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ASSESSING TEMPORAL VARIABILITY AND CONTROLLING FACTORS ON THE HYDROSEDIMENTARY RESPONSE IN MEDITERRANEAN CATCHMENTS

Josep Fortesa Bernat

Universitat
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MEDhyCON
Mediterranean Ecogeomorphological and
Hydrological Connectivity Research Team

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Doctoral Programme of History, History of Art and Geography

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Josep Fortesa Bernat

Supervisor and Tutor: Dr. Joan Estrany Bertos
Co-supervisor: Dr. Jérôme Latron

Doctor by the Universitat de les Illes Balears

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Fortesa J, Latron J, García-Comendador J, Company J, Estrany A. 2020. Runoff and soil moisture as driving factors in suspended sediment transport of a small mid-mountain Mediterranean catchment. *Geomorphology* 368, 107349. DOI: 10.1016/j.geomorph.2020.107349 (JCR: Geosciences Q1 28/200; IF-2019: 3.819).

Fortesa J, Ricci GF, García-Comendador J, Gentile F, Estrany A, Sauquet E, Datry T, De Girolamo AM. 2021. Analysing hydrological and sediment transport regime in two Mediterranean intermittent rivers. *Catena* 196, 104865. DOI: 10.1016/j.catena.2020.104865 (JCR: Geosciences Q1 21/200; IF-2019: 4.333).

Contents

LIST OF ACRONYMS

AEMET - Agencia Estatal de Meteorología

AP1d - Antecedent precipitation one day before

AP3d - Antecedent precipitation three days before

BFI - Base flow index

DH1 - Maximum annual flow of 1-day duration

DL6 - Number of zero-flow days

E - Episodic-ephemeral

ET_o - Evapotranspiration

FDC - Flow duration curve

Fdi - Multi-annual frequencies of zero-flow months for the contiguous six wetter months

Fdj - Multi-annual frequencies of zero-flow months for the remaining six drier months

FI - Richards-Baker flashiness index

GOIB - Govern de les Illes Balears

HIs - Hydrological indicators

IF - Impact factor

I-D - Intermittent-dry

IHA - Indicators of hydrologic alteration

I-P - Intermittent-pools

$IP_{max}30$ - Maximum 30' rainfall intensity

$IP_{mean}30$ - Average rainfall intensity

INE - Instituto Nacional de Estadística

IRESs - Intermittent Rivers and Ephemeral Streams

JCR - Journal Citation Report

MEDhyCON - MEDiterranean Ecogeomorphological and hydrological CONnectivity research team

NSMLT - Normalised soil moisture lag time

NTU - Nephelometric turbidity units

P - Perennial

PT - Precipitation

P_{tot} - Total precipitation

Q - Discharge

Q_0 - Baseflow at the start of the flood

Q_{dur} - Flood duration

Q_{max} - Maximum peak discharge

R - Runoff

R_a - Annual runoff

R_c - Runoff coefficient

SD - Standard deviation

SD6 - 6-month seasonal predictability of dry periods

SDC - Sediment duration curve

SFI - Sediment flashiness index

SL - Sediment load

SM - Soil moisture

SM_{av} - Soil moisture average

SS - Suspended sediment

SSC - Suspended sediment concentration

SSC_m - Mean suspended sediment concentration

SSC_{max} - Maximum suspended sediment concentration

SSY - Suspended sediment yield

SY - Sediment yield

TH1 - Date of maximum flow

TL1 - Date of minimum flow

LIST OF FIGURES

Chapter 2

Chapter 3

LIST OF TABLES

Chapter 1

Chapter 3

Chapter 7

Abstract

Assessing the hydrological response and suspended sediment transport in rivers is fundamental to improve the knowledge and management of water resources, floods, droughts, transmission of pollutants and soil erosion at catchment scale. The Mediterranean regions received special attention due to the seasonality of their climate, which promotes large differences in water resources availability between years and seasons. Furthermore, the land cover of most Mediterranean catchments have been strongly modified by humans over millennia creating a complex landscape causing a significant influence on the hydrosedimentary behaviour of fluvial systems.

This thesis aims to determine the effects of basin lithology, land uses and temporal scales on runoff generation and suspended sediment transport dynamics in representative Mediterranean catchments. Continuous measurements in hydrometric stations were used over a five-year period at:

a) Small Mediterranean catchments (i.e. < 10 km^2) characterised by contrasting land uses and lithology, where rainfall-runoff relationships were carried out at multiple temporal scales to achieve a better understanding of the hydrological response.
b) A representative small mid-mountainous Mediterranean catchment (i.e. Es Fangar, 3.4 km^2), where the role of soil moisture in water and suspended sediment fluxes were investigated during five hydrological years.
c) Two medium size Mediterranean catchments (i.e. Búger in Mallorca, 68.2 km^2; Carapelle, in Southern Italy, 506 km^2) selected to analyse the most relevant driven factors affecting the flow regime and to quantify the runoff and suspended sediment yields at different temporal scales.

In the small Mediterranean catchments, the assessment of the hydrological response at multiple temporal scales depicted how non-linearity increased from annual to event scale in the rainfall-runoff relationships according to basin lithology. At the annual scale, the rainfall-runoff relationship in impervious catchments showed a significant linearity, whereas pervious lithology increased substantially the non-linearity of this relationship. A large intra-annual variability was observed in the seasonal runoff contribution according to the dynamics of rainfall and evapotranspiration throughout the year that leads to a succession of wet (winter), dry (summer) and transition periods (last autumn and early spring). Such periods generated different seasonal catchment moisture conditions for runoff generation at the event scale, being a breakdown point for the non-linearity of the rainfall-runoff relationship. As a result, at the event scale the non-linearity of the seasonal rainfall-runoff relationship increased from spring and winter to summer. Furthermore, differences in runoff amount and rainfall-runoff linearity were observed in relation to lithology and land use characteristics. The event scale rainfall-runoff relationships showed that floods occurred in catchments with impervious lithology had stronger linearity and larger runoff values than catchments with pervious lithology. In addition, the assessment of rainfall-runoff relationships according to land uses showed how agriculture promoted the highest correlations attributable to lower vegetation cover.

In the small mid-mountainous Es Fangar catchment and also in the medium size Búger and Carapelle catchments, the spatial distribution of physical driving factors (lithology and land cover) and human structures (terraces and check dams) influenced the annual sediment yields. In Es Fangar and Búger catchments, the afforested headwaters characterised by carbonate materials promoted low runoff and suspended sediment response. Lowland areas were characterised by higher suspended sediment availability than headwaters due to higher coupling with the main channel system in areas with deeper soil profiles over softer marl soils predominantly covered by rainfed herbaceous crops. However, in these areas soil conservation structures avoided rill erosion, laminated runoff and retained soil. In Carapelle catchment, median annual sediment yield were two orders of magnitude higher (i.e. 267.8 t km^2 yr^{-1}) than in Es Fangar (i.e. 4.5 t km^2 yr^{-1}) and Búger (i.e. 1.4 t km^2 yr^{-1}) catchments because agricultural areas with seasonal vegetation cover and less pervious materials were the driving factor of suspended sediment transport. Additionally, collapsed check dams in Carapelle promoted riverbed erosion increasing the sediment supply. A large inter- and intra-annual variability of the sediment load was also observed. As a result, the seasonal assessment in Es Fangar and Búger catchments showed that >80% of sediment was generated during autumn and winter. At the event scale, soil moisture and rainfall depth accumulated during one day before the event strongly correlated with the runoff response in Es Fangar and Búger catchments because limestone lithology promoted a high threshold for runoff generation. This process was observed mainly during wet periods, when the highest values of runoff, peak discharge and sediment load were recorded. In Es Fangar catchment, runoff and peak discharge showed the closest correlations with sediment load, being most significant in autumn and winter. In the Carapelle catchment, the largest sediment contributions were controlled by rainfall amount and intensities and largest runoff events, suggesting that the larger area covered by agriculture controlled the hydrological response and suspended sediment transport. In Es Fangar and Búger catchments, the highest frequency of clockwise discharge-suspended sediment concentration hysteresis revealed that most of the sediment was generated from nearby sources, illustrating the strong influence of the spatial distribution of basin lithology, land use and terraces on the suspended sediment transport. Thus, in Es Fangar catchment the soil moisture-discharge hysteresis illustrated how high moisture content during the wet period enabled the increase of flow and sediment conveyance by activating less available sediment sources as counter-clockwise discharge-suspended sediment concentration hysteresis occurred. In the Carapelle catchment, the highest frequency of counter-clockwise discharge-suspended sediment concentration hysteresis confirmed that the larger area of agricultural land promoted the sediment availability from the whole catchment.

The results of this thesis confirmed that physical driving factors (lithology and land cover) and the conservation state of human structures (terraces and check dams) exerts a strong control in the hydrological response and suspended sediment transport. The spatial distribution, patchiness and interaction between these driving factors explained water and sediment yields of the study catchments. The analysis of the runoff response and suspended sediment transport from the annual to the event scale allowed to identify the hydro-meteorological driving factors and how these are related to the physical and human features of the catchments. The

characterization of catchment features from a evidence-based approach has demonstrated to be essential for understanding the hydrosedimentary response to move towards an integrated management catchment process useful to simulate multiple future scenarios of land use and climate change.

Keywords: Mediterranean catchments, runoff generation, suspended sediment transport, physical drivers, antecedent conditions, soil conservation structures

Resum

Avaluar la resposta hidrològica i el transport de sediment en suspensió a escala de conca de drenatge és fonamental per millor el coneixement i la gestió dels recursos hídrics, inundacions, sequeres, transmissió de contaminats i l'erosió del sòl. La regió mediterrània ha rebut una atenció especial ja que l'estacionalitat del seu clima promou grans diferències en la disponibilitat dels recursos hídrics entre anys i estacions. A més, els usos del sòl de la majoria de les conques mediterrànies han estat modificats per l'home durant segles creant -amb la interacció de la litologia- un paisatge complex, el qual influencia la resposta hidrològica i el transport de sediment.

Aquesta tesi té com a objectiu determinar els patrons d'escolament i les dinàmiques del transport de sediment en suspensió en conques mediterrànies representatives, avaluant com aquests patrons canvien al llarg del temps a causa de la variabilitat inter- i intra-anual. La monitorització contínua del cabal i la concentració del sediment en suspensió a partir de xarxes hidromètriques s'ha analitzat durant un període de cinc anys a:

a) Petites conques de drenatge mediterrànies (i.e. < 10 km^2) caracteritzades per usos del sòl i litologies, on la relació precipitació-escolament a múltiples escales temporals es va dur a terme per comprendre millor la seva resposta hidrològica.
b) Una petita conca mediterrània representativa de mitja muntanya (Es Fangar; 3,4 km^2), on el paper de la humitat del sòl en els fluxos d'aigua i sediment en suspensió s'analitzaren durant cinc anys hidrològics.
c) Dues conques mediterrànies (Búger 68,2 km^2 i Carapelle 506 km^2) foren seleccionades per tal d'identificar els factors principals que influeixen en el règim hidrològic i quantificar la generació d'escolament i el transport de sediment en suspensió a diverses escales temporals.

A les conques mediterrànies petites, l'avaluació a múltiples escales temporals de la resposta hidrològica mostrà com la no linealitat de la relació precipitació-escolament incrementà de l'escala anual a l'escala d'episodi. A escala anual, la relació precipitació-escolament mostrà una linealitat significativa en conques de litologia impermeable, mentre que la no linealitat incrementà en conques de litologia permeable. Una gran variabilitat intra-anual s'observà a la contribució estacional de l'escolament en concordança a les dinàmiques de precipitació i l'evapotranspiració al llarg de l'any, els quals van generar una successió de períodes humits (hivern), secs (estiu) i de transició (final de tardor i principi de primavera). Aquests períodes generaren diferents condicions estacionals de la humitat del sòl a la conca per a la generació d'escolament a escala d'episodi, sent-ne el punt clau de partida per a la no linealitat en la relació precipitació-escolament. Com a resultat, a escala d'episodi la no linealitat estacional de la relació precipitació-escolament incrementà des de l'hivern i la primavera fins a l'estiu. A més, s'observaren diferències en el volum d'escolament i la linealitat de la precipitació-escolament segons la litologia i els usos del sòl. En concordança amb els resultats obtinguts a escala anual, els episodis en conques de litologia impermeable tingueren una major linealitat i un major volum d'escolament que els episodis de les conques amb litologia impermeable. Endemés,

la relació precipitació-escolament establerta sota diferents usos del sòl mostrà com els usos agrícoles obtingueren la correlació més alta a causa d'una menor cobertura vegetal.

A les conques des Fangar, Búger i Carapelle els valors anuals d'exportació de sediment obtinguts estan influenciats per la distribució espacial dels factors físics (litologia i usos del sòl) i les estructures antròpiques (marjades, parats i preses de laminació). A les conques des Fangar i Búger, les capçaleres aforestades caracteritzades per materials carbonatats varen promoure una resposta baixa en la generació d'escolament i en el transport de sediment. Les zones baixes de la conca es caracteritzen per una major disponibilitat de sediment que les capçaleres per mor d'una major connectivitat amb el canal principal en àrees amb major desenvolupament edàfic en zones agrícoles margoses. No obstant això, en aquestes zones les estructures de conservació del sòl eviten l'erosió, laminen l'escolament i retenen el sòl. A la conca de Carapelle, els valors mitjans de taxa anual de producció de sediment (i.e. 267,8 t km^2 a^{-1}) foren majors que a les conques des Fangar (i.e. 4,5 t km^2 a^{-1}) i Búger (1,4 t km^2 a^{-1}) perquè les zones agrícoles amb cobertura vegetal estacional i els materials menys permeables foren els factors físics impulsors del transport de sediment, generant així les majors contribucions de sediment. Per afegitó, a la conca de Carapelle el col·lapse de preses de laminació afavorí l'erosió del llit del riu incrementat el volum de sediment. No obstant això, s'observà una gran variabilitat inter- i intra-anual de l'exportació de sediment. Així doncs, l'anàlisi realitzada a les conques des Fangar i Búger demostrà que el 80% del sediment es generà durant la tardor i l'hivern. En aquest sentit, a escala d'episodi la humitat del sòl i la precipitació antecedent un dia abans de l'episodi afectaren significativament la resposta de l'escolament de les conques des Fangar i Búger, respectivament. Aquest fet va ocórrer principalment durant períodes humits quan s'observaren els valors majors en escolament, pic de cabal i exportació de sediment. A més, a la conca des Fangar la correlació de l'escolament i el pic de cabal foren significatives amb l'exportació de sediment, incrementant aquesta significança durant la tardor i l'hivern. A la conca de Carapelle, les majors contribucions de sediment foren controlades pel volum i intensitat de la precipitació i els valors més grans d'escolament, els quals suggereixen que la gran extensió agrícola controla la resposta hidrològica i el transport de sediment en suspensió. A les conques des Fangar i Búger, la major freqüència de les histèresis horàries entre cabal i concentració de sediment en suspensió indicaren que la major part del sediment fou generat d'àrees pròximes a la sortida de la conca, confirmant la forta influència de la distribució espacial de la litologia, usos del sòl i marjades sobre el transport de sediment en suspensió. De fet, a la conca des Fangar les histèresis entre humitat del sòl i cabal mostraren com les situacions d'elevada humitat del sòl durant períodes humits incrementaren l'eficiència en els fluxos d'aigua i sediment connectant aquelles zones de sediment menys disponibles ja que la histèresi cabal-concentració de sediment en suspensió fou de gir antihorari. A la conca de Carapelle, la major freqüència de les histèresis antihoràries de cabal-concentració de sediment en suspensió confirmà que les àrees agrícoles estenen les fonts de sediment disponibles a gran part de la superfície de la conca.

Els resultats d'aquesta tesi confirmen que els factors físics (litologia i usos del sòl) i l'estat de preservació de les estructures de conservació del sòl (marjades, parats i

preses de laminació) exerceixen un control fort sobre la resposta hidrològica i el transport de sediment en suspensió. La distribució espacial, l'heterogeneïtat i la interacció entre aquests factors explicaren els volums d'aigua i de sediment de les conques seleccionades. L'anàlisi de la resposta hidrològica i del transport de sediment en suspensió ha permès identificar els factors hidrometeorològics més importants i com aquests estan relacionats amb les característiques físiques i humanes de les conques. Per tant, caracteritzar les conques des d'aquest punt de vista científic ha demostrat ser fonamental per comprendre la generació d'escolament i el transport de sediment per tal d'avançar cap a un procés de gestió de conques que ha de permetre simular múltiples escenaris futurs front al canvi d'usos del sòl i canvi climàtic.

Paraules clau: conques mediterrànies, generació d'escolament, transport de sediment en suspensió, factors físics, condicions antecedent, estructures de conservació del sòl.

Resumen

Evaluar la respuesta hidrológica y el transporte en suspensión a escala de cuenca de drenaje es fundamental para mejorar el conocimiento y la gestión de los recursos hídricos, inundaciones, sequías, transmisión de contaminantes y la erosión del suelo. La región mediterránea ha recibido una especial atención debido a que la estacionalidad de su clima genera importantes diferencias inter- e intra-anuales en la disponibilidad de los recursos hídricos. Además, los usos del suelo de la mayoría las cuencas mediterráneas han sido ampliamente modificados durante siglos creando -juntamente con la interacción de la litología- un paisaje complejo, influenciando la respuesta hidrológica y del transporte de sedimento.

Esta tesis tiene como objetivo determinar los patrones de escorrentía y las dinámicas del transporte de sedimento en suspensión en cuencas mediterráneas representativas. La monitorización continua del caudal y la concentración del sedimento en suspensión mediante redes hidrométricas se analizó durante un periodo de cinco años en:

a) Pequeñas cuencas de drenaje mediterráneas (i.e. < 10 km^2) caracterizadas por usos del suelo y litologías distintas, donde se analizó la relación precipitación-escorrentía a múltiples escalas temporales para comprender mejor su respuesta hidrológica.
b) Una pequeña cuenca mediterránea representativa de ambientes de media montaña (Es Fangar; 3,4 km^2), donde la humedad del suelo interviene notablemente en los flujos de agua y sedimento, analizándose estas variables durante cinco años hidrológicos.
c) Dos cuencas mediterráneas (Búger 68,2 km^2 y Carapelle 506 km^2) se seleccionaron para identificar los factores principales que influyen en el régimen hidrológico, la generación de escorrentía y el transporte de sedimento en suspensión en multitud de escalas temporales.

En pequeñas cuencas mediterráneas, la evaluación a múltiples escalas temporales de la respuesta hidrológica reflejó como la no linealidad de la relación precipitación-escorrentía se incrementó de escala anual a escala evento. A escala anual, la relación precipitación-escorrentía tuvo una linealidad significativa en cuencas con litología impermeable, mientras que la no linealidad fue mayor en cuencas con litología permeable. Una gran variabilidad intra-anual se observó en la contribución estacional de la escorrentía de acuerdo con la alternancia de dinámicas de precipitación y evapotranspiración a lo largo del año, generando la sucesión de periodos húmedos (invierno), secos (verano) y de transición (finales de otoño e inicio de primavera). Estos periodos impusieron distintas condiciones estacionales de humedad del suelo en la cuenca para la generación de la escorrentía a escala evento, siendo un elemento clave de partida para la no linealidad en la relación precipitación-escorrentía. Como resultado, a escala evento la no linealidad estacional de la relación precipitación-escorrentía fue incrementándose de invierno y primavera a verano. Además, se observaron diferencias en el volumen de escorrentía y la linealidad precipitación-escorrentía según litología y usos del suelo. De acuerdo con los resultados obtenidos a escala anual, los eventos en cuencas con litología impermeable obtuvieron una mayor linealidad y un mayor volumen de

escorrentía que los eventos en cuencas con litología permeable. Además, la relación precipitación-escorrentía establecida según usos del suelo demostró como los usos agrícolas tuvieron mayor correlación atribuible a una menor cobertura vegetal.

En las cuencas de Es Fangar, Búger y Carapelle los valores anuales de exportación de sedimento obtenidos están influenciados por la distribución espacial de los factores (litología y usos del suelo) y las estructuras antrópicas (terrazas y presas de laminación). En las cuencas de Es Fangar y Búger, las cabeceras forestadas caracterizadas por materiales carbonatados promovieron una respuesta baja de la generación de escorrentía y del transporte de sedimento. Las zonas bajas de las cuencas, se caracterizan por una mayor disponibilidad de sedimento que las cabeceras ya que tienen una mayor conectividad con el canal en áreas con mayor desarrollo edáfico en zonas agrícolas margosas. No obstante, en estas zonas las estructuras de conservación del suelo evitan la erosión, laminan la escorrentía y retienen el suelo. En la cuenca de Carapelle, la mediana de los valores de la tasa anual de producción de sedimento (i.e. 267,8 t km^2 a^{-1}) fue mayor que en las cuencas de Es Fangar (i.e. 4,5 t km^2 a^{-1}) y Búger (1,4 t km^2 a^{-1}) debido a que las zonas agrícolas con cobertura vegetal estacional y materiales menos permeables fueron aquellos factores físicos que promovieron el transporte de sedimento, generando así una mayor contribución de sedimento. Además, en la cuenca de Carapelle, el colapso de las presas de laminación favoreció una mayor aportación de sedimento al incrementar la erosión del cauce. Sin embargo, se observó una gran variabilidad inter- e intra-anual de la exportación de sedimento. De hecho, el análisis en las cuencas de Es Fangar y Búger demostró que el 80% del sedimento se generó durante otoño e invierno. De este modo, a escala de evento la humedad del suelo y la precipitación antecedente un día antes del evento influenciaron de forma significativa la generación de escorrentía en las cuencas de Es Fangar y Búger, respectivamente. Este proceso tuvo lugar principalmente durante periodos húmedos en los que se registraron los mayores valores de escorrentía, pico de caudal y exportación de sedimento. Además, en la cuenca de Es Fangar la correlación de la escorrentía y pico de caudal fue significativa con la exportación de sedimento, siendo mayor esta significancia en otoño e invierno. En la cuenca de Carapelle, las mayores contribuciones de sedimento se generaron debido al volumen e intensidad de la precipitación y los valores mayores de escorrentía, los cuales sugieren que la gran extensión agrícola controla la respuesta hidrológica y el transporte de sedimento en suspensión. En las cuencas de Es Fangar y Búger, la mayor frecuencia de histéresis horarias entre caudal y concentración de sedimento en suspensión indicaron que la mayor parte del sedimento fue generado en áreas cercanas a la salida de la cuenca, confirmando la fuerte influencia de la distribución espacial de la litología, usos del suelo y terrazas en el transporte de sedimento en suspensión. Así, en la cuenca de Es Fangar las histéresis entre humedad del suelo y caudal reflejaron como en situaciones de máxima humedad del suelo se incrementó la eficiencia en los flujos de agua y sedimento conectando zonas de sedimento menos disponibles ya que las histéresis caudal-concentración de sedimento en suspensión fueron de giro antihorario. En la cuenca de Carapelle, la mayor frecuencia de las histéresis antihorarias de caudal-concentración de sedimento en suspensión confirmó que las áreas agrícolas extienden las fuentes de sedimento disponibles a la mayoría de la superficie de la cuenca.

Los resultados de esta tesis confirman que los factores físicos (litología y usos del suelo) y el estado de preservación de las estructuras de conservación del suelo (terrazas y presas de laminación) ejercen un fuerte control sobre la respuesta hidrológica y el transporte de sedimento en suspensión. La distribución espacial, la heterogeneidad y la interacción entre estos factores explican los volúmenes de agua y sedimento de las cuencas seleccionadas. El análisis de la respuesta hidrológica y del transporte de sedimento en suspensión ha permitido identificar los factores hidrometeorológicos más relevantes y cómo estos interaccionan con las características físicas y humanas de las cuencas. Por lo tanto, caracterizar las cuencas desde este punto de vista científico ha demostrado ser fundamental para comprender la generación de escorrentía y el transporte de sedimento y así avanzar hacia un proceso de gestión de cuencas que debería permitir simular múltiples escenarios futuros de cambio en los usos del suelo y del cambio climático.

Palabras clave: cuencas mediterráneas, generación de escorrentía, transporte de sedimento en suspensión, factores físicos, condiciones antecedentes, estructuras de conservación del suelo.

1. Introduction: hydrosedimentary response of Mediterranean fluvial systems

Freshwater resources represents 3.5% of the water on the Earth, being the river discharge only the 0.0002% (Gleick, 1993). Consequently, freshwater as resource is scarce and its demand will increase due to the global population grow (Oki and Kanae, 2006). The importance of water as a resource is one of the main reasons for its study, as the understanding of hydrological processes is for example essential to improve the knowledge on water resources management, floods, droughts and transmission of pollutants (Lloyd-Hughes and Saunders. 2002; López-Moreno et al., 2004). Hence, it is necessary to understand the Earth as large and complex system, whose component parts (i.e. atmosphere, lithosphere, hydrosphere, and biosphere) operate on time scales from seconds to millions of years. Thus, within the Earth system, water and sediment fluxes move at multiple spatial and temporal scales through the hydrologic cycle and sediment cycle (Vörösmarty et al., 2004).

The hydrological cycle in Mediterranean catchments is strongly influenced by their climate, as the marked dynamics of rainfall and evapotranspiration throughout the year strongly determine water available for the hydrological response. Such seasonality linked to tectonic, lithological, and physiographic characteristics promote a wide variety of non-perennial flow regimes called temporary rivers, which are characterised by a cease of flow at some point in time or space (Busch et al., 2020).

The sediment cycle begins with the sediment origin from mechanical and biogeochemical disintegration of rocks by tectonic stress and weathering in a source area (Hinderer, 2012). Then, sediment is transported and deposited in a sink region by fluid-driven erosion agents (i.e. rivers, wind, ocean currents and glaciers). Therefore, the generation and movement of water and sediment fluxes, understood as runoff generation processes and suspended sediment transport, are assessed at the catchment scale as a useful functional unit to study the hydrological and sediment cycles (Ambroise 1994; cited in Latron, 2003). Hydrometric networks allow the water and sediment fluxes monitoring through gauging stations to characterize hydrological and suspended sediment dynamics at catchment scale (Mishra and Coulibaly, 2009). Nonetheless, these dynamics operate at different temporal and spatial scales often requiring their assessment through a nested approach; i.e. more than one gauging station (Ferreira et al., 2008).

Furthermore, hydrometric networks are fundamental for the management of water resources in fluvial systems, which necessarily implies their assessment, characterization and accurate quantification. The studies carried out must be valued from an environmental and socio economic point of view. However, in 1950 the runoff amount over half of the word was unknown, therefore hydrological sciences had to be promoted to optimise the water resources on Earth (Keller, 1976). Consequently, the International Association for Hydrological Sciences (IAHS) in the International Union of Geodesy and Geophysics (IUGG) encouraged to the UNESCO for organizing the International Hydrological Decade 1965-1974 (IHD), a research program on water problems that began on January in 1965. The most important activities of the International Hydrological Decade were the study of water balance, hydrological mapping of surface waters (i.e. general problems, runoff regimes) and the influence of man on hydrological processes. Specifically, the Water Resources Law approved in 1963 in the United Kingdom was one of the most important driver for the development of hydrological studies, especially in the Anglo-Saxon world (Ward, 1967). This law was a breakpoint as the following studies established the scientific basis of data collection, water balances, research systems and a methodology to classify representative and experimental catchments. These studies pointed out the need to design and develop hydrometric networks for the study of the different water cycle components as precipitation, evaporation, surface water and groundwater (Gregory, 1964). Initial studies used simple instruments to measure the water depth by means of a conventional float type that recorded the oscillations of water stage depth. However, technological advances allowed continuous monitoring with high temporal resolution (i.e., minute scale), monitoring of more than one variable, improvement of gauging techniques, automation of recording systems and collection of data in real time. This led to higher volume and better quality of the hydrological information collected, that also helped accurate forecasts of flood events (Le Coz, 2008; Volkman et al. 2010).

Different types of hydrometric networks exist depending on the variables to record or the specific objectives to achieve (i.e. monitoring of surface water, groundwater, water quality and/or sediment transport). The overall general objective of these networks is to study water resources, and how they may be affected by global change (i.e. combination of climate change and land uses change). The implementation of a hydrometric network seeks to know and monitor the main hydrological processes at catchment scale to use this knowledge in flood risk planning, the water resources management and for carrying out ecohydrological assessments. Ideally, networks must have an optimal density (i.e. number of stations, temporal scale, measurement and time interval and spatial scale of the network) to include the diverse climatic, geological, water use and land uses characteristics of the fluvial systems (Mishra and Coulibaly, 2009).

Furthermore, obtaining representative hydrometric values is fundamental to detect erroneous data, to characterize extreme events, hydrological dynamics and their possible changes. It is necessary to consider that few data at temporal scale can lead to unrepresentative values, especially in the calculation of the average discharge in ephemeral and intermittent hydrological regimes (Westberg et al., 2011). The *International Hydrological Decade* established a minimum period of ten years of data collection (Ward, 1967). Authors such as Boudevillain et al. (2011) coincide in a monitoring superior than ten years to obtain representative results. Nonetheless, authors such as Sene and Farquharson (1998) recommend a period between 15 and 20 years for data collection. Boudevillain et al. (2011) claim that a triple strategy must be followed: current studies, study of extreme events and historical data.

1.1. Hydrology of Mediterranean catchments

The first hydrological studies were carried out in representative catchments, which integrated the physiographic characteristics of the region to analyse. Thus, the study of the hydrological response in representative catchments improved the understanding of the runoff generation processes and main controlling factors (Hewlett et al., 1969). Besides, small experimental and representative catchments can be considered as outdoor laboratories useful to observe the hydrological response under different or specific land use, lithology and human effect characteristics (Latron and Lana-Renault, 2018). At the beginning of the 20th century, an experimental catchment was installed in the Swiss Alps to assess flood events related to deforestation (Engler, 1919). Close to this period, the theory of runoff generation due to precipitation exceeding the infiltration capacity of the soil was proposed (Horton, 1933). Later on other studies proposed that groundwater contribution was a larger component than surface flow (Linsley et al., 1949) in runoff generation. The Horton theory was the simplistic one in terms of runoff processes explanation. In the 1960s, further research was developed leading to new concepts such as the subsurface flow (Freeze, 1972; Hewlett and Hibbert, 1966) or runoff generation due to saturation excess (Cappus, 1960; cited in Latron, 2003), which were strongly related to physical soil characteristics (Kirkby and Chorley, 1967).

Most of the hydrological studies carried out until the end of the 20th century were focused in catchments under temperate climate (Dunne et al., 1975). During this period, primary studies about surface hydrology in Mediterranean catchments (Gallart et al., 1994; Latron and Gallart, 1995; Piñol et al., 1991) started to bridge the knowledge gap between humid-temperate and Mediterranean catchments. However, the knowledge obtained from humid-temperate environments cannot be directly transferred to the Mediterranean catchments because their hydrological response is highly marked by seasonality (Llorens, 1991).

Mediterranean catchments are subject to high inter- and intra-annual variability of the precipitation, which generates wet and dry periods along a hydrological year (García-Ruiz et al., 2011). Thus, the hydrological response of these catchments is conditioned by the huge inter- and intra-annual variability of the precipitation. At the annual scale, mean annual precipitation of the hydrological boundary of the Mediterranean Sea basin ranges from 5 to 2975 mm (Allam et al., 2020), with globally a general increase in annual runoff as annual rainfall increase (Merheb et al., 2016).

Seasonality is one of the most significant issues in Mediterranean areas fluvial systems due to an alternation of some periods with large rainfall and other with high evapotranspiration throughout the year leading to wet (mostly winter), dry (summer) and transition periods (late autumn and early spring)(Gallart et al., 2002). Such periods play a key role in the runoff generation processes, promoting the non-linearity of the rainfall-runoff relationship at the event scale (Ceballos and Schnabel, 1998; López-Tarazón et al., 2010). In winter and early spring, saturation processes are dominant, due to large water reserves triggering runoff generation (Latron et al., 2008). The same authors observed that high rainfall intensities during late spring, summer and early autumn can also generate runoff under Hortonian conditions. Thus, seasonal assessment of runoff generation showed how different runoff mechanisms can co-exist within a catchment (Manus et al., 2009), although generally, flood events under wet antecedent conditions enable a larger hydrological response (Efstratiadis et al., 2014; Estrany et al., 2010a; Lana-Renault et al., 2007).

1.1.1. Geographical features influencing the Mediterranean hydrological response

The lithology of the Mediterranean Sea Region is a significant factor influencing the runoff response of the fluvial systems as the proportion of carbonate rocks and karst features are significantly higher than in other landscapes (Woodward, 2009). Carbonate rocks develop zones of high permeability promoting infiltration and percolation (Legrand and Stringfield, 1973). Karst areas offer freshwater from aquifers for agricultural irrigation, human consumption and groundwater-dependent ecosystems (Bakalowicz, 2005), being 9.2% of the global population supplied by freshwater from karst (Stevanović, 2019). Karst regions cover 7-12% of the Earth’s continental area (Ford and Williams, 2013). In the Mediterranean, 33% of the area is covered by carbonate sedimentary rocks, allowing a large development of karst areas (Allam et al., 2020). However, the spatial distribution of lithology in Mediterranean catchments is non-uniform, promoting a complex mosaic for runoff generation with non- and contribution runoff areas also depending on soil deep and/or soil moisture content (Yair, 1983).

The spatial pattern of soil moisture depends on the spatial distribution of soil physical and hydraulic properties, subsequently conditioning the runoff response (Zucco et al., 2014). Hydrologic response units are unique combinations of land use, soil and slope within subbasin. These units have different thresholds for runoff generation according their physical characteristics (Flügel, 1995), although runoff generation can occur under dry or wet states. Moreover, runoff may occur from all lithological units under soil saturated conditions and above the critical wetness threshold (Yair, 1992; cited in Fitzjohn et al. 1998). Nevertheless, soil infiltration and percolation rates in limestone areas are great, promoting a higher runoff generation threshold (Calvo-Cases et al., 2003). Under dry conditions, isolated and unconnected areas may act as sinks for runoff whereas under wet conditions hydrological pathways may be more active (Fitzjohn et al., 1998). Therefore, initial conditions play a key role for runoff generation and also spatial linkages within a catchment (Sharma et al., 1987). Low runoff is generally produced in catchments with unconnected source areas (i.e. spatially isolated) and discontinuous hydrological pathways. However, runoff contributing areas can be connected (at least temporarily) when the effective catchment area increases triggering the activation of hydrological pathways and larger runoff. These relations are more complex in larger catchments due to nested effects of mosaic patterns, which alternate a great number of isolated and interactive areas. At the whole catchment scale, variable active areas are responsible for runoff generation but conveyance losses may avoid the downstream water transfer to the catchment outlet. Meanwhile, contributing areas are active areas which runoff is transferred to the catchment outlet (Ambroise, 2004). In this way, both Hortonian and saturation mechanisms have been identified in Mediterranean catchments according to the degree of soil development, lithology, land use and topography (Gallart et al., 1997; Martínez-Mena et al., 1998).

Assessing the hydrological response at event scale is complex given the spatiotemporal variability of precipitation, soil moisture and infiltration as an interaction of multiple drivers in the rainfall-runoff relationship. Besides, catchment response during flood events is strongly related to the spatiotemporal characteristics of the storm over a catchment (Woods and Sivapalan, 1999). Specially, the spatial rainfall distribution is important when the mass centre of precipitation is located over the impervious catchment areas, enabling larger runoff responses (Mejía and Moglen, 2010). However, karst areas difficult the hydrological assessment due to their non-linear behaviour within the runoff response as high infiltration and percolation rates and also interbasin groundwater flow, causing a large variability of the initial catchment conditions (Le Mesnil et al., 2020).

The catchment hydrological response assessment linking the soil moisture variability and the lithology may help to understand their hydrological connectivity. This useful concept helps to better understand the hydrological functioning through the different compartments or landforms within a catchment (e.g. hillslopes, floodplains, channels). The water transfer and the connection of these different compartment depends on the landscape elements and their longitudinal, lateral and vertical interaction over time (Ward, 1989; Ward et al., 2002). Accordingly, the spatial distribution of the landscape elements and its relation to each other is essential in influencing transfer pathways (Bull et al., 2003). Consequently, catchment compartments may be connected or disconnected according to buffers, barriers and blankets features and the magnitude of the event timescale (Fryirs et al., 2007). Hydrological connectivity has been mainly classified as structural and functional. Structural connectivity refers to the spatial distribution of the landscape (i.e. physical characteristics) whereas functional connectivity refers to the interaction of these spatial patterns with catchment processes (i.e. runoff generation) (Turnbull et al., 2008). A holistic understanding of the catchment is needed to assess the complexity of the hydrological connectivity (i.e. rainfall, soil moisture, infiltration, soil type, vegetation cover, slope, runoff, management decisions), field knowledge is an approach that may lead to a better understanding of hydrological connectivity (Lexartza-Artza and Wainwright, 2009). Given the relevance of soil moisture in the hydrological response, connectivity indices incorporated soil moisture or saturation within the parameterization (Kalantari et al., 2019; Nunes et al., 2009). After evaluating the response in terms of connectivity of five surface runoff and erosion models to landscape connectivity features in a small agricultural catchment, Baartman et al. (2020) suggested that soil moisture approaches should be generalized to other models. Furthermore, these authors pointed out that (1) research should be developed in catchments with important structural connectivity features (i.e. mountain landscape) as well as important land use changes (i.e. afforestation, wildfires, urbanisation); and (2) the sharing of spatially distributed data of water and sediment fluxes should be increased to better understand how fluxes are moving between the different compartments in a landscape.

Mediterranean Region is composed by catchments with important structural connectivity features and land use changes described by Baartman et al. (2020), as they have been modified during millennia (i.e. deforestation, terracing and irrigation schemes) and severely in recent decades (i.e. urban development, dam construction, channelling of water, land abandonment, afforestation, reforestation) (Hooke, 2006). The current landscape in the Mediterranean region is a complex mosaic with dichotomous patterns as a result of socioeconomic changes. On the one hand, gradual abandonment of farmland in marginal areas led to afforestation since mid-20th century (García-Ruiz et al., 2020). On the other hand, this abandonment was promoted by the rural exodus from mountain areas to the coast where population density and urbanisation increased. Consequently, in mountain areas traditional agricultural practices were abandoned reducing the maintenance of water and soil conservation structures; i.e. terraces and check dam terraces, etc. Such structures were built to control overland flow and prevent erosion (Tarolli et al., 2014). However, their abandonment and degradation may increase the transfer of water and sediment (Calsamiglia et al., 2018), generating feedback processes between structural and functional hydrological connectivity (Calsamiglia et al., 2020). Land use changes have implications over the hydrological cycle such as the increase of rainfall interception and evapotranspiration (Cosandey et al., 2005), the decrease of the annual water yield in fluvial systems (Buendia et al., 2016a) and the reduction of the runoff coefficient and peak flow at the event scale (Lana-Renault et al., 2018).

Finally, the Mediterranean region is one of the main hotspots of the global change (land use and climate change; Paeth et al., 2017; Schröter et al., 2005). Climate change projections in southern Europe predict an increase of temperatures and a decrease in precipitation, especially during the warm season (Giorgi and Lionello, 2008). In agreement, trends in streamflow will decrease due to afforestation processes (Buendia et al., 2016b) and climate change (Blöschl et al., 2019; Masseroni et al., 2020). Consequently, long-term data in experimental and representative catchments are needed for example to observe and predict trends of floods and mitigate their effects (Tetzlaff et al., 2017).

1.2. Suspended sediment transport of Mediterranean rivers

Catchments are affected by soil erosion, which transfer water and sediment from headwaters to coastal areas within the cycle of sediment (Jones et al., 2012). However, accelerated erosion leads to the decline of agricultural productivity, increase dam siltation, pollution of water bodies, eutrophication problems and damage ecological habitats (Gamvroudis et al., 2015). Accordingly, the knowledge of transported particle size characteristics is fundamental to understand the sediment transport and sediment-associated contaminants because particle size characteristics exert a fundamental control on transport, settling velocity and deposition (Walling, 1996; cited in Walling et al., 2000). The mobilization and transport of fine sediment is particle size selective and the preferential deposition of the coarser size fractions may result in downstream fining of the suspended sediment load. As a result, the 70% of the total sediment load in rivers correspond to the suspended sediment fraction (<63 µm; Morgan, 2009). Consequently, particle size composition reflects the important links between sediment source(s), sediment conveyance and deposition, being a key feature of the sediment delivery dynamics (Stone and Walling, 1997). The 95% of the sediment transfer from land to the ocean is transported by rivers, corresponding the largest proportion of the sediment flux to the suspended sediment (i.e. 64%) (Syvitski et al., 2003). Sediment transport by rivers is a key component of the global denudation system, being an important measure of land degradation associated to soil as resource (Walling and Fang, 2003). Therefore, sediment delivery dynamics can be globally assessed at catchment scale by a continuous monitoring of water and sediment fluxes. Long-term monitoring programs allow the assessment of the non-stationary behaviour of sediment load due to water and sediment fluxes change in response to natural and human perturbations (Walling, 2006).

The assessment of this hydrosedimentary processes within a catchment can be used as desertification indicator in a context of landscape management (Vanmaercke et al., 2011). Sediment yield (t km-^{2}) is the integrated result of all erosion and sediment transporting processes operating in a catchment and is therefore of high value for environmental studies (Poff et al., 1997; Prat et al., 2014). However, sediment yield does not accurately represent the spatio-temporal variability of erosion processes that occur within a catchment (Walling, 1983) because the amount of sediment reaching the channel and outlet depends on the catchment connectivity. Traditionally, sediment transfer in catchments has been explained through the simile of the conveyor belt sediment transfer, which was divided in sediment generation zone (headwaters), transfer zone (transition zone) and deposition zone (estuaries, deltas) (Schumm, 1977). Under this context, sediment yield has been assumed to decreases with larger drainage areas. However, de Vente et al. (2007) developed a scientific literature review of the relation between catchment area and sediment yield revealed a large regional variation, caused by a combination of land use, climate, lithology and topography. Negative relations (i.e. decreasing sediment yield) between area and sediment yield are mainly found in catchments with intensive agricultural areas with an important contribution of hillslope erosion processes to sediment yield (Dedkov and Moszherin, 1992). Positive relations (i.e. increasing sediment yield) between area and sediment yield were observed in catchments with large vegetation cover, limited human disturbance and a dominance of channel erosion (Dedkov, 2004). Hence, the variable area is a poor predictor of the sediment transfer processes as it only explains a small part of its variation. Indeed, area-sediment yield relation can be disturbed by the spatial differences in rainfall characteristics, topography, soil erodibility and land use, which may act as sediment sources or sinkholes (de Vente et al., 2007). After the basic conceptualization of sediment transfer by Schumm (1977), concepts such as river sensitivity or coupling enabled a better understanding of the driving factors in catchment sediment generation (Brunsden and Thornes, 1979; Harvey, 2002;

Phillips, 1992). Later, the non-linear relation of the sediment transport was assessed by defining sediment coupling (Fryirs et al., 2007), sediment cascades (Fryirs et al., 2013) and sediment connectivity (Bracken et al., 2015). These concepts were mainly based on the idea that sediment transfer depends on the relation between structural (i.e. morphology, source, sink) and functional components (flow of energy) (Bracken et al., 2015; Wainwright et al., 2011). Understanding hydrosedimentary response in catchments is challenging because of the patchy nature of physical and hydrological soil data. Accordingly, hydro-sedimentological monitoring in river gauging stations may provide a validation for similar areas in Mediterranean ecosystems, and beyond, those temporary rivers hindered by water shortage. Therefore, on-site agricultural and forest soil-water management will certainly have off-site impacts (at the catchment scale). Long-term catchment datasets are here fundamental to assess on-site and off-site effects in catchments. Thus, the hydro-sedimentological monitoring can shed light on the magnitude of water and sediment fluxes providing a measure of land degradation and the associated reduction in the global soil resource. In this way, there is a strong emphasis in fluvial geomorphology on the analysis of the yield or 'output' of sediment from catchments (Walling 1983; Phillips 1986; Serrat, 1999).

1.2.1. Spatio-temporal driving factors of suspended sediment transport

Differences in specific suspended sediment yields between regions have been observed, being the Mediterranean and mountainous regions generally those with highest suspended sediment yield. Sediment yield in catchments from these regions were characterized by 85% of the suspended sediment yield > 40 tkm^{-2} yr^{-1} and more than 50% of the suspended sediment yield >200 tkm^{-2} yr^{-1} (Vanmaercke et al., 2011). Such differences were related to a combination of factors (i.e. climate, topography, lithology and land use), even if the identification of the individual importance of the various controlling factors of sediment yield at spatial and temporal scales (Phillips, 2016; Vercruysse et al., 2017) still remains difficult.

The distribution of climatic, geological, topographical and land cover features determines the spatial sediment generation, sediment transfer and sediment transport within a catchment (Walling, 1983). The sediment load measured in a river gauging station is strongly influenced by the sediment availability within the catchment according to these driving factors. Geology and lithology are conditioning the soil erodibility. Schists and marls materials promote larger runoff and suspended sediment than limestone due to high infiltration rates of the carbonate materials and to their own hardness (Cantón et al., 2011). Land use changes were also identified as driver of suspended sediment, showing an increase of sediment load when forests are replaced by agriculture uses (García-Ruiz, 2010). Forest areas promote less suspended sediment in rivers because increase rainfall interception and modify soil structure promoting higher infiltration rates (Cosandey et al., 2005; García-Ruiz et al., 2015). Topography also exerts a control over runoff and erosion as large contributions of sediment yield were identified in catchments with a mean slope >40% (Pepin et al., 2010). Furthermore, anthropogenic structures can limit the suspended sediment availability through check dams and terraces to laminate runoff, avoid rill erosion and retain soil (Arnáez et al., 2015; Tarolli et al., 2014; Estrany et al., 2010b). The wide range of factors within a catchment and their possible spatial distribution leads therefore to a complex landscape, which may be delimitated in different catchment compartments. The spatial distribution of soil moisture should be also taken into account because soil moisture patterns vary according to lithology, land uses, topography and landscape position (Jancewicz et al., 2019; Liang and Chan, 2017; Meles et al., 2020).

A key issue is the temporal scale selected to analyse the dynamic of the suspended sediment transport, as geomorphic changes are strongly influenced by different timescales due to the frequency-magnitude distribution of sediment detachment (Wolman and Miller, 1960) and the degree of connectivity of the river system (Harvey, 2002). Many studies are focused mainly at a specific temporal scale assessing trends at decadal-annual (Major, 2004; Shi, 2016) or flood scales (De Girolamo et al., 2015; Rovira and Batalla, 2006). Therefore, assessing the relevance of the different timescales is fundamental to a better comprehension of process interactions and feedbacks between different drivers across timescales (López-

Tarazón et al., 2009; Sun et al., 2016). At long timescale (i.e. > 10 yr), sediment load dynamics may indicate general trends of sediment transport within a catchment. Potential changes in the general trend may be associated to breakpoints (i.e. dam construction, wildfires, land use change) related with the drivers that affect the sediment transport, therefore providing information related to the impacts of climatic changes and human interventions on water and sediment yields (Stone et al., 2015; Wohl, 2015). At the long timescale (i.e. > 10 years), rainfall and discharge (Bussi et al., 2014), land cover changes (Buendia et al., 2016b) and dam construction (Rovira et al., 2015) have been identified as major drivers of suspended sediment. Medium term (i.e. 5-10 years) studies allow to understand inter-annual suspended sediment variability according to representative years (i.e. dry, average and wet years) of rainfall and runoff (Esteves et al., 2019). At seasonal scale, the intra-annual variability allows a better understanding of the storage-release phases of sediment due to seasonal variations in hydro-meteorological conditions and sediment availability (Vercruysse et al., 2017). A large variability of sediment load is related to the intra-annual distribution patterns of rainfall, soil moisture, vegetation, snowmelt and storm events, generating different sediment load amounts (Dominic et al., 2015; Knapen et al., 2007; Lana-Renault et al., 2011; Latron and Gallart, 2007; Regüés and Gallart, 2004; Taguas et al., 2013). Among these factors, antecedent soil moisture has been identified as key factor in runoff and sediment load dynamics in temperate, arctic, tropical, alpine and Mediterranean catchments (Favaro and Lamoureux, 2014; Palleiro et al., 2014; Penna et al., 2011; Rodríguez-Blanco et al., 2019; Seeger et al., 2004).

The sediment regime of a river is characterised by discontinuous sediment supply. At the short time scale, the event scale allows to analyse the large spatio-temporal variability of the suspended sediment transport to quantify when major sediment load occurs. Thus, few events are responsible for the main loads transported during short periods of time (Estrany et al., 2009; Zabaleta et al., 2007). The characterisation of these events shows that high discharge flow with a low exceedance frequency is the most important driver for suspended sediment concentration in Mediterranean catchments (De Girolamo et al., 2018). Additionally, a wide number of hydro-meteorological factors also explain the suspended sediment transport variability at the event scale. Variables are separated according to forcing variables or pre-event conditions (i.e. antecedent rainfall, antecedent soil moisture, duration of the rainfall event, rainfall depth, average and maximum rainfall intensity) and response variables or event conditions (i.e. duration of the flood event, runoff, runoff coefficient, peak discharge, average and maximum suspended sediment concentration and sediment load) (Estrany et al., 2007; García-Ruiz et al., 2008; Lana-Renault et al., 2007; Latron et al., 2008; López-Tarazón and Estrany, 2017; Penna et al., 2011; Sala and Farguell, 2002; Seeger et al., 2004; Zabaleta et al., 2007).

Furthermore, the frequency and magnitude of the events and also the time between events (release and storage periods) exerts a control over the sediment transport. Wolman and Miller (1960) highlighted that it cannot be assumed that highest or less frequent events explain simply the larger proportion of sediment transport. Moderate magnitude events rework the sediment for the following events. Consecutive events in a short time do not promote large suspended sediment amount as sediment supply tends to exhaust due to the wash of the first event. Events of high frequency and small magnitude will provide sediments from hillslope or channel bank. Storage of sediment increase with the time between two events as sediments available for transport are accumulating. Furthermore, in-channel sediment storage is favoured in temporary rivers because precipitation is often insufficient to produce uninterrupted flow into the entire length of the river (García-Comendador et al., 2017). Thus, sediment is stored in channel until the succession of a high magnitude event, which energy input to the system causes the sediment (re)mobilization (Bracken et al., 2015).

Other factors involved in sediment transport are lithology and vegetation cover in karst and non-karst areas, playing a key role in runoff generation and soil erosion. Accordingly, lower runoff coefficients and soil loss were observed in vegetated karst areas than in non-vegetated karst areas (Peng and Wang, 2012). These authors associated the low water and sediment yields to the epikarst zone (i.e. subcutaneous zone) of carbonate materials, because of their high porosity and permeability, storage of water, causing a delay of the rainfall impact and redistributing the precipitation (Williams, 2008). The low rates of sediment yield observed in karst areas are related with the poor soil formation over limestones, with a soil loss tolerance ranging from 0.2 and 55 t km^2 yr^{-1} in continuous pure limestone and dolomites areas (Cao et al., 2020; Li et al., 2017, 2006). Sediment yield overcoming the soil loss tolerance promotes rocky desertification, modifying vegetation cover and soil in karst landscapes into exposed basement rocks (Zhang et al., 2011). Furthermore, two types of soil losses may occur in karst environments: ground and underground soil losses. Ground soil loss is due to surface water erosion and underground soil loss to underground piping. The underground piping occurs because carbonate rocks are highly soluble with developed fissures and pores. Thus, voids generated from bedrock dissolution are filled up with soil in solution grooves, channels and depressions, increasing rocky desertification (Zhang et al., 2011). As a result of all these factors, soil cover is scarce and soil layers are thin due to the low soil formation rate of carbonate (i.e. < 50 t km^2 yr^{-1}), especially in steep areas (Jiang et al., 2014). Because of thin soil profiles, the C-horizon (which is an important layer that keeps the soil attached to the bedrock) is missing making also topsoil susceptible to soil erosion.

Sediment transfer through river systems is mainly understood in terms of the (dis)connections between the components of the drainage basin (i.e. hillslopes, channels, floodplains) (Poeppl et al., 2020). Sediment (dis)connectivity in catchments is caused by the spatial distribution of sediment sources, sinks and transfer pathways (i.e. structural component) as well as the interactions between landscape compartments and the frequency-magnitude relationships of the geomorphic processes (i.e. the functional component) (Bracken et al., 2015; Wainwright et al., 2011). Therefore, the sediment (dis)connectivity and the frequency-magnitude relationships are needed to improve the understanding of spatiotemporal distribution of sediment sources and catchment management (Fryirs, 2015; Fuller and Death, 2018; Poeppl et al., 2019). Nonetheless, the large spatiotemporal variability of suspended sediment transport difficult the quantification of suspended sediment concentration and the identification of sediment sources over multiple timescales (Vercruysse et al., 2017). Besides, sediment sources may change in a short and long term due to seasonal vegetation, exhaustion in sediment supply, mass movements, land use change or dam construction (De Girolamo et al., 2015; Rovira et al., 2015; Rovira and Batalla, 2006; Sun et al., 2016). To assess the spatiotemporal variability between discharge and suspended sediment concentration hysteresis patterns should be analysed to deduce information about processes controlling suspended sediment availability, transport and sources (Aich et al., 2014; Fang et al., 2015; López-Tarazón and Estrany, 2017; Williams, 1989). Furthermore, initials conditions of catchment soil moisture investigated through soil moisture-discharge hysteresis (Penna et al., 2011), may provide useful information to link hydrological and sediment connectivity (Keesstra et al., 2019). Therefore, the assessment of the runoff response and suspended sediment transport at multiple time scales provides an integrated framework to analyse the catchment response according to the different moisture conditions and drivers, enabling a better understanding of the hydrosedimentary response variability.

1.3. Aim, hypothesis and objectives

This thesis aims to better understand the runoff generation and suspended sediment transport in representative Mediterranean catchments at different temporal scales (annual, season and event scale). The working **hypotheses** are:

H1: *The temporal dynamics of runoff generation in Mediterranean catchments are promoted by combination of rainfall intensities and soil saturation.*

H2: *Seasonal changes of soil moisture are a driving factor for suspended sediment transport in Mediterranean catchments.*

H3: *Spatial distribution of lithology and land uses strongly influences the runoff generation and suspended sediment transport.*

According to these hypotheses the two **general objectives** are:

GO1: To identify the main drivers and determine patterns of runoff generation and suspended sediment transport in representative Mediterranean catchments

GO2: To assess patterns of runoff generation and suspended sediment transport variations over the time as a result of inter- and intra-annual variability in Mediterranean catchments.

The general objectives are developed in three chapters through the following **specific objectives**:

SO1: *To identify the main drivers of runoff generation in small representative Mediterranean catchments (< 10 km^2) at different temporal scales (i.e. annual to event scale).*

SO2: *To assess the role of soil moisture in sediment load and its intra- and inter-annual variability in a small Mid-mountain Mediterranean catchment.*

SO3: *To investigate the relationship between flow and sediment regime in two Mediterranean catchments under contrasted lithology and land uses.*

1.4. Structure of the thesis

This thesis is composed as a paper compendium and has been dived in 7 chapters. Three of the chapters (Chapter 4, 5 and 6) correspond to manuscripts published in scientific journals (Table 1.1).

Chapter 1 introduces the state of the art related to the influence of antecedent conditions and physical and human catchment characteristics on the hydrological response and suspended sediment transport, specifically in Mediterranean catchments.

Chapter 2 presents the selected study areas used in this thesis.

Chapter 3 details the methods (i.e. sampling, monitoring, laboratory and data computation) used in this thesis.

Chapter 4 (related to SO.1) assesses the rainfall-runoff relationships in small Mediterranean catchments at annual and event scale. A detailed analysis of this relationship is Es Fangar Creek allows the downscaling comprehension of this relation at annual, seasonal and event scale.

Chapter 5 (SO.2) analyses the key role of soil moisture as driving factor in suspended sediment transport of a small mid-mountain Mediterranean catchment.

Chapter 6 (SO.3) compares the hydrological and suspended sediment dynamics of two Mediterranean catchments under contrasted lithological and land uses characteristics.

Chapter 7 discuss and extract the main conclusions of the previous results.

Table 1.1. Title, keywords, journal and status of the research articles of the thesis.

Chapter	Title	Keywords	Journal	Status
Chapter 4	Multiple temporal scales assessment in the hydrological response of small Mediterranean catchments	rainfall-runoff, multiple temporal scales, non-linearity, small catchments, Mediterranean	Water	Published
Chapter 5	Runoff and soil moisture as driving factors in suspended sediment transport of a small mid-mountain Mediterranean catchment	suspended sediment transport, soil moisture conditions, hysteretic patterns, Mediterranean catchment	Geomorphology	Published
Chapter 6	Analysing hydrological and sediment transport regime in two Mediterranean intermittent rivers	Mediterranean catchments, intermittent rivers, hydrological regime, suspended sediment transport	Catena	Published

1.5. References

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Chapter 1. Introduction: hydrosedimentary response of Mediterranean fluvial systems

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2. Study areas

This thesis is assessing the runoff generation and suspended sediment transport in 45 Mediterranean catchments. The area of the catchments ranged from 0.05 to 506 km^2. The studied catchments are grouped in three study areas sections according to their geographical location: (1) worldwide small Mediterranean catchments (i.e. < 10 km^2), (2) catchments in Mallorca Island (i.e. Sant Miquel River basin) and (3) Apulia region (i.e. Carapelle River basin). The small Mediterranean catchments (i.e. <10 km^2) are representative of the different Mediterranean climate areas in the world, with a wide range of annual rainfall amount, lithology and land uses. The Sant Miquel River basin is a representative mountainous catchment highly shaped for the human activity (i.e. agriculture, terracing, check dams, channelization) and land abandonment (i.e. afforestation processes). The Carapelle River basin is a representative agricultural Mediterranean catchment were crop rotation, fertilization and tillage are applied.

2.1. Geography of the Mediterranean catchments

The Mediterranean climate lies between 32° and 40° N and S of the Equator and is characterized by a wet and mild winter, a warm and dry summer and a high inter- and intra-annual variability in rainfall patterns. Mediterranean climate regions (Csa and Csb) comprise the Mediterranean Sea Region, the coast of California, Central Chile, the Cape region of South Africa and the south-western and southern parts of Australia (Kottek et al., 2006). Focusing on the geography of the Mediterranean Sea region, several boundaries have been performed (Figure 2.1) according to administrative, hydrographic, olive cultivation and climatic limits (Allam et al., 2019). Furthermore, the Mediterranean Sea region is characterised by a sensitive ecosystem compared to the other Mediterranean climate regions, the islands. More than 5,000 islands are spread over the Mediterranean Sea Region hosting a large number of biota and cultural elements. At the same time these islands are subjected to the most intense environmental and socio-economic pressures (Vogiatzakis et al., 2008).

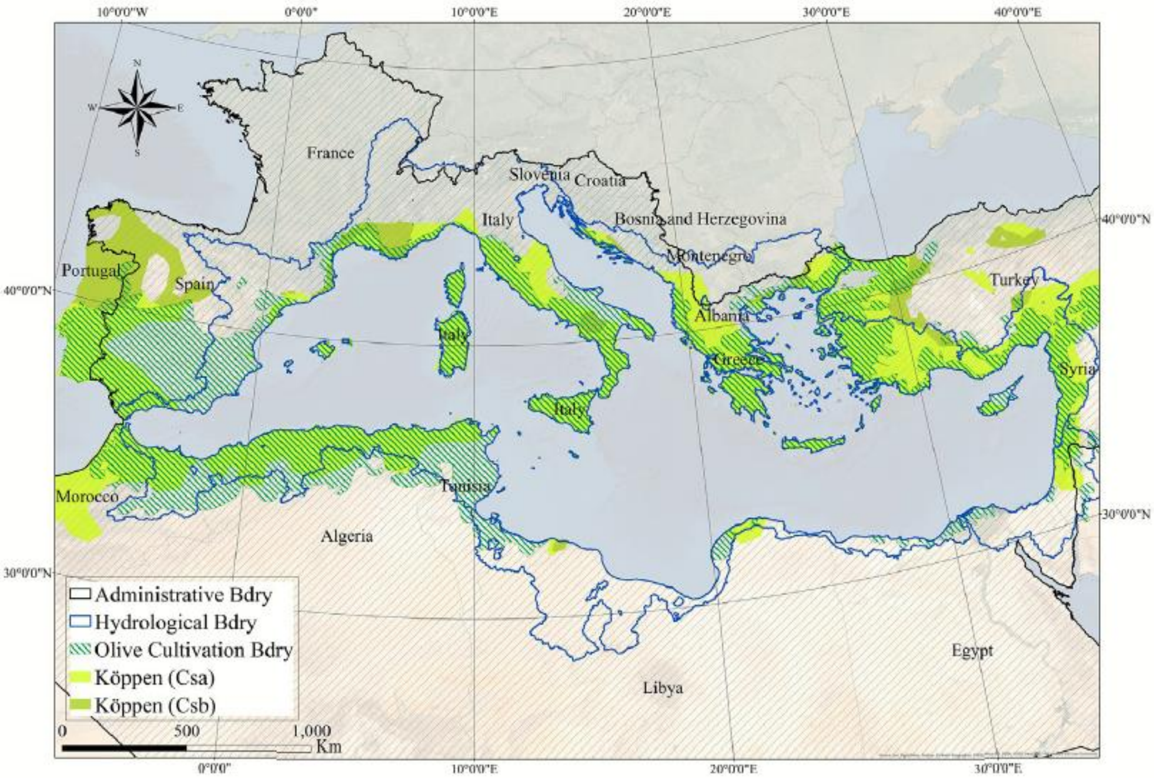

Figure 2.1. Four Mediterranean region boundaries from Allam et al. (2019) based on administrative, hydrological (Milano et al., 2013), olive cultivation (Moreno, 2014) and climatic (Peel et al., 2007) boundaries.

The mean annual precipitation of the hydrological boundary of the Mediterranean Sea basin ranges from 5 to 2975 mm (Allam et al., 2020), generally increasing annual runoff as rising the annual rainfall (Merheb et al., 2016). However, the irregular distribution of precipitation, the catchment geology and the long history of vegetation, hillslope and floodplain modification by human activity in small mountainous headwaters catchments generate that the large area draining to the Mediterranean Sea is complex and non-uniform in terms of the key controls on catchment hydrology (Thornes et al., 2009). These characteristics make that there is not, in hydrological terms, a strict single Mediterranean river type. Therefore, seasonal distribution of river flow is controlled mainly by the seasonal distribution of rainfall, promoting a cease of flow in temporary rivers at some point in time or space. Besides, in temporary rivers and streams many local names can be found such as winterbournes, torrent, wadis, barranco, oued, arroyos, fiumara and ramblas among others (Steward et al., 2012).

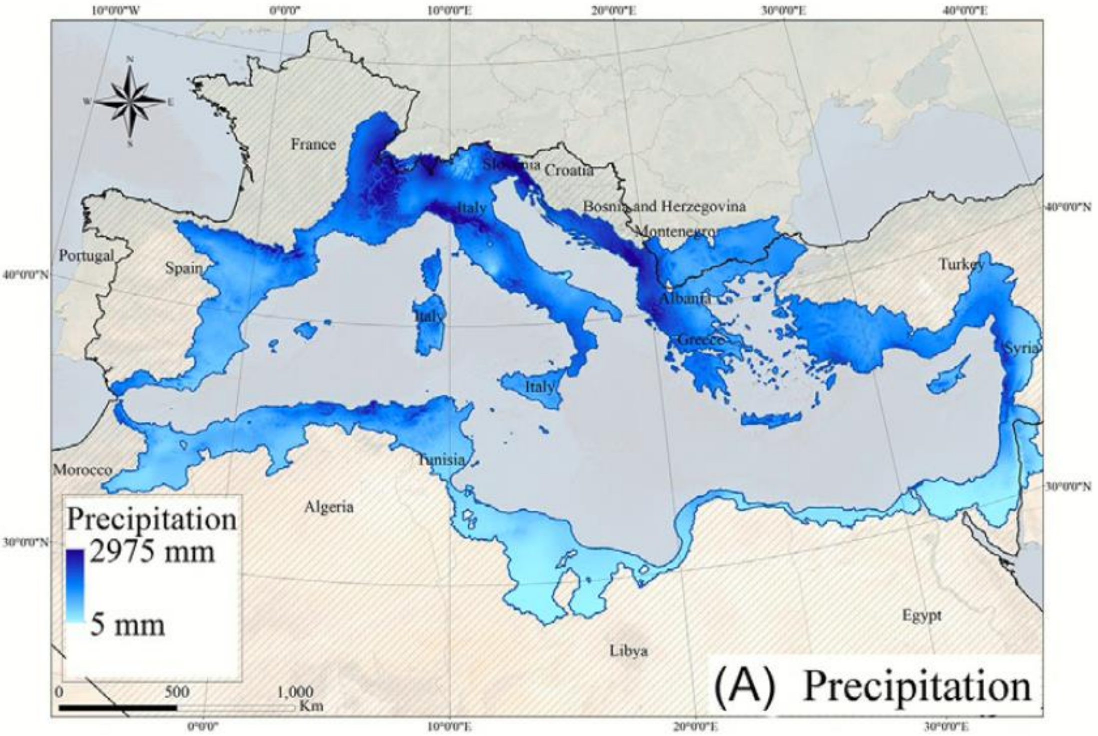

Figure 2.2. Mean annual precipitation of the Mediterranean region within the hydrological boundary from Allam et al. (2019). Data obtained from Fick and Hijmans (2017).

2.2. Small Mediterranean catchments

A total of 43 small catchments (i.e. <10 km^2) of the Mediterranean climate regions (Figure 2.3) were selected to analyse the hydrological response. The geographical distribution of the catchments was grouped into the main climate regions, as follows: (1) Western coast of USA, (2) Western Mediterranean Sea Region (from Spain to Italy), (3) Eastern Mediterranean Sea Region (Israel) and (4) South Africa. The area of the catchments ranged from 0.05 to 9.61 km^2, being 1.03 km^2 and 2.6 km^2 the median value and the standard deviation, respectively. The mean annual rainfall ranged from 367 to 1794 mm y^{-1}, with a median value of 833 mm y^{-1} ± 334 mm y^{-1}. The mean annual temperature ranged from 6.6 to 17.2 °C with a median value of 13.9 °C ± 3 °C. The predominant lithology was pervious in 12 catchments and impervious in the other 31. Within the 43 catchments, the study of 12 of them also contained information related to the main land uses, which was used for assessing their hydrological response at the event scale. The main land uses were agriculture (3 catchments), agroforestry (3), forestry (1) and shrub (5).

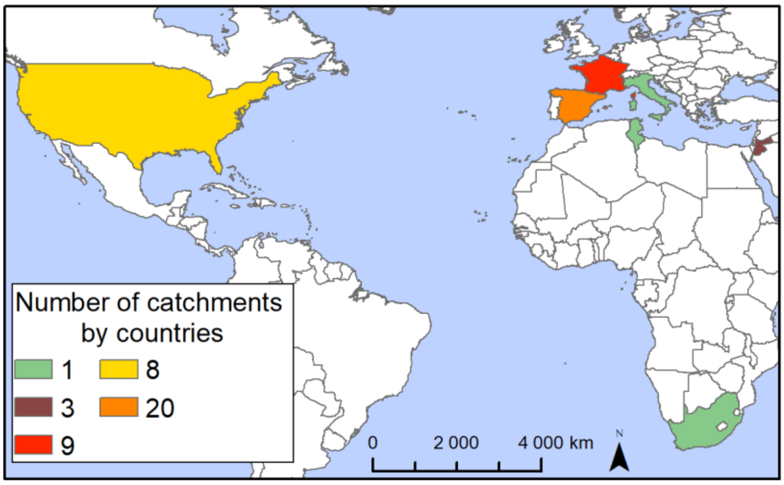

Figure 2.3. Location map by countries of the selected small Mediterranean catchments for assessing the rainfall-runoff relationship at the annual and event scale.

2.3. Mallorca Island

Located in the western Mediterranean Sea, the island of Mallorca covers an area of 3,640 km^2 (Figure 2.4a). Mallorca is the emerged part of the Balearic promontory, a continuation of the Betic Ranges generated during the Alpine orogeny (30 M.A.). It is characterised by a basin-and-range topographical configuration mainly constituted by limestone geology (Jenkins et al. 1990). This structure is composed by a horst-graben system, which generates the three main ranges oriented from NE to SO: Tramuntana Ranges, Central Ranges and Llevant Ranges (Figure 2.4b). Between the different horsts, grabens or catchments were filled with sediments from upper Miocene to Quaternary (Figure 2.4c). Tramuntana Range is mainly composed by dolomites from Jurassic and Triassic. Central Ranges contains silt, clay, conglomerates and sandstone from Miocene and limestone from Lower Jurassic. Llevant Ranges are composed by dolomites from Lower Jurassic and Upper Triassic and also limestone from Upper Miocene. Carbonate rocks only represents a 12% in Earth, whilst in the Mediterranean Sea Basin a higher surface cover is attributed to the regional fall in base level associated with the Messinian Salinity Crisis. Carbonate rocks frequently activate the formation of very deep multiphase karst systems in the Mediterranean basin (Lewin and Woodward, 2009). Accordingly, the 53% of the island of Mallorca contains limestone or dolomite materials as main lithology. Consequently, karst features play a key role in the groundwater because influence the hydrological regime, the morphology and sedimentology of the channels, water quality and ecology (Estrany et al., 2009; Sear et al. 1999). However, impervious materials that reduce infiltration are also present through marls from Triassic (Keuper) and Cretaceous (Ginés and Ginés, 2011).

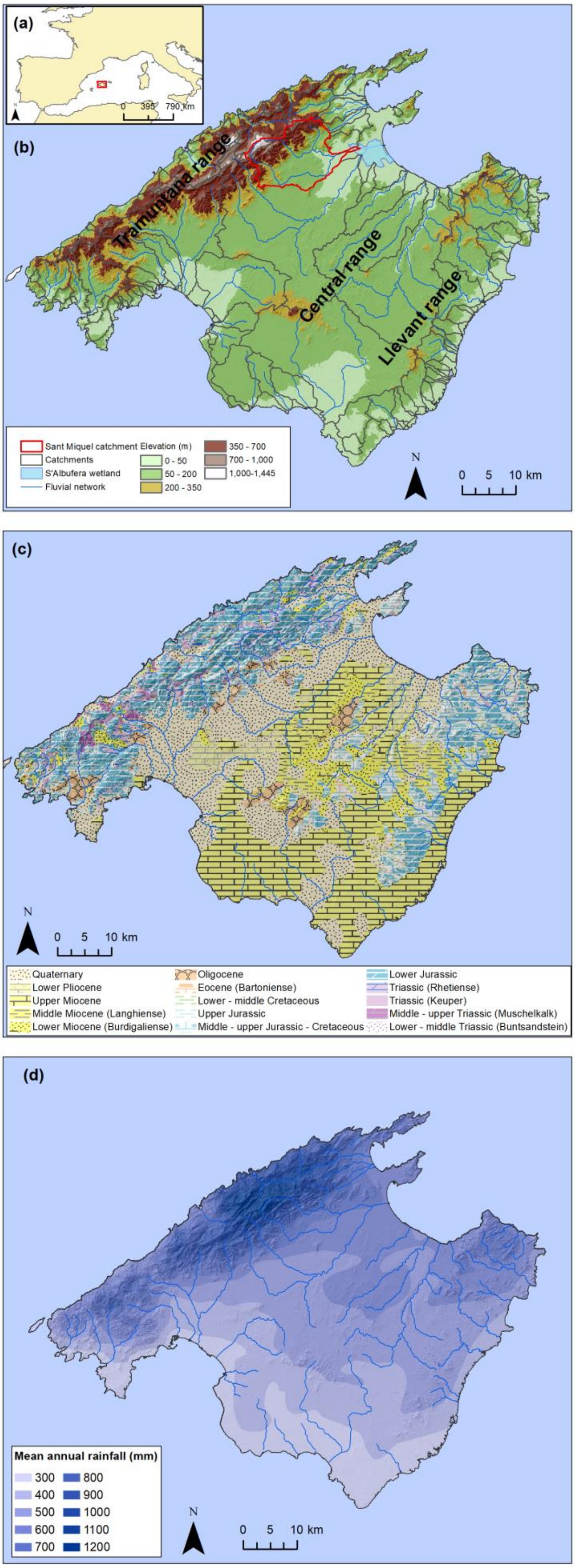
(a)
0
395
790 km
(b)
Tramuntana range
Central range
Llevant range
Sant Miquel catchment
Elevation (m)
Catchments
S'Albufera wetland
Fluvial network
0 - 50
50 - 200
200 - 350
350 - 700
700 - 1,000
1,000-1,445
N
0 5 10 km
(c)
N
0 5 10 km
Quaternary
Lower Pliocene
Upper Miocene
Middle Miocene (Langhiense)
Lower Miocene (Burdigaliense)
Oligocene
Eocene (Bartoniense)
Lower - middle Cretaceous
Upper Jurassic
Middle - upper Jurassic - Cretaceous
Lower Jurassic
Triassic (Rhetiense)
Triassic (Keuper)
Middle - upper Triassic (Muschelkalk)
Lower - middle Triassic (Buntsandstein)
(d)
Mean annual rainfall (mm)
300
400
500
600
700
800
900
1000
1100
1200
N
0 5 10 km

Figure 2.4. (a) Location of Mallorca Island in the Western Mediterranean Sea basin. Maps showing physical characteristics of Mallorca Island: (b) elevation, catchments boundaries and fluvial network, (c) lithology and (d) rainfall distribution. Map (b) is also showing the location of the Sant Miquel River catchment.

According to the Emberger classification, the climate in Mallorca is classified as Mediterranean (Guijarro, 1986). Nonetheless, different subtypes of Mediterranean climate are located in the island, ranging from wet (i.e. central part of Tramuntana Range) to semiarid (i.e. south Mallorca). The different subtypes establish a threshold for the annual rainfall (Figure 2.4d), which ranges from 400 mm to more than 1.200 mm from south to central Tramuntana Range. In the northeast of Llevant Ranges, rainfall is 700 mm being < 600 mm in the Central Ranges. Rainfall amount in 24 h for a 25 years of return period is 110 mm in Tramuntana Range (increasing until 250 mm in the central part), between 110 and 150 mm in the northeast of Llevant Ranges and 80-90 mm in the south of the island (Grimalt, 1989a). Mean annual temperature is 16.5ºC with a gradient temperature from north to south due to topographic effects as occur with the rainfall amounts.

Geological structure and climate shape surface and groundwater hydrology. The fluvial network of Mallorca is divided in five main hydrographic hillslopes (northeast, Palma, Alcúdia, Campos and southeast) and two secondary (Andratx and Pollença) (Grimalt, 1989b). Fluvial systems are mainly under ephemeral hydrological regime, resulting from the combination of geology and Mediterranean climate. The hydrological regime is characterized by an intra- and inter-annual variability as well as high recurrence of severe flash-flood events (Estrany and Grimalt 2014). The hydrographic network is formed by small catchments; only 7 exceed 100 km^2 and the largest, Muro, reaches a surface area of 456 km^2. In mountainous areas, streams are short and very steep in headwaters; catchments are small and receive a medium-high annual precipitation (i.e. 700-1,200 mm; Pardo and Olsen 2004). These mountainous streams represent 20% of the hydrographic network total length. In lowland areas, where annual precipitation is lower (400-600 mm), streams have gentler slopes with lengths representing 63% of the hydrographic network. The remaining 17% of the river streams are located on impervious materials allowing different degrees of intermittency and even punctually perennial hydrological regimes.

Land uses percentage distribution are rainfed tree crops (40.8%), rainfed herbaceous crops (16.9%), forests (16.8%), shrub (15.9%), urban (5.5%), irrigated crops (3.5%) and wetlands (0.6%) (CLC, 2012). Nevertheless, land uses have been deeply changed since 1950s due to socio-economic changes, where marginal agricultural areas from Tramuntana and Llevant Ranges were abandoned due to rural exodus, starting afforestation processes. As a result, forest surface increase from 176,590 (1971) to 220,785 (2010) hectares, increasing their surface a 79% (IFN1, IFN3). Since 1960s, rural exodus was accelerated due to a large proportion of the population changed agricultural activities for services activities. This population movement generated an increase of the urban surface firstly at the coast and secondly to residential rural areas (Grimalt et al., 2002). Accordingly, Pons (2011) quantified the increase of urban areas, being the 1.1% in 1956 and the 6.2% in 2006.

The rural exodus of marginal agricultural areas that caused the land use change previously explained, caused an abandonment of the traditional human activities (i.e. terraces, lime kilns, huts and charcoal furnaces, ice houses, rural farms) and also a mismanagement of the territory. This process has specially impacted the Tramuntana Range, where the development of these traditional activities had been intense during the Early modern period. As a result, UNESCO recognised the human shape in the Tramuntana Range as World Heritage Site in the category of cultural landscape by UNESCO in 2011. The landscape of Tramuntana Range exemplifies the interchange between the Muslim and Christian cultures, which is representative of the Mediterranean area, combining the Arabic water harvesting and management technology with the agricultural know-how and the territorial control system introduced by the Christian. As a result of this cultural interaction, a terraced agricultural landscape was created, featured by an articulated waterworks network, orchards, vegetable gardens and olive groves, which were earlier organised around small farm holdings, and later in large estates (i.e. possessions) and which nowadays make up the physical and functional features of the Tramuntana Range (UNESCO, 2011).

The exploitation of water, a scarce and highly prized resource, has given rise to the construction of a complex traditional water engineering system. The farmed landscape combines an interconnected and highly specialised system of waterworks for collecting and storing water, featuring qanats (i.e. underground channels to harvest and transport water), channels, ditches, storage basins, with a system of terraces supported by dry-stone walls so as to make possible the cultivation of vegetables, fruit and olive trees in the terraced plots and including a drainage system to avoid soil erosion. Given the relevance of terraces 20,000 kilometres of dry-stone wall were built in Tramuntana Range (GMM, 2017).

2.1.2. Sant Miquel River

Sant Miquel River is a mesoscale mountainous catchment (145 km^2) which collects water from the south-eastern parts of Tramuntana Range (Mallorca, Spain; Figure 2.5). The main tributaries are the Búger River (68.2 km^2) and the homonymous Sant Miquel River (52 km^2). Altitude ranges from 7 to 1,366 m.a.s.l. In the catchment headwaters (800 – 1,300 m.a.s.l; Figure 2.5) the average gradient of the channels is >20%, which are mainly covered by dense forests. The lowest part of the catchment (i.e. 7%) is occupied by the most important irrigated area on the island, providing concern for the deterioration of the Sant Miquel fluvial system and the s'Albufera (1,708 ha), a wetland situated at the outlet of the catchment and protected by the RAMSAR list of wetlands of international importance. Sant Miquel has an intermittent hydrological regime due to the predominance of karstic processes, despite receiving the highest mean annual precipitation of the island (i.e. 1,262 mm; 1993-2011, Lluc AEMET station, see location in Figure 2.5).

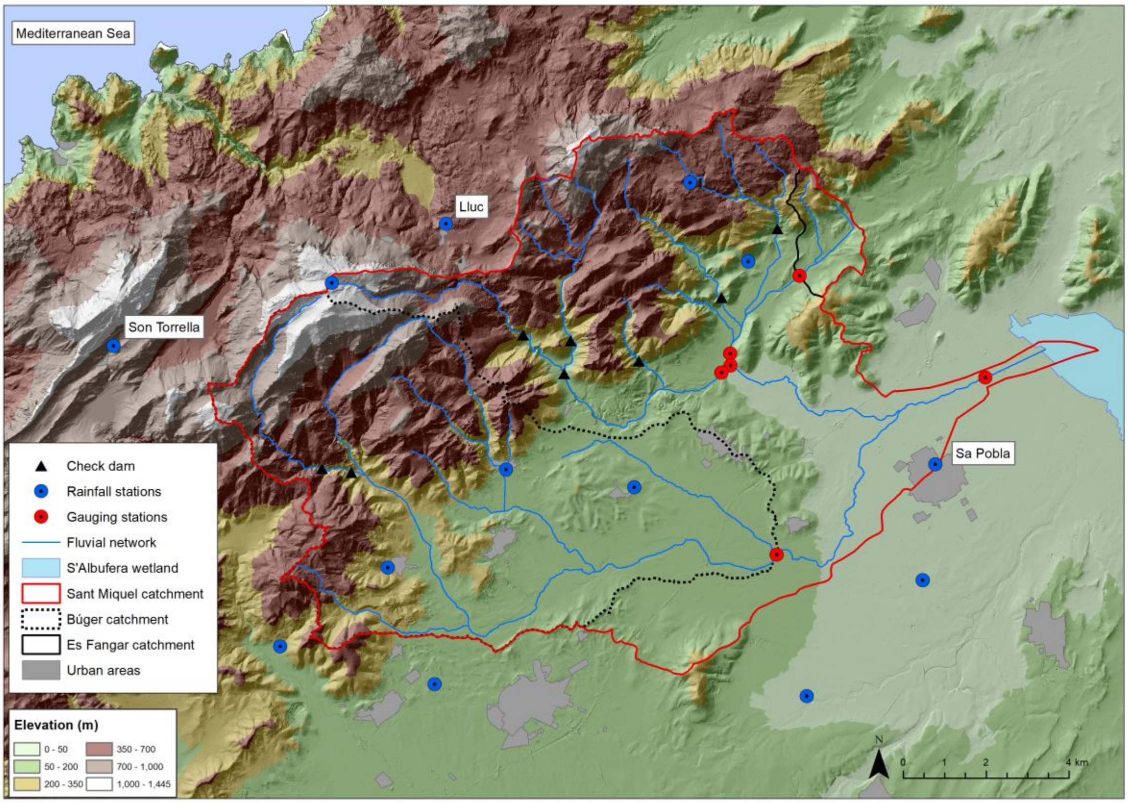

Figure 2.5. Map showing Es Fangar Creek and Búger River catchments within Sant Miquel River catchment and fluvial network, gauging stations and rainfall stations.

Climate is classified on the Emberger scale as Mediterranean temperate sub-humid in lowlands and cool-humid in headwaters, reaching the cool-superhumid in the highest part of the catchment (Guijarro, 1986). Mean annual rainfall in lowland areas is 645 mm (1970-2000, Sa Pobla AEMET station) and at the headwaters is 1,262 mm (1993-2011, Lluc AEMET station). Rainstorms with a recurrence period of 2 years (headwaters) and 10 years (lowlands) may generate 100 mm of rainfall in 24 h (YACU, 2002).

Sant Miquel River catchment is a flood prone area as the downstream area is a geomorphic unit composed by an alluvial plain (Sastre, 2015), which receives discharge from the rainiest area of Mallorca. Fifty storms with rainfall amounts >100 mm in 24 h were recorded between 1981 and 1990 at Son Torrella AEMET station (see location in Figure 2.5). This station is located in the same major rainfall area than Sant Miquel River headwaters, as Sumner et al. (1993) established for the whole island of Mallorca, with a maximum of 536.5 mm the 22nd October in 1959 (Grimalt, 2001). During three centuries, between 1691 and 1991, 27 severe floods affected Sa Pobla village or their surroundings (Canyelles et al. 2003). For this reason, the main headwater subcatchments located in the Tramuntana Range were regulated by 8 check-dams constructed in the 1980s, in addition to traditional terracing and check-dam terraces.

The groundwater bodies in the relief areas are characterised by free intermediate aquifer (piezometric levels between 20 and 50 m). The lithology is mainly composed by limestone and dolomites (Rhaetian-Lias). The aquifers contain good water quality, being the annual average extraction of the biggest aquifer 0.47 $hm^3\ yr^{-1}$ (PHIB, 2011). The most important drainage of these aquifers is the spring called "Fonts Ufanes de Gabellí". The recharge capacity of this spring is the percolation of 37% of the annual rainfall (i.e. 1,000 mm yr^{-1}) over 43 km^2 of limestone materials (Périz et al. 1995). The annual water volume of this spring is between 10 and 12 $hm^3\ yr^{-1}$ directly released to the Sant Miquel River (Mateos et al. 2006).

In lowland areas, surface aquifers (piezometric levels between 0 and 20 m) are semiconfined, characterised by limestone, dolomites, conglomerates, silts and clays materials. The annual average extraction is 21.9 $hm^3\ yr^{-1}$, mainly used for agricultural purposes. As a result of the agricultural activity and use of fertilisers, high concentrations of nitrate (i.e. 300 mg l^{-1}) and chloride are found in these aquifers (PHIB, 2011).

Since 1950, important socio-economic changes have caused a gradual abandonment of farmland in marginal areas, leading to afforestation. Forest cover in 1956 was 22% of the catchment area and currently forest cover represents the 36% of the area. Most of this increase is located in areas with elevations > 200 m.a.s.l. In these areas, since 1956 to 2012, forest area increased from 22.3 to 43.8 km^2, which correspond an increase of the forest cover from 13% to 26%.

2.1.2.1. Es Fangar Creek

Es Fangar Creek catchment (i.e. 3.4 km^2) is a headwater tributary of the Sant Miquel River located in the north-eastern part of Mallorca Island (Figure 2.6), being representative of Mediterranean mid-mountainous catchments.

Altitudes range from 72 m.a.s.l. to 404 m.a.s.l. (Figure 2.6a). The mean slope of the catchment is 26% and the length of the main channel 3.1 km (average slope of 22%). The lithology is mainly composed by marl and marl-limestone formations from the Medium–Upper Jurassic and Cretaceous period in the valley bottoms (Figure 2.6b). In the headwaters, massive calcareous and dolomite materials from the Lower Jurassic period and dolomite and marl formations from the Triassic period (Rhaetian) are dominant.

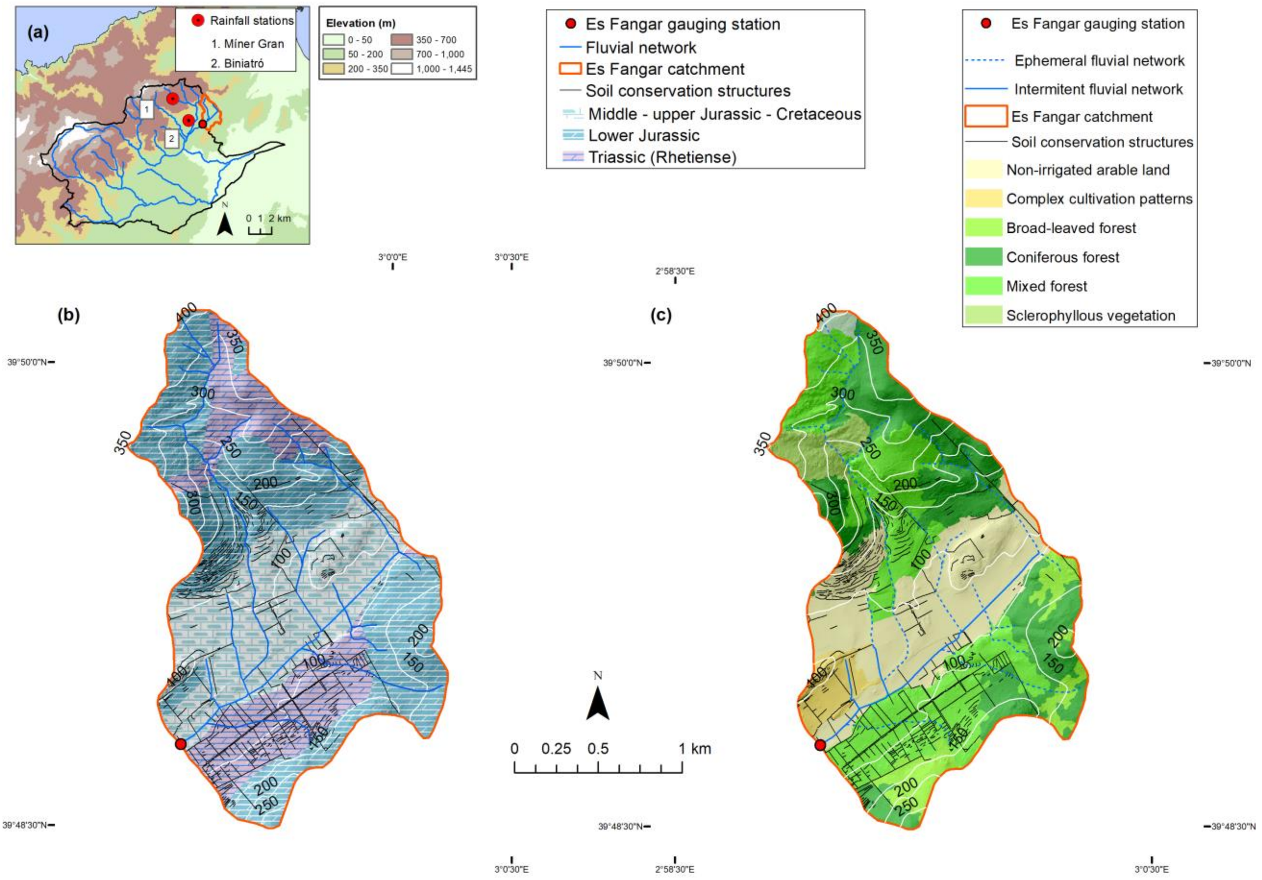

Figure 2.6. (a) Map of the Sant Miquel River catchment with the location of rainfall stations. (b) Geological and (c) land uses maps of the Es Fangar Creek catchment, showing the fluvial network, the location of soil conservation structures and of the gauging station.

The climate of the area is classified on the Emberger scale as Mediterranean temperate sub-humid (Guijarro, 1986). The mean annual rainfall (1965–2016, Biniatró AEMET station) is 927 mm y^{-1} with a variation coefficient of 23%, and the mean annual temperature is 15.7°C. A rainfall amount of 180 mm in 24 h is estimated to have a recurrence period of 25 years (YACU, 2002). The Es Fangar streamflow regime can be classified according to Oueslati et al. (2015) as intermittent flashy (49% zero-flow days), with an annual variability from intermittent (35% zero-flow days) to harsh intermittent (62% zero-flow days).

The drainage network is natural in the headwater parts. In the bottom valley, flow lamination is applied, with check-dam terraces and also the straightening and diverting of the main stream, with the banks fixed with dry-stone walls for flood control and erosion prevention (Figure 2.6c). In addition, subsurface tile drains are also installed to facilitate drainage due to the impervious materials which would impede agricultural activity during wet periods. As a result, 16% of the surface catchment is occupied by soil and water conservation structures (i.e. 32.4 km of dry-stone walls). Since 1950, important socio-economic changes have caused a gradual abandonment of farmland in marginal areas, leading to afforestation. The land uses in 1956 were rainfed herbaceous crops (54%), forest (31%) and scrubland (15%). Nowadays, the main land uses (Figure 2.6c) are forest (63%), rainfed herbaceous crops (32%) and scrubland (5%). In addition, 54% of terraced land is currently covered by forests (Figure 2.6c), demonstrating the consolidation of the forest transition.

2.1.2.2. Búger River

The Búger River is the western tributary of Sant Miquel River catchment, which drains a catchment area of 68.2 km^2 (Figure 2.7a). Altitudes range from 55 to 1,360 m.a.s.l. with an average catchment slope of 31% (Figure 2.7a). The River is 21.6 km long with an average channel slope of 5% (13% in the first 7 km and 1% downstream). The catchment headwaters are characterized by massive limestone, marls and breccia. The lithology in lowland areas is alluvial Quaternary, with clays and gravels (Figure 2.7b).

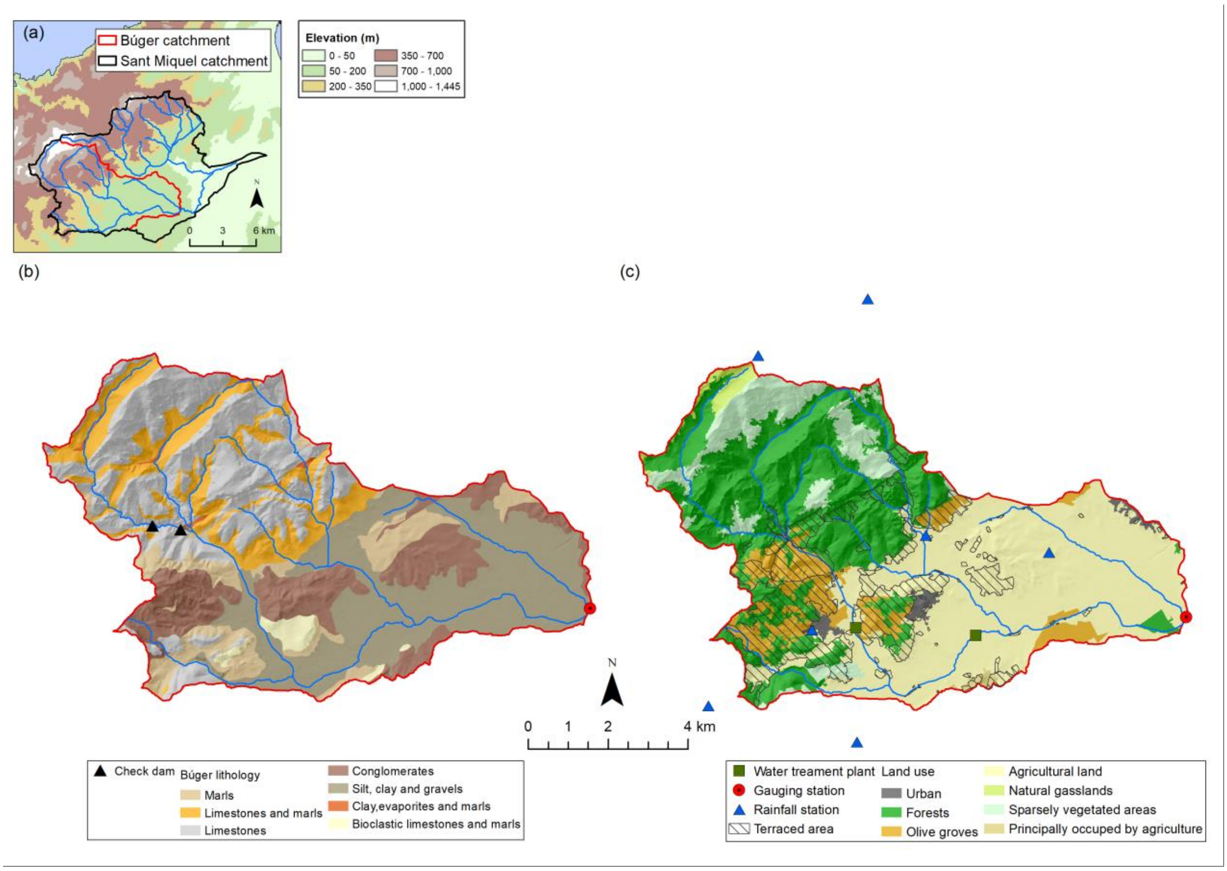

Figure 2.7. (a) Map of the Sant Miquel River catchment with the location of Búger catchment. (b) Geological and (c) land uses maps of the Búger catchment, showing the fluvial network, the location of soil conservation structures, the gauging station and water treatment plants.

The climate of the area is classified on the Emberger scale as Mediterranea temperate sub-humid in lowlands and cool-humid in headwaters, reaching the cool-superhumid in the highest part of the catchment (Guijarro, 1986). Mean annual rainfall in lowland areas is 760 mm (1985-2006, Selva-Moscari AEMET station) and at the headwaters is 1,262 mm (1993-2011, Lluc AEMET station). Rainstorms with a recurrence period of 2 years (headwaters) and 10 years (lowlands) may generate 100 mm of rainfall in 24 h (YACU, 2002).

Agriculture is the main land use of the catchment: this is, mainly located in lowlands, while forest mostly covers mountain areas (Figure 2.7c). Percentage land uses distribution are agricultural (43.7%), forest (34.9%), sparsely vegetated areas

(9.5%), olive groves (9%), natural grasslands (1.3%), urban (1.3%) and land principally occupied by agriculture with significant areas of natural vegetation (0.4%). The main headwater tributaries are regulated by check-dams constructed in the 1980s as a result of the development of basin -scale erosion- control schemes by the Spanish Forest Administration. Traditional farm terraces occupy 20% of the catchment (i.e. 485 km of dry-stone walls). Furthermore, two water treatment plants at the villages of Selva (4,014 inhabitants; INE, 2019) and Mancor de la Vall (1,509 inhabitants; INE, 2019), located 6 and 10 km upstream of the hydrometric station (Figure 2.7c), spilled into the main channel during the period 2013-2017 an average monthly wastewater volume of 12,727 m^3 and 4,267 m^3, respectively (GOIB, 2020).

2.4. Apulia region: Carapelle River catchment

Apulia Region is located in the south-eastern part of the Italian Peninsula (Figure 2.8a) and covers a surface area of 19,500 km^2. The region is divided in five physiographic units: (1) *Daunian Sub-Apennine*, (2) *Tavoliere delle Puglie* (Apulian tableland) and (3) *Gargano* promontory situated in the province of Foggia from northwest to northeast, respectively. (4) *Le Murge* hill covers predominantly the Central part of the region (Province of Bari) and the (5) *Peninsula of Salento* located in the South in the provinces of Brindisi, Lecce and Taranto. Most of the region is flat to slightly sloping land except for the Mount Gargano area situated in the North-East, and the Sub-Apennine part located mainly in the North-West of the region. The dominant soils are Cambisols, Luvisols and Vertisols, characterized by cretaceous limestone, marl and clayey to sandy deposits (Figure 2.8c).

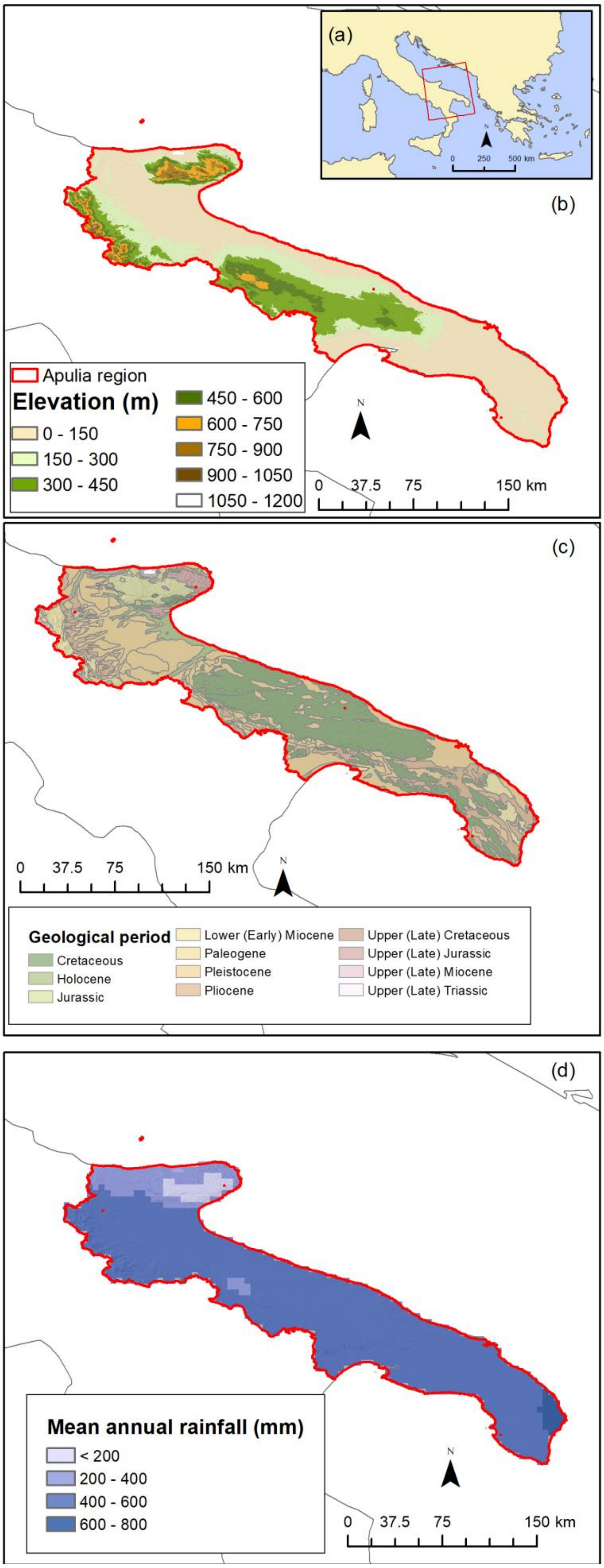
(a)
N
0
250
500 km
(b)
Apulia region
Elevation (m)
0 - 150
150 - 300
300 - 450
450 - 600
600 - 750
750 - 900
900 - 1050
1050 - 1200
N
0
37.5
75
150 km
(c)
0
37.5
75
150 km
N
Geological period
Cretaceous
Holocene
Jurassic
Lower (Early) Miocene
Paleogene
Pleistocene
Pliocene
Upper (Late) Cretaceous
Upper (Late) Jurassic
Upper (Late) Miocene
Upper (Late) Triassic
(d)
Mean annual rainfall (mm)
< 200
200 - 400
400 - 600
600 - 800
N
0
37.5
75
150 km

Figure 2.8. (a)Location of Italy and Apulia region in the Mediterranean Sea. Maps showing physical characteristics of Apulia region: (b) elevation, (c) lithology and (d) rainfall distribution.

The climate is classified as Mediterranean hot-summer (Csa), except in the northern province (Foggia) where the climate is classified as warm temperate humid (Cfa) and arid (Bsk) (Kottek et al. 2006). The highest mean annual rainfall (900 mm yr^{-1}) is in the Gargano area (NE). The lowest values of mean annual rainfall (400 mm yr^{-1}) are in the area of *Tavoliere*, in the province of Foggia (NW). However, in the greatest part of the region mean annual rainfall range between 450 and 550 mm yr^{-1} (Ladisa et al. 2012) (Figure 2.8d). Agriculture is the main land use (81.4%) while forest and semi-natural areas cover the 13.3% of the region (Corine, 2000).

The Carapelle catchment is located in northern Apulia (SE Italy; Figure 2.8a and 2.8b), which drains a catchment area of 506 km^2 with a main channel length of 52.2 km that flows with an average channel slope of 1.8%. Altitude ranges between 120 and 1,089 m.a.s.l and the average catchment slope is 16%. The headwaters are in the neighbouring Campanian Apennine region, and most of the upper watercourse crosses the orographic system of the Daunia Hills. The channel is confined to the hilly part of the basin and assumes a meandering form in the alluvial plain, where the coarser material is deposited.

In the mountainous part of the catchment, the lithology is mainly characterized by clayey-limestone and limestone-marly units which make up the flyschoid unit, while on the plain the main lithological classes are sands and conglomerates, clays and alluvial terraces (Figure 2.9c).

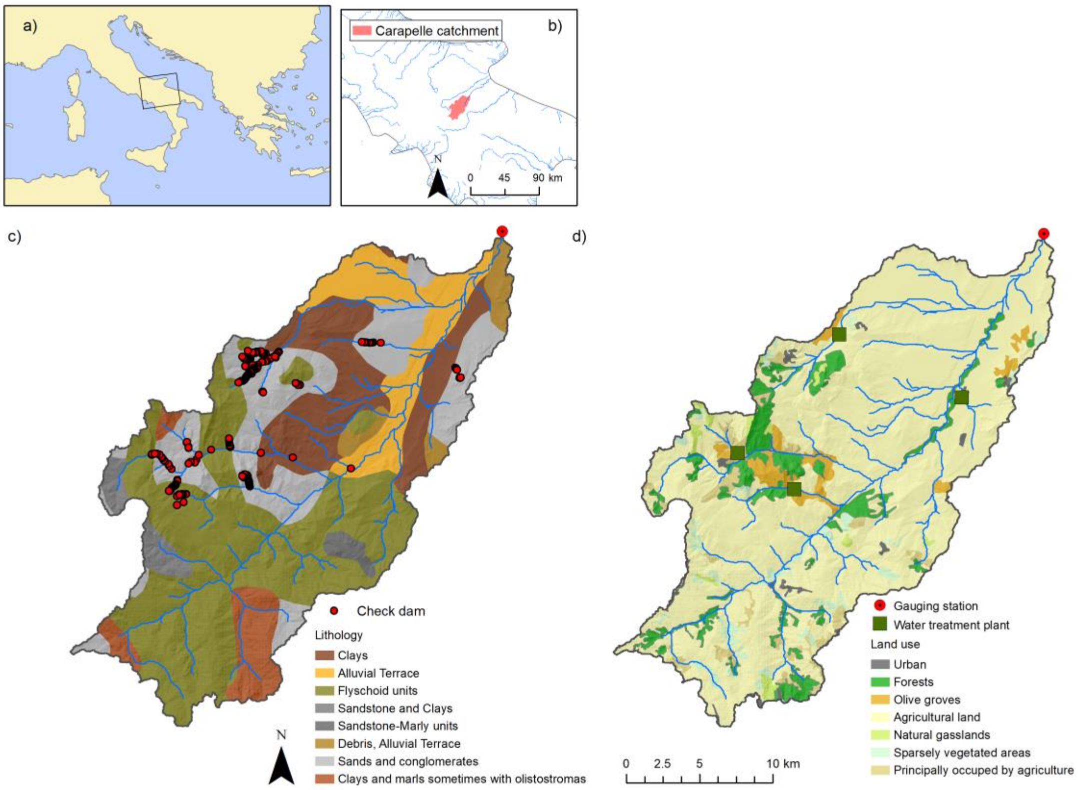

Figure 2.9. Maps showing (a) the location of Italy in the Mediterranean Sea and (b) the location of the Carapelle catchment in the Southern Italy. (c) Geological and (d) land uses maps of the Carapelle catchment, showing the fluvial network, check dams and the gauging station.

The climate classification (Kottek et al., 2006) is Mediterranean, varying between warm (Cfa) at the headwaters and arid (Bsk) at the basin outlet. The mean annual rainfall at the headwaters is 778.9 mm (1921-2012, Bisaccia, Department of Civil Protection station) and 531.4 mm in lowlands (1921-2012, Castelluccio dei Sauri, Department of Civil Protection station). The maximum 24 h rainfall, with a recurrence period of 25 years is 110 mm. The rainiest months are March and November, being August the driest month. The hydrological regime is characterized by high variability during a year, with extremely low flow conditions during the summer months (June to September) and high flow conditions recorded in winter and early spring.

The Carapelle catchment is characterised by a strong presence of agricultural activities, occupying 79.5% of the catchment, mainly winter wheat (Figure 2.8d). Forest and pastures are located in the mountainous areas. Traditionally, a 4-year crop rotation is adopted with mineral fertilizer applications in December and February. Besides, farmers usually practice the conventional tillage over the area, which consist of ploughing up and down slopes (25–40 cm depth). In the mountainous areas of the North-Western part of the catchment, many check-dams were built in the period 1960-1980. Sheet wash and concentrated water erosion are the main active erosion processes in the area, with no noticeable form of gully erosion. Bank erosion is also an active process, especially in the upstream river reaches.

There are four water treatment plants in the basin (17,302 inhabitants), which contribute with an average monthly wastewater volume of 105,180 m^3.

2.5. References

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3. Materials and methods

This chapter describes the fieldwork and laboratory methods undertaken for this thesis. Section 3.1. addresses the hydrology and suspended sediment monitoring network and gauging stations. Section 3.2. illustrates the laboratory methods.

3.1 Monitoring and data acquisition

3.1.1. Small Mediterranean catchments

To analyse the hydrological response of 43 small catchments (i.e., <10 km^2), data of annual rainfall, runoff, temperature (Cº) and catchment area (km^2) were collected from 22 published studies. When temperature information was not available, it was obtained according to Fick and Hijmans (2017). Besides, information related soil, lithology and land uses were collected to assess the rainfall-runoff relationship under different lithology and land uses. Soil information was the scarcest data of the different studies found in the literature due to the contrasted aims of these studies. For this reason, catchments were classified as pervious or impervious by using the information regarding the catchments' characteristics (e.g. soil type, soil texture or lithology materials) extracted from research papers. The predominant lithology was pervious in 12 catchments and impervious in the other 31. Within the 43 catchments, the studies of 12 of them also contained information related to the main land uses, which was used in this paper for assessing their hydrological response at the event scale. The main land uses were agriculture (3 catchments), agroforestry (3), forestry (1) and shrub (5).

3.1.2. Sant Miquel River catchment

In 2012, the Sant Miquel hydrometric network was created to investigate the changing patterns of hydrological and sediment connectivity induced by the global change in Mediterranean catchments (Figure 3.1) through the project "CGL2012-32446 Assessing hydrological and sediment connectivity in contrasting Mediterranean catchments. Impacts of Global Change. MEDhyCON -1", funded by the

Spanish Ministry of Economy and Competitiveness. This catchment was instrumented following a nested approach with catchment sizes from 3.4 to 145 km^2. Six gauging stations are continuously monitoring water stage and dissolved and suspended sediment concentrations, with readings in a sample interval of 1 min and a log interval of 15 min. Devices are linked to data loggers powered by a 12 V batteries connected to solar panels. Besides, two rainfall stations were built at headwater catchment (see Figure 3.1). During flood events and baseflow conditions, water stages are measured to calibrate water level probes, whilst flow velocity measurements were carried out to develop stage-discharge rating curves and water and sediment samples collected to calibrate the turbidimeter. Every two or three months the data was downloaded during fieldwork.

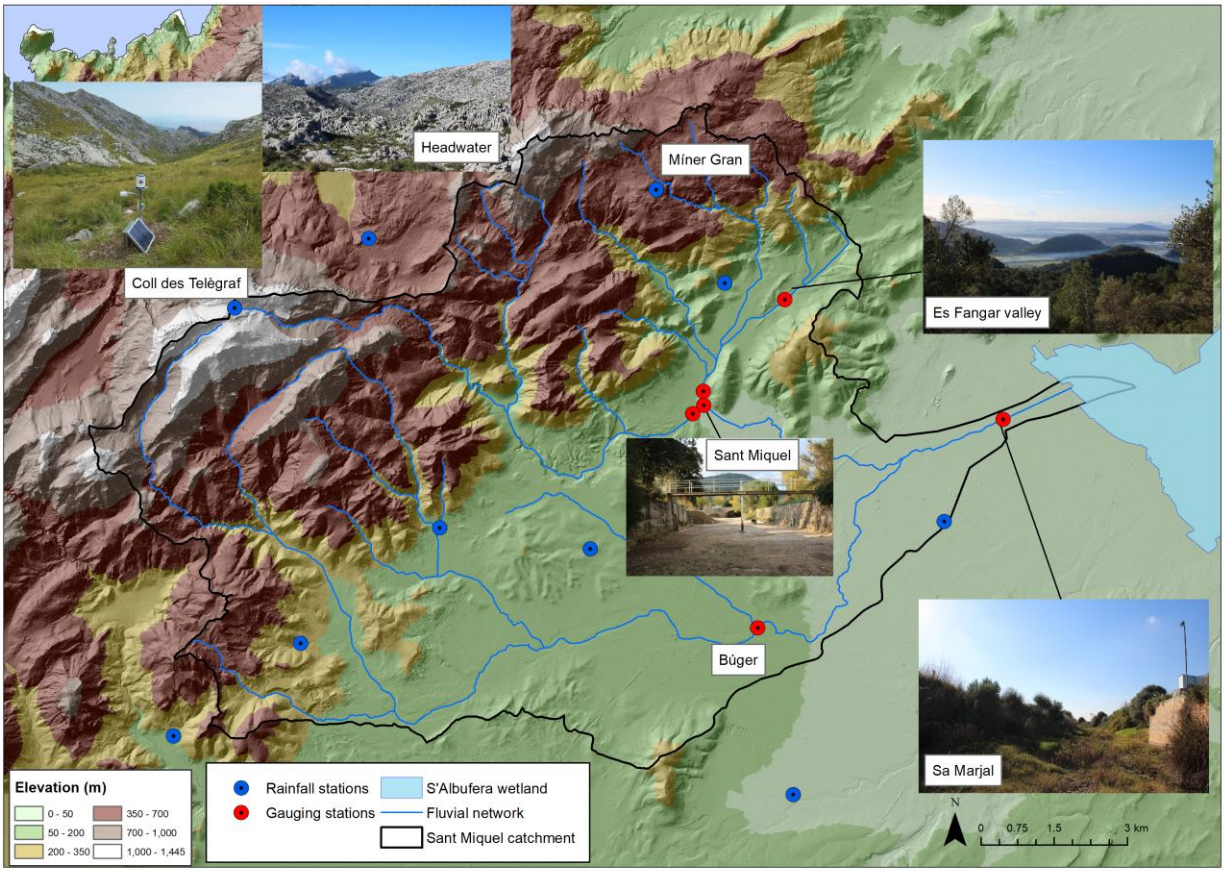

Figure 3.1. Sant Miquel hydrometric network. Map showing fluvial network, gauging stations, rainfall stations and pictures of catchment locations.

3.1.2.1. Es Fangar Creek catchment

The gauging station of Es Fangar Creek was constructed in July 2012. The cross section has a rectangular broad-crested weir for low water stages to better measure low flows (cross section 2.2 m wide x 1.7 m height; see Figure 3.2). A *Campbell Scientific CR200X* data logger continuously measures the water stage by using a Campbell CS451 pressure sensor, as well as the turbidity by an OBS-3+ turbidimeter with a double measurement range of 0–1,000/1,000–4,000 Nephelometric Turbidity Units (hereinafter NTU). In October 2014, a Water Content Reflectometer (Campbell Scientific CS625) was installed in a rainfed herbaceous crop, 3 m away from the gauge station, provide continuous soil moisture information at 0-30 cm depth. The soil moisture measurements are assumed to be representative of that of the valley bottom (i.e., 32% of the catchment area). The datalogger takes readings every minute and records average readings every 15 minutes. Between 2012 and 2017, 17 direct flow velocity measurements were performed during baseflow conditions and flood events with a Q range between 0.004 and 2.166 $m^3 s^{-1}$ by using an OTT MF Pro electromagnetic water flow meter. These flow velocity measurements were used to establish the stage-discharge relationship (R^2=0.98). In addition, samples were collected with a rising-stage sampler modified from Schick (1967) and manually during storm events and baseflow periods.

Figure 3.2. Upstream view of Es Fangar cross section and gauge station.

The rainfall data were obtained between 2012 and 2014 from the B696 Biniatró AEMET station (Figure 3.1). In October 2014, a rainfall gauge station (Míner Gran) was installed less than 2.5 km away from the catchment, in a representative location of the headwaters. The rainfall gauge is installed 1 m above the ground and connected to a HOBO Pendant® G Data Logger - UA-004-64 that records precipitation at 0.2 mm resolution. A linear regression was established (n = 978; R^2: 0.88) for daily rainfall (2014–2017) between the Biniatró and Míner Gran stations to reconstruct rainfall data series from 2012 to 2014 for the Míner Gran station. Due to the lack of temperature data available in the studied catchment, the data of neighbouring AEMET weather stations (i.e., less than 8 km away from the catchment) were used to estimate the catchment's temperature by using the block kriging technique. With this information, the monthly evapotranspiration (i.e., ET_o) was estimated using the equation from Hargreaves and Samani (1985).

3.1.2.2. Búger River catchment

The Búger River gauging station was also built in July 2012 (cross section 11.3 m wide x 1.6 m height; see Figure 3.3). Water stage is continuously measured using a pressure sensor (Campbell CS451) and turbidity was recorded by a turbidimeter (OBS-3+ turbidimeter with a double measurement range of 0–1.000/1.000–4.000 NTU) connected to a Campbell Scientific CR200X data logger, which performs a 1 min reading and records an average value every 15 min. Between 2012 and 2017, 12 direct flow velocity measurements were performed during baseflow conditions and flood events with a Q range between 0.108 and 6.725 $m^3 s^{-1}$ by using an OTT MF Pro electromagnetic water flow meter. These flow velocity measurements were used to establish the stage-discharge relationship (R^2=0.97). A rising-stage sampler modified from Schick (1967) was installed to provide more information on SSC. Besides, SSC samples were collected manually during storm events and baseflow periods. The rainfall data since 2012 were obtained from AEMET-the Spanish Meteorological Agency (6 rainfall stations) and the MEDhyCON research group (2 rainfall stations).

Figure 3.3. Downstream view of Búger River cross section and gauge station during the flood event occurred 20th January 2017.

3.1.3. Carapelle River catchment

Daily and sub-daily (30-min) rainfall data from 8 rainfall stations were obtained from the Department of Civil Protection between 2007 and 2011. In the Carapelle gauging station water stage was measured using an electromechanical and ultrasound stage meter (see Figure 3.4). Turbidity was measured with an infrared optical probe (Hach-Lange Solitax) with a range of 0.001-4000 NTU (0-150 g l^{-1}). The probe was housed in a protection case to avoid the impact of flowing coarse material. The monitoring was controlled by a data acquisition set and a telemetry system for remote measurements was also provided. Both systems recorded data every 30 minutes.

Figure 3.4. Upstream view of Carapelle cross section, gauge station and probe housing device.

3.2. Laboratory analysis

In Es Fangar and Búger, the water and suspended sediment samples (250 ml) collected by the rising stage, during baseflow and flood events were filtered with 0.45 µm filters, which were subsequently dried at room temperature and weighed on high-precision scales (i.e., 0.0001 g) to determine suspended sediment concentrations. Finally, these suspended sediment concentrations values were used to calibrate the turbidity probes through a SSC – NTU relationship (Table 3.1).

Table 3.1 Number of samples collected for the turbidimeter calibration, range of suspended sediment concentration (SSC) and R^2 obtained.

Catchment	Number of samples	SSC range (g l^{-1})	R^2 turbidimeter calibration
Es Fangar	38	< 0.1 - 0.9	0.81
Búger	18	< 0.1 - 2.3	0.91
Carapelle	65	0.1 - 21	0.95

In the Carapelle, the turbidimeter was calibrated firstly in the laboratory with material collected from the riverbed of the Carapelle. In this stage, 31 suspensions having fixed granulometric mixtures and 36 suspensions with varying ratios between sandy and fine fractions were used. A second calibration was done using 65 samples collected during flood events (Gentile et al. 2010).

3.3. Analysing hydrological response and suspended sediment transport

To assess the hydrological response and suspended sediment transport of Mediterranean catchments, a relationship assessment encompassing rainfall, soil moisture, discharge and suspended sediment was carried out at different temporal scales (annual, seasonal, monthly and event scale). In the small Mediterranean catchments, rainfall and runoff at the annual and event scale were used to carry out bivariate relationships. In Es Fangar, rainfall, runoff, and suspended sediment load were calculated at annual, seasonal, and event scales. Additionally, a water balance was computed at the monthly scale and at the event scale the soil moisture was included into the analysis. At the event scale, for each runoff event (i.e., when the water stage exceeds the low-flows channel; i.e., 0.036 m3 s−1), a simple hydrograph separation between quickflow and baseflow components was performed through a visual technique based on the breakpoints detected on the logarithmic falling limb of the hydrograph (Maidment, 1985). In Búger and Carapelle, the flow regime was classified in relation to the degree of intermittence. Rainfall, runoff and sediment load were calculated at annual, monthly and event scale. Figure 3.5 summarizes the methodological workflow for the analysis of the hydrological response and suspended sediment transport.

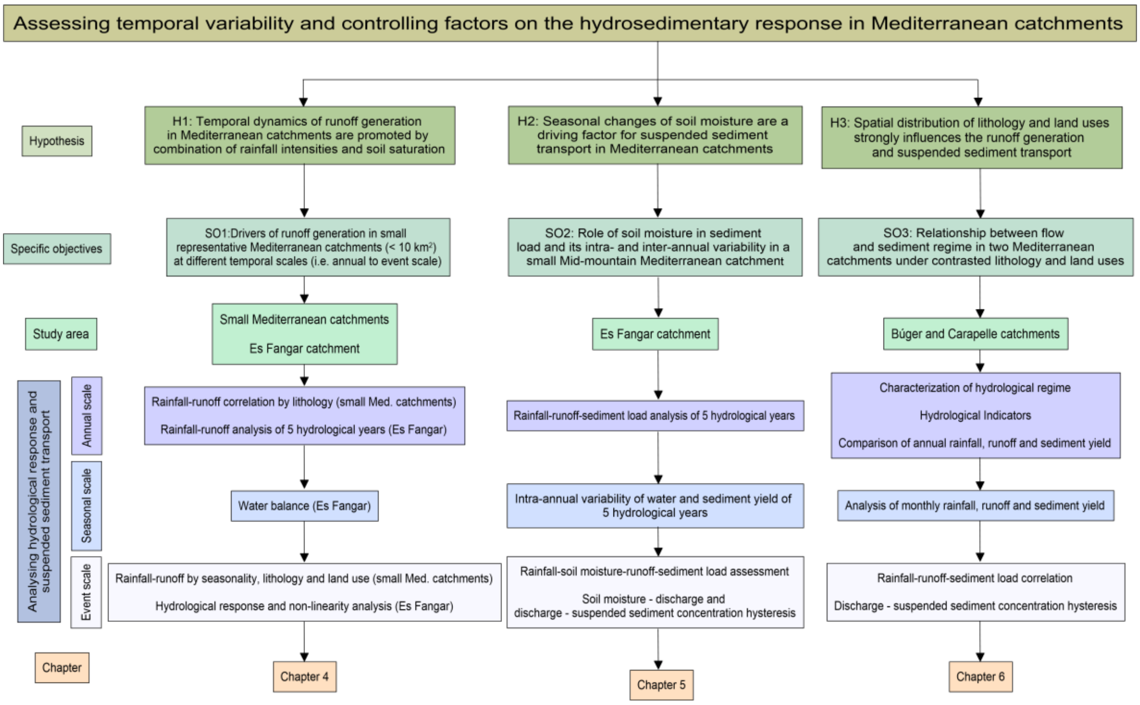

Figure 3.5. Hypothesis, specific objectives and methodological workflow for the analysis of the hydrological response and suspended sediment transport in the small Mediterranean catchments, Es Fangar, Búger and Carapelle catchments.

The hydrological regime was characterized by means of a set of hydrological indicators (HIs; Richter et al., 1996) and the degree of intermittence (Gallart et al., 2012). The selected HIs, computed on measured daily Q, proved to be relevant in temporary rivers as pointed out by Oueslati et al. (2015) and by D'Ambrosio et al. (2017). To characterize the time during which a specified flow or suspended sediment yield was exceeded, flow and sediment duration curves were computed (hereinafter FDC and SDC respectively). To assess the inter- and intra-annual variability, rainfall, runoff and sediment load amounts were computed at annual, seasonal and monthly scale.

At the event scale, several variables were computed from rainfall, soil moisture, discharge and suspended sediment. To assess the relationship of these variables bivariate and multiple correlations were carried out to identify the main drivers of the hydrological response and sediment transport. The non-linearity of the rainfall-runoff relationship was analysed using rainfall events with a similar rainfall amount but a different runoff response occurred with different antecedent conditions or rainfall dynamics. Non-parametric statistics were applied to check if significant differences (i.e., $p < 0.01$) existed between groups of events.

The spatiotemporal relationship between soil moisture, discharge and suspended sediment concentrations were analysed by a double hysteresis analysis. The first one was focused on the relationship between Q and SSC using the hysteresis classification reported by Williams (1989). The second hysteretic analysis was carried out to assess the antecedent condition of the R event generation. An analysis of soil moisture - discharge hysteretic loops following the method by Penna et al. (2011) was used to identify dry or wet antecedent conditions.

3.4. References

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4. Multiple temporal scales assessment in the hydrological response of small Mediterranean catchments

Fortesa J, Latron J, García-Comendador J, Tomàs-Burguera M, Calsamiglia A, Estrany A. 2020. Multiple temporal scales assessment in the hydrological response of small Mediterranean-climate catchments. *Water* 12, no. 1 299. DOI:10.3390/w12010299. (JCR: Water resources Q2 31/94; IF-2019: 2.544).

5. Runoff and soil moisture as driving factors in suspended sediment transport of a small mid-mountain Mediterranean catchment

Fortesa J, Latron J, García-Comendador J, Company J, Estrany A. 2020. Runoff and soil moisture as driving factors in suspended sediment transport of a small mid-mountain Mediterranean catchment. *Geomorphology* 368, 107349. DOI: 10.1016/j.geomorph.2020.107349 (JCR: Geosciences Q1 28/200; IF-2019: 3.819).

6. Analysing hydrological and sediment transport regime in two Mediterranean intermittent rivers

Fortesa J, Ricci GF, García-Comendador J, Gentile F, Estrany J, Sauquet E, Datry T, De Girolamo AM. 2021. Analysing hydrological and sediment transport regime in two Mediterranean intermittent rivers. Catena 196, 104865. DOI: 10.1016/j.catena.2020.104865 (JCR: Geosciences Q1 21/200; IF-2019: 4.333)

7. Discussion and conclusions

7.1. Discussion

7.1.1. Hydrology of Mediterranean catchments

7.1.1.1. Hydrological regimes in Mediterranean catchments

Temporary rivers is a broad term used to define waterways that cease flow during some time of the year (Busch et al., 2020). These rivers account over 50% of the global fluvial network present in all continent and climates (Acuña et al., 2014) and are expected to increase with climate change and anthropogenic activities (Costigan et al., 2017; Sauquet et al., 2020). Hydrological regimes are influenced by fluctuations in the groundwater table and the nature of the flow pathways into and out of the river channel (Sear et al., 1999). Thus, the relevance of temporary rivers in how and where groundwater recharge occur is a key issue for water resources management, making essential the understanding of the transition from dry to flowing state (Gutiérrez-Jurado et al., 2019).

Under this framework, soil permeability, lithology and geological features have been found to be the most relevant factors affecting the flow regime and the intermittence of the Búger and Carapelle catchments. The lithological features in catchments promoted a huge difference in the duration of no-flow conditions which is a good variable to describe temporary rivers (Oueslati et al., 2015). Consequently, an Intermittent-Dry and Intermittent-Pool regimes were estimated for Búger and Carapelle rivers, respectively. Zero-flow day is one of the most important hydrological metrics in temporary rivers because it has major ecological implications for aquatic and terrestrial biota and ecosystem processes (Datry et al., 2017; von Schiller et al., 2017). Thus, karst areas of Búger catchment headwaters and sand and coarse sediments composing alluvial deposits in downstream areas promoted high transmission losses causing a high threshold for runoff generation (Estrany et al., 2010a). Accordingly, a large mean number of zero-flow day was observed (i.e. 237 ± 50). In Carapelle, although the median annual rainfall (546 mm) was lower than Búger (868 mm), a lower mean number of zero-flow day was observed (i.e. 2.5 ± 26). Furthermore, land use also exerts a control over runoff generation. In the Carapelle catchment, 80% of its surface is covered by seasonal crops. Conversely, forests in Búger cover the 35% of the catchment, mainly located in steepest headwaters, promoting a higher rainfall interception than the arable land of the Carapelle catchment (Cosandey et al., 2005). As a result, flow permanence observed was 26% and 99% in Búger and Carapelle catchments, respectively. Similarly to the Búger catchment, karst areas in Es Fangar catchment also promoted a large mean number of zero-flow day (i.e. 178 ± 38). Búger and Es Fangar values can be classified in the range of high number of zero-flow day if compared with the 40 temporary rivers in Europe under different climate and lithology (Table 7.1). The classification of the 40 temporary rivers by non- Csa climate and non- calcareous lithology depicted how catchments under Csa climate and/or calcareous lithology had the largest values of zero-flow day (Table 7.1). Although temporary rivers are not only present in arid and Mediterranean areas, a weak tendency was observed in the zero-flow day increasing as mean annual temperature increase and as mean annual rainfall decrease (Sauquet et al., 2020).

Table 7.1. Compiled data of mean zero-flow day and standard deviation of 40 temporary rivers from Sauquet et al. (2020).

	Mean Zero-flow day	Standard deviation
All catchments	74	87
Catchments with Csa climate	134	99
Catchments without Csa climate	29	36
Catchments with calcareous lithology	141	109
Catchments without calcareous lithology	38	42
Catchments with Csa climate and calcareous lithology	183	103

Geological characteristics promote a high spatial variability of intermittency controlling the hydrological regime (Borg Galea et al., 2019; Gutiérrez-Jurado et al., 2019; Shanafield et al., 2020). As a result catchments with calcareous lithology showed the highest standard deviation of zero-flow day due to the presence of karst sources with an irregular and flashy behaviour highly dependent on rainfall amounts and spatial distribution, that increased or decreased the zero-flow day observations. For example in the Spanish Pyrenees, a gauging station located at the outlet of a karstic system (1.4 km^2) maintained a near-permanent regime, whereas in a downstream station of the same catchment (35 km^2) the flow regime was ephemeral (Gallart et al., 2012). Likewise, transmission losses in a small catchment were observed from headwaters (1.1 km^2) to the outlet (4.8 km^2) where flow duration decreased from 32% to 13% of the time, respectively (García-Comendador et al., 2017). Contrarily, streams under chalk material increased flow permanence downstream due to hydrological regime was dominated by groundwater contributions (Sefton et al., 2019). Understanding the expansion and contraction of the wet and dry stream length by applying techniques such spatiotemporal monitoring using flow intermittency sensors (Assendelft and van Meerveld, 2019; Jensen et al., 2019) will finally improve the comprehension of the spatiotemporal distribution of flow states and runoff generation processes and therefore the hydrological functioning of temporary rivers.

7.1.1.2. Hydrological response in Mediterranean catchments

Mediterranean catchments are within the most complex environments due to the seasonality of their climate, the catchment geology and the long history of landscape modification by human activity, which strongly influenced their hydrological response (Thornes et al., 2009). These characteristics make this region sensitive to the global change (i.e. land uses and climate changes) and therefore subject to changes that will affect the sustainability, quantity, quality and management of water resources (García-Ruiz et al., 2011). Thus, assessing the relevance of the hydrological response at different timescales is fundamental for a better comprehension of process interactions and feedbacks between different drivers across timescales (Sun et al., 2016)

7.1.1.2.1. Annual scale

Hydrological response in Mediterranean catchments showed a significant annual rainfall-runoff correlation, depicting the importance of the annual rainfall amount

(Merheb et al., 2016). Such result is in agreement with the conceptual model developed by Borg Galea et al. (2019) were climate is the main exogenous driver of the rainfall-runoff relationship at catchment scale in Mediterranean environments. However, rainfall-runoff is also influenced by endogenous variable (i.e. catchment geology), promoting non-linearity in this relationship. Accordingly, this non-linearity was observed in the rainfall-runoff relationship the small Mediterranean catchments where catchments with pervious and impervious lithology showed linear correlations of $R^2 = 0.47$ and $R^2 = 0.82$, respectively. Highest values of annual runoff were observed in catchments characterised by impervious materials or with karst sources, while low annual runoff were observed in catchments characterised by deep percolation or transmission losses. Similarly, the annual runoff coefficient showed a higher median value in the non-karst catchment (i.e. Carapelle, 16.5%) than in karst areas (i.e. 8.7 for Es Fangar 8.7% and 3% for Búger catchments). The median runoff coefficient of the Carapelle catchment is comparable with the values of runoff coefficient reported in catchments of the Eastern Mediterranean region with a median value and interquartile range of 17% and 6-57%, respectively (Merheb et al., 2016). The median runoff coefficient of Es Fangar and Búger catchments is similar to the values of runoff coefficient reported in catchments of the Southern Mediterranean region with a median value and interquartile range of 8% and 5-14%, respectively. However, the median annual rainfall (376 mm yr^{-1}) and interquartile range (327-433 mm yr^{-1}) of the Southern Mediterranean region are lower than the median values of Es Fangar (874 mm yr^{-1}) and Búger (868 mm yr^{-1}) catchments, where in spite of larger annual rainfall limestone lithology led to a decrease of the runoff coefficient values (Ries et al., 2017). Annual runoff coefficients are also subject to a large inter-annual variability and ranged between 3-14%, 2-10% and 14-35% in Es Fangar, Búger and Carapelle catchments, respectively.

The spatial distribution of lithology and land use in Es Fangar, Búger and Carapelle catchments allows a better understanding of runoff generation patterns. The spatial distribution of land uses in Es Fangar and Búger catchments follow a common landscape pattern in Mediterranean regions; i.e., forests at headwaters and agriculture in the valley bottom. This land use distribution promoted a reduction effect in runoff response, as the steepest parts of the catchments are covered by natural vegetation. Accordingly, runoff response becomes governed by areas differing in land use (i.e. patches) and their interaction according to the spatial distribution within a catchment (Fiener et al., 2011). Runoff response increased where larger patches are connected to the drainage pathway instead of being randomly distributed (Western et al., 2001). Furthermore, it is essential to analyse the linear structures and the density of patches for assessing the effects of human-made patchiness on runoff response (Fiener et al., 2011). Linear structures may increase (i.e. forest roads) or decrease (i.e. terraces and drainage systems) hydrological connectivity at the catchment scale (Calsamiglia et al., 2018; López-Vicente et al., 2017). Terraces reduce the slope length and gradient, increasing water infiltration and soil retention (Tarolli et al., 2014). However, the collapse of these structures may promote an increase of runoff generation as in Mediterranean areas runoff coefficient on abandoned terraces ranged from 20% to 40%, depending on the percentage of plant cover (Arnáez et al., 2015). The annual runoff coefficient values in Es Fangar and Búger catchments may indicate that terraces were still working well during the study period, reducing runoff generation. Additionally, subsurface tile drains in flat areas facilitated drainage during wet and dry periods by reducing soil saturation and increasing infiltration, respectively (Estrany et al. 2010b; Moussa et al., 2002). Furthermore, in Es Fangar catchment, hydrological connectivity is modified through a check-dam system in the bottom valley (disconnecting slope and channel) where the natural stream is diverted to a margin of the floodplain, providing further fertile agricultural land and avoiding erosion. Besides, two roads following the bottom valley direction reduce hillslope-floodplain lateral connectivity. In Es Fangar and Búger catchments some of the soil conservation structures were abandoned since the middle of the twentieth century due to rural exodus. Accordingly, afforestation processes increased forest coverto 54% and 37% of the terraced areas in Es Fangar and Búger, respectively. Additionally, land use change has been identified as a main factor controlling hydrological connectivity, promoting low and more stable values of connectivity when afforestation processes occur (López-Vicente et al., 2017) resulting in a potential reduction of the sediment cascade. However, when minor changes in vegetation occur the changes in linear structures play a key role in hydrological pathways. As a result, the degree of maintenance or abandonment of terraces and their current land use determine the (dis)connectivity between compartments according to preferential pathways promoted by a cascade effect of collapse within the terraced areas (Calsamiglia et al., 2018). In the Carapelle catchment, check dams characterised by a low Leaf Area Index values and scarce vegetation were eroded or destroyed, therefore increasing in-channel connectivity (Ricci et al., 2019). However, check dams with high Leaf Area Index showed positive effects on riparian vegetation promoting riverbed stability.

7.1.1.2.2. Seasonal scale

Mediterranean climate is characterised by a wet and mild winter, a warm and dry summer and a high inter- and intra-annual variability in rainfall patterns. Rainfall is not equally distributed between seasons as 65% and often 80% or more of the rain falls in winter, with most of the precipitation falling during few major events (Gasith and Resh, 1999). Therefore, seasonal rainfall patterns and evapotranspiration generate wet (winter) and dry (summer) periods alternated throughout the year, separated by transition periods (last autumn and early spring). These periods cause different initial conditions for runoff generation, which generally follows the rainfall pattern. According to the seasonal dynamics of rainfall the highest runoff contributions in Mediterranean catchments were in winter (i.e. wet period), followed by autumn and spring (i.e. transition periods) (Peña-Angulo et al., 2020a). The observed seasonality depicted how large amounts of runoff occurred during wet periods when catchments reserves enable the runoff generation (Latron et al., 2008). Accordingly, in Es Fangar and Búger catchments, seasonality and antecedent soil moisture conditions played a key role in runoff generation (Lana-Renault et al., 2007). The alternation of the wet, dry and transition periods is reflected in the seasonal runoff coefficients. Thus, winter was the season with the highest runoff coefficient in Es Fangar (17%), Búger (9%) and Carapelle (36%) catchments as a result of the rainfall accumulated during autumn -and maintained in winter- and low evapotranspiration demand (Estrany et al., 2010b). During autumn and spring, similar runoff coefficients in Es Fangar (9.1% and 5.1%), Búger (2.6% and 1.4%) and Carapelle (15.6% and 18.1%) catchments were observed as autumn and spring encompass the wetting-up and the drying-down period, respectively (Gallart et al., 2002). The beginning and the end of these seasons triggered quite different values of runoff as depicted the monthly runoff contributions of Es Fangar, Búger and Carapelle catchments, increasing from October to December and decreasing runoff from from April to June. The lowest runoff coefficient in the three catchments was observed in summer (1.4%, 0.4% and 11.8% in Es Fangar, Búger and Carapelle catchments). Similar results of summer runoff coefficients (< 10%) were obtained in Mediterranean catchments as the driest period of the year limited the hydrological response (Estrany et al., 2010b; Lana-Renault et al., 2007; Serrano-Muela, 2012).

These seasonal differences in runoff generation were observed in Es Fangar, Búger and Carapelle catchments. However, differences in the duration of the wet and dry period were observed in Es Fangar and Búger compared to Carapelle catchment. In Es Fangar and Búger catchments the months with highest rainfall and runoff amounts were from November to January and from November to April, respectively. Runoff started to decrease in mid-spring (i.e. transition period) as reference evapotranspiration increase and water reserves decreases. From mid-spring until summer, dry conditions for runoff generation were established and the catchments had a null or limited response until the wetting-up period, when succession of rainfall events filled again the water reserves, similarly to findings reported by Latron et al. (2008) in the Vallcebre research catchments. Although the Carapelle catchment had lower rainfall amount than Es Fangar and Búger catchments, rainfall amounts were homogeneously distributed throughout the year enlarging the duration of the wet period from October to June. Despite the duration of wet and dry period were different between catchments, the date of maximum and minimum flow coincide in the wet and dry period, respectively.

Seasonality plays a key role in runoff generation processes increasing their non-linearity due to the temporal patterns in rainfall and catchment moisture conditions (Gómez et al., 2014). Thus, runoff mechanisms can co-exist within a catchment even if during the wet period saturation processes likely are dominant whereas during dry period Hortonian processes may control most of the runoff generation (Manus et al., 2009; Merheb et al., 2016).

7.1.1.2.3. Event scale

The temporal distribution of the analysed events in the small Mediterranean catchments, Es Fangar, Búger and Carapelle fits with the temporal pattern observed in the eastern and southern Mediterranean Sea Basin as half of the events occurred between November and February (Merheb et al., 2016), the period with the largest rainfall events in the Mediterranean Sea Basin.

In Es Fangar catchment, runoff response was assessed using soil moisture variables (normalised soil moisture lag time and soil moisture average) instead of antecedent rainfall, which is an indirect measure of soil moisture that does not take into account the spatial and temporal variability of multiple factors related to soil moisture (i.e. soil texture, topography, vegetation; Brocca et al., 2010; Zucco et al., 2014). Results showed how major runoff contributions were generated under situations of wet soil moisture conditions characterised by a shorter lag time between the beginning of the rainfall event and moisture peak. Besides, soil moisture-discharge hysteresis in Es Fangar catchment revealed that 76% of the events were generated under wet antecedent conditions (Penna et al., 2011). Thus, in wet conditions the expansion of the stream length promotes in temporary rivers a higher hydrological connectivity enlarging the hydrological response if compared to events under dry conditions (Marchamalo et al., 2016). On the other hand, in the Carapelle catchment, drivers of runoff generation were related to the amount and intensities of the rainfall event, showing how different catchments characteristics (i.e. lithology and land use) may influence runoff generation. In this way, small Mediterranean catchments under impervious lithology showed larger runoff values and larger rainfall-runoff correlation than catchments under pervious lithology due to transmission losses (Tzoraki and Nikolaidis, 2007). Accordingly, soils characteristics are less pervious in the Carapelle than in Es Fangar and Búger, therefore infiltration excess processes could be more dominant in response to the rainfall (Latron et al., 2008). Furthermore, as 80% of the catchment in Carapelle acts as main driver for runoff generation as arable land has been demonstrated to be a driver for runoff generation (Cerdan et al., 2004). Similarly, rainfall-runoff of the small Mediterranean catchments under agricultural land use promoted larger runoff values than forest, agroforest and shrub land uses. Accordingly, low mean runoff (i.e.

< 6 mm) and coefficients (i.e. < 16 %) during events were observed in Es Fangar and Búger catchments as headwaters of both catchments were forested increasing rainfall interception (Cosandey et al., 2005). Hence, agricultural land use or impervious lithology are favourable for runoff generation during events due to low rainfall interception and low infiltration capacity. However, seasonality played also an important role as highest runoff contributions were obtained in winter independently of the land use and lithology. Accordingly, runoff coefficients in Es Fangar and Búger showed a large variability caused by seasonality. In these catchments, runoff coefficient ranged from 1% to 80% (12% median value) and from 0.1% to 42% (2.3% median value), respectively. The median values of runoff coefficient obtained are closer to the Eastern Mediterranean region (12%) than to the North-Western (40%) or Southern Mediterranean region (36%) (Merheb et al., 2016). However, in both catchments runoff coefficients > 10% only occurred between November and March as water reserves in winter were higher than autumn and spring (Lana-Renault, 2007). Indeed, in Es Fangar catchment these events were characterised by a baseflow at the beginning of the flood above 0.04 m^3 s^{-1}, confirming that they occurred under favourable water reserves conditions enabling larger runoff generation and higher discharge peaks than in other seasons (Tuset et al., 2016). Therefore, the largest hydrological responses in Es Fangar and Búger was due to the events occurred during winter season with wet antecedent conditions (antecedent baseflow and antecedent precipitation one day before) that promoted the largest values of runoff, runoff coefficient and discharge peak (Estrany et al., 2010b; Zocctaelli et al., 2019). In the Carapelle catchment, runoff coefficients ranged from 16% to 100% with a median value of 80%, being higher than the median values reported in the three Mediterranean subregions (Merheb et al., 2016). The high median runoff coefficient in the Carapelle catchment is explained due to antecedent baseflow during small rainfall events (i.e < 5mm).

7.1.2. Suspended sediment transport in Mediterranean catchments

The distribution of the climatic, geological, topographical and land cover features determines the spatial sediment generation, sediment transfer and sediment transport within a catchment (Walling, 1983). In Mediterranean catchments, these characteristics are based mainly in the inter- and intra-annual variability of the rainfall, non-uniform spatial distribution of lithology and highly modified land uses, generating a global change hotspot and multiples future scenarios for erosion trends (García-Ruiz and Lana-Renault, 2011; Yair, 1983; Zdruli, 2014). Assessing the suspended sediment transport under global change at different time scales allows a better understanding of when major loads take place and which factors are involved, which is crucial to elaborate suitable adaptive management strategies for soil resource (Lagacherie et al., 2018).

7.1.2.1. Annual scale

European catchments located in the Mediterranean climatic zone had the highest sediment yield (Vanmaercke et al., 2011). The median of sediment yield obtained in Es Fangar (4.5 t km^2 yr^{-1}), Búger (1.5 t km^2 yr^{-1}) and Carapelle (267.8 t km^2 yr^{-1}) catchments showed large differences between them. Es Fangar and Búger values can be classified in the European catchment group with the lowest sediment yield (i.e., $<$ 40 t km^2 yr^{-1}) whereas Carapelle catchment can be classified in the group with the highest sediment yield (i.e., $>$ 200 t km^2 yr^{-1}) (Vanmaercke et al., 2011). Although Mediterranean catchments had the highest sediment yield, they also had the highest standard deviation due to differences in climate, topography, land use and lithology. The land use distribution in Es Fangar and Búger catchments is characterised by a more complex pattern than in the Carapelle catchment due to a larger patchiness between forest, shrub and agricultural land uses. Furthermore, forest land use in Es Fangar and Búger headwaters promoted low sediment yield values as the natural vegetation protects the steepest slope. Thus, land use and vegetation coverage are a key factor for sediment yield as larger values of sediment yield are obtained under bare soil, agricultural land and badlands than forest and scrubland (García-Ruiz et al., 2013). Accordingly, the 80% of the Carapelle catchment is covered by seasonal crops being arable land the driver for the suspended sediment transport. Additionally, the contrasted lithology between catchments also promoted differences in sediment yield values. Es Fangar and Búger headwaters are characterised by limestone materials, which trigger high transmission losses and low soil loss rates (Cantón et al., 2011). Furthermore, another factor to consider is the soil aggregation as it determines the pore structure and dispersion resistance of soil. Calcareous soils tend to have a great aggregate stability as calcium ions promotes aggregation (USDA, 2008). A well-structured soil can be promoted by a minimal tillage that may reduce aggregate destruction because they are not physically or mechanically broken; adding organic matter to enhances aggregate strength and stability; the application of organic fertilizer and agricultural abandonment (Liu et al., 2020a, 2020b). Soils with high aggregate stability are less susceptible to erosion as aggregated soils enhanced water infiltration reducing runoff and erosion. Hence, the concept of soil loss tolerance (T-value) was suggested to express the maximum acceptable soil loss from an area (Stamey and Smith, 1964). However, limestone materials are characterised by low rates of soil formation that promote low values of soil loss tolerance, which ranges from 0.2 to 55 t km^2 yr^{-1} with an average of 4.3 t km^2 yr^{-1} in continuous pure limestone and dolomites areas (Cao et al., 2020; Li et al., 2017, 2006). Nonetheless, these rates were calculated in the karst plateau in southwest China, an area characterised with a subtropical humid monsoon climate, mean annual temperature and rainfall of 14.3º C and 1338 mm, respectively. Thus, 80% of the rainfall occur when temperature is high promoting the soil formation. Soil formation and soil loss tolerance in Mediterranean karst areas may likely be lower than on the karst plateau as the rainiest period (i.e. autumn and winter) do not coincide with the warmest period (i.e. summer) when the formation factors can be more active. Contrarily in the Carapelle catchment, pervious lithology is composed of sandstone with clays or marls and occupying a lower extension (3.6%) than in Es Fangar (44%) or Búger (28%) catchments. Therefore, the interaction between land use and lithology play a key role in soil erosion, especially in karst areas where catchments with vegetation cover close to 50-60% showed a limited sediment transport (Gao et al., 2018). Additionally, the different conservation state of the soil conservation structures in Es Fangar and Búger catchments (mainly maintained) than Carapelle catchment (some of them destroyed) may act differently decreasing (in the first case) or increasing (in the second case) the sediment transfer (Calsamiglia et al., 2018).

7.1.2.2. Seasonal scale

Seasonal sediment yield variability can be seen better when major suspended sediment transport takes place as large events are known to strongly control annual sediment yield values (Gonzalez-Hidalgo et al., 2010; Li et al., 2020). A marked seasonality was observed in the sediment yield contributions in Es Fangar, Búger and Carapelle catchments as major sediment yield contributions occurred in autumn and winter, although at the beginning or end of summer relevant contributions may occur. Despite runoff and sediment yield contributions showed the same seasonality, the time compression (i.e. short periods where major soil losses take place) of the sediment yield was larger for runoff values. Accordingly, this seasonal pattern was observed in Mediterranean-climate catchments if compared to Mediterranean-oceanic climate catchments (Smetanová et al., 2018). Furthermore, compiled data from Mediterranean studies at plot (17) and catchment (29) scale showed that highest sediment yield contributions were generally observed in autumn, followed by spring, winter, and summer. However, a huge sediment yield variability was observed for all seasons, being only significant the difference in sediment yield between summer and autumn (Peña-Angulo et al., 2020a). Additionally, these authors linked the highest rainfall, runoff and sediment yield contribution to the weather types, showing that westerly and easterly weather types promoted the highest rainfall, runoff and sediment yield contribution in autumn-winter and spring-summer, respectively. Accordingly, Es Fangar location in the northernmost part of Mallorca and the SW-NE orientation of the reliefs promoted that the northern flow and convergence highly influence the hydrosedimentary response. North and north-east weather types generated 57% of the flood events and the 63% of the sediment yield (Peña-Angulo et al., 2020b). Finally, sediment yield in Mediterranean catchments showed a higher intra-annual variability than runoff suggesting more complex and local process associated with sediment dynamics, also dependent on relief, connectivity, land cover and land management practices (Keesstra et al., 2018) .

7.1.2.3. Event scale

Large floods are responsible for most of the sediment transport in catchments as few events are able to transport more than the 80% of the SS load during less than the 10% of the time (Estrany et al., 2009; Rovira and Batalla, 2006). Accordingly, the 91%, 86% and 80% of SL was transported in 5%, 0.5% and 1% of the time in Es Fangar, Búger and Carapelle catchments, respectively. The identification of the sediment load driving factors allows to understand how this suspended sediment transport takes place. Es Fangar and Búger catchments had the same drivers of suspended sediment transport as total precipitation and maximum 30' rainfall intensity do not showed correlation with sediment load and maximum suspended sediment concentration. Largest sediment load contributions were related to highest values of runoff and maximum peak discharge, and similar to the hydrological response, the events that promoted the highest values of sediment load were related to wet antecedent conditions (antecedent precipitation one and three days before, antecedent baseflow and normalised soil moisture lag time) (Seeger et al., 2004). Accordingly, in Es Fangar catchment correlations of total precipitation, runoff, maximum peak discharge and soil moisture average with sediment load increased in autumn and winter, depicting how during the wet period high sediment yield values were obtained. The role played by wet conditions was demonstrated by the events characterised with normalised soil moisture lag time < Q50, which had highest runoff, maximum peak discharge and sediment load values. Large sediment load contributions occurred during situations of high catchment connectivity as wet conditions triggered shorter travel time and lag time between the beginning of the rainfall event and the water table peak than events under dry conditions due to the expansion of the wet stream length (Jensen et al., 2019; van Meerveld et al., 2019). Accordingly, soil moisture-discharge revealed that 76% of the events were generated under counter-clockwise hysteresis (i.e. wet antecedent conditions), which generated 99% of sediment load in the 28 events analysed using soil moisture (as in Penna et al., 2011). Thus, in Es Fangar and Búger catchments, when soil was wet or saturated higher sediment load contributions were observed, suggesting the saturation processes may be the dominant process for runoff generation and sediment transport. Sediment load contributions related to high rainfall intensities only occurred at the beginning or end of summer (i.e. dry period) as this type of event was infrequent, occurring under cyclonic weather type (Peña-Angulo et al. 2020b). These type of events were characterised by high maximum suspended sediment concentration values as infiltration excess processes were dominant due to high rainfall intensities (Nadal-Romero et al., 2016). Indeed, in Es Fangar and Búger catchments, largest maximum suspended sediment concentration were observed in summer followed by winter. In both catchments highest maximum suspended sediment concentration in summer were related to rainfall intensities (> 20 mm h^{-1}) whereas maximum suspended sediment concentration in winter were related to the highest events in runoff and discharge peak promoted by favourable moisture conditions (Seeger et al., 2004). Nonetheless, suspended sediment availability of the limestone material was low as the maximum suspended sediment concentration ranged from < 0.1 to 2.6 g l^{-1} and 93% and 72% of the maximum suspended sediment concentration were < 0.5 g l^{-1} in Es Fangar and Búger catchments, respectively.

Contrarily, in the Carapelle catchment, total precipitation and maximum 30' rainfall intensity instead of antecedent conditions were the driving factors for sediment yield. The same variables also controlled the runoff response and maximum peak discharge, which had the highest correlations with sediment yield. Thus, infiltration excess may be the dominant processes in runoff generation and suspended sediment transport an rainfall intensities controlled both runoff and sediment yield amounts (Nadal-Romero et al., 2008). Maximum suspended sediment concentration had a large influence on sediment load as large values of the maximum suspended sediment concentration were obtained, ranging from 3 to 63 g l^{-1} and 52% of the the maximum suspended sediment concentration was > 20 g l^{-1}. However, large differences between seasons did not exist as seasonal average values decreased from autumn (25.2 g l^{-1}) to summer (15.2 g l^{-1}).

Furthermore, although hydrosedimentary drivers controlled the runoff response and suspended sediment transport the spatial distribution of the physical driving factors and humans structures influenced their response and suspended sediment availability (Bywater-Reyes et al., 2017; Gellis, 2013). Accordingly, Es Fangar and Búger headwaters were characterised by forest land use and limestone lithology.

Forest cover decrease sediment detachment (Cosandey et al., 2005) whereas limestone lithology promotes deep percolation and low soil formation rates (Peng and Wang, 2012). Consequently, these headwater catchments are characterised by low suspended sediment availability (promoting low sediment yield values) compared to agricultural land use and more erodible materials (Haddadchi and Hicks, 2019). The role played by lithology and landscape variables suggested that karst coverage and patchiness characteristics exerted substantial influence on reducing sediment yield (Li et al., 2019). Thus, in Es Fangar and Búger catchments, the areas of highest suspended sediment availability correspond to lowland areas characterised by agricultural or bare lands with deeper soil profiles and marl and clay materials. However, in these areas terraces structures help to conserve agricultural soils controlling floods, preventing erosion and decoupling catchment compartments (Calsamiglia et al., 2018). In Es Fangar and Búger catchments, according to the spatial distribution of the human structures (terraces) and physical driving factors (lithology and land cover) clockwise hysteresis were the more frequent type and those that promoted the highest SL contributions, suggesting that the main sediment sources are close to the outlet catchment (Regüés and Gallart, 2004). A deeper hysteretic analysis in Es Fangar catchment showed that clockwise hysteresis was the common pattern in the wet season and that counter-clockwise and figure eight hysteresis occurred during the late autumn and early spring when water reserves were high. Hence, the low frequency of counter-clockwise (18%) and figure-eight (9%) hysteresis and their seasonality indicated that antecedent wet conditions in some flood events activated hydrological pathways and consequently new sediment-contributing areas (Seeger et al., 2004). Accordingly, fingerprinting analysis in Es Fangar catchment demonstrated that most of the suspended sediment was generated from sources that are relatively close to the main channel system; i.e., agricultural fields over marl materials with high suspended sediment availability (García-Comendador et al., in preparation).

Contrarily, in the Carapelle catchment, counter-clockwise loops were more frequent due to catchment size, spatio-temporal distribution of rainfall and land use. Thus, in smaller catchments like Es Fangar and Búger clockwise loops may prevail because flowpaths from the source areas of the sediment are short, decreasing the lag between discharge and suspended sediment concentration (Aich et al., 2014). In addition, the elongated shape of Carapelle catchment increased the lag between discharge and suspended sediment concentration peak when rainfall events occur far from the outlet (García-Rama et al., 2016). Furthermore, the large presence of agricultural fields (80% of the catchment) that generate a low patchiness land use, the conventional practices ploughing up and down the slopes and the fine composition of the soils led to sediment generation from source areas all over the study site (Ricci et al., 2020). Additionally, the low conservation state of check dams promoted streambed erosion increasing sediment supply (Ricci et al., 2019). Counter-clockwise pattern similar to those of the Carapelle catchment have been observed in Mediterranean catchments when rainfall occur in headwater catchments (López-Tarazón et al., 2009) or in catchments with highly erodible materials (Nadal-Romero et al., 2008).

7.2. Conclusions

This thesis intended to improve the understanding of the hydrological response and suspended sediment transport in Mediterranean catchments through the assessment of hydrological and sediment transport dynamics using medium term datasets (i.e. 5 hydrological years). The analysis of this dataset helped to characterise the inter- and intra-annual variability of the water and sediment yield contributions. Analysis of these dynamics at multiple temporal scales (i.e. annual, seasonal and event) allowed to identify drivers and patterns of runoff generation and suspended sediment transport, as well as to stress the role played by physical and human catchments characteristics over the hydrological response and sediment transport. The main conclusions of the thesis can be summarised as follow:

- The rainfall-runoff relationships at the annual scale in small Mediterranean catchments showed a significant linearity where the increase in annual runoff follows the increase of annual rainfali evidencing the importance of the annual rainfall amount. However, lithology effects introduce some scatter in this global rainfall-runoff relationship. Larger runoff contributions and stronger linearity was observed in catchments with impervious materials compared to pervious ones. These lithology effects were observed comparing Búger and Carapelle catchments. Although Búger had larger annual rainfall than Carapelle the large proportion of limestone in Búger headwaters triggered lower annual runoff amounts and runoff coefficient values than Carapelle due to transmission losses. Limestone lithology also exerted a large influence over hydrological regime increasing the mean zero-flow day value in Es Fangar and Búger compared with Carapelle catchments or other catchments without Csa climate and/or limestone lithology. Thus, pervious materials promote intermittent and ephemeral hydrological regimes.

- Seasonality of the Mediterranean climate strongly influences seasonal runoff generation due to the combined dynamics of rainfall and evapotranspiration throughout the year that leads to a succession of wet (winter), dry (summer) and transition periods (last autumn and early spring). Highest seasonal runoff contributions and runoff coefficients were obtained in winter, autumn, spring and summer, respectively in Es Fangar, Búger and Carapelle catchments. Seasonality generates different catchment moisture conditions for runoff generation at the event scale, being a starting point for a lack of clear relation in rainfall-runoff relationship. Hence, the scattering of the rainfall-runoff relationship at the event scale increased from spring and winter to summer. The rainfall-runoff according to pervious or impervious lithology confirmed the results carried out at the annual scale, and events occurring in catchments with impervious lithology showed a higher linearity and runoff values than catchments with pervious lithology. The rainfall-runoff relationship under different land uses showed that agricultural land uses promoted the highest correlation in the rainfall-runoff relationships due to lower vegetation cover. The comparison between Búger and Carapelle catchments demonstrated the importance of the joint role between lithology and land uses for runoff generation as Búger headwaters, characterised by forest cover and limestone lithology, presented a higher threshold for runoff generation than the large agricultural Carapelle catchment. In addition, lithology and land use influence the dominant runoff generation mechanism with saturation processes dominating in Es Fangar, and Búger catchment and iniltration excess processes dominating in the Carapelle catchment.

- Annual sediment yield in Es Fangar, Búger and Carapelle catchments can be attributed to the spatial distribution of the physical driving factors (lithology and land cover) and human structures (terraces, check dams). In Es Fangar and Búger catchments, forest land cover and carbonate materials at headwaters led to low runoff and suspended sediment response due to high infiltration rates and low suspended sediment availability. Besides, forest cover increased interception and sediment retention in these areas. Soil conservation structures, mainly located in lowland agricultural areas, laminated runoff and retained soil from these areas with higher suspended sediment availability. In the Carapelle catchment, large agricultural areas led to sediment generation from sources all over the catchment. Degraded soil conservation structures promoted and increase sediment pathways also increasing riverbed erosion. Therefore, catchments characterised by agricultural land use land and low patchiness landscape may promote a higher connectivity between catchments compartments and higher values of sediment yield. However, despite catchments with limestone materials triggered low sediment yield values, these ones should be compared with the soil tolerance loss of carbonate materials, which are characterised by a low soil formation rates and even lower under Mediterranean climate conditions.

- The analysis of the driving factors in the suspended sediment transport in Es Fangar, Búger and Carapelle catchments at the event scale showed that different drivers exists in Mediterranean catchments. In Es Fangar and Búger catchment, wet antecedent conditions and large runoff contributions, especially in winter, were the situations were largest amount of sediment load were obtained. The soil moisture analysis in Es Fangar catchment showed that situations of high catchment connectivity generated large runoff amounts and large sediment load contributions due to wet or saturated soils. During such situation, counter-clockwise hysteresis occurred due to a high catchment connectivity that activated less available sediment sources. In the Carapelle catchment, largest sediment load amounts were obtained due to the combination of rainfall amount and intensity. The large extension of agricultural areas made sediment available from the whole catchment, but the elongated shape of the catchment increased the lag between discharge and suspended sediment concentrations peak when rainfall events occur far from the outlet promoting counter-clockwise hysteresis. Runoff and sediment was both generated in remote areas of the catchment. This same origin promoted the lag between discharge and sediment peaks because water was displaced by a kinematic wave whilst sediment by a mass water flow. Additionally, the elongated shape of the catchment further increased this lag time

The thesis carried out elucidated how the complexity of the Mediterranean landscape exerts a strong influence over the hydrological response and suspended sediment transport at different temporal scales (i.e. annual, seasonal and event) through the interaction of the physical (lithology and land use) and human (i.e. terraces) factors. The analysis of these dynamics through representative catchments are useful to observe the hydrological response and sediment transport under different or specific land use, lithology and human effect characteristics with the current climatic conditions. The maintenance and continuation of these records will generate long-term data sets that will be provide robust data for modelling global change scenarios.

7.3. Limitations of the thesis and future works

The limitations of the analysis presented in this thesis are classified by chapters, as well as proposals derived for future works:

In Chapter 4, the assessment of multiple temporal scales in contrasting small Mediterranean catchments has improved the understanding of the role played by lithology and land use in the hydrological response from annual to event scale. However, at the event scale a large database should further be constructed including a larger number of catchments and variables. To improve the understanding of the annual rainfall-runoff, catchments should be also classified by land use type. For a better assessment of runoff generation at the event scale under different lithologies and land uses, variables as antecedent precipitation, rainfall intensity and discharge peak should also be included. Thus, future works to do using for example the current hydrometric network of Mallorca Island (i.e. 32 gauging stations) could be: (1) to assess the effects of catchment characteristics on runoff response at the event scale and (2) to focus on the analysis of the hydrological response of extreme rainfall events linked to the contrasting land use, seasonality and lithology of the catchments.

In Chapter 5, the analysis of soil moisture, runoff and sediment load dynamics at different temporal scales improved the comprehension of erosion processes in a mid-mountain small Mediterranean catchment. However, the assessment of the soil moisture was limited at the temporal (i.e. a short monitoring period) and spatial (i.e. one monitoring site) scales. With these limitations, results showed that wet moisture conditions promoted the largest runoff response and sediment transport. However, given the potentially large spatio-temporal variability of soil moisture under different land use and lithology, an upscaling soil moisture monitoring using remote sensing should be explored to evaluate the runoff response and suspended sediment transport. Future works should oriented towards (3) an upscaling spatiotemporal soil moisture conditions monitoring to assess the runoff generation and suspended sediment transport dynamics through a nested approach in the Sant Miquel catchment, quantifying discharge-suspended sediment and soil moisture-discharge hysteresis. Special attention should be paid to identify moisture conditions according to lithology and land use.

In Chapter 6, lithology and land use characteristics were found to be the main drivers controlling the hydrological regime, river type classification and water and sediment yields from annual to event scale. Furthermore, these physical characteristics of the catchments influenced the hysteretic loop type. Besides, soil conservation structures played a key role in runoff generation and sediment transport. Nevertheless, given the influence of lithology on the hydrological regime future work should (4) assess the hydrological regime focusing on the karst and forest covered area of the 32 catchments monitored by the hydrometric network of Mallorca Island. Nonetheless, a gauging station cannot achieve alone a holistic spatiotemporal variability of the flow permanence. Therefore, future work should also be done in Búger catchment (5) to analyse the spatiotemporal variability of stream length intermittency. As lithology and soil conservation structures exerts a high control over runoff response and suspended sediment transport, future work in Sant Miquel catchment should also focus on the (6) comprehension of the spatial location of terraces and check-dam terraces according to elevation, slope, lithology, type of terraces, distance between dry stone walls and hillslope-floodplain location. Besides, the spatio-temporal abandonment processes of these structures should be analysed. In addition, (7) the effects of check dam in peak discharge, peak lag time and reduction in suspended sediment concentrations should be assessed through a nested approach.

7.4. References

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