HYDROMED

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Characterization of extreme flash floods in Mediterranean Spain

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AGENCIA ESTATAL DE INVESTIGACIÓN

1. Background

In Spain:

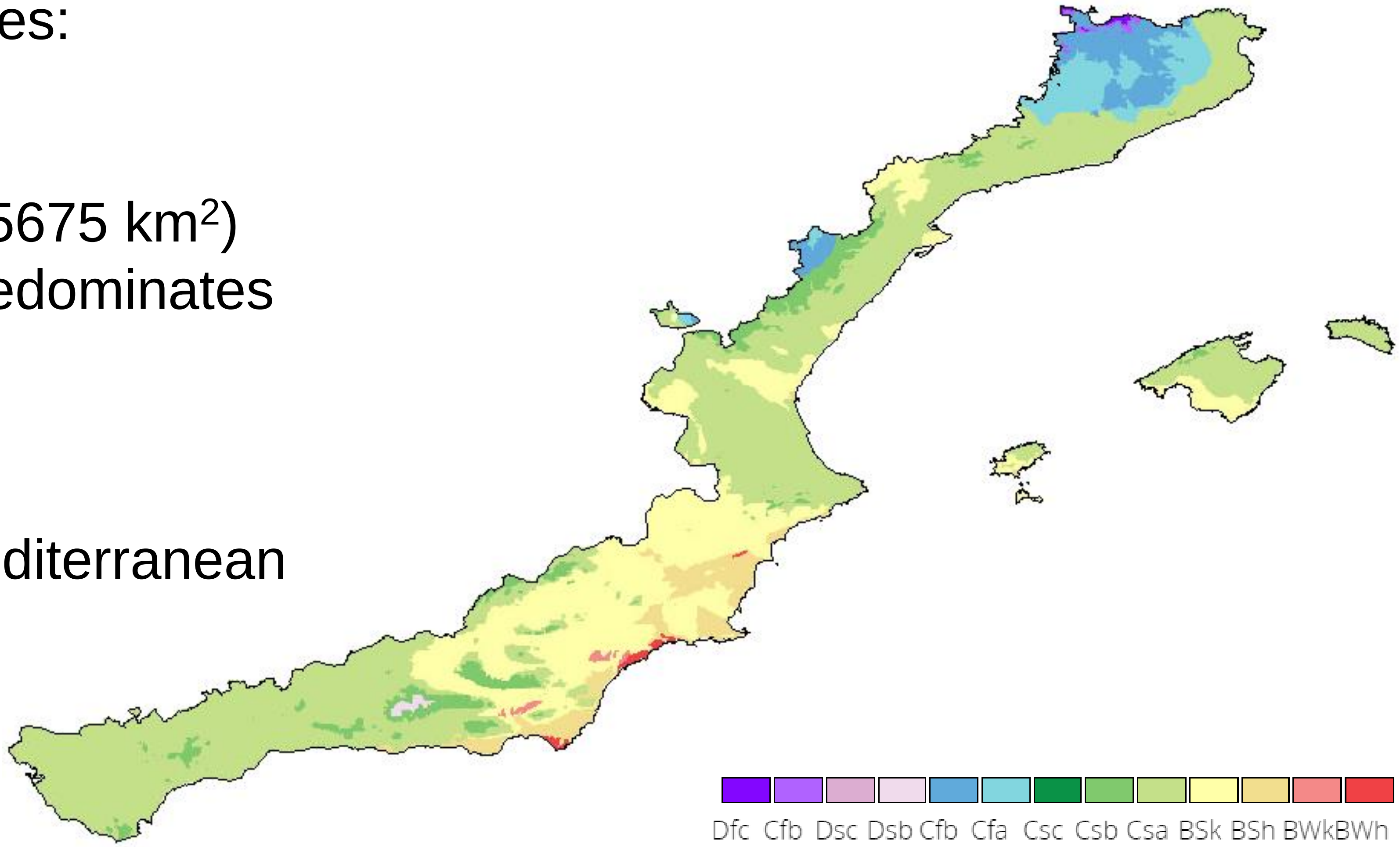
- Floods are the most devastating natural hazard
  - 1987-2023: 329 fatalities and EUR 7.8 billion in material damages
  - 82.5/72.3% of all casualties/expenses related to natural hazards
  - 74.6% of damages occur during the extended warm season (May-November), when convectively-driven precipitation predominates
- Flash floods were responsible of nearly 94% of natural hazard casualties involving at least 10 fatalities between 1950 and 2000
- Mediterranean Spain is the most affected by heavy precipitation episodes (HPEs) and subsequent flash flooding. Climatic, orographic and socioeconomic factors

1. Background

Spanish Mediterranean climates:

- Semi-arid (B’s)
  - 32% of the total area (95675 km^2)
  - Cold semi-arid (BSk) predominates

- Mediterranean (C’s)
  - 68% of the total area
  - Dry, hot-summer Mediterranean (CSa) dominates



Rainfall regime is highly variable and irregular. Precipitation is concentrated in a limited number of days. A significant portion of the annual total occurs during a few torrential episodes

2. Scientific objectives

Flash floods have been characterized across Europe, but it lacks a characterization for Mediterranean Spain

Difficulty: Establish a comprehensive database that collates quantitative information. Sparse and heterogeneous nature of the available data

- Collate a comprehensive database of extreme flash floods in Mediterranean Spain during the extended warm season

- Provide an extensive characterization using standardized methods to compare and complement findings from existing databases

3. Extreme daily rainfall regime: Spatial distribution

Different types of heavy rainfall-bearing structures: isolated organized storms, orographic rainfall, mesoscale convective systems (MCSs), and frontal systems. All labelled as HPEs

Typical flash-flood-producing HPEs: ≥ 100 mm within a few hours over relatively small areas

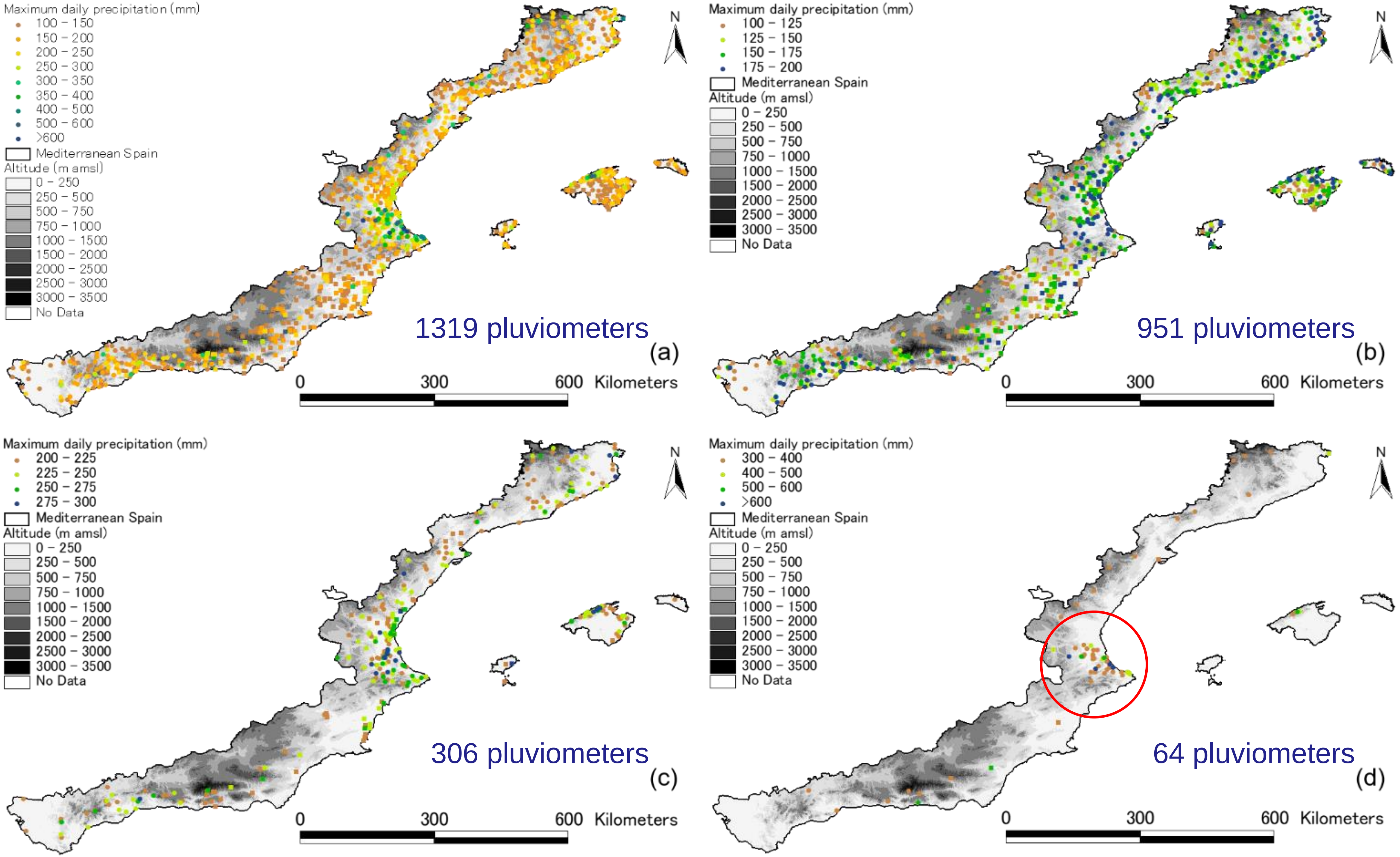
Absolute maximum precipitation recorded by the daily pluviometer network of AEMET up to 2023

1319 stations ≥ 100 mm

1 station per 72.5 km^2

771.8 mm on 29 October 2024. Torís, València

Date	Total daily depth (mm)	Location
3 November 1987	817.0	Oliva, València
4 November 1987	790.0	Pobla del Duc, València
3 November 1987	720.0	Gandia, València
20 October 1982	632.0	Bicorp, València
19 September 1973	600.0	Zurzena, Almería
19 September 1973	600.0	Albuñol, Granada
22 October 1959	536.5	Son Torrella, Illes Balears
4 November 1987	520.0	Sucamarcer, València
11 September 1996	520.0	Tavernes de Valldigna,València
11 September 1996	500.0	Benifairó de Valldigna, València


Maximum daily precipitation (mm)
100 – 150
150 – 200
200 – 250
250 – 300
300 – 350
350 – 400
400 – 500
500 – 600
>600
Mediterranean Spain
Altitude (m amsl)
0 – 250
250 – 500
500 – 750
750 – 1000
1000 – 1500
1500 – 2000
2000 – 2500
2500 – 3000
3000 – 3500
No Data
1319 pluviometers
(a)
0
300
600
Kilometers
N
Maximum daily precipitation (mm)
100 – 125
125 – 150
150 – 175
175 – 200
Mediterranean Spain
Altitude (m amsl)
0 – 250
250 – 500
500 – 750
750 – 1000
1000 – 1500
1500 – 2000
2000 – 2500
2500 – 3000
3000 – 3500
No Data
951 pluviometers
(b)
0
300
600
Kilometers
N
Maximum daily precipitation (mm)
200 – 225
225 – 250
250 – 275
275 – 300
Mediterranean Spain
Altitude (m amsl)
0 – 250
250 – 500
500 – 750
750 – 1000
1000 – 1500
1500 – 2000
2000 – 2500
2500 – 3000
3000 – 3500
No Data
306 pluviometers
(c)
0
300
600
Kilometers
N
Maximum daily precipitation (mm)
300 – 400
400 – 500
500 – 600
>600
Mediterranean Spain
Altitude (m amsl)
0 – 250
250 – 500
500 – 750
750 – 1000
1000 – 1500
1500 – 2000
2000 – 2500
2500 – 3000
3000 – 3500
No Data
64 pluviometers
(d)
0
300
600
Kilometers
N

3. Extreme daily rainfall regime: Spatial distribution

Climate	Number of stations	Mean (mm)	Std dev (mm)	Median (mm)	Max (mm)
Mediterranean	985	181.4	75.9	167.0	817.0
Semi-arid	334	162.7	54.6	150.0	600.0

Mediterranean climate:

- Slightly higher absolute daily rainfall values and a broader range
- Wider variability in rainfall rates, with higher intensities contributing to extreme flash flooding

3. Extreme daily rainfall regime: Temporal distribution

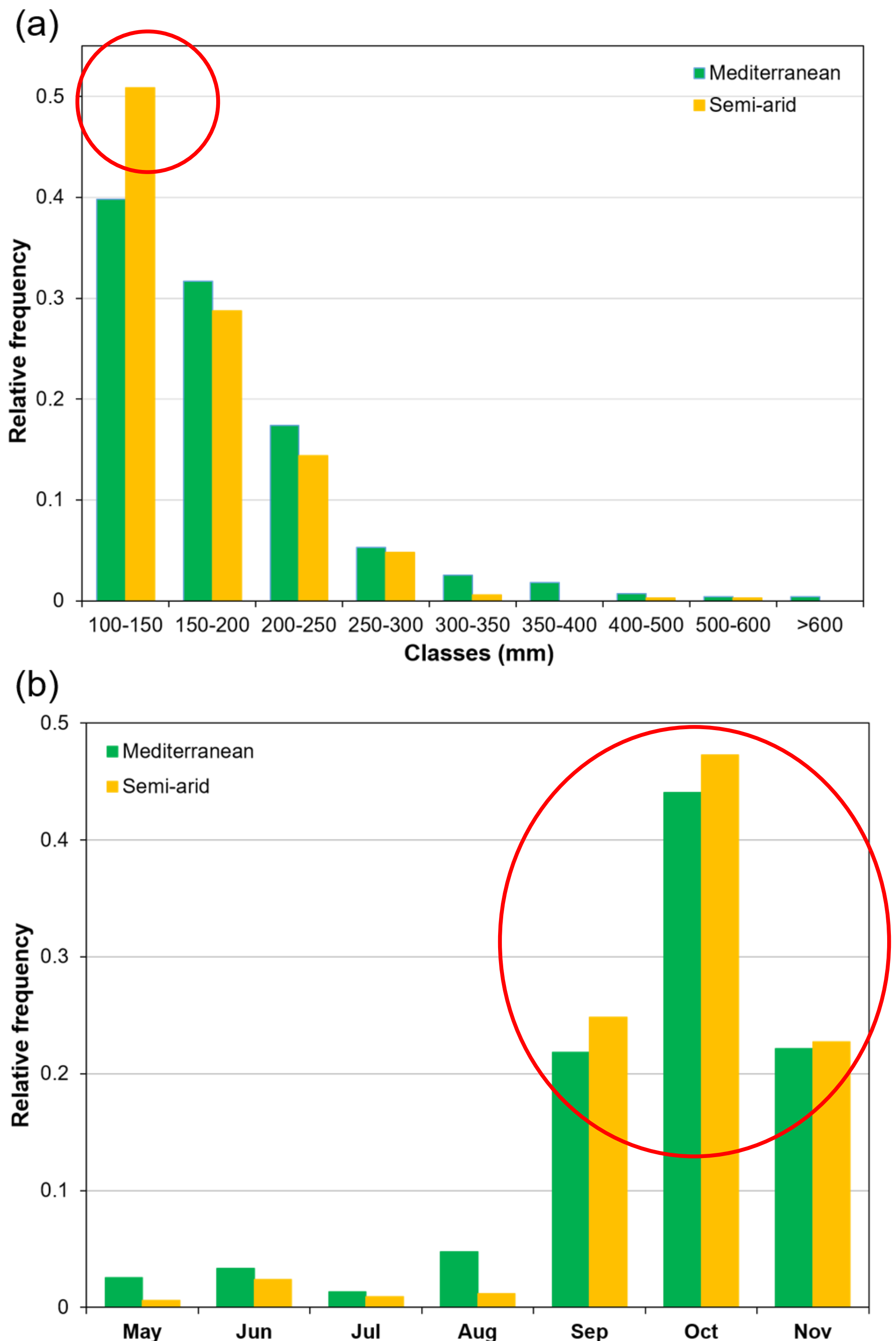
Relative frequency distribution by rainfall classes

Semi-arid climate: > 50% population in the 100-150 mm range. More pronounced decrease in relative frequency. Less variability

Monthly distribution of absolute maximum precipitation

Both climates peak in autumn, with the maximum in October

Semi-arid climate: relative frequencies more concentrated between September and November



3. Extreme daily rainfall regime: Rainfall rates

Absolute maximum 30-min rainfall rates (2000-2019)

171 automatic stations. 1 station per 559.5 km^2

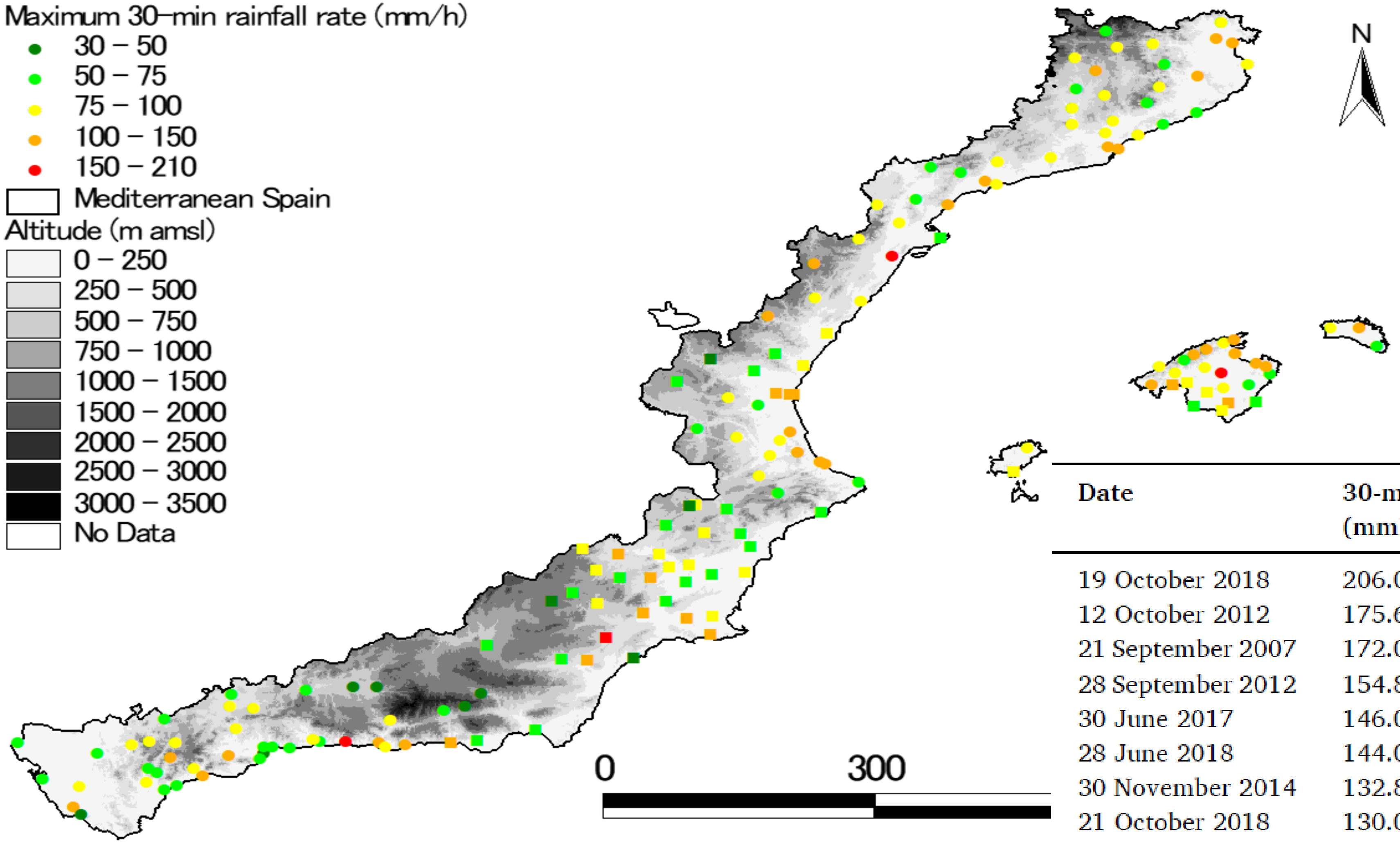
Climate	Number of stations	Mean (mmh^{-1})	Std dev (mmh^{-1})	Median (mmh^{-1})	Max (mmh^{-1})	Min (mmh^{-1})
Mediterranean	118	86.6	27.0	82.9	206.0	33.6
Semi-arid	53	81.8	22.9	78.4	154.8	44.8

Mediterranean climate: slightly higher extreme rainfall rates and a broader variability contributing to extreme flash flooding

Semi-arid climate exhibits a more concentrated distribution

3. Extreme daily rainfall regime: Rainfall rates

Spatial distribution rather uniform: diversity of forcings generating such extremes



Date	30-min rainfall rate (mmh^{-1})	Location
19 October 2018	206.0	Vinarós, Castelló
12 October 2012	175.6	Sineu, Illes Balears
21 September 2007	172.0	Nerja, Málaga
28 September 2012	154.8	Puerto Lumbreras, Murcia
30 June 2017	146.0	Girona, Girona
28 June 2018	144.0	La Pobla d'Arenós, Castelló
30 November 2014	132.8	Figueres, Girona
21 October 2018	130.0	Alpandeire, Málaga
6 September 2018	125.2	Barcelona, Barcelona
9 July 2001	123.4	Vandellòs, Tarragona
26 July 2011	123.2	Es Mercadal, Illes Balears

3. Extreme daily rainfall regime: Rainfall rates

Relative frequency distribution by rate classes

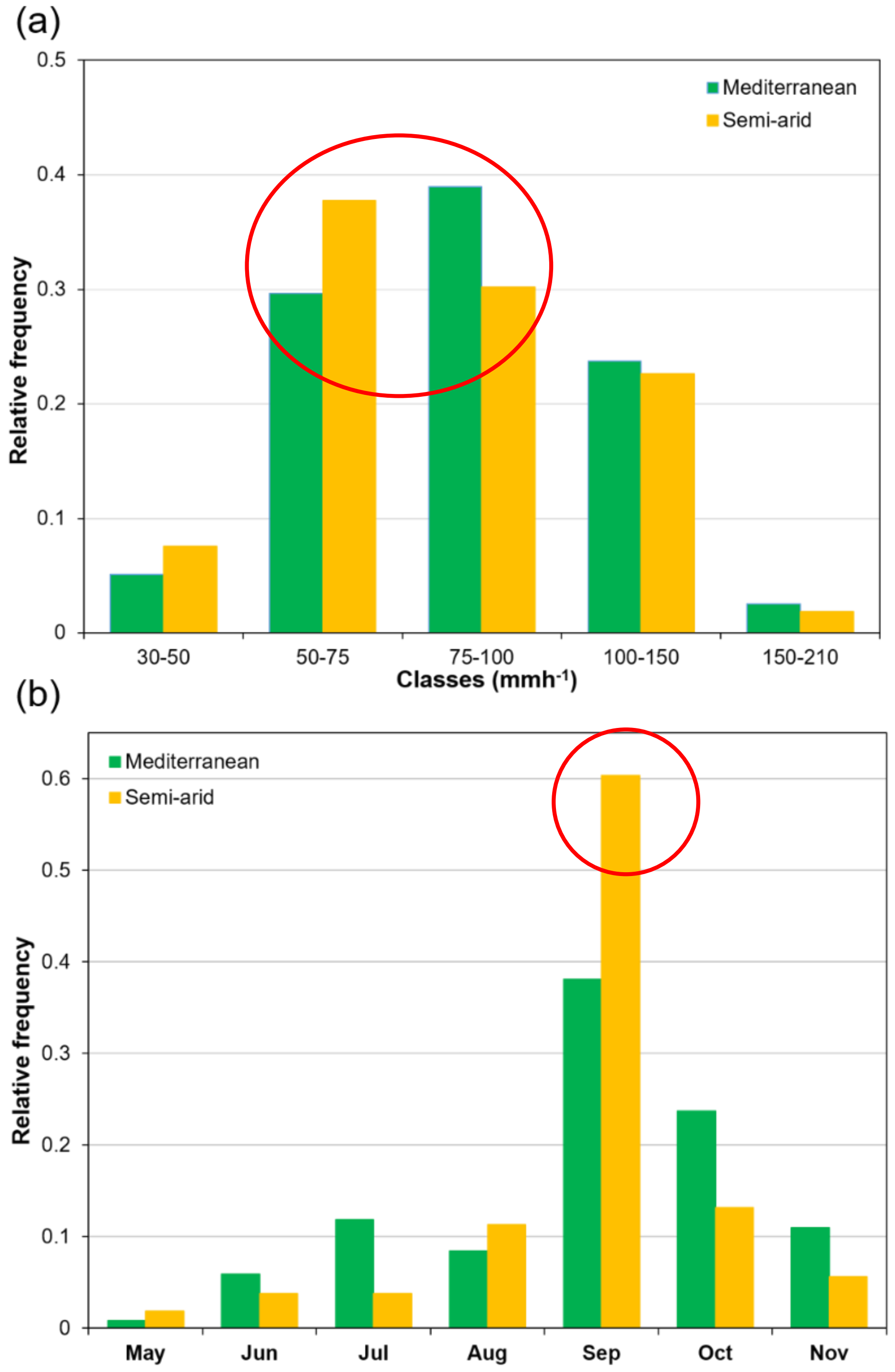
Mediterranean climate

Peaks at 75-100 mmh^{-1} range

Semi-arid climate

Peaks at the 50-75 mmh^{-1} category

September accounts ~60% of occurrences



4. Flash flood catalogue

Include as many events as possible to create a representative sample during the extended warm season

The most extreme flash floods have devastating impacts: well remembered and documented

Date: 28-31 Oct 2024

Daily precipitation: 771.8 mm

Provinces: Illes Balears, Andalucía, Murcia, Comunitat Valenciana, Catalunya

Casualties: 236

Material losses: 17 B€ just in València

Date	Daily precipitation (mm)	Province/ Autonomous community	Casualties	Material damages (uninflated; M€)
20–21 September 1850	Unknown	Catalunya	85	0.003 (Recasens, 1966)
4–5 November 1864	294.0	València	21	0.02 (Olcina, 2012; Mateu, 2014)
23 September 1874	Unknown	Tarragona	570	>0.02 (Iglèsies, 1971; Pino et al., 2016)
14–15 October 1879	> 600.0	Almería, Murcia, Alacant	804	0.74 (Olcina, 1968; García-Tornel et al., 2001; Benito et al., 2010; López, 2014)
6 September 1888	Unknown	Almería	78	Unknown (Capel, 1974)
11 September 1891	158.3 in 3 h	Almería	20	0.012 (García-Tornel et al., 2001)
25 September 1906	Unknown	Murcia	31	Unknown (Castejón and Romero, 2014)
24 September 1907	Unknown	Málaga	21	0.03 (López-Bustos, 1981)
20 October 1907	411.0	Catalunya	20	0.03 (López-Bustos, 1981)
20 September 1919	Unknown	València	19	Unknown (Conesa and García, 2003
18–19 October 1930	348.0 (in 14 h)	Catalunya	14	Unknown (Llasat et al., 2022)
17–19 October 1940	352.0 (743 in 72 h)	Catalunya	90	>136 (of 2013; Llasat et al., 2016)
27 September 1949	Unknown	Málaga	20	Unknown (Benito et al., 2016)
28 October 1949	Unknown	València	30	0.89 (Portugués, 2012)
14 October 1957	361.0	València	81	96.2 (Puertes and Francés, 2016)
25 September 1962	360.0 (200.0 in < 2 h)	Barcelona	815	533 (of 2013; Martín-Vide and Llasat; 2018)
19–23 September 1971	308.0 (639.0 in 96 h)	Barcelona	19	> 835 (of 2013; Llasat et al., 2016)
17–19 October 1973	600.0 (< 6h)	Almería, Granada, Murcia, Alacant	300	400 (Capel, 1974; López-Bustos, 1981; Barredo, 2007; Benito et al., 2010)
19–21 October 1982	500.0–700.0 (> 1000 in 48 h)	València, Alacant	40	630 (Barredo, 2007)
8–11 November 1982	610.0 (in 48 h)	Andalucía, Catalunya	30	300 (Barredo, 2007)
2–4 October 1987	431.0	Catalunya	14	6 (of 1987; Ramis et al., 1994)
3–5 November 1987	817.0	Murcia, València	16	17.1 (Barredo, 2007)
12–13 November 1988	222.0	València, Catalunya	11	16.75 (of 1988; Romero et al., 1997)
4–7 September 1989	250.0	Andalucía, València, Catalunya, Illes Balears	11	Unknown (Capel, 1989)
14 November 1989	292.0 (180.0 in 1.5 h)	Málaga	18	375 (Barredo, 2007)
9–10 October 1994	450.0 (240.0 in 2.5 h)	València, Catalunya, Illes Balears	19	90.15 (Ramis et al., 1998; Martín-Vide and Llasat, 2000)
30 September 1997	270.0 (in 5 h; 156.0 in 1 h)	València	5	30 (Olcina, 2017)
10 June 2000	257.0	Catalunya	5	>90 (of 2013; Martín et al., 2007; Llasat et al., 2016)
21–24 October 2000	> 250 (in 24 h)> 500 (in 48 h)	Murcia, València, Catalunya	8	100 (Homar et al., 2002)
27–29 September 2012	320.0 (223.0 in 2 h)	Andalucía, Murcia, València	13	64 (Amengual et al., 2015; Sánchez-García et al., 2019)
9 October 2018	257.0	Illes Balears	13	91.1 (Lorenzo-Lacruz et al., 2019)
10–14 September 2019	320.6 (492 in 48 h)	Andalucía, Murcia, València	7	425 (Hermoso et al., 2021)
22 October 2019	292.6	Catalunya	7	44 (Martín-Vide et al., 2023; Amengual et al., 2024)

4. Flash flood catalogue

Limitation: Availability of primary data

Minimum requirements to qualify a flash flood: Occurrence date, location, peak discharge and catchment area

Criteria for a working definition of a flash flood:

- Flood magnitude: $q_p \geq q_{p_{th}} = 0.5\, m^3 s^{-1} km^{-2}$

- Spatial extent: $A \leq A_{th} = 3000\, km^2$

If a HPE triggers multiple flash floods across several catchments: multiple events are reported on the same date, each corresponding to a different basin, but it is classified as a single episode

Two episodes are considered independent if they are separated by > 96 h

5. Flash flood regime: Representativeness

99 episodes identified from 1905 to 2023, some of them impacting both climatic regions

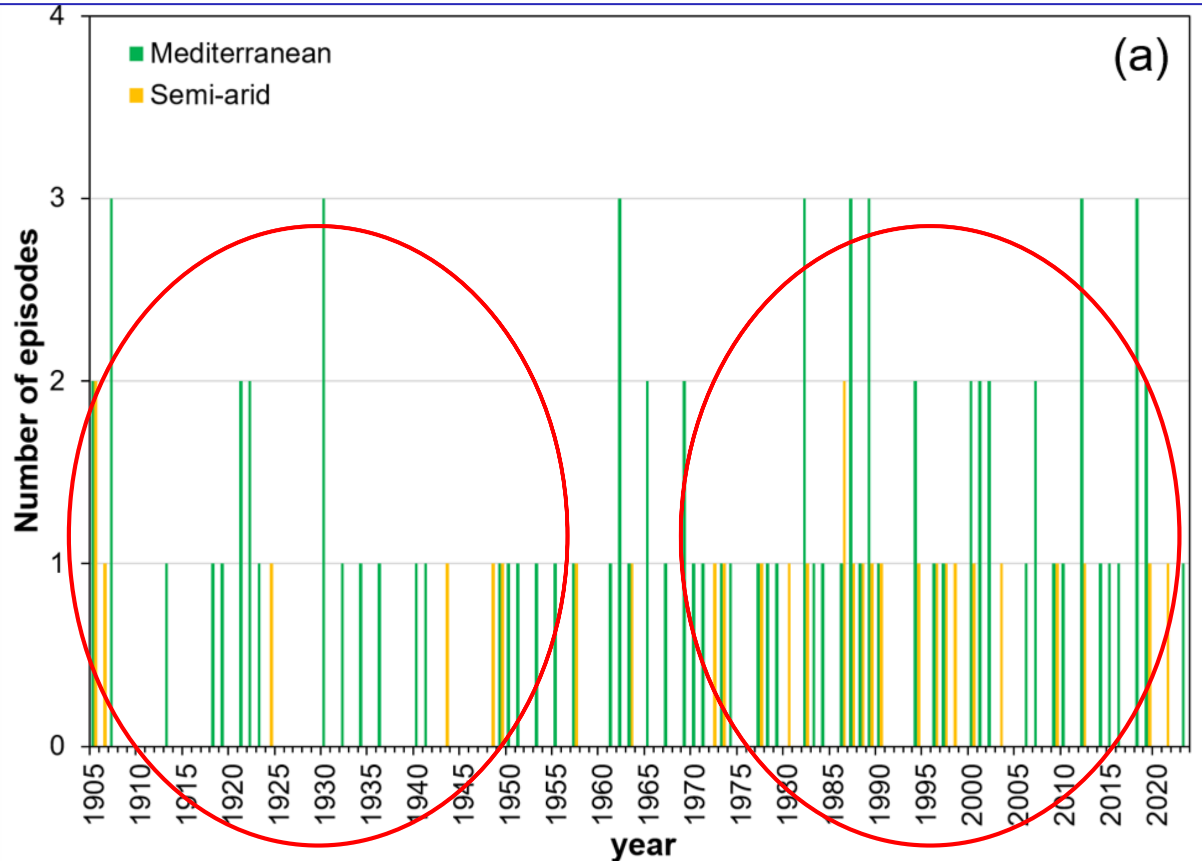
Climate	Episodes	River sections	Data population
Mediterranean	85	174	333 (75.5%)
Semi-arid	30	55	108 (24.5%)

Flash flood regime

Several years with no episodes

Maximum of 3 per year in a climatic region

Inter-annual variability has decreased



5. Flash flood regime: Representativeness

- Compilation coverage (Cov): total watershed area × time period considered
- Compilation density (D): number of episodes ÷ compilation coverage

Climate	Period	Area (*10^4 km^2)	Number of events	Cov (yr*area*10^{-5} km^2)	D (episodes*yr^{-1}*area^{-1}*10^5 km^2)
Mediterranean	1905-2023 (119 yrs.)	6.3	85	75.1	1.1
Semi-arid		1.8	30	20.9	1.4
Mediterranean	1905-1964 (60 yrs.)	2.4	32	14.3	2.2
	1965-2023 (59 yrs.)	4.6	53	27.0	2.0
Semi-arid	1905-1964	0.8	9	5.0	1.8
	1965-2023	1.3	21	7.9	2.7

Drainage extent and number of episodes have increased over time

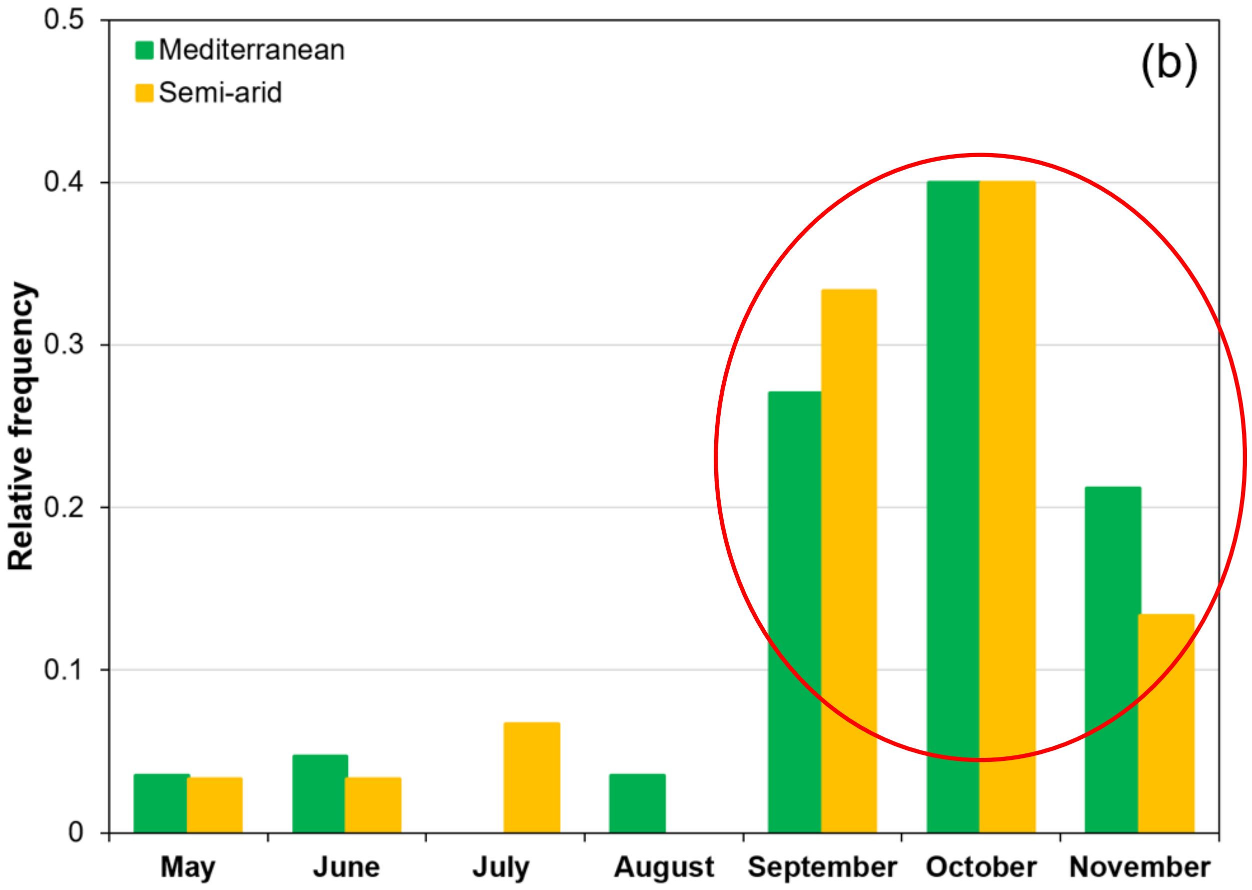
Expansion of observational networks, advancements in information dissemination, population growth, and increased awareness

5. Flash flood regime: Temporal distribution

The relative frequency peaks in autumn. October accounts for 40% of all occurrences in both climatic regions

This pattern mirrors the monthly distribution of absolute maximum daily rainfall

Extreme daily amounts arise as a key factor



6. Envelope curves

Envelopes curves assess the influence of catchment area on flash flood peaks

The following power-law relationship has been used to derive the envelope curve, representing its upper limit:

$$q_p = q_r A^{\beta}$$

$q_p\ [m^3 s^{-1} km^{-2}]$ ≡ unit peak discharge

$A\ [km^2]$ ≡ catchment area

$q_r\ \left[m^3 s^{-1} km^{-2(1+\beta)}\right]$ ≡ reduced peak discharge. Independent of A

β ≡scaling exponent

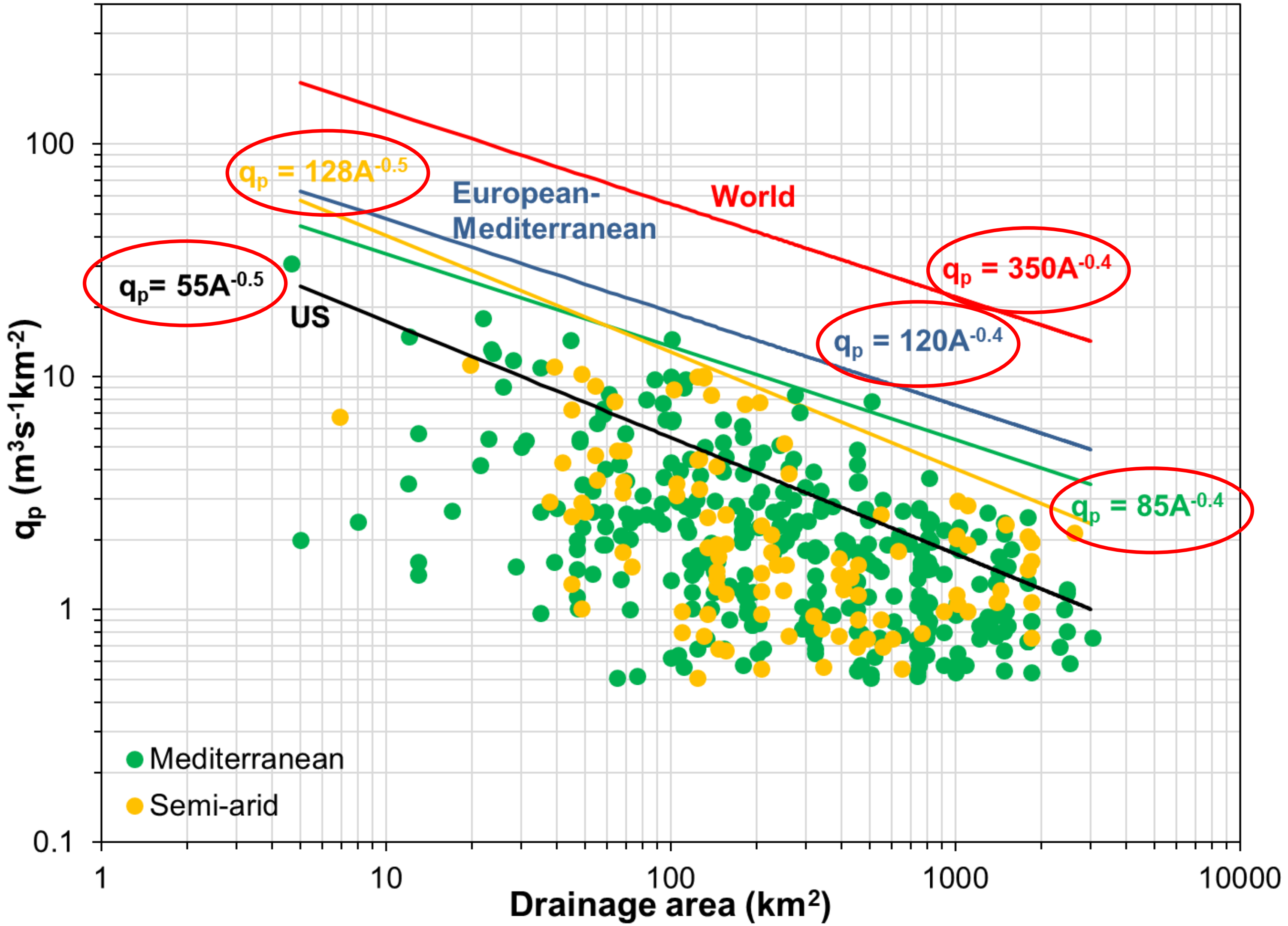
Quantile regression of $\log(q_p)$ vs $\log(A)$, after determining the quantile exceeded by less than one data point

6. Envelope curves

Envelope curves are consistent in shape with previous research

Spanish Mediterranean climate with Europe-Mediterranean and World, but less intense events

Semi-arid climates in Spain and US, but are more intense events



q_r varies depending on database size

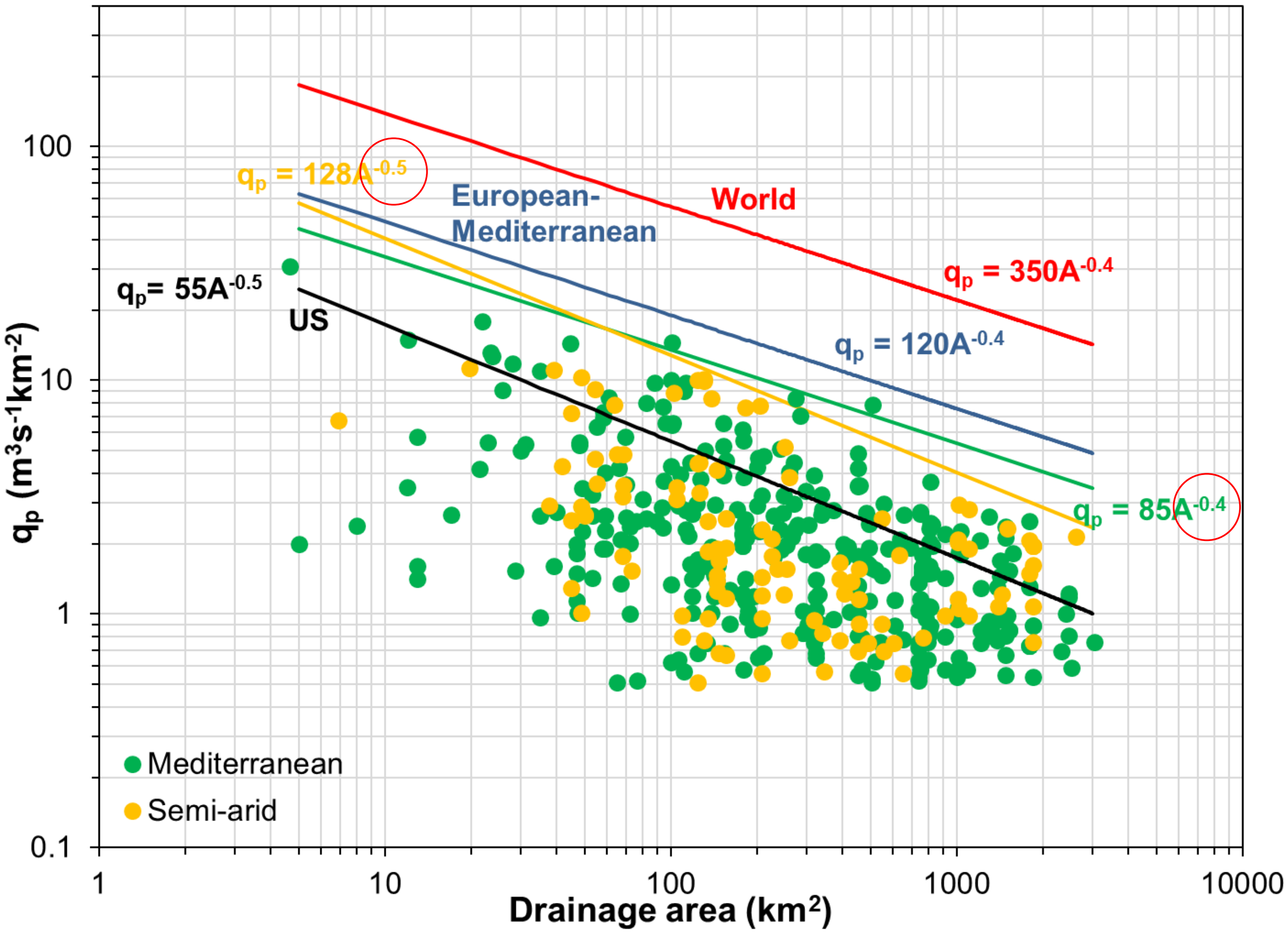
Scaling exponents are influenced by climatic and physiographic factors

6. Envelope curves

Scaling exponents influenced by:

- Variations in: mean annual precipitation, storm coverage relative to catchment area, rainfall intensity, duration and amount between both climates

- Effect of runoff threshold exceedance: Impact in peak discharge as catchment size increases



- Flood wave attenuation and transmission losses can more significantly reduce peak discharges in semi-arid catchments with relatively long channels

7. Spatial distribution

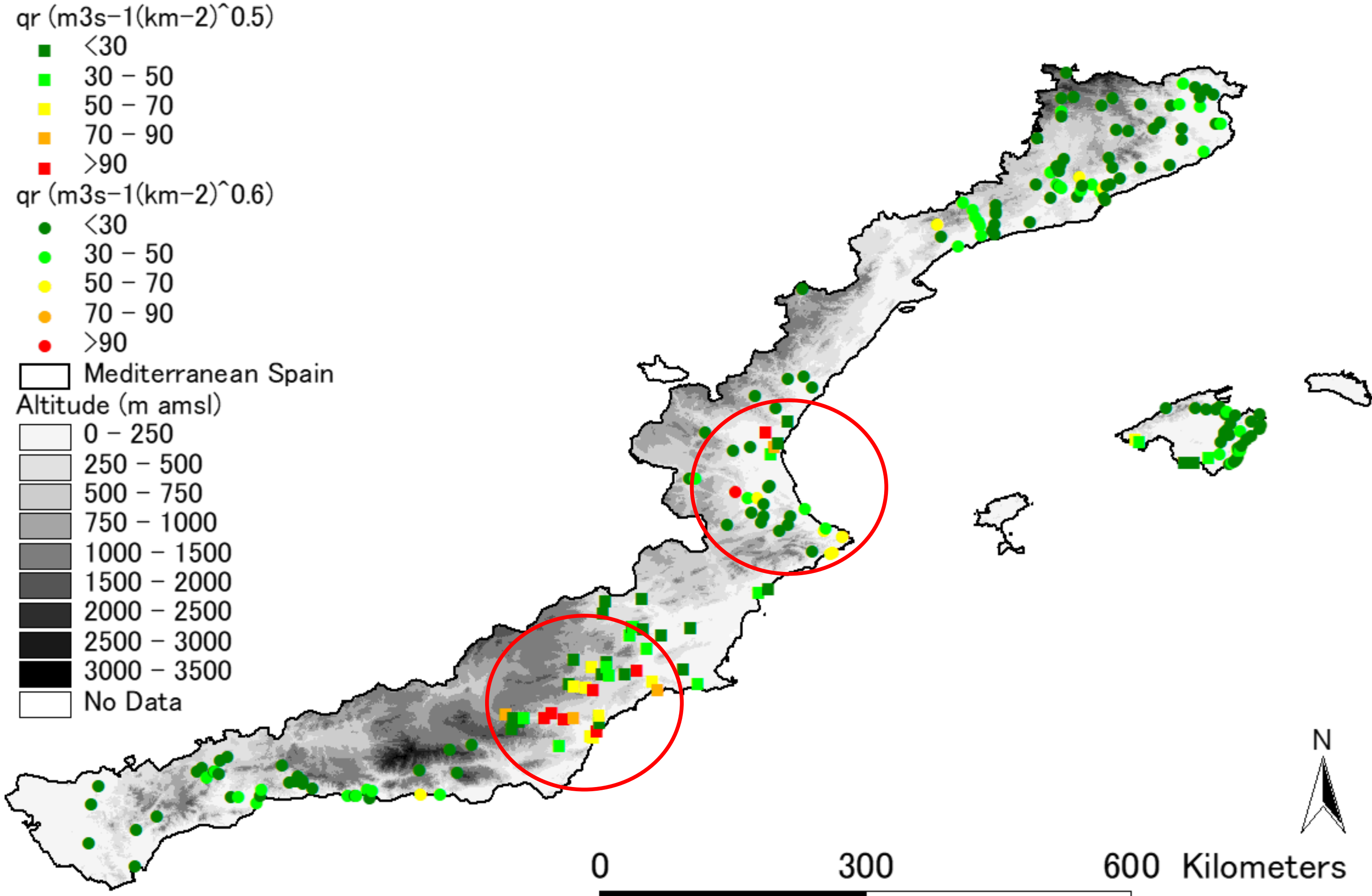
Spatial distribution of q_r based on the maximum q_p for each river section and climatic region

Hotspots:

Mediterranean climate: Central València and northern Alacant

Semi-arid climate: Southern Murcia and northern Almería

Magnitude is higher in semi-arid region



8. Characterization for selected flash floods

13 flash floods: 7 in Mediterranean and 6 in semi-arid catchments

Database:

- DTMs from 25-50 m
- QPEs (1000 m; 10 min)
- Automatic discharge data (10 min)
- Post-flood field estimates
- Hydrological simulations with KLEM model (10 min)

Additional criteria for a working definition of flash flood:

- Storm duration: $D_{th} \leq 48\ h$
- Basin dynamics: $T_{lag_{th}} \leq 6\ h$

Basin impacted and province	Range of climates	Date of peak flood	No. of river sections (No. of stream-gauges)	Available data	Range of drainage area (km^2)	Storm duration (h)	Range of unit peak discharge (m^{3}s^{-1}km^{-2})	Range of flooding rise time (h)	Lag time (h)
Llobregat, Barcelona	Cfa-CSa	09 Jun 2000	8 (4)	R-G, S-G, PFFE	12.4–2851.1	8.0	0.4–14.9	1.5–5.7	–
Serpis, València	CSa	12 Oct 2007	2 (2)	S-G, QPEs, HS	101.6–465.8	32.0	0.5–3.1	0.5–7.0	3.0–4.7
Guadalentín, Murcia	BSh-BSk	28 Sep 2012	7 (4)	S-G, PFFE, QPEs, HS	52.2–1021.3	16.3	1.1–4.6	0.5–1.0	1.5–4.8
Nogalte, Murcia	BSh	28 Sep 2012	4 (1)	S-G, PFFE, QPEs, HS	6.7–128.2	15.5	6.7–11.1	0.8–1.3	2.2–2.3
Ses Planes, Illes Balears	CSa	09 Oct 2018	1 (0)	PFFE, QPEs, HS	23.2	8.7	13.1	0.5	1.2
Cànyoles, València	CSa	12 Sep 2019	1 (1)	S-G, QPEs, HS	877.8	26.0	0.6	1.0	3.7
Albaida, València	CSa	12 Sep 2019	1 (1)	S-G, QPEs, HS	318.1	35.2	2.2	3.8	5.7
Albujón, Murcia	BSh	13 Sep 2019	1 (1)	S-G, QPEs, HS	395.2	20.3	0.3*	5.2	5.8
Benipila, Murcia	BSh	13 Sep 2019	1 (1)	S-G, QPEs, HS	141.3	20.8	2.0	2.3	4.5
Canalejas, Murcia	BSh	12 Sep 2019	1 (1)	S-G, QPEs, HS	126.9	7.5	4.5	1.0	2.3
Almanzora, Almería	BSk-BWh	13 Sep 2019	1 (1)	S-G, QPEs, HS	1077.2	36.0	0.2*	3.0	4.3
Francolí, Tarragona	CSa-CSb	22 Oct 2019	17 (1)	S-G, PFFE, QPEs, HS	9.5–809.1	22.7	1.5–11.1	0.5–2.5	1.5–3.7
Rubí, Barcelona	CSa	13 Jun 2023	1 (1)	S-G, QPEs, HS	121.7	4.0	1.5	0.4	1.8

- *Event runoff coefficient*

Valuable metric to assess catchment response and to understand the influence of climate and geomorphology on hydrological behavior

Proportion of runoff to rainfall volumes averaged over the watershed during the whole event

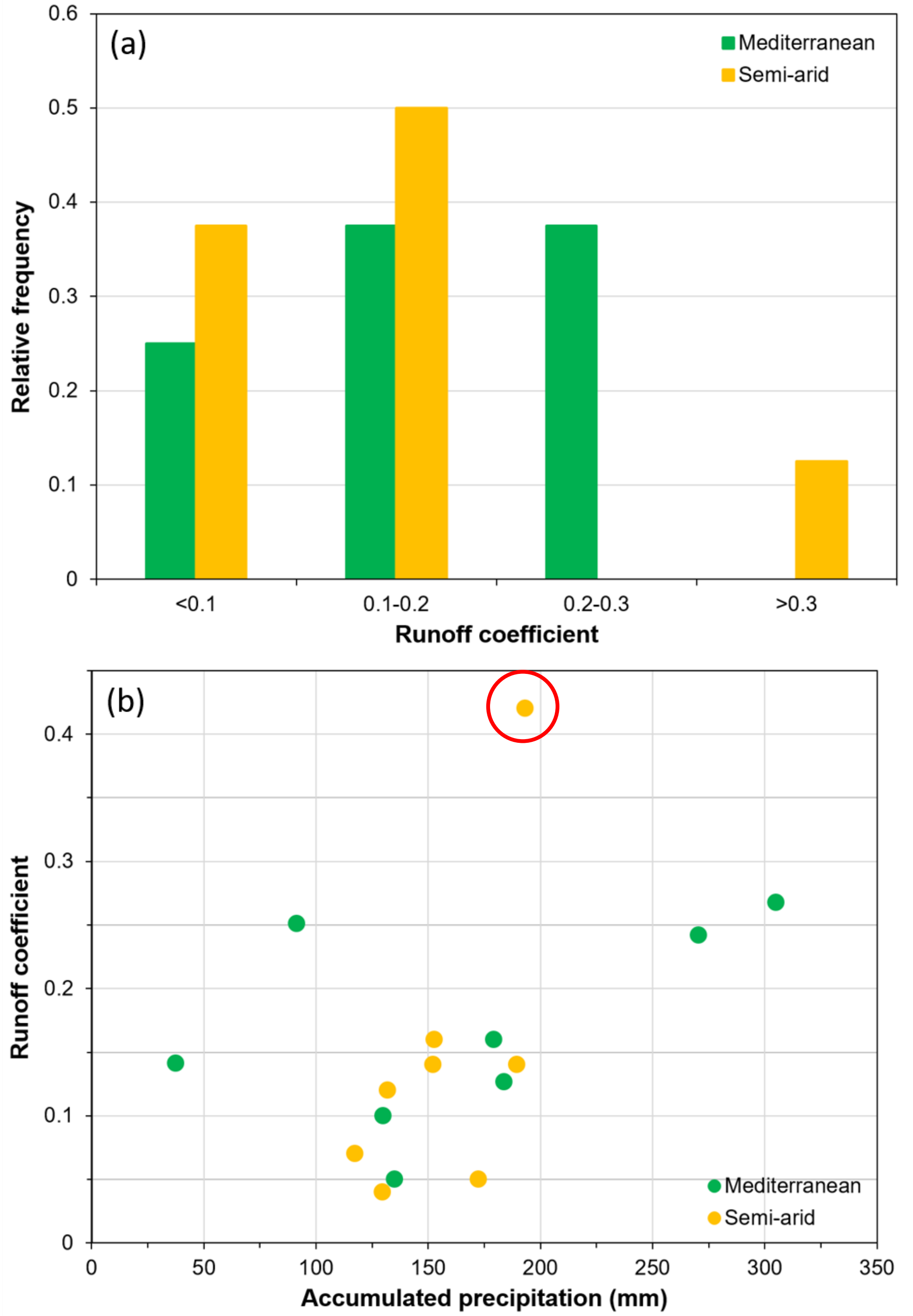
Features in frequency distribution

Mediterranean watersheds:

mean=0.17; std dev=0.08; median= 0.15

Semi-arid catchments:

mean=0.14; std dev=0.12; median=0.13



8. Characterization for selected flash floods

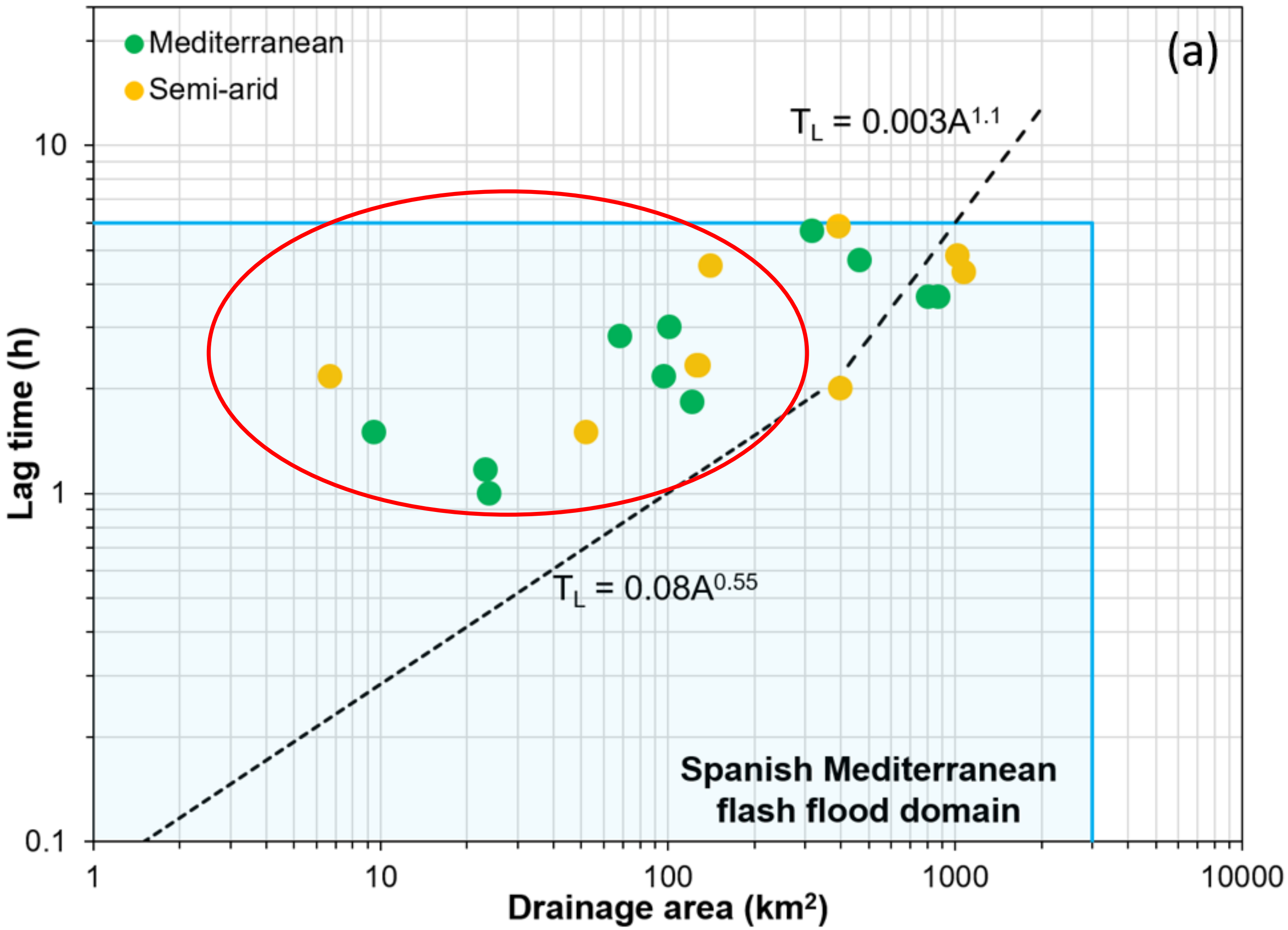
- *Response time*

Flash flood envelope curves in Europe, characterizing the lower limit of T_{lag} against A:

$$T_{lag} = \begin{cases} 0.08 \cdot A^{0.55} & for\ A \leq 350\ km^2 \\ 0.003 \cdot A^{1.10} & for\ A > 350\ km^2 \end{cases}$$

Lag times for $A < 350\ km^2$ are generally well above the lower envelope bound

Delayed hydrological responses due to soil moisture replenishment and runoff threshold exceedance



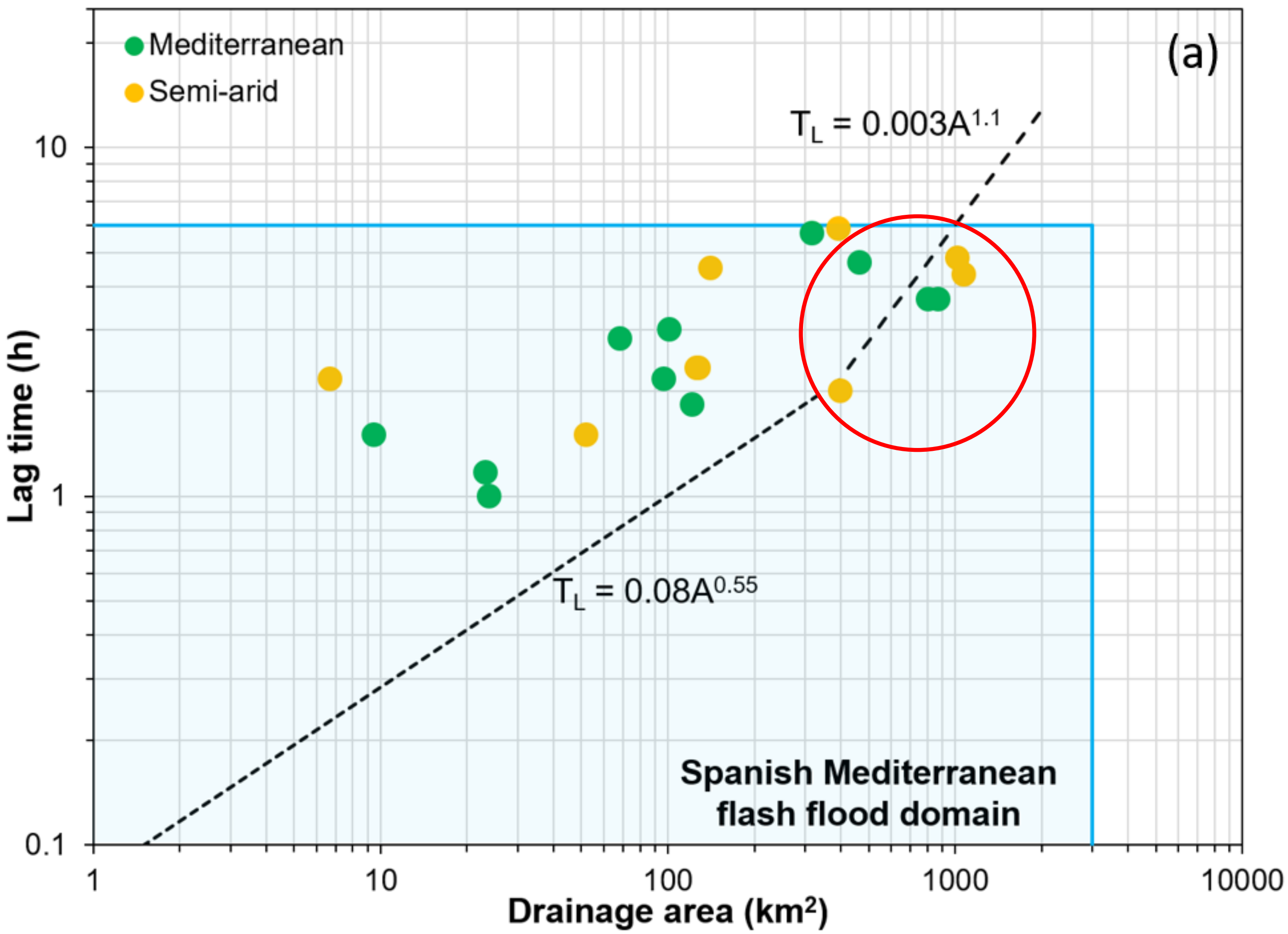
8. Characterization for selected flash floods

- *Response time*

For $A > 800\,km^2$, T_{lag} fall below the lower limit of the envelope curve

T_{lag} is more influenced by the velocity of the flood bore, which is governed by flow hydraulics (stream slope, channel roughness, network geometry)

Relatively wide, braided channels with sparse vegetation offering less resistance to flow?



8. Characterization for selected flash floods

- *Flashiness*

Flashiness measures the severity of a flood by capturing how fast the hydrograph rises, encompassing both the magnitude and timing of the event

Maximum time derivative of streamflow during the rising limb of the hydrograph:

$$F = \frac{max(Q_{i+1} - Q_i)}{A\Delta t}, \qquad \forall\, i = 1,2,\dots,N-1$$

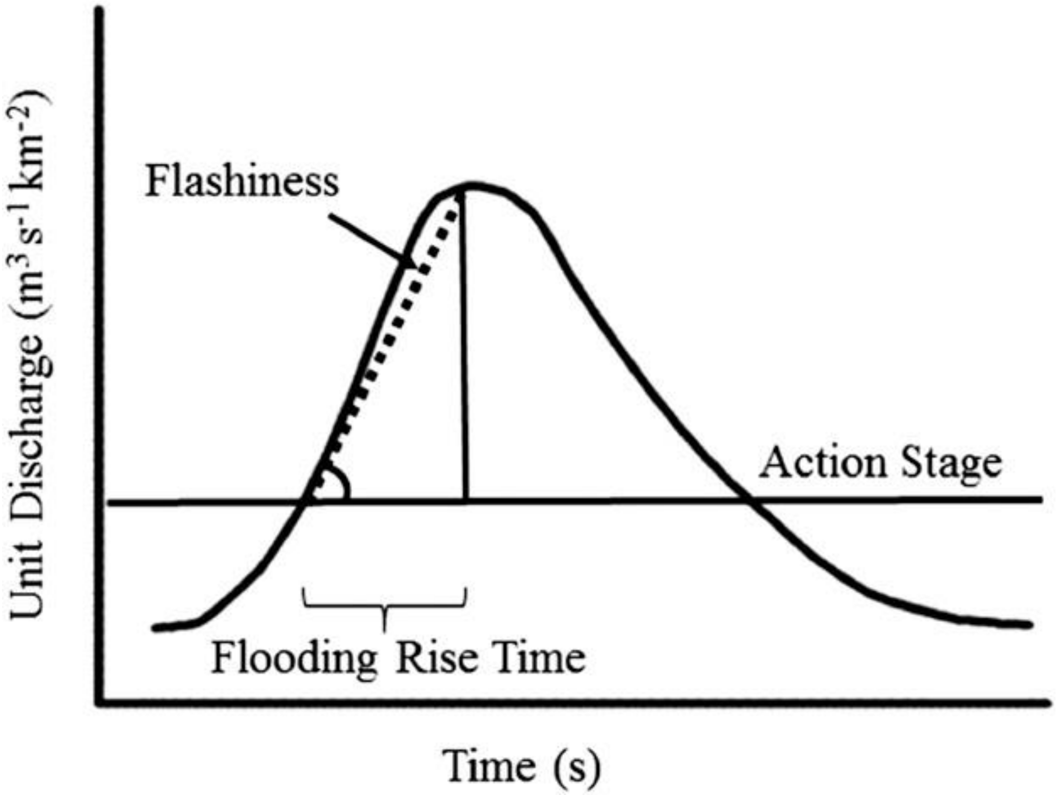
$F\ [ms^{-2}]$ ≡ flashiness

$Q_i [m^3 s^{-1}]$ ≡ discharge at time t_i

Δt ≡ temporal frequency

$A\ [m^2]$ ≡ catchment area

N ≡ number of values up to peak discharge



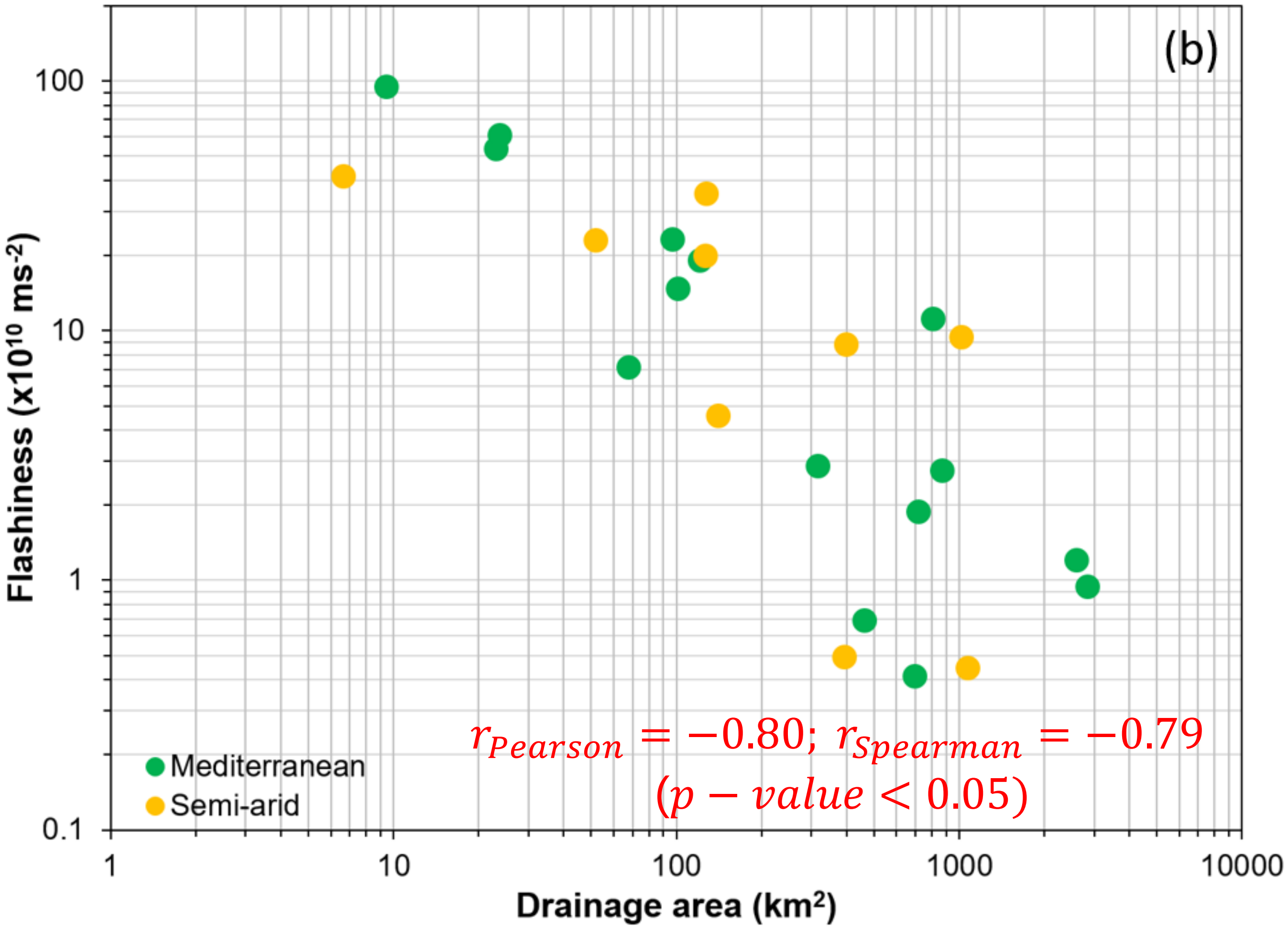
8. Characterization for selected flash floods

- *Flashiness*

Minimal differences with drainage area based on climate.

Significant variability for similar drainage sizes: It integrates rainfall features, antecedent soil moisture, geo-morphology, and land use

Basin size is a crucial determinant of flashiness as it significantly increases with smaller watershed sizes



These drainage extents correspond to river headwaters: steep topography promoting fast surface flow

8. Characterization for selected flash floods

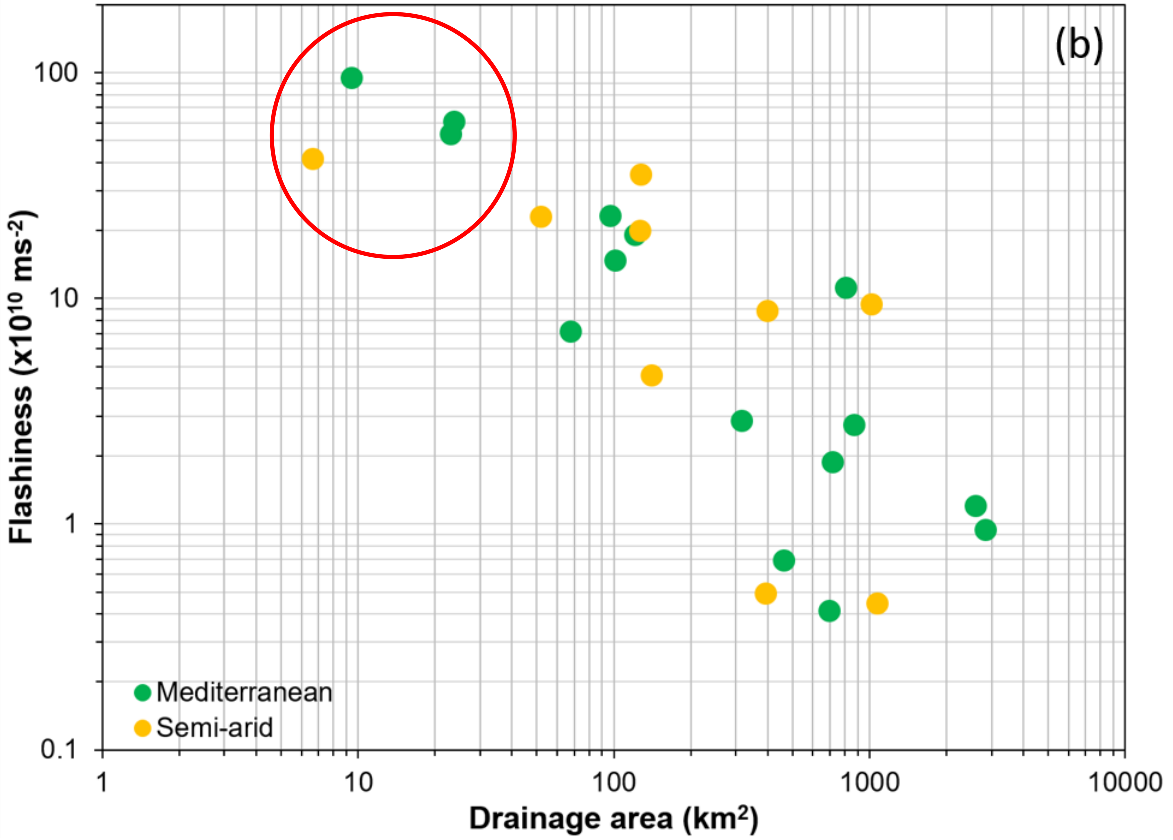
- *Flashiness*

Higher flashiness implies more severe events

Small drainage areas may have the potential for a high number of flash flood-related casualties

8–9 September 2002 episode in the Gard river France: 12 fatalities in drainage areas ~ 10 km^2

9 October 2018 episode in Mallorca, Spain: 13 fatalities in basins < 25 km^2



Risk= hazard nature + exposure + vulnerability

Further technical details and results:

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