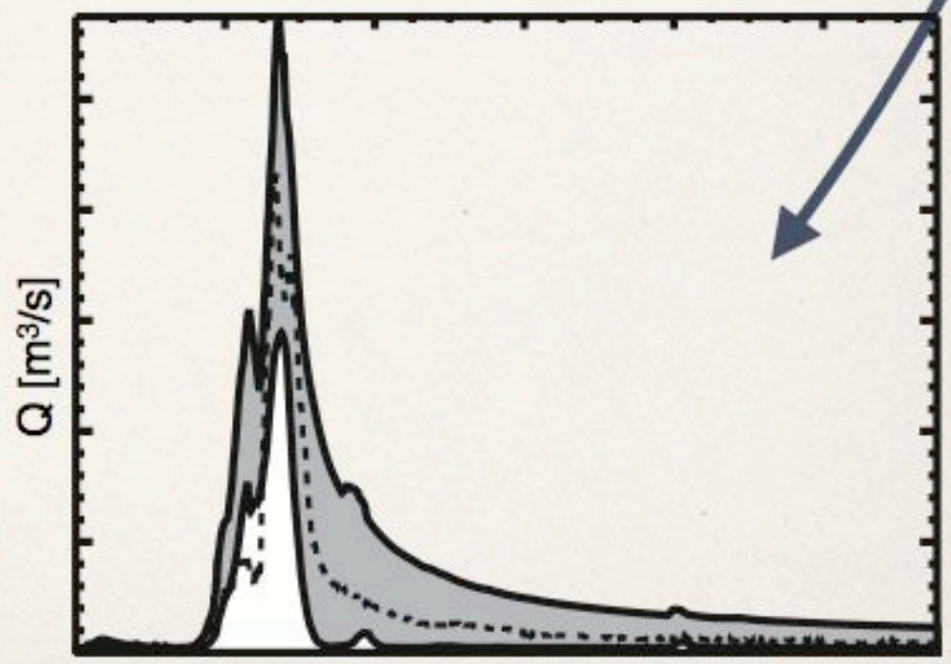
Observed discharge

evaluate likelihood

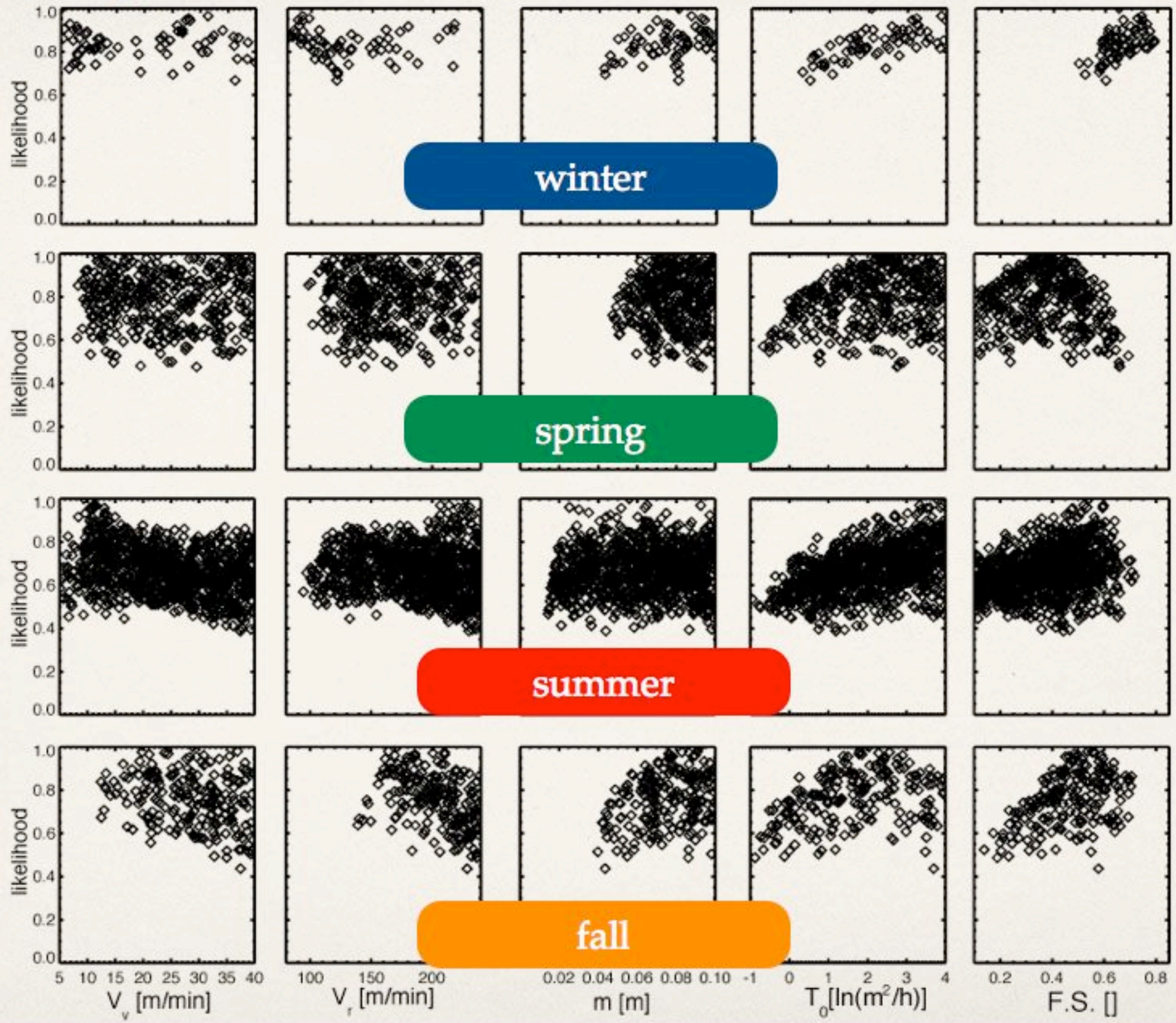
Nash efficiency

Acceptable parameter sets

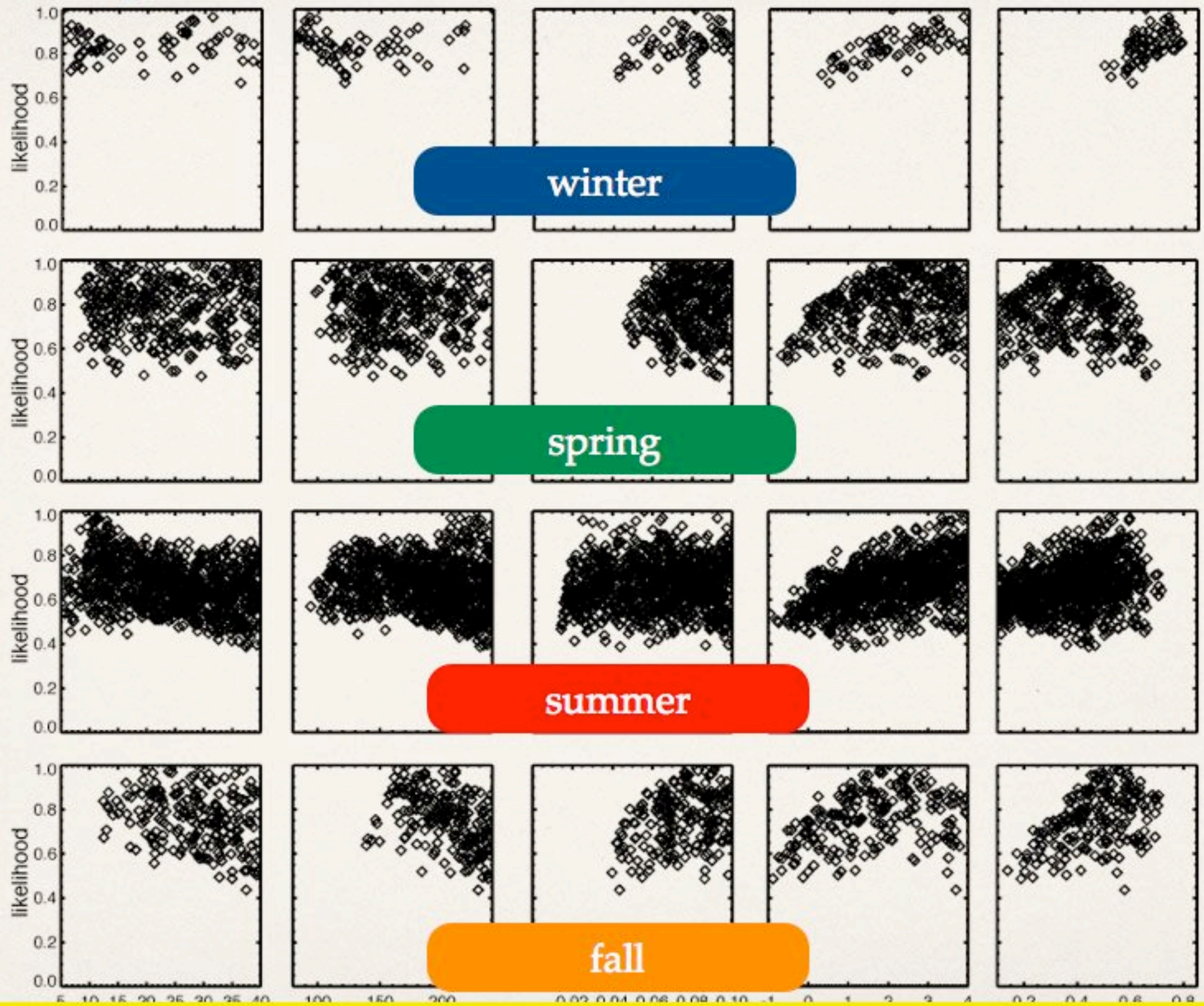




Model parameter distribution

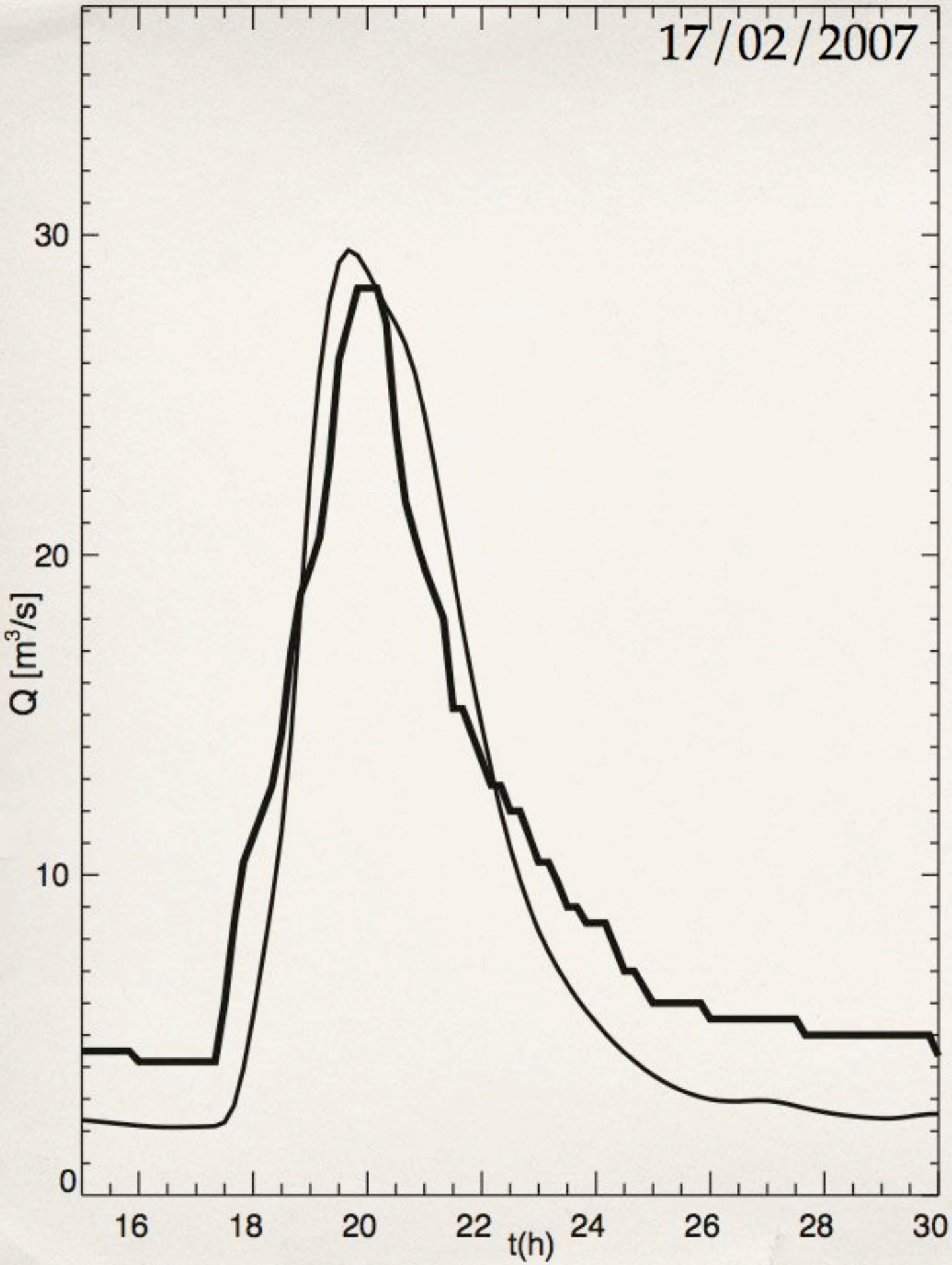


Model parameter distribution



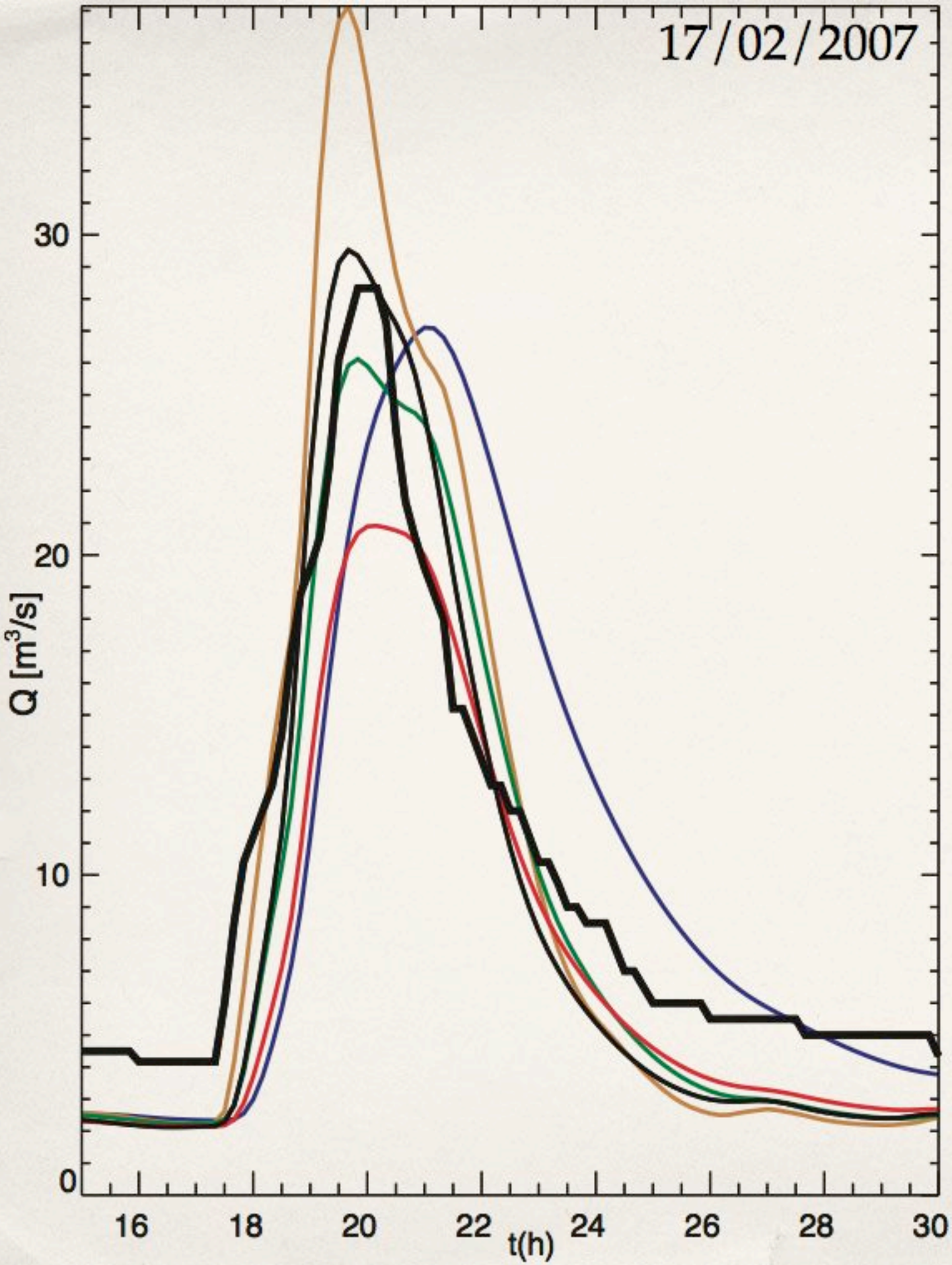
Gain knowledge about parameter distribution for specific scenarios

calibration results



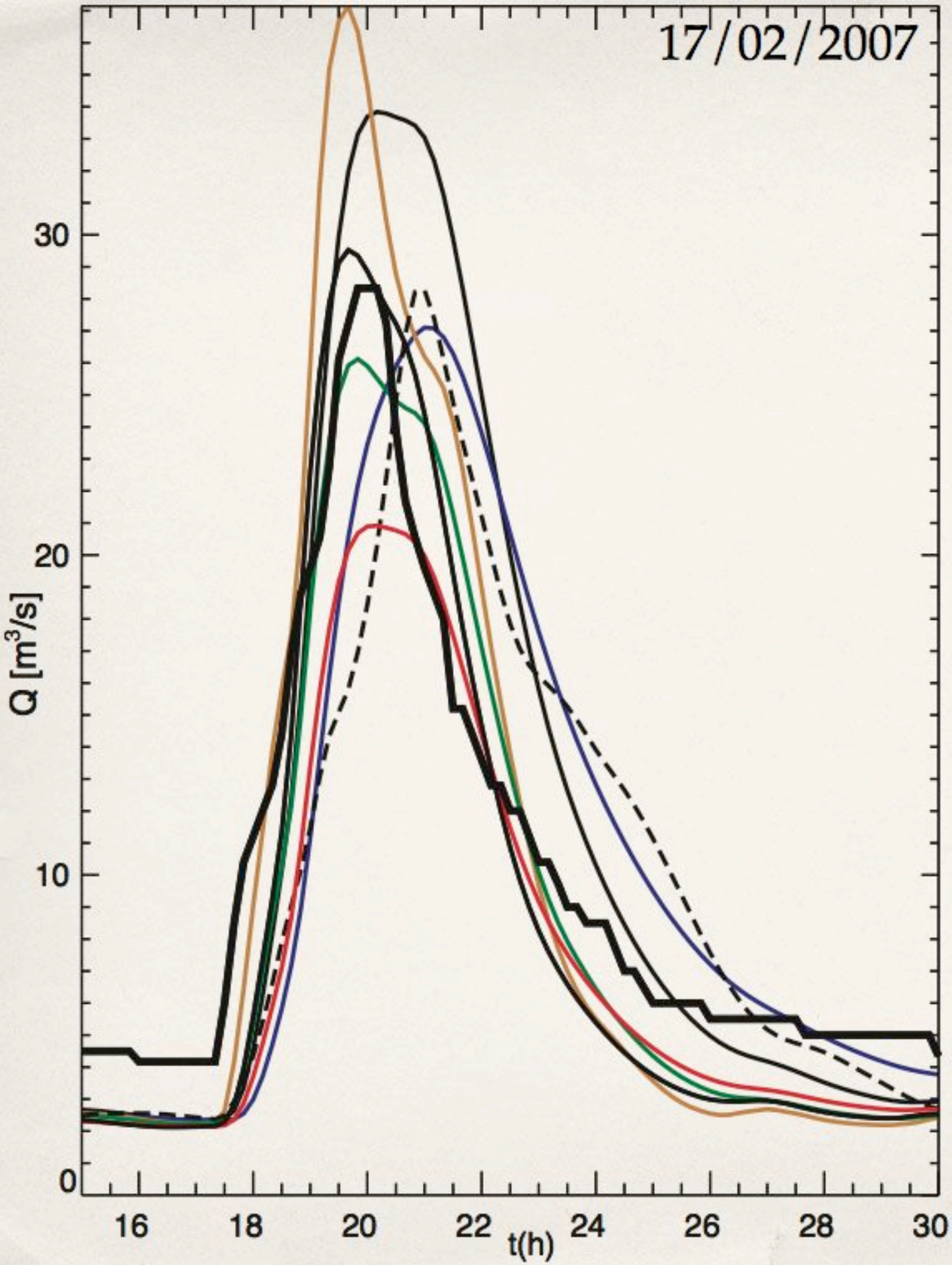
obs

global



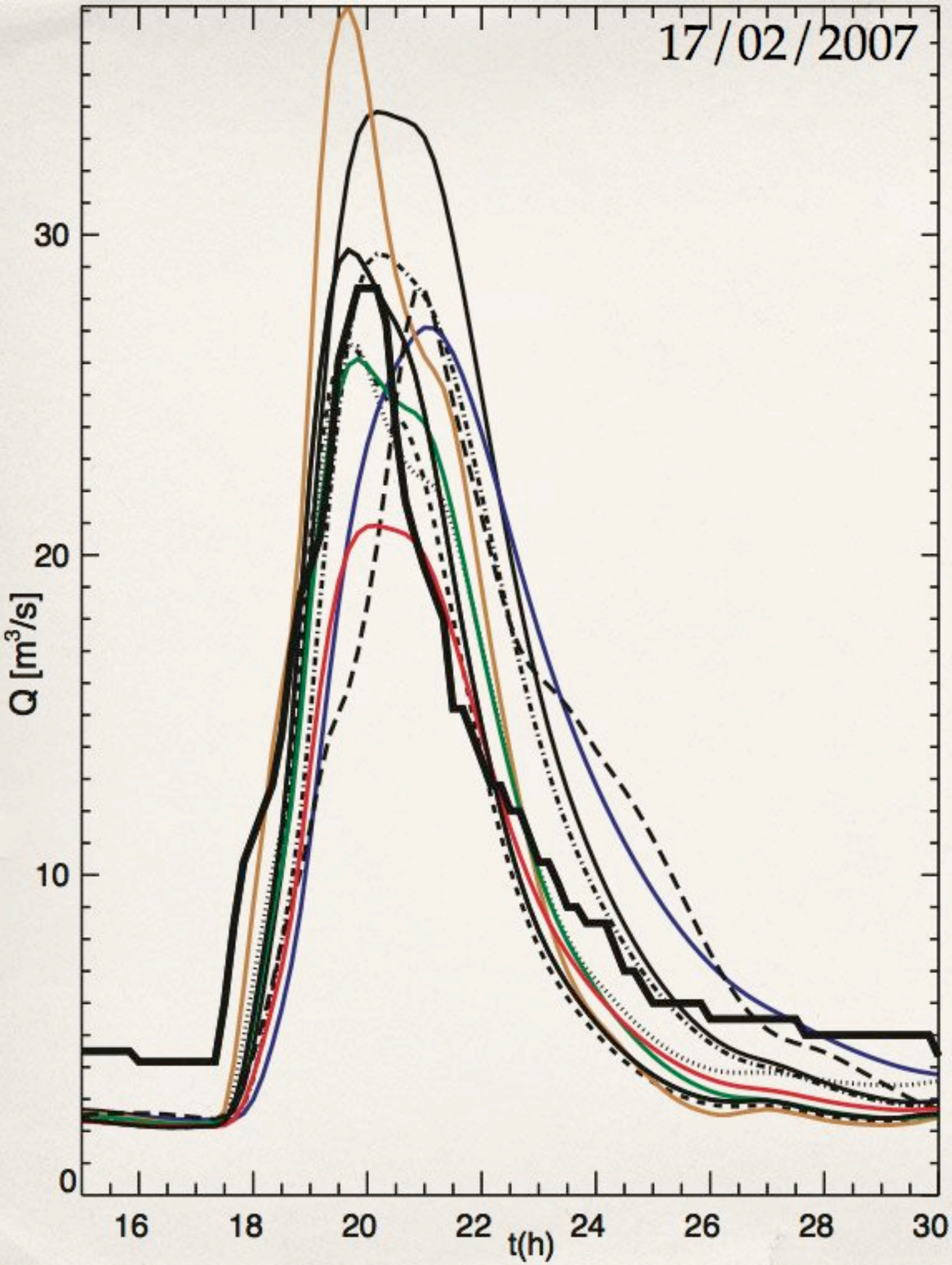
calibration results

- obs
- global
- winter
- spring
- summer
- fall



calibration results

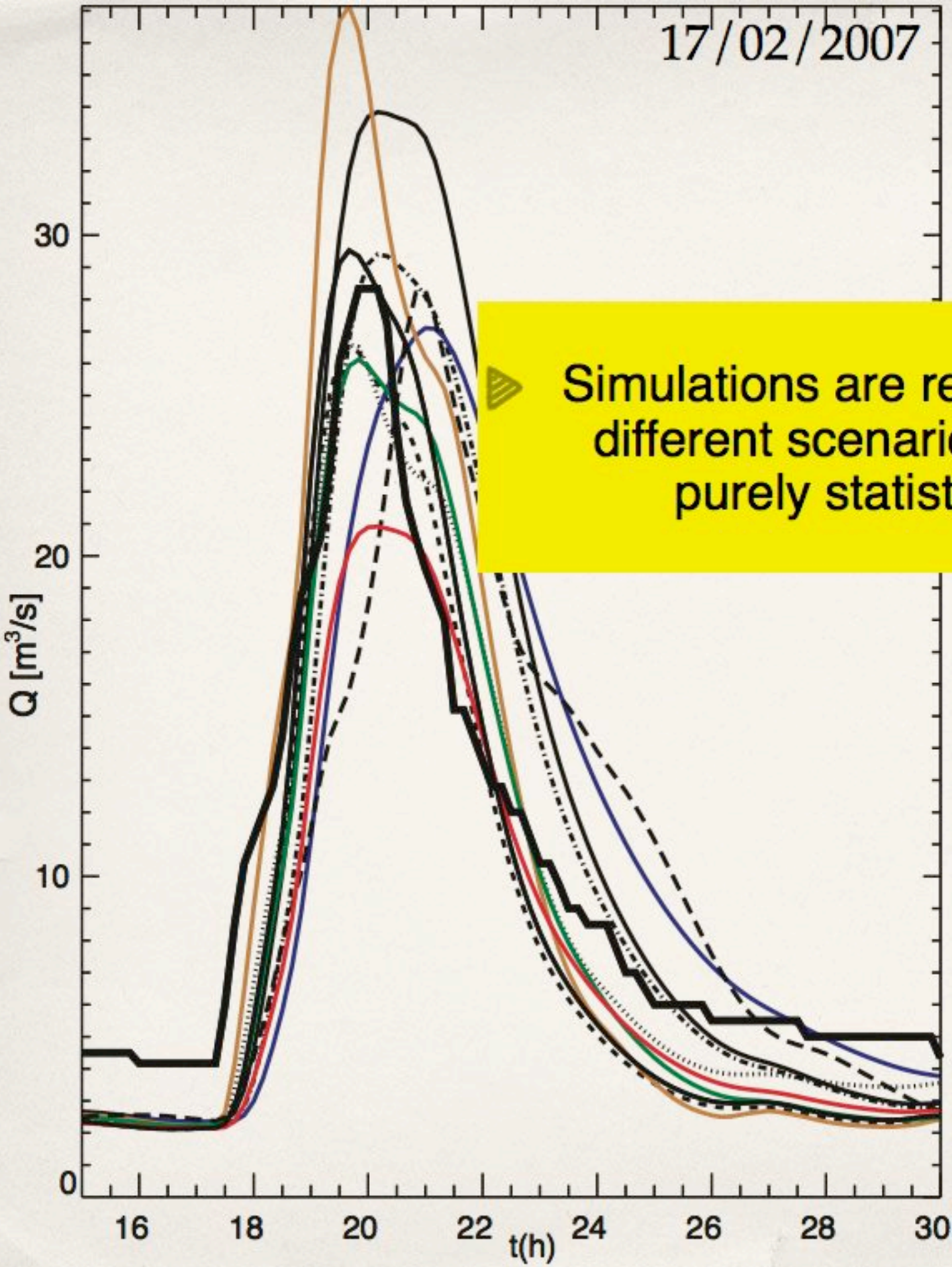
- obs
- global
- winter
- spring
- summer
- fall
- uzs(1)
- uzs(2)



calibration results

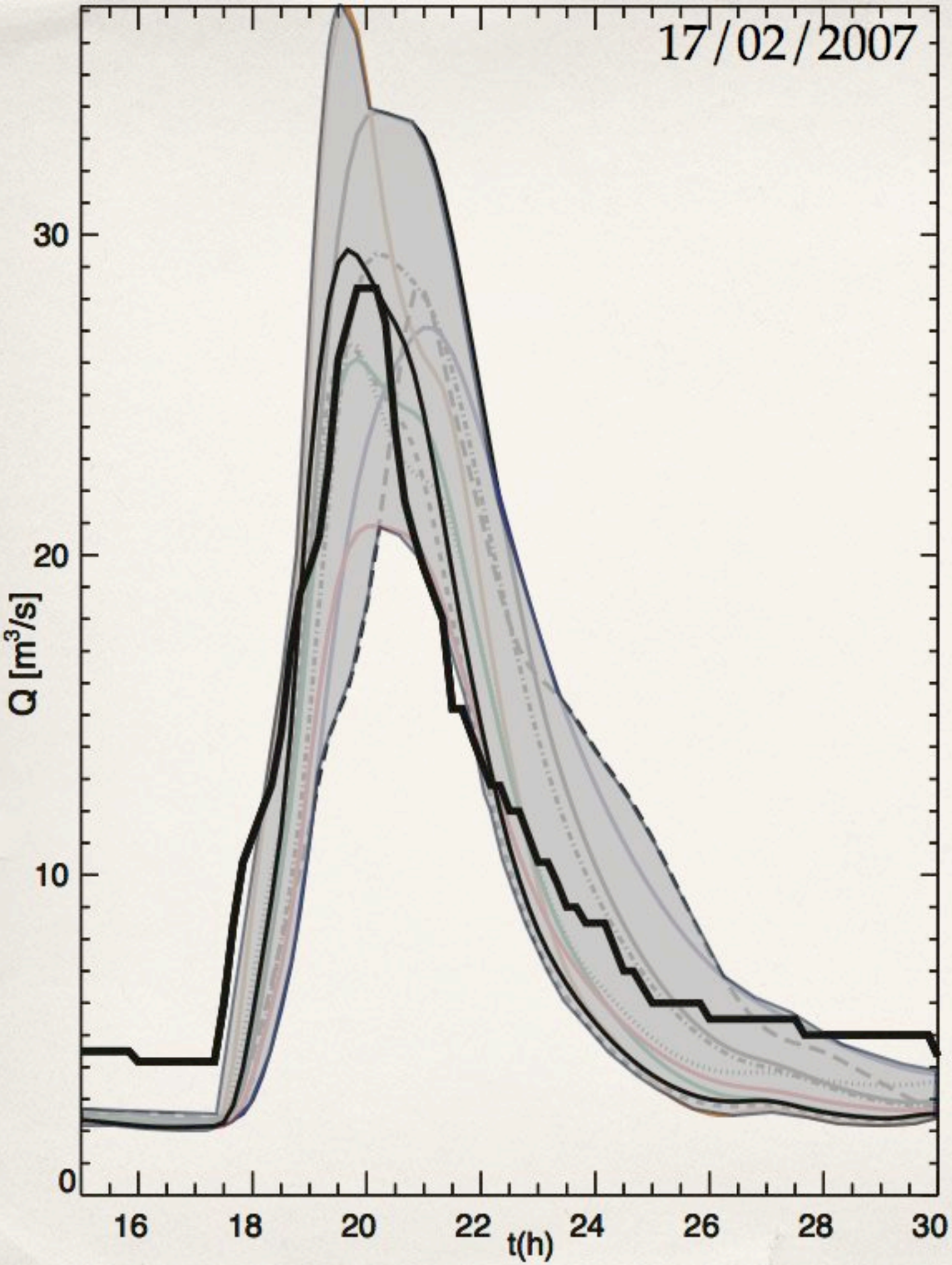
- obs
- global
- winter
- spring
- summer
- fall
- uzs(1)
- uzs(2)
- runoff(1)
- runoff(2)
- runoff(3)

calibration results



Simulations are related to different scenarios, not purely statistics

- obs
- global
- winter
- spring
- summer
- fall
- uzs(1)
- uzs(2)
- runoff(1)
- runoff(2)
- runoff(3)



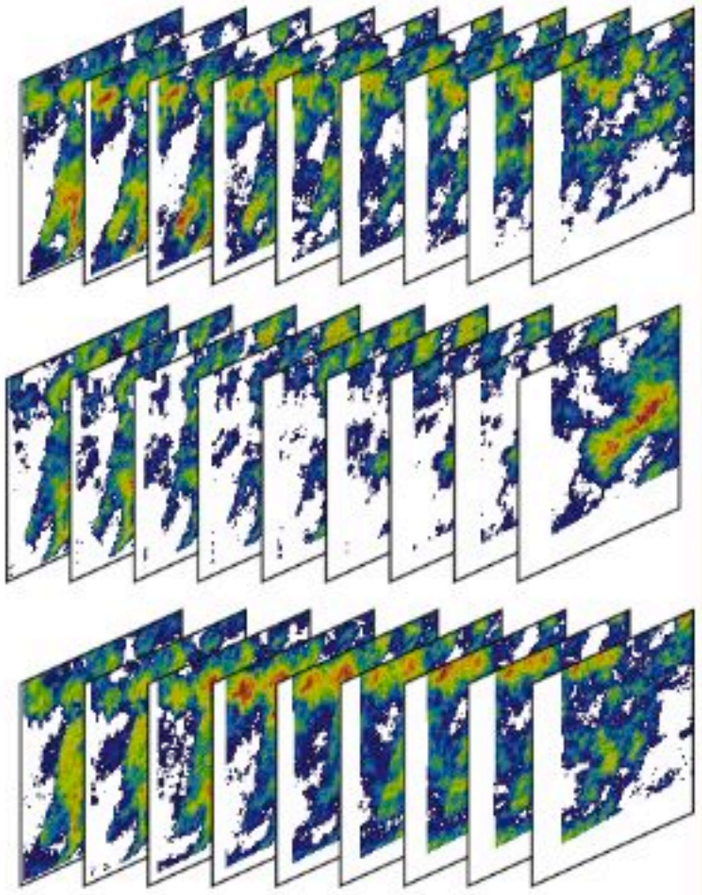
calibration results

obs

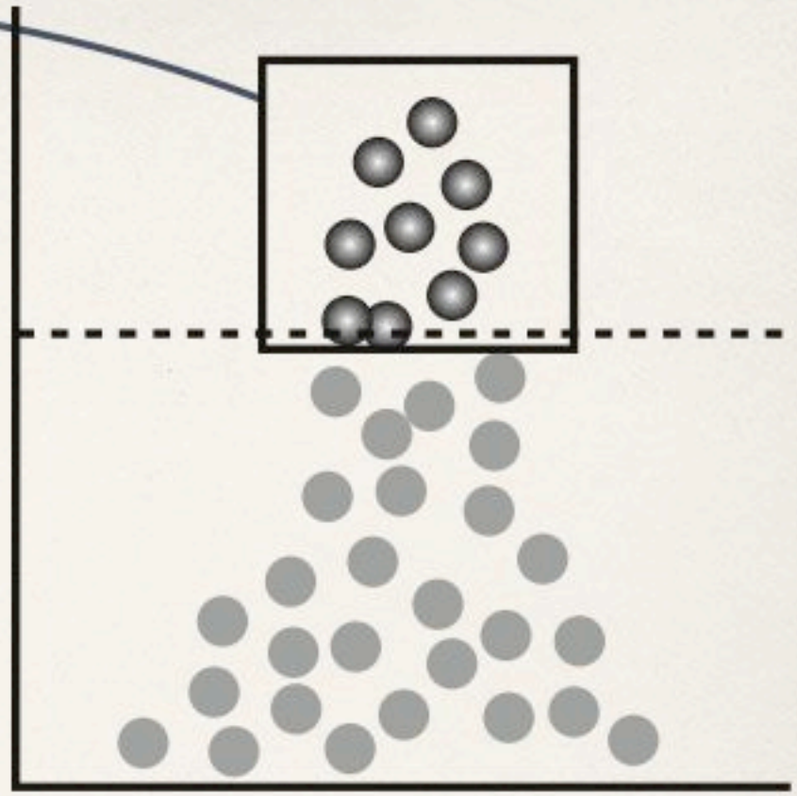
global

simulation limits (5-95%)

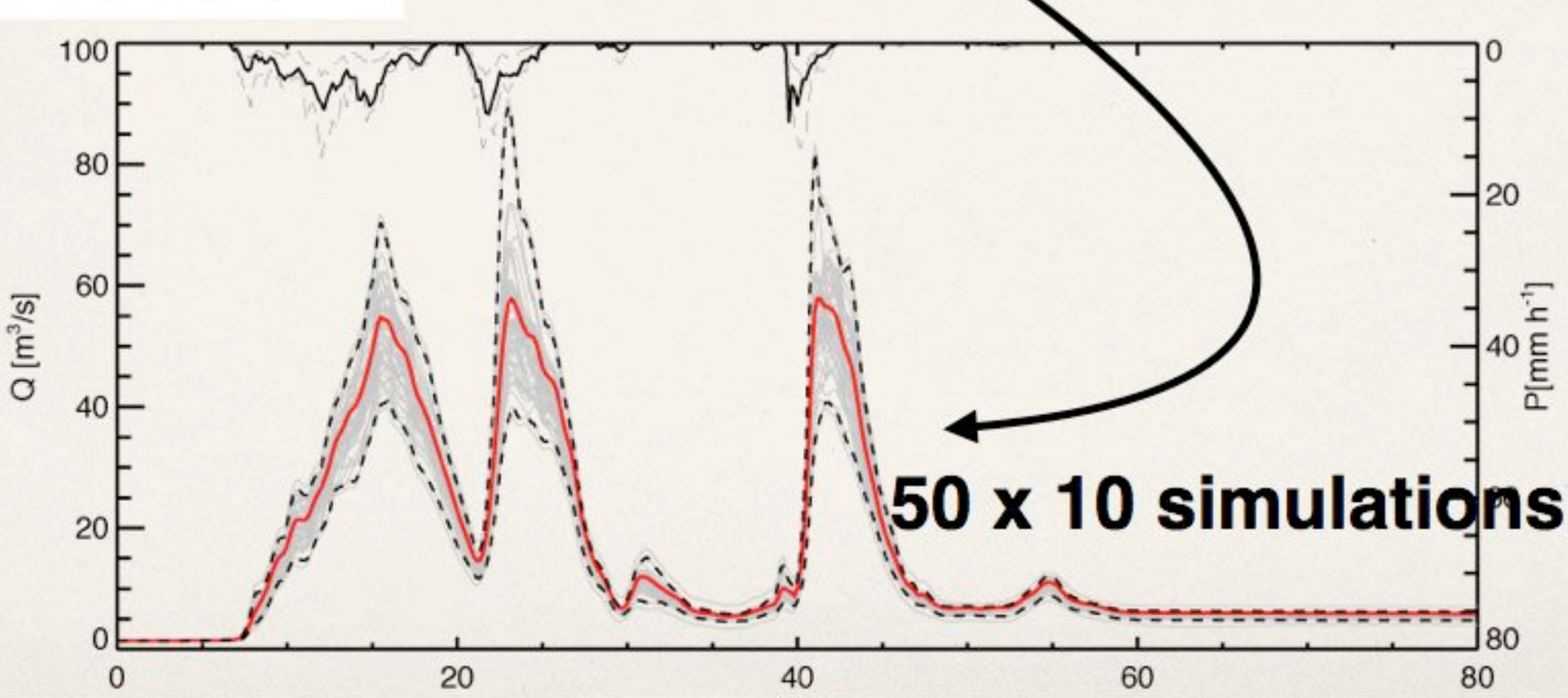
50 ensemble members



10 acceptable parameter sets

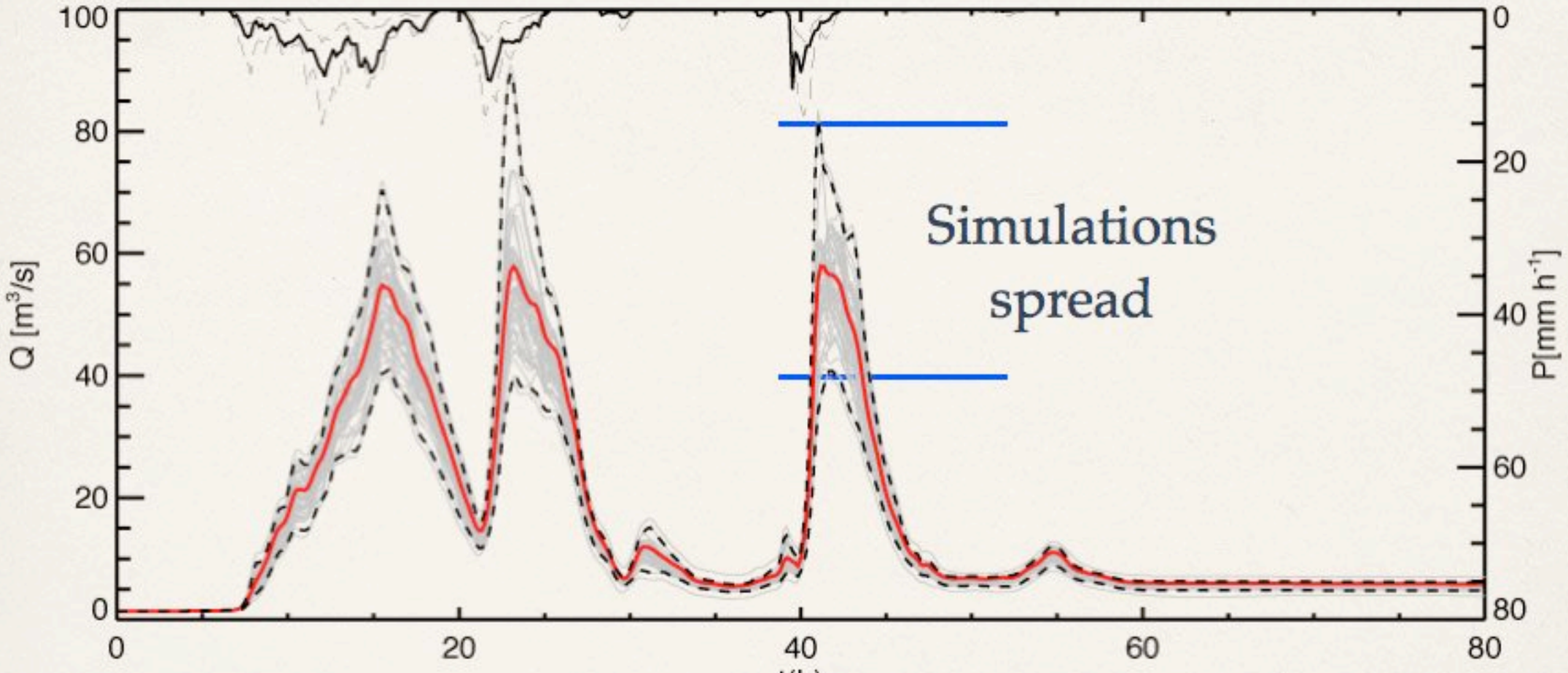


Hydrological model



50 x 10 simulations

Quantifying the effect of uncertainty

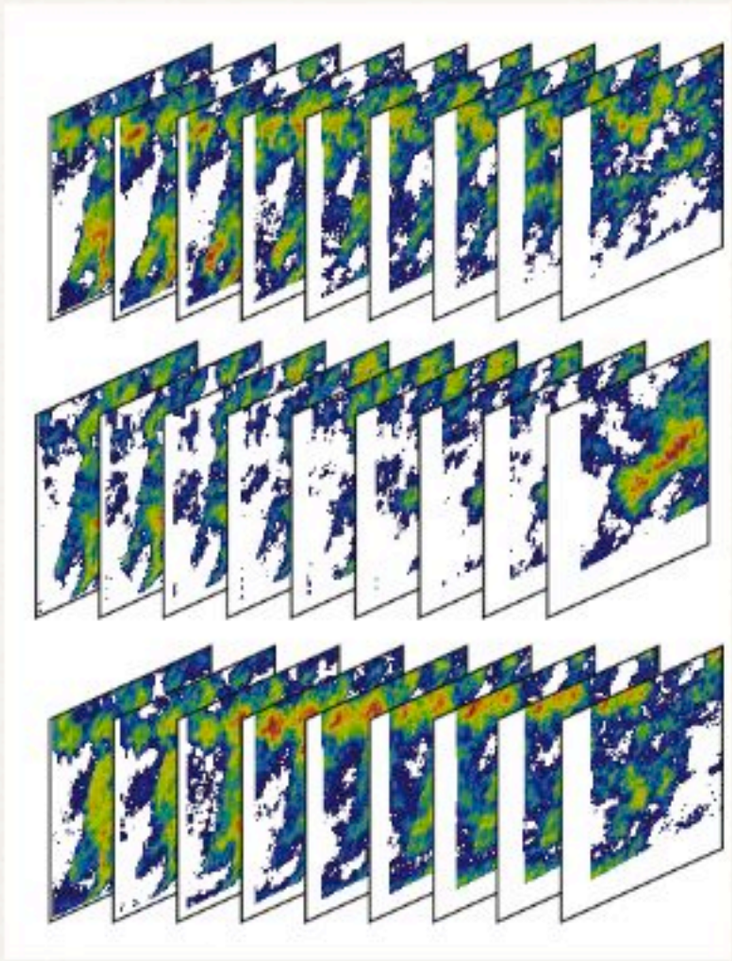


Mean Spread

$$\bar{D}_Q = \frac{\bar{Q}_{90} - \bar{Q}_{10}}{\bar{Q}_{Pobs}}$$

Framework for comparing the different effects

50 ensemble members

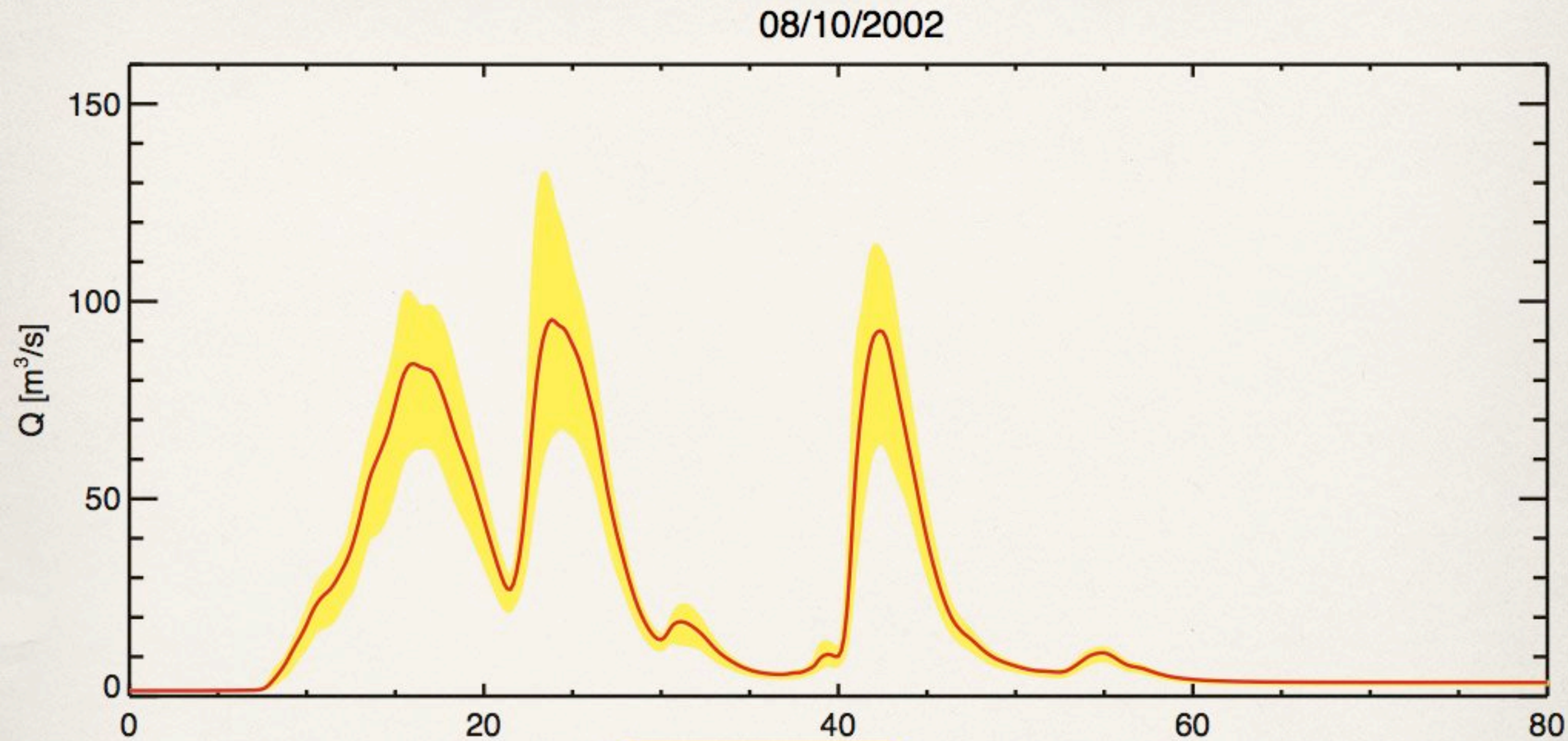


X

- Optimal model parameter set

Global Calibration

Framework for comparing the different effects

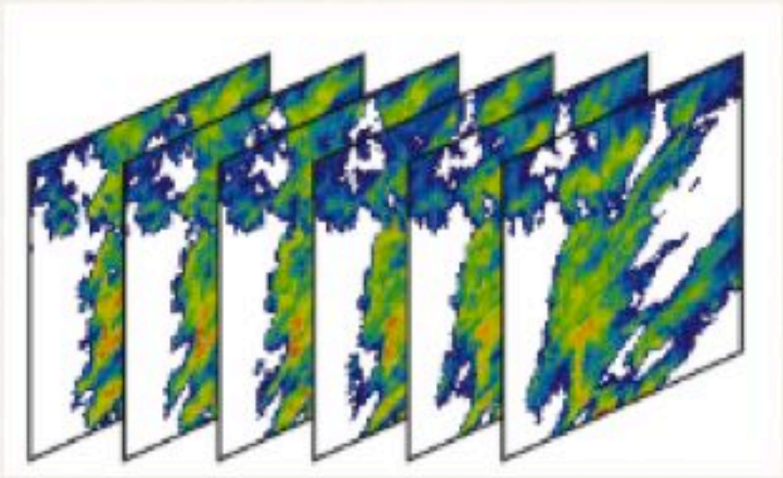


Q (Observed P. + optimal parameter set)

precipitation uncertainty effect

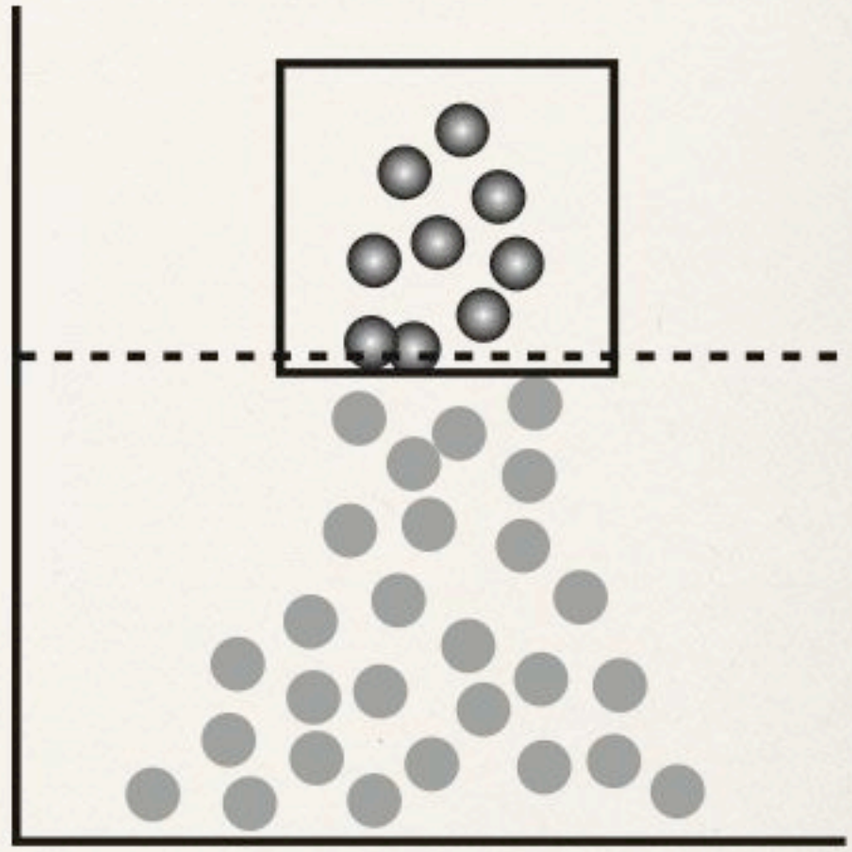
Framework for comparing the different effects

Observed Precipitation

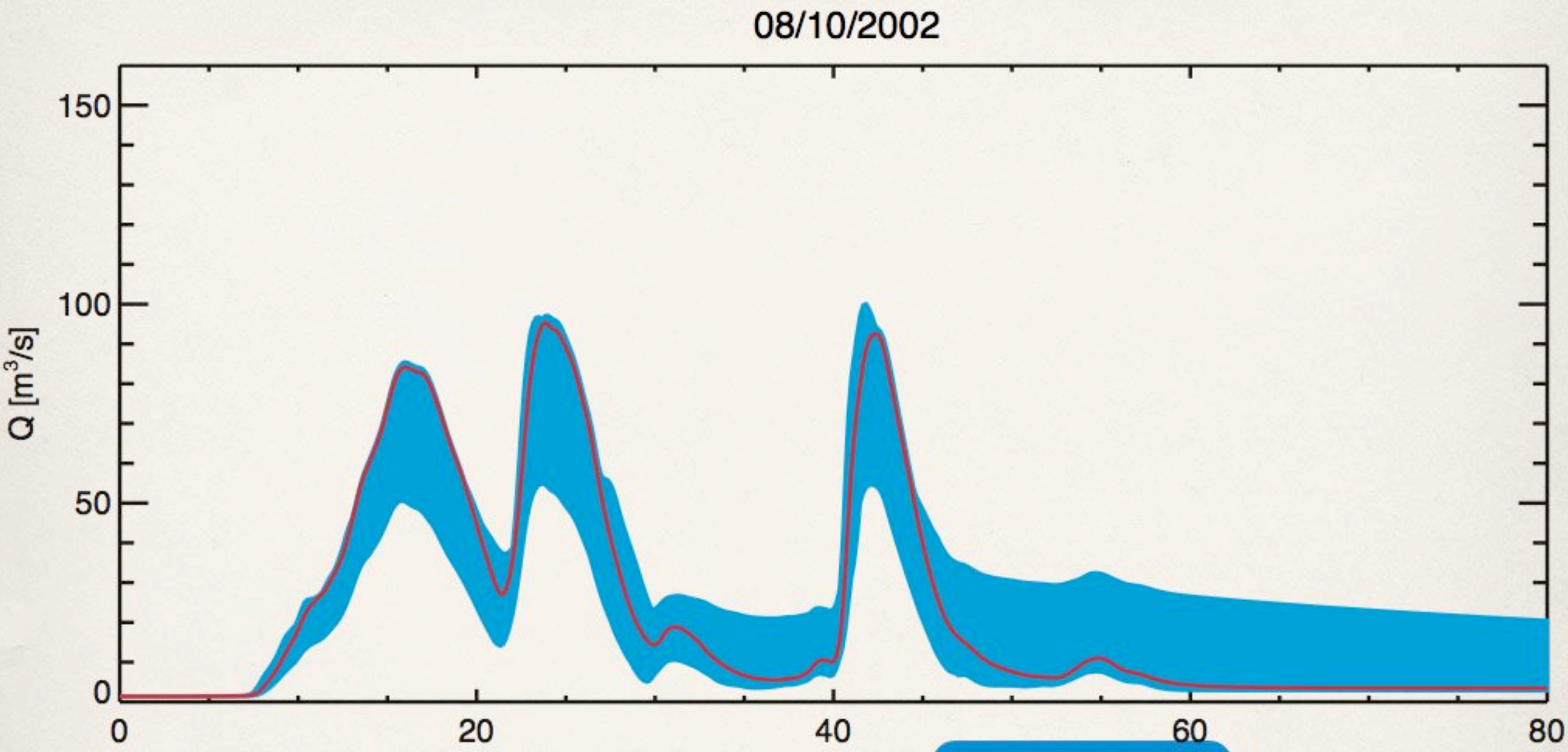


X

10 acceptable parameter sets



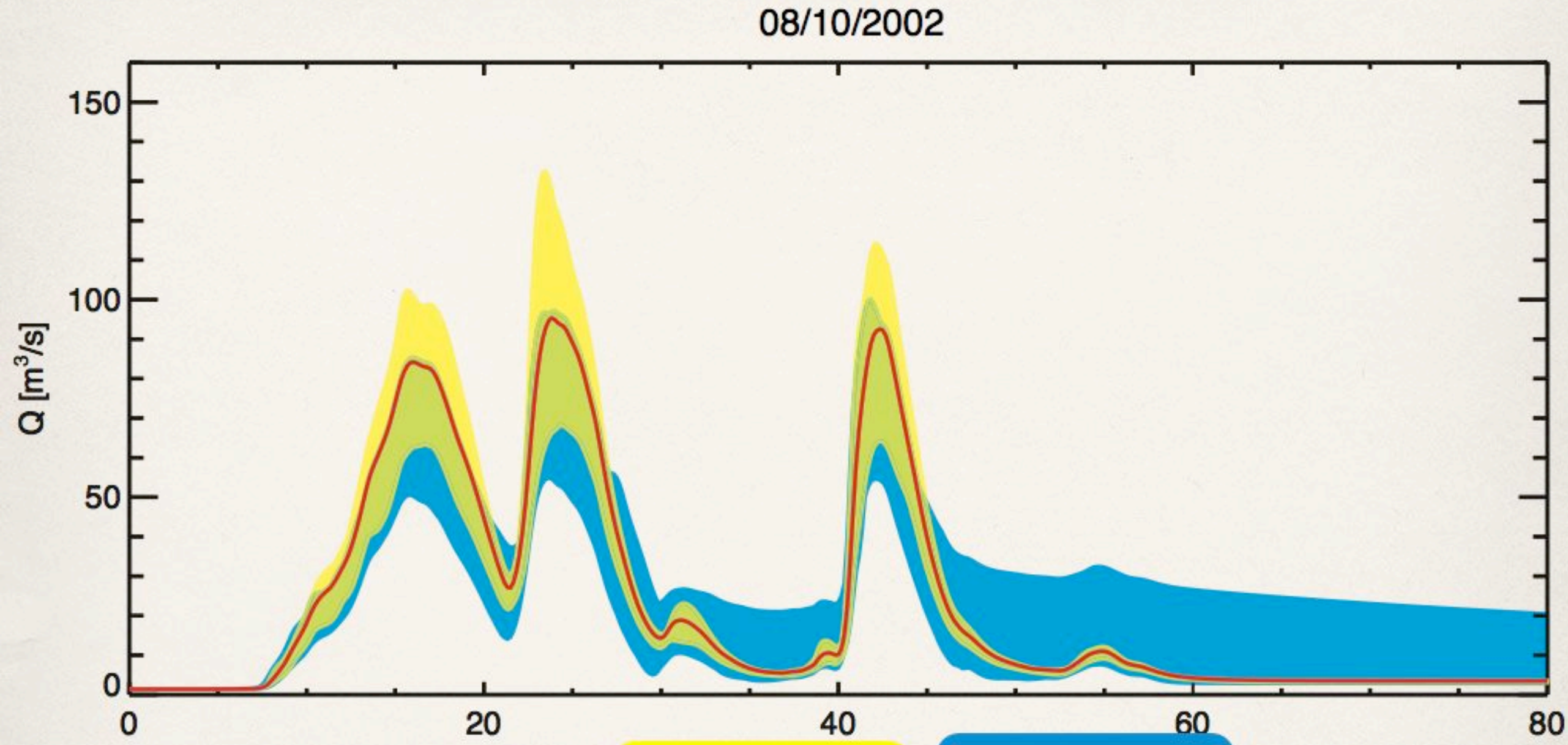
Framework for comparing the different effects



Q (Observed P. + optimal parameter set)

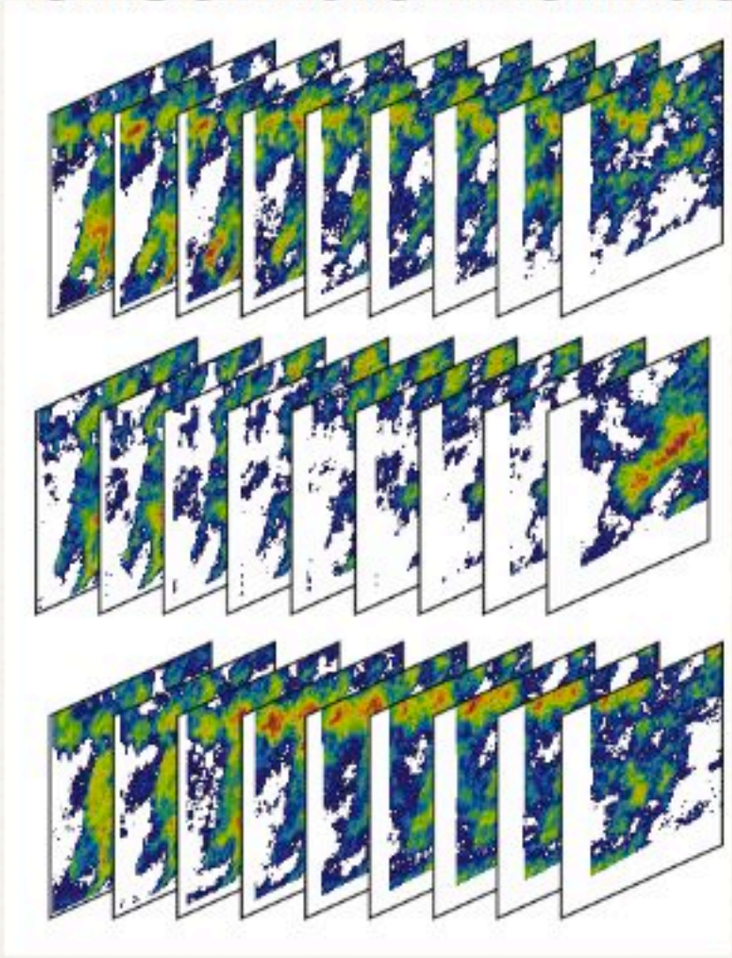
parameter uncertainty effect

Framework for comparing the different effects



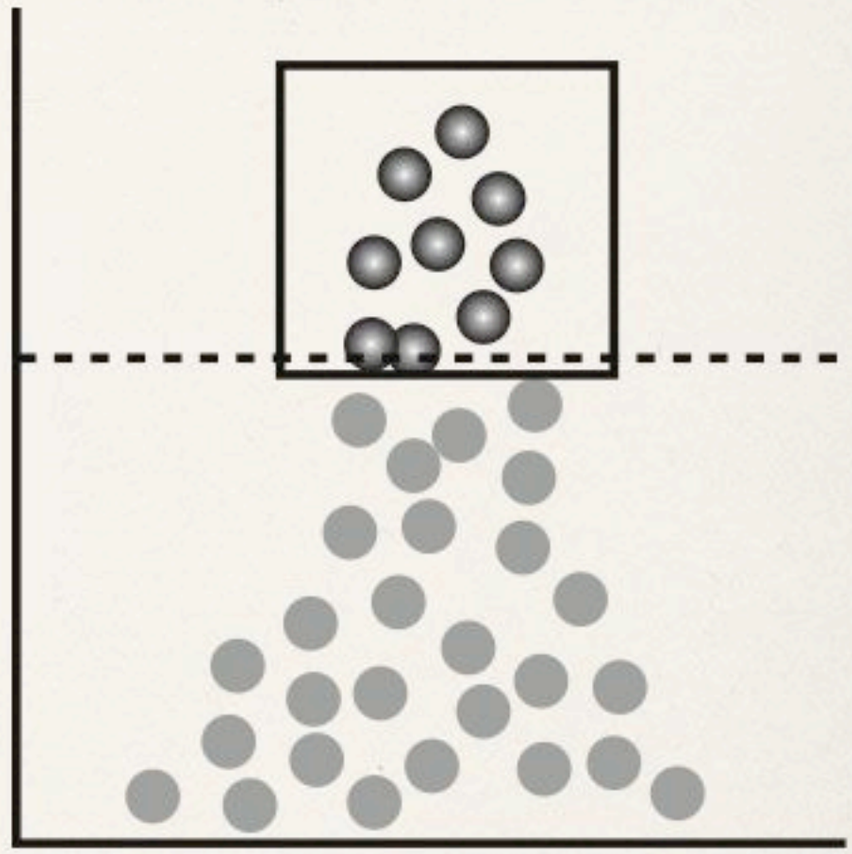
Framework for comparing the different effects

50 ensemble members

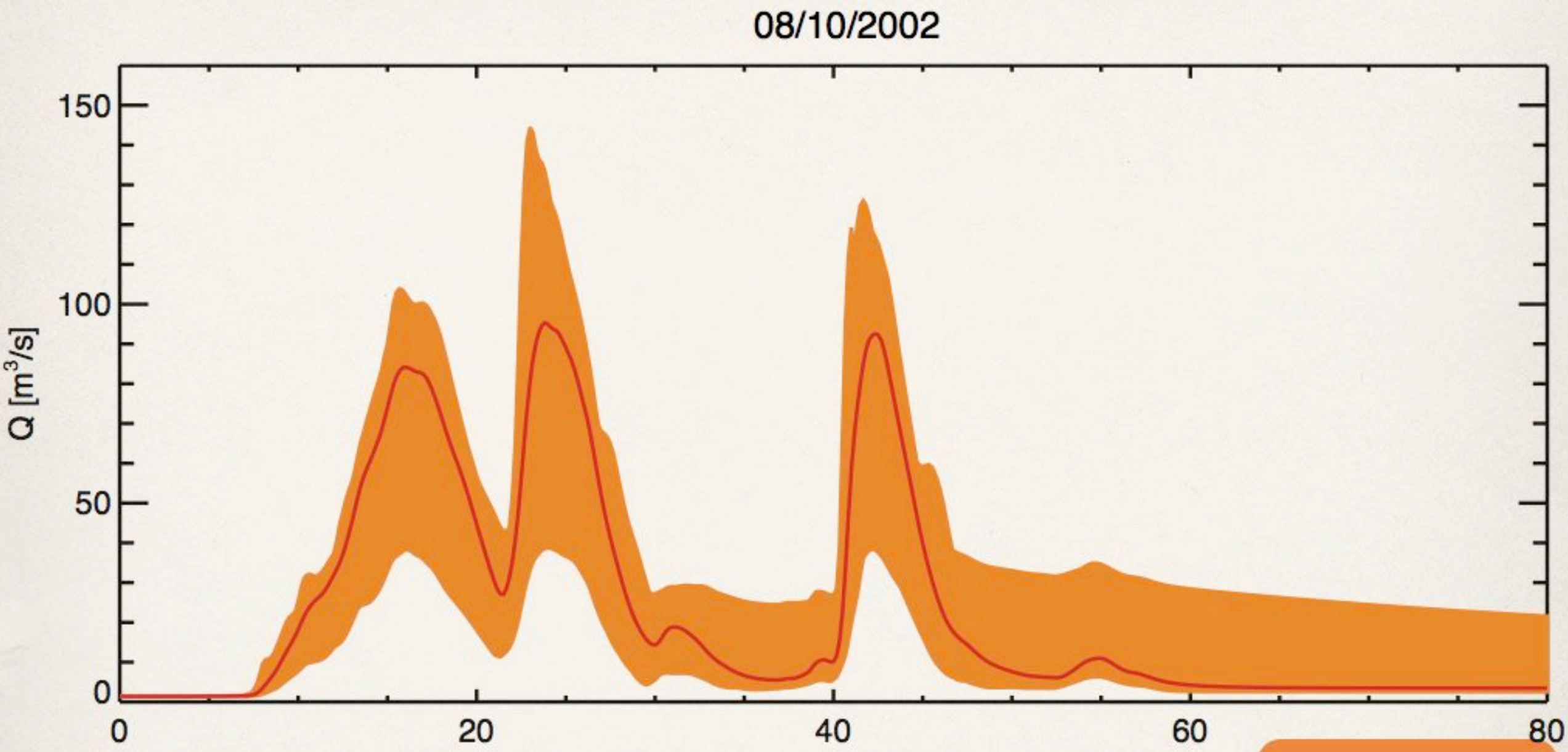


X

10 acceptable parameter sets



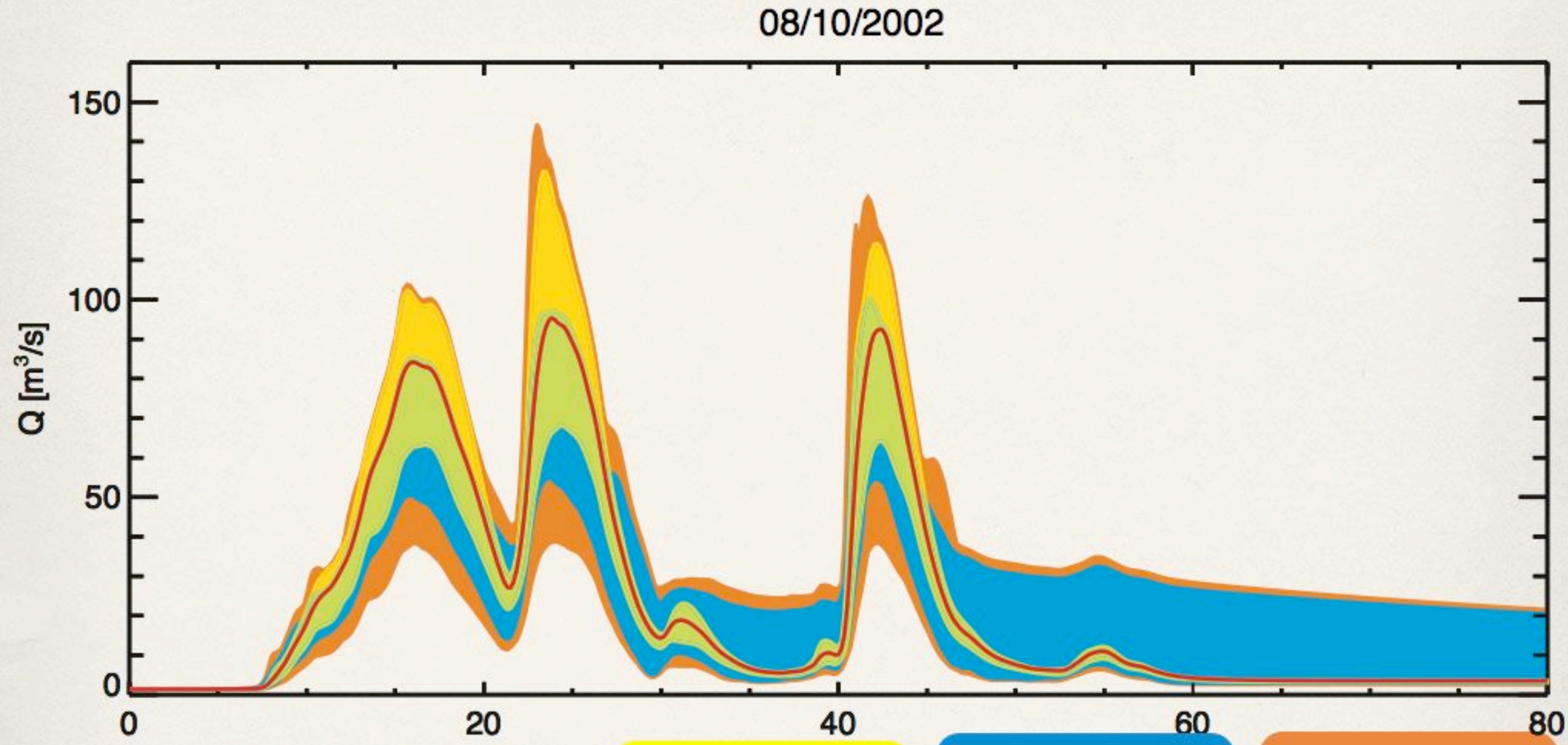
Framework for comparing the different effects



Q (Observed P. + optimal parameter set)

interaction uncertainties effect

Framework for comparing the different effects



Q (Observed P. + optimal parameter set)

precipitation uncertainty effect

parameter uncertainty effect

interaction uncertainties effect

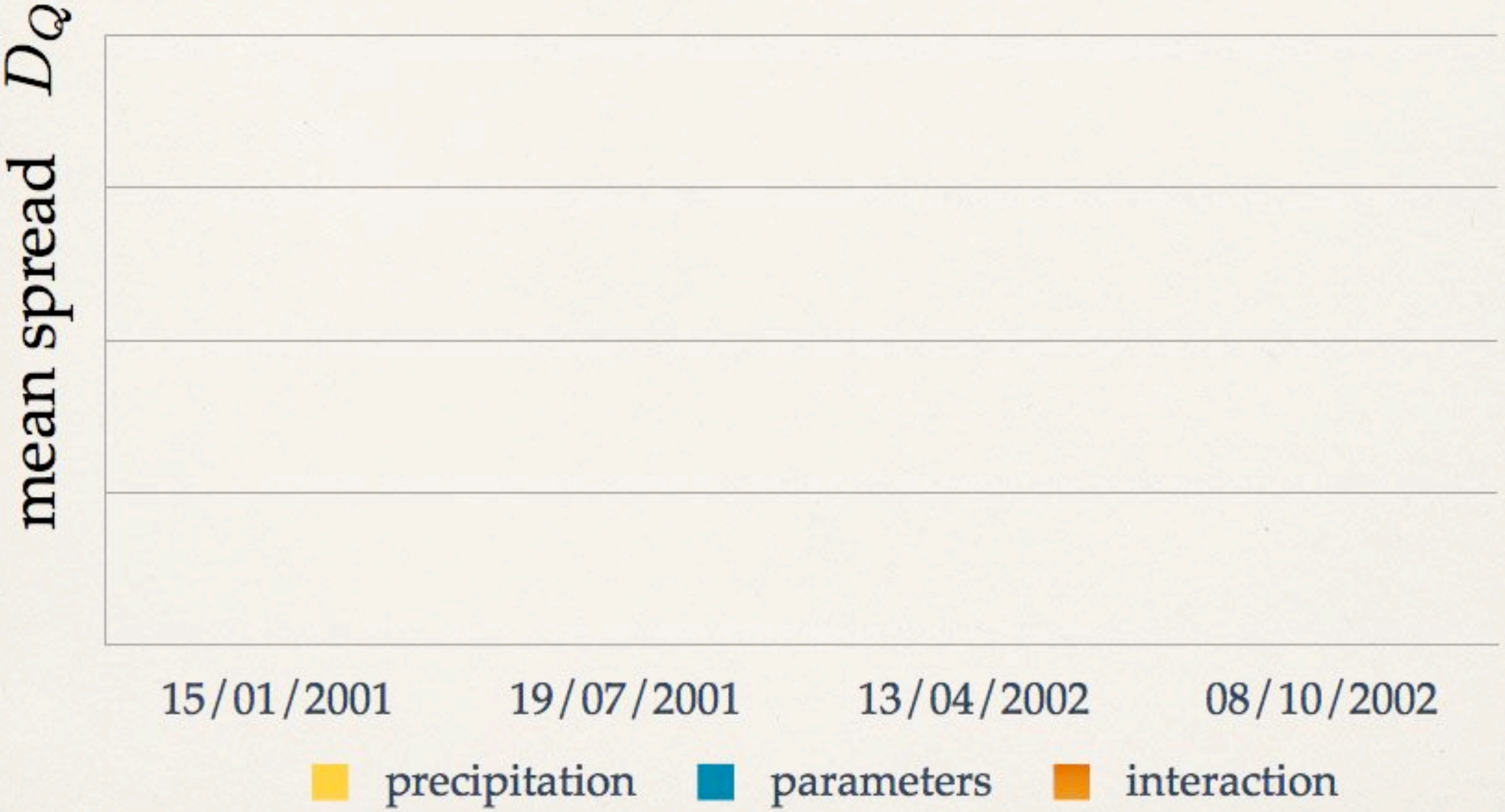
The effect from different sources of uncertainty

$\bar{D}_Q$

precipitation parameters interaction

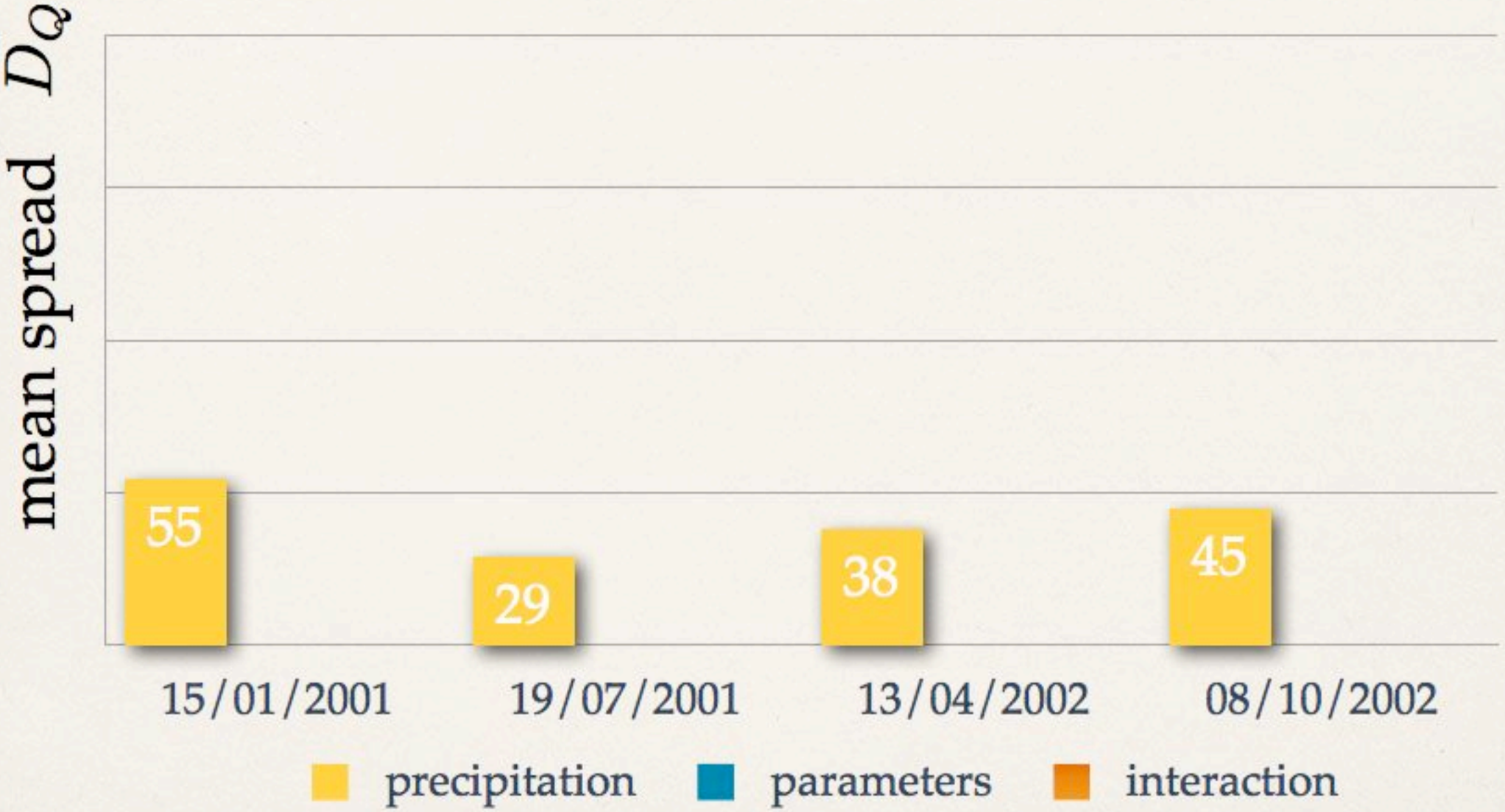
$$\bar{D}_Q = (\bar{Q}_{90} - \bar{Q}_{10})/\bar{Q}_{Pobs}$$

The effect from different sources of uncertainty



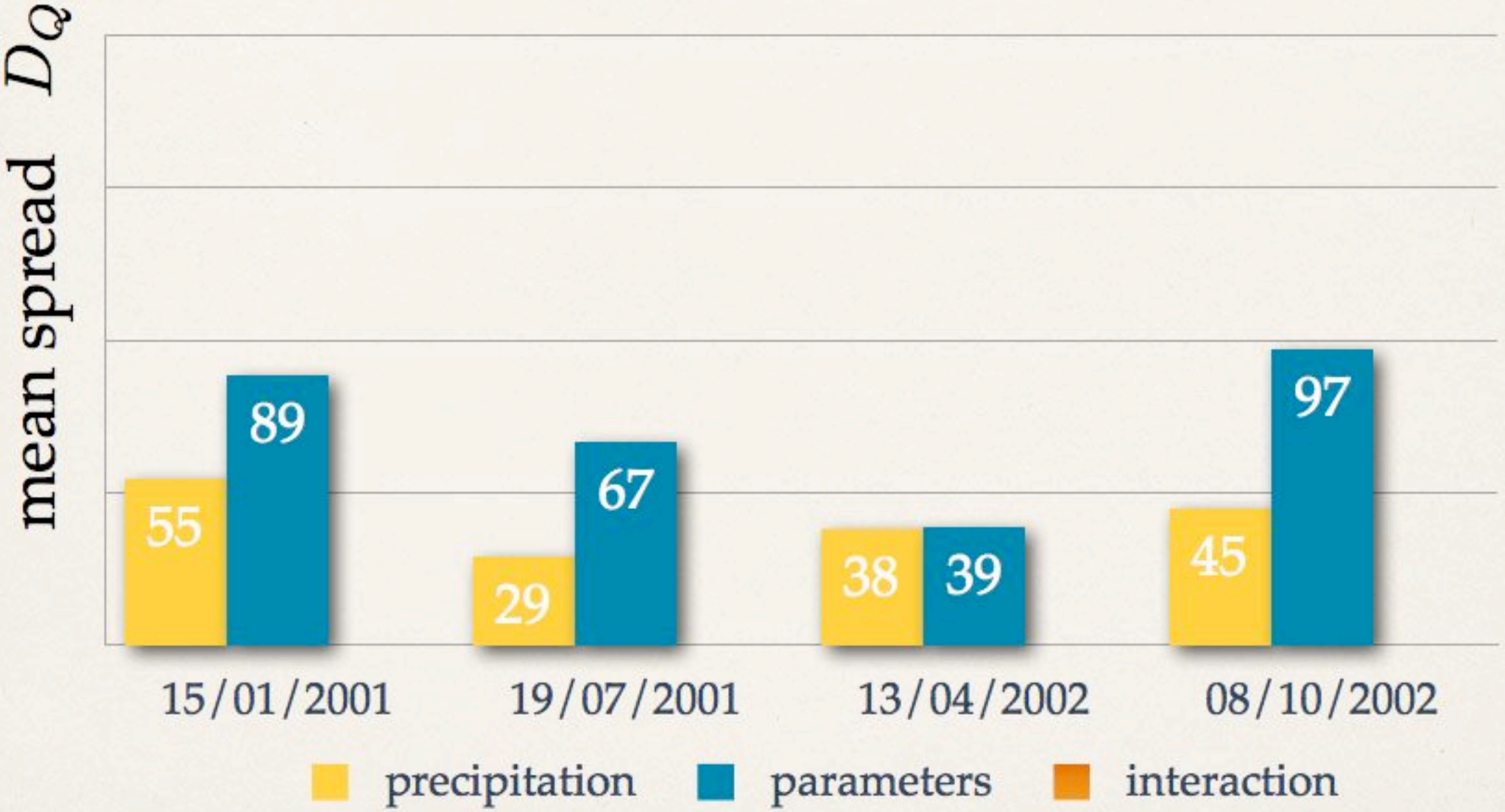
$$\bar{D}_Q = (\bar{Q}_{90} - \bar{Q}_{10})/\bar{Q}_{Pobs}$$

The effect from different sources of uncertainty



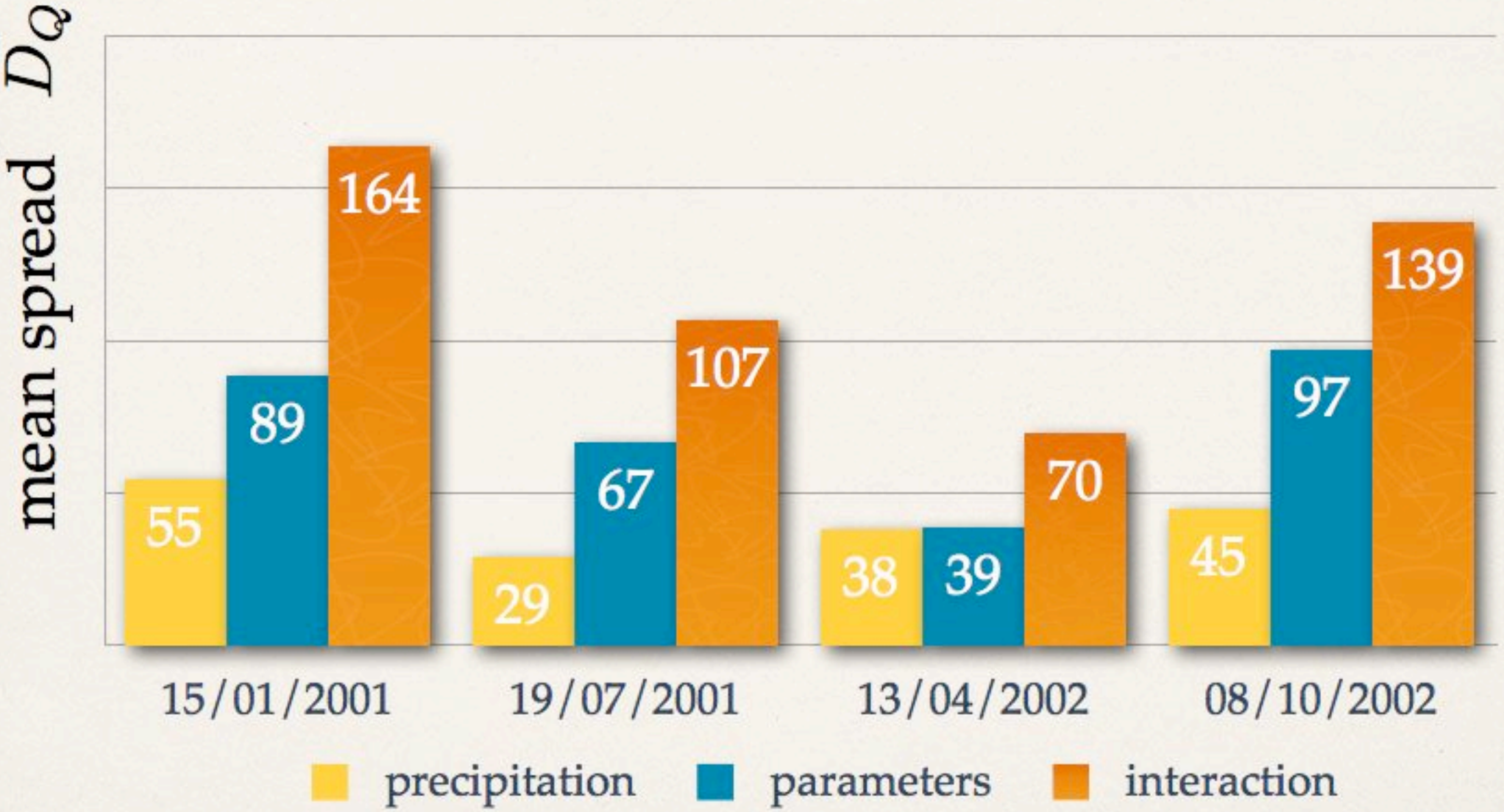
$$\bar{D}_Q = (\bar{Q}_{90} - \bar{Q}_{10})/\bar{Q}_{Pobs}$$

The effect from different sources of uncertainty



$$\bar{D}_Q = (\bar{Q}_{90} - \bar{Q}_{10})/\bar{Q}_{Pobs}$$

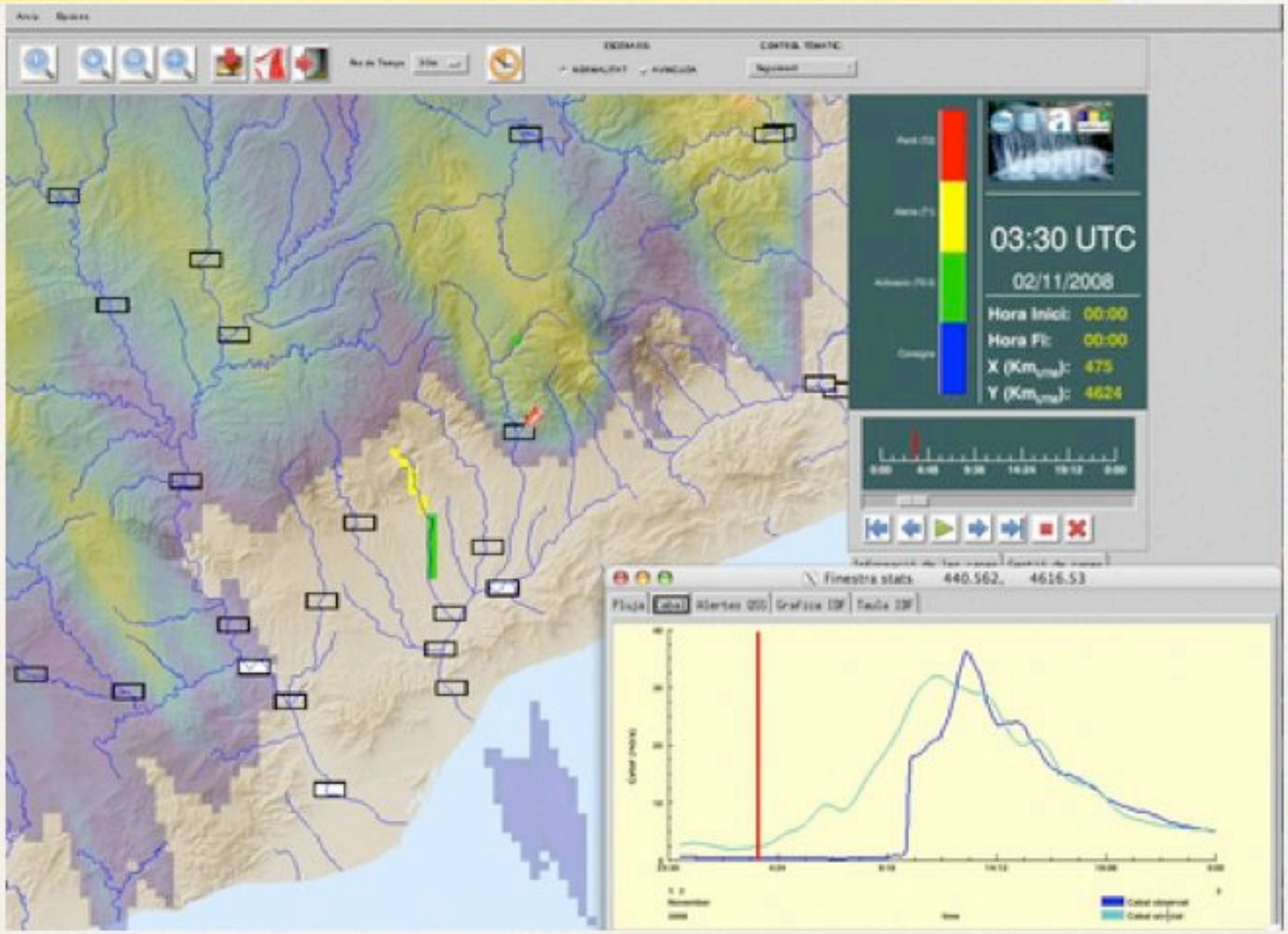
The effect from different sources of uncertainty



$$\bar{D}_Q = (\bar{Q}_{90} - \bar{Q}_{10})/\bar{Q}_{Pobs}$$

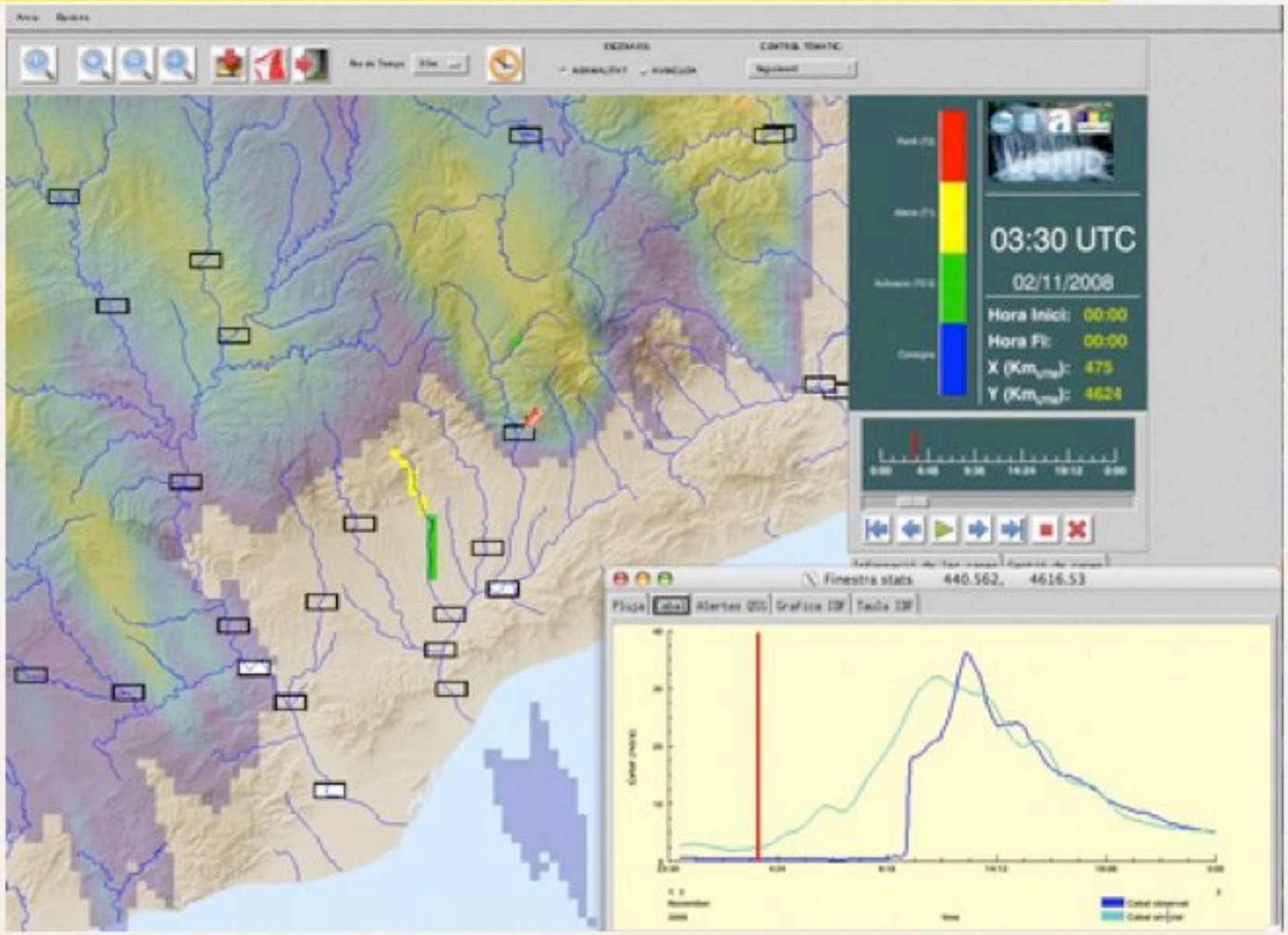
Early warning systems

- Advanced tools for Flash flood forecasting



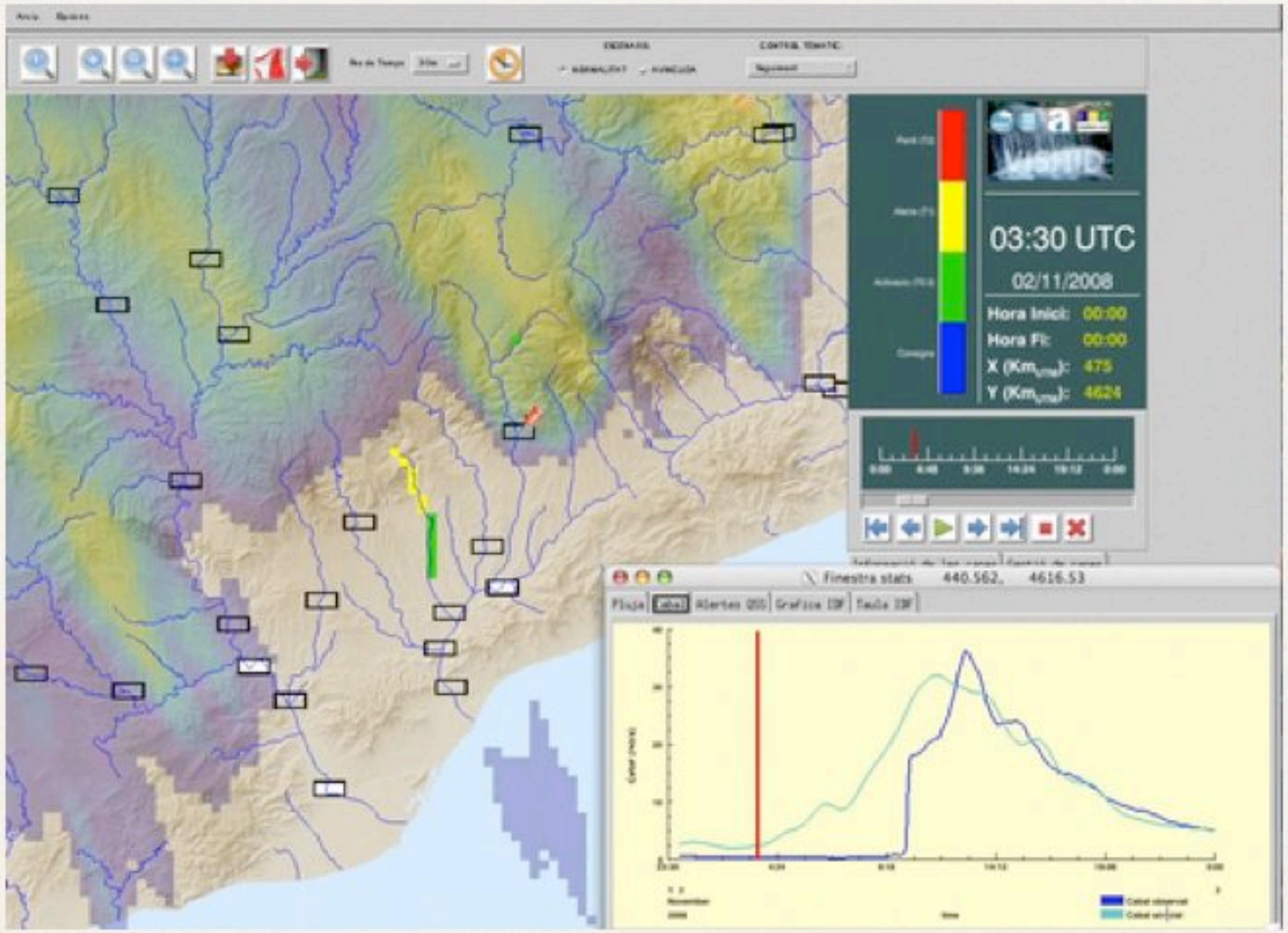
Early warning systems

- Advanced tools for Flash flood forecasting



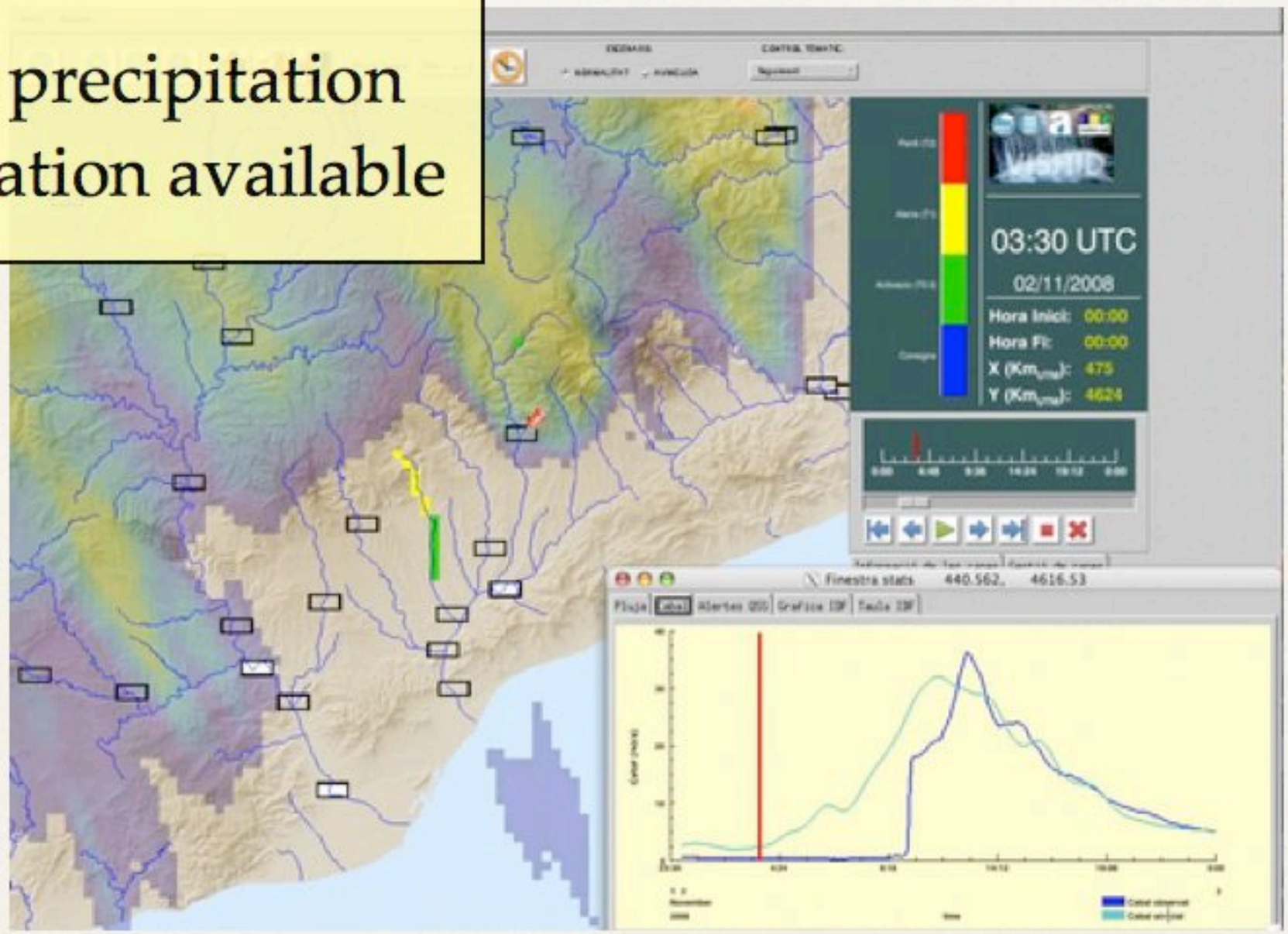
- QPE / QPF and hydrological modelling

Early warning systems



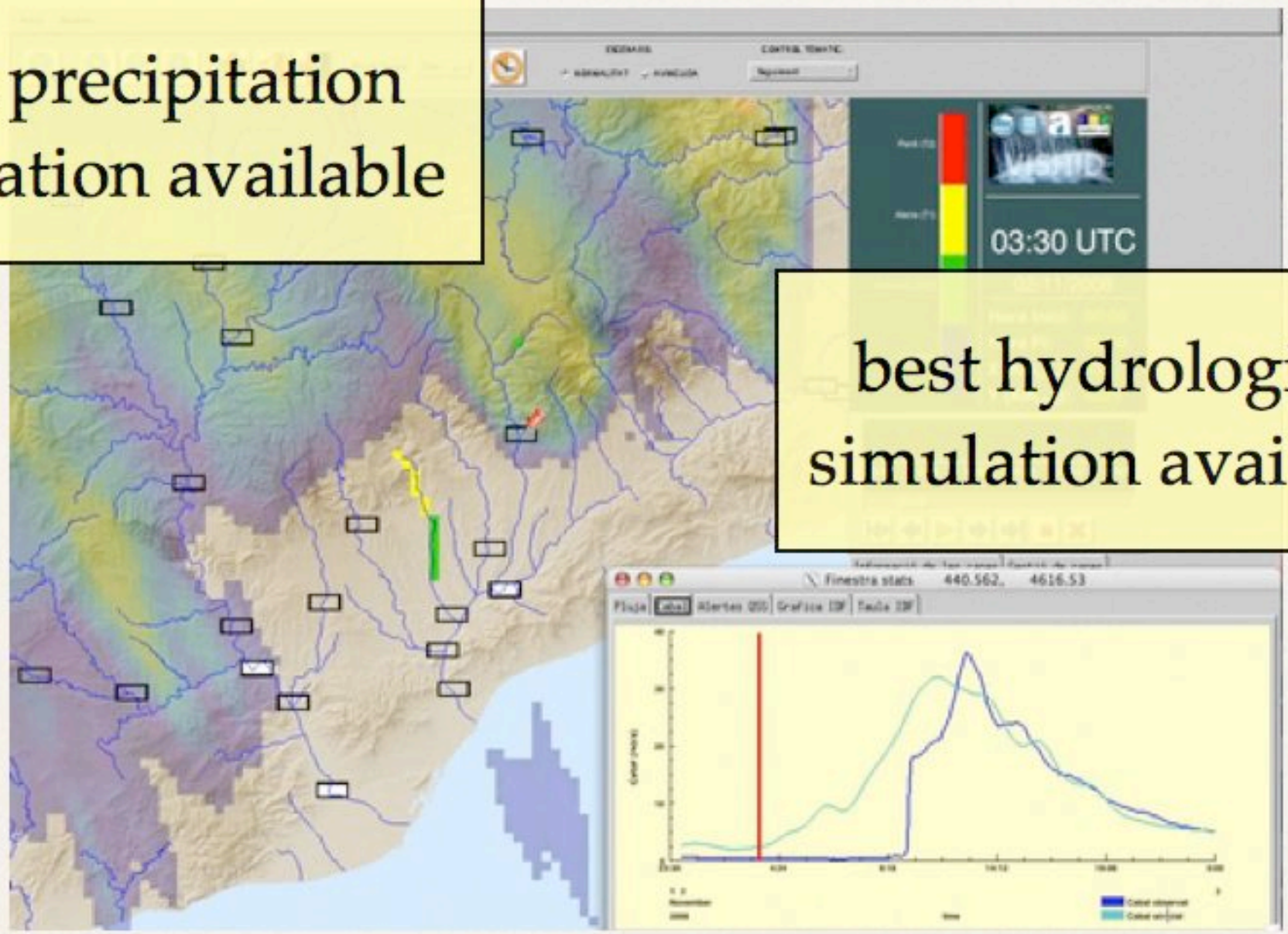
Early warning systems

best precipitation estimation available



Early warning systems

best precipitation estimation available



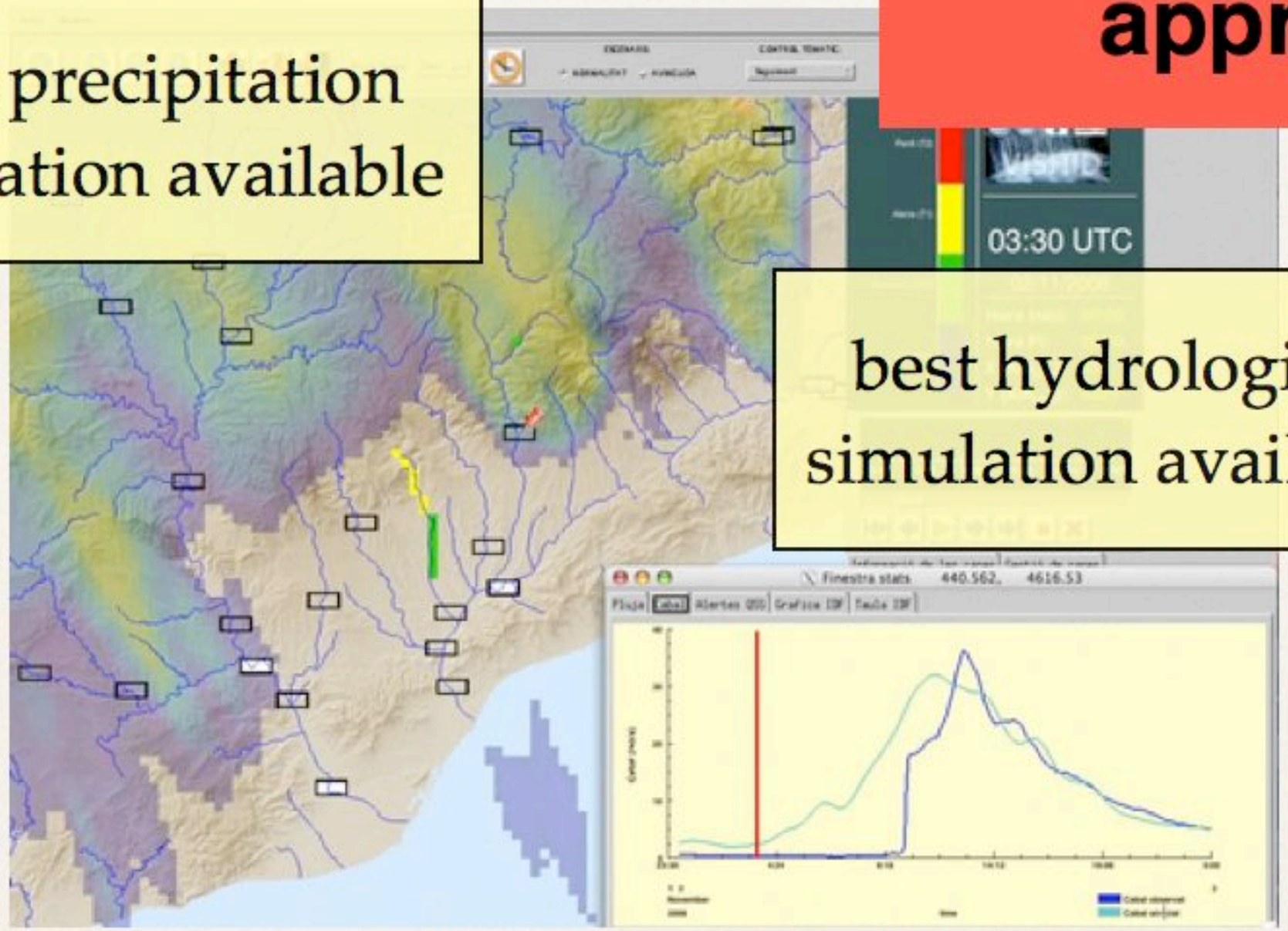
best hydrological simulation available

Early warning systems

Deterministic approach

best precipitation estimation available

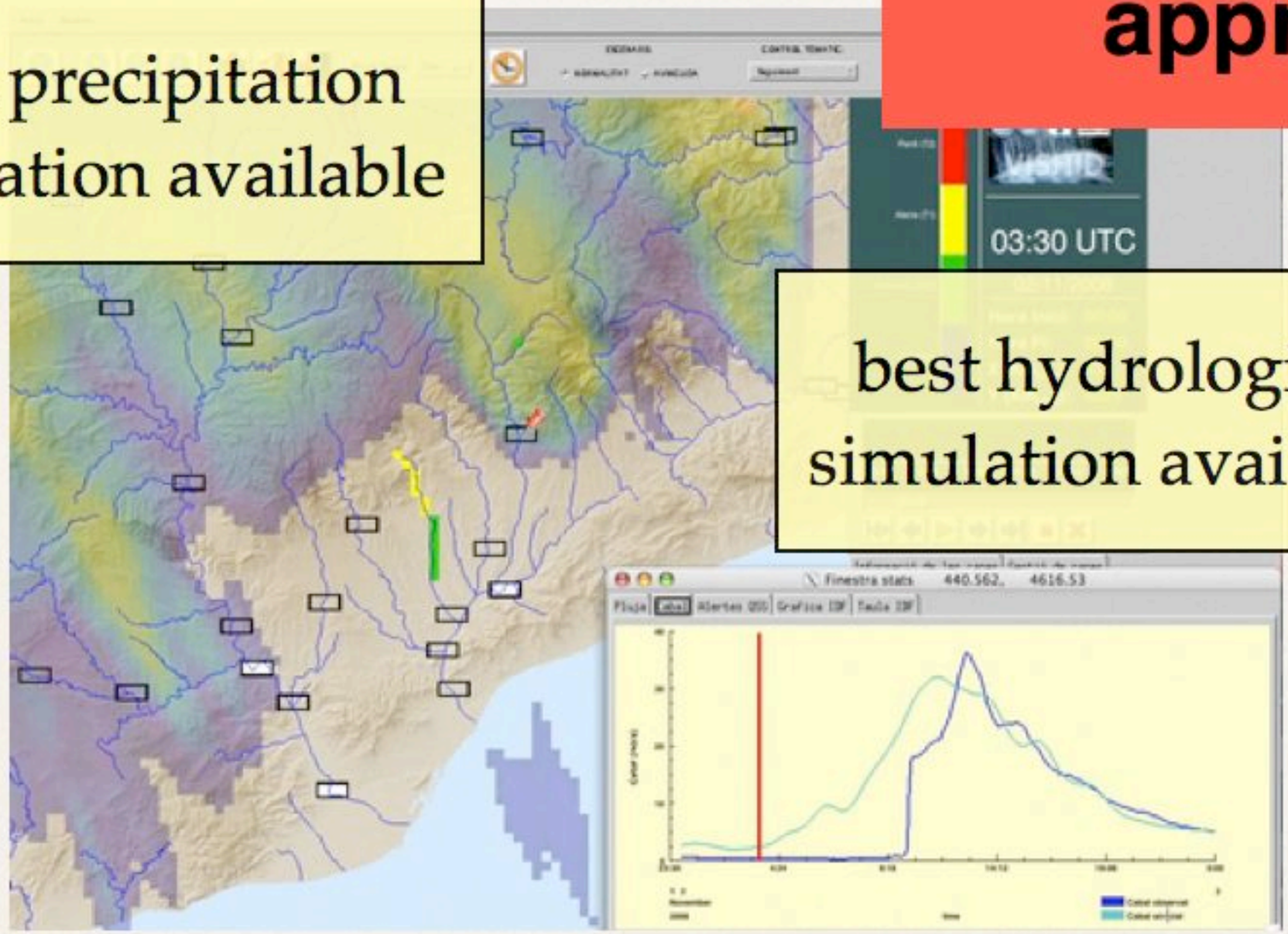
best hydrological simulation available



Early warning systems

Deterministic approach

best precipitation estimation available



best hydrological simulation available

Do **not** consider error from hydrological modelling

IMPRINTS Platform Prototype

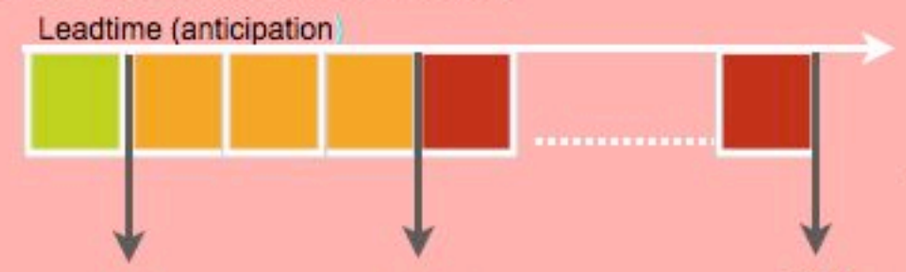
High resolution NWP forecasts

Radar Quantitative Precipitation Estimates

Raingauges

Streamgauges

Probabilistic rainfall forecasting



JRC EUROPEAN COMMISSION

EFAS

Early Warnings by probability exceedance

- Aggregated Drained Rainfall Index
- EPIC & EFAS-FF Warnings
- Debris Flows Warnings

Probabilistic Hydrological Forecasts

- DBM Automatic updating system
- PREVAH probabilistic model
- Probabilistic DiCHiTop

High resolution forecasted rainfall fields

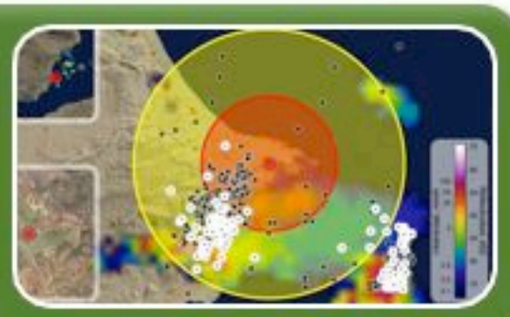
Warnings and dynamic Hazards and Risks Maps

High resolution forecasted hydrograms

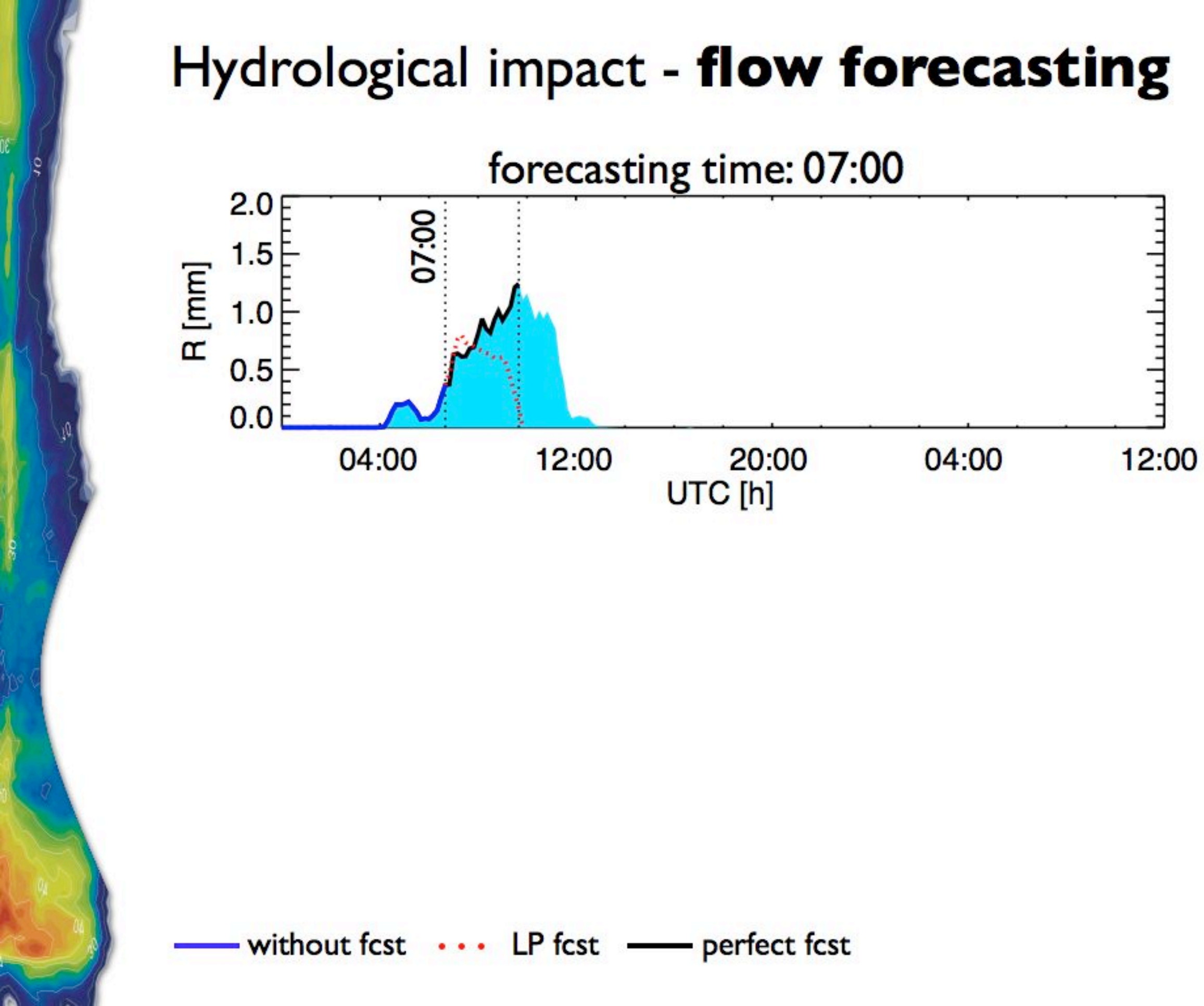
Associated forecasting uncertainties (ensemble scenarios)

Advanced visualization Tools

- Data
- Probabilistic forecasts
- Warnings
- Hazard and Risk dynamic maps

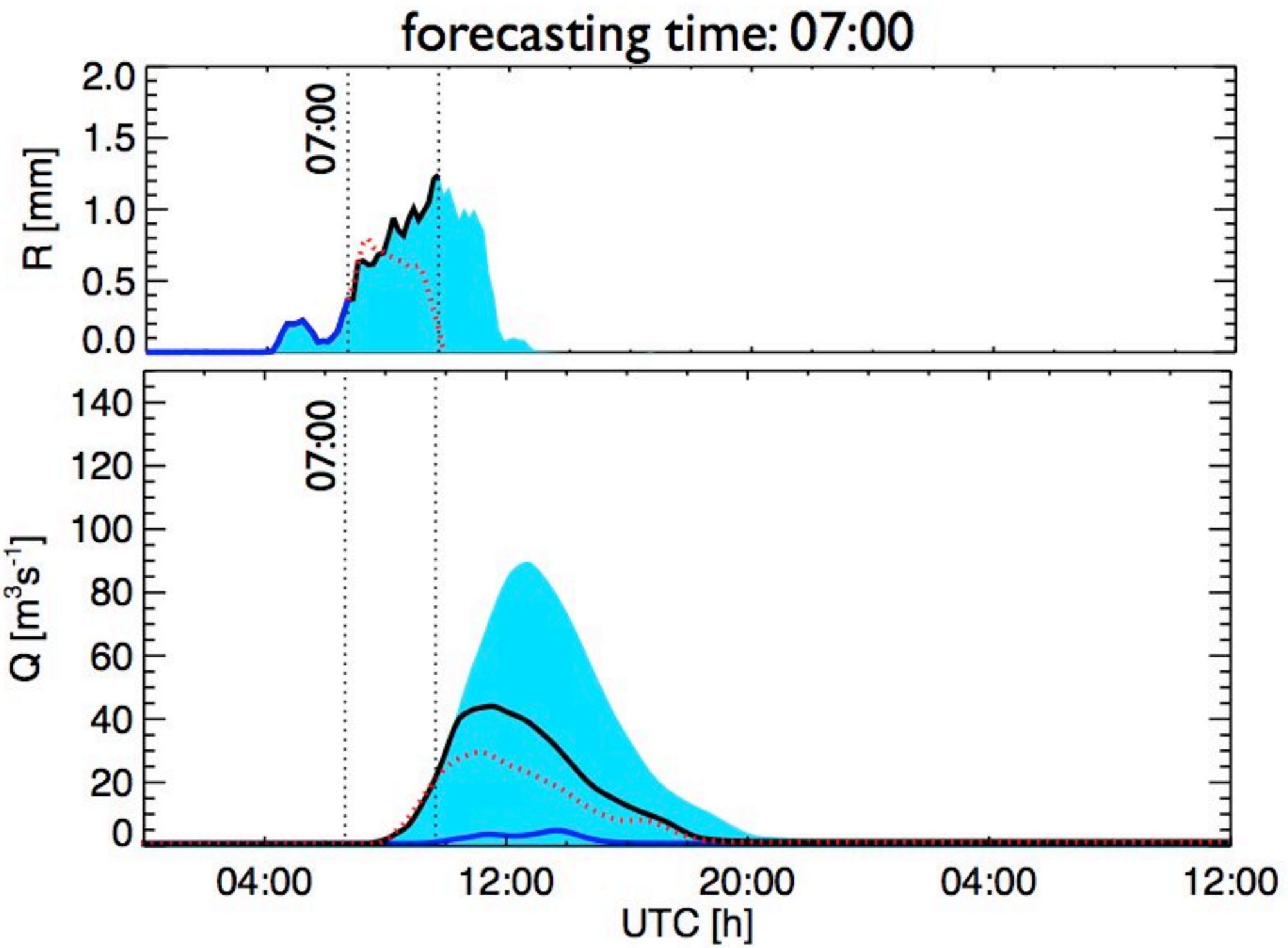


Hydrological impact - **flow forecasting**



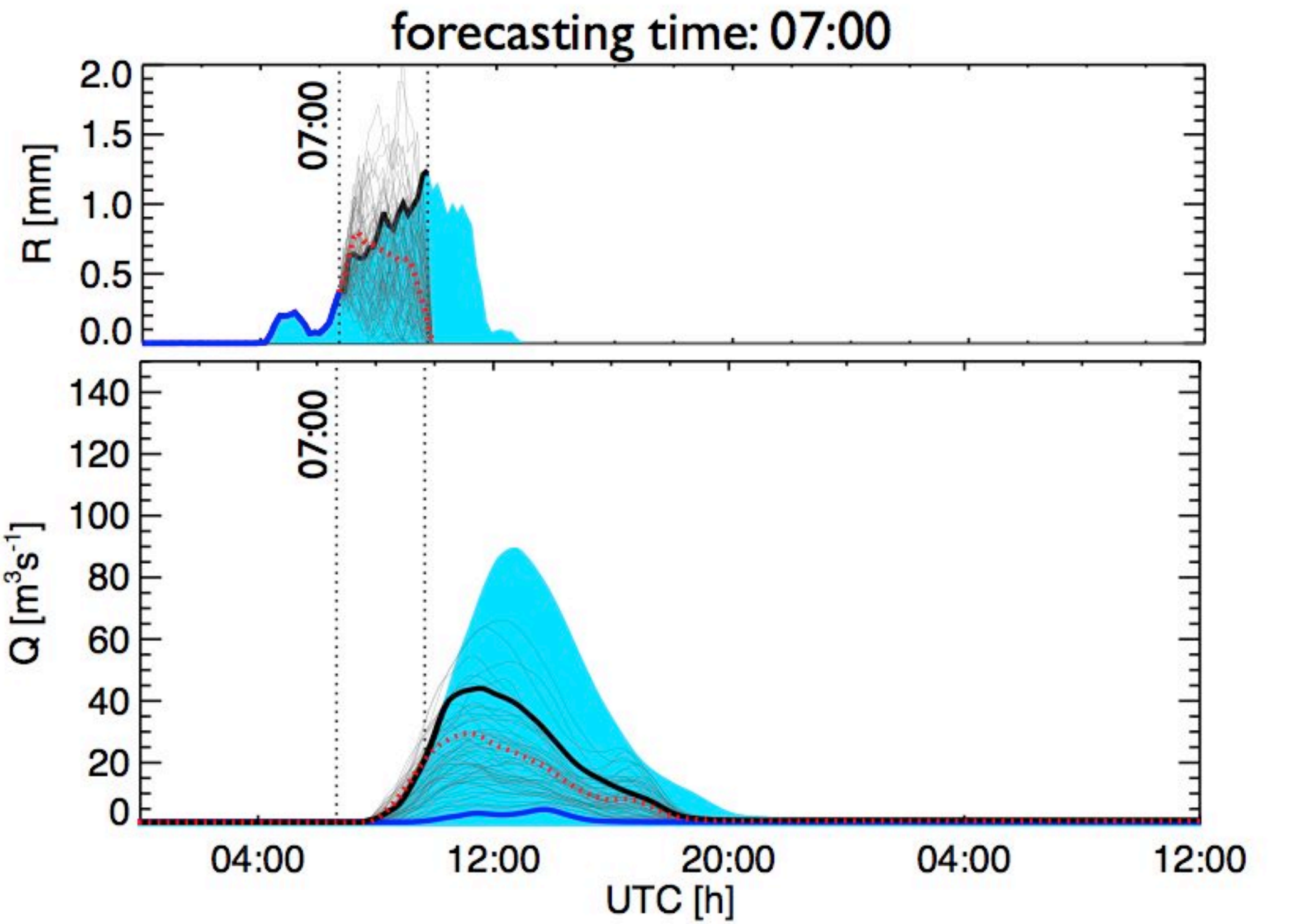
Hydrological impact - **flow forecasting**





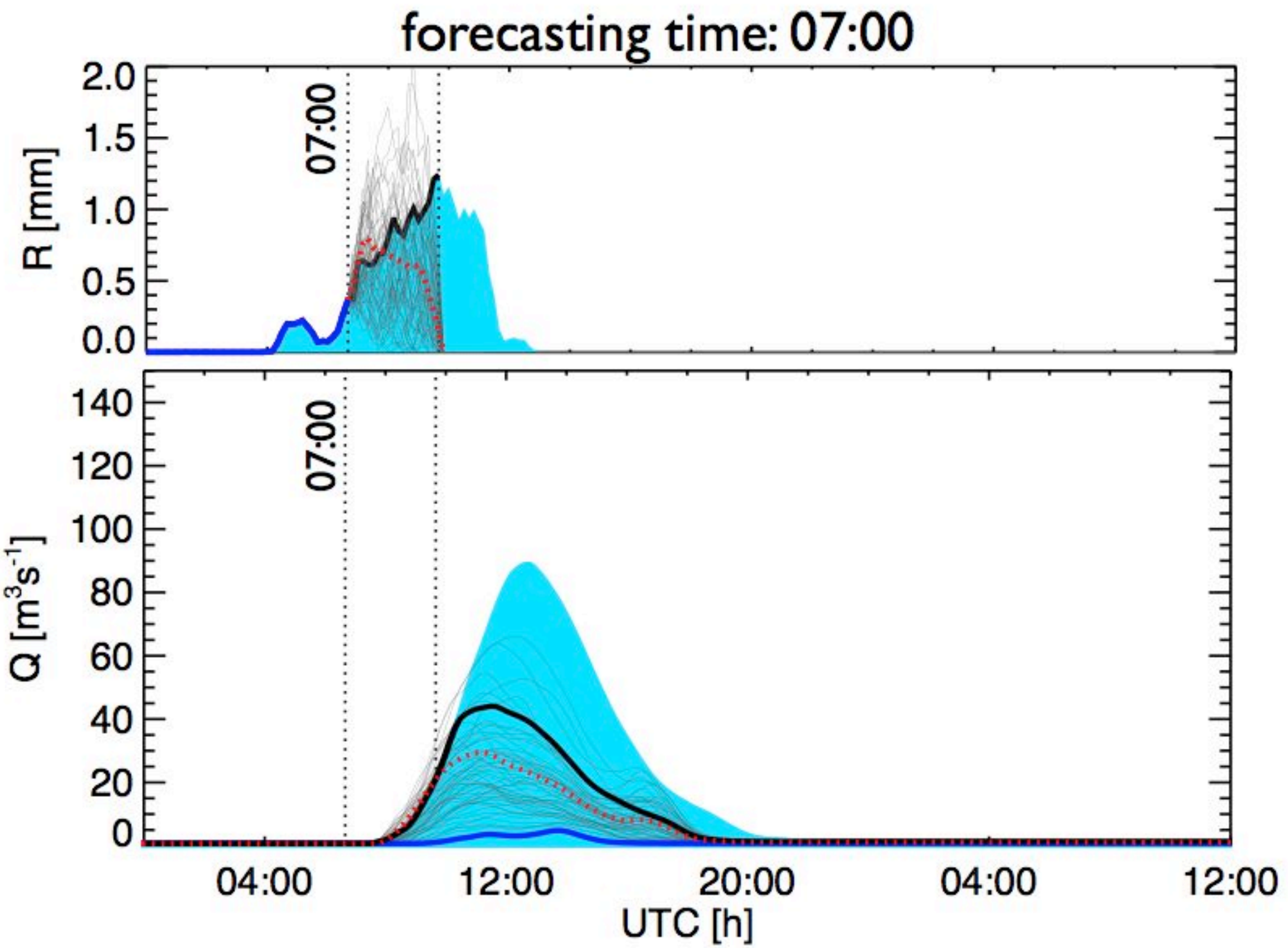
Hydrological impact - **flow forecasting**





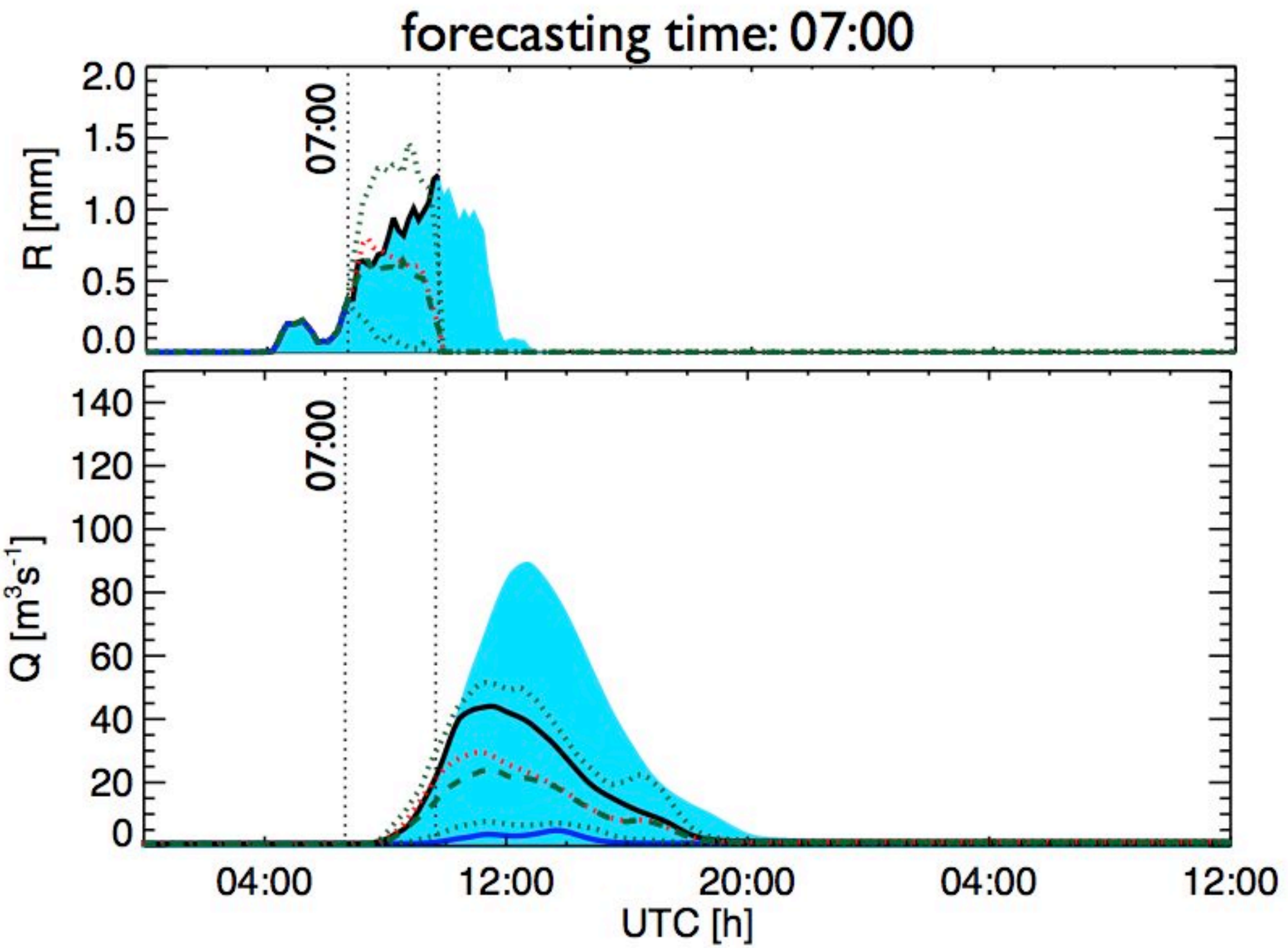
Hydrological impact - **flow forecasting**



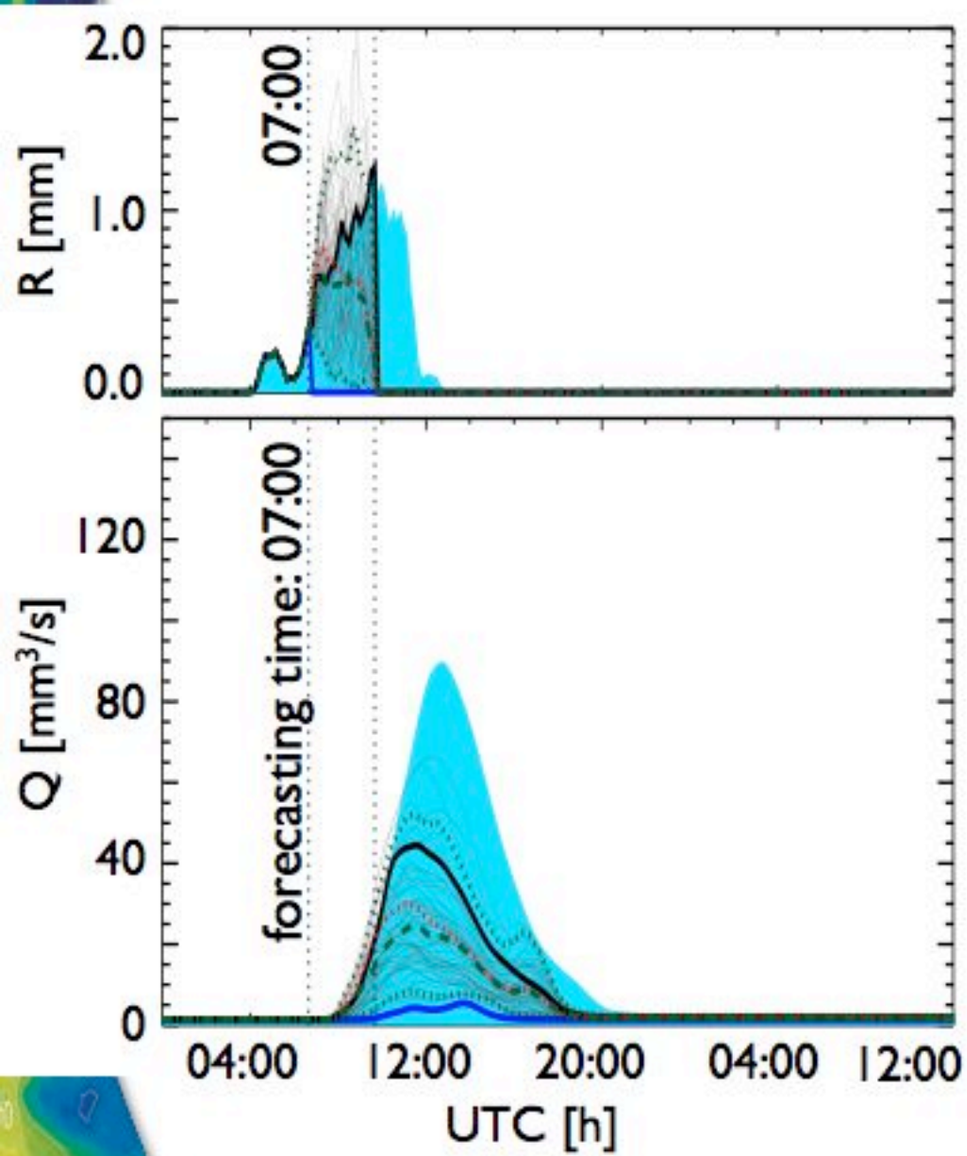


Hydrological impact - **flow forecasting**



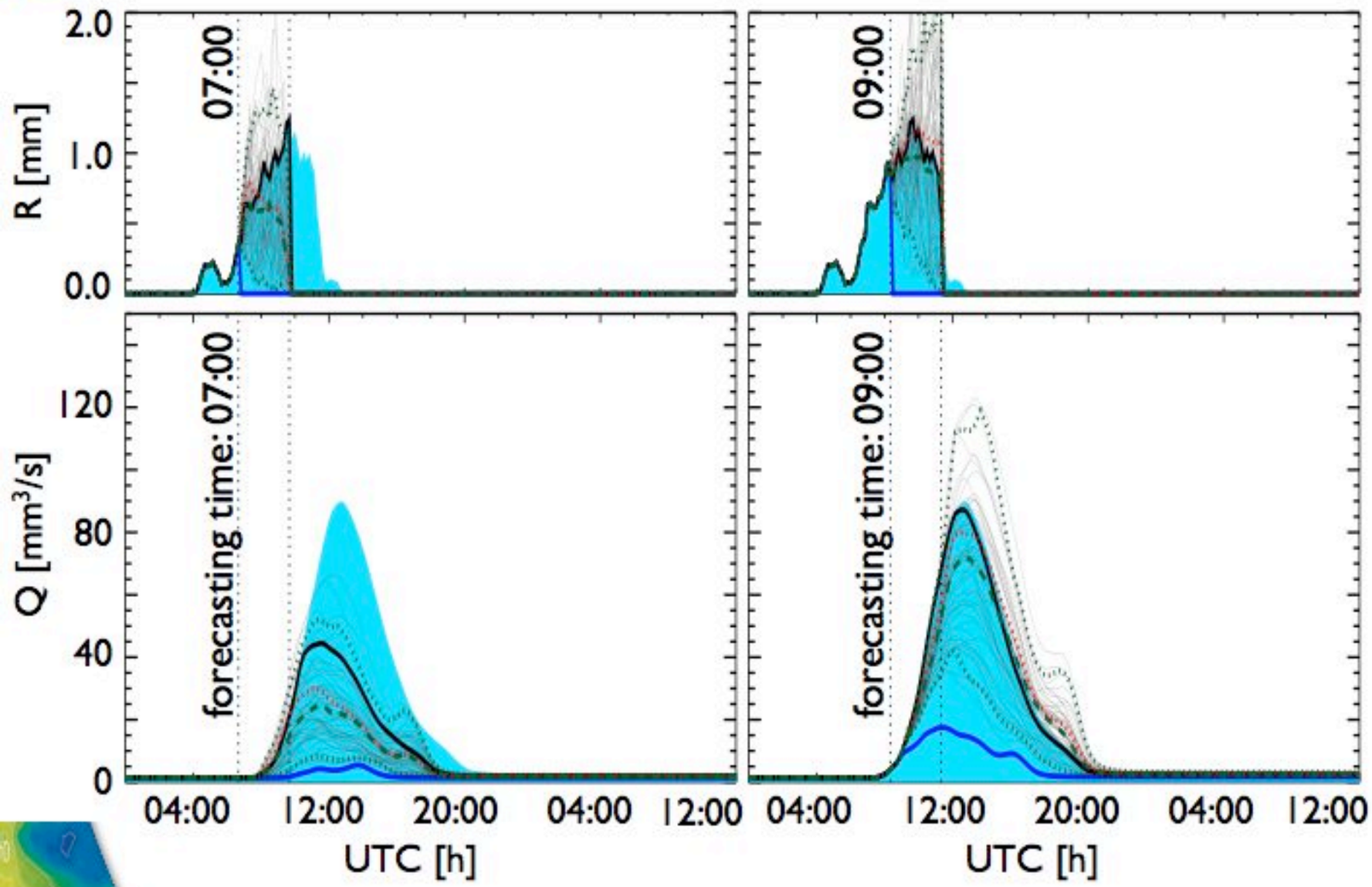


Hydrological impact - **flow forecasting**



without fcst · · · LP fcst —— perfect fcst - - - SBMcast 5%- 50%- 95%-perc.

Hydrological impact - **flow forecasting**



without fcst LP fcst perfect fcst SBMcast 5%- 50%- 95%-perc.

Hydrological impact - **flow forecasting**

