INVESTIGATING THE DISTINCT ECOHYDROLOGICAL CHARACTERISTICS OF MEDITERRANEAN INTERMITTENT AND EPHEMERAL STREAMS AND CONSIDERATIONS FOR THEIR MANAGEMENT

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ABSTRACT

Even though intermittent rivers and ephemeral streams (IRES) in the Mediterranean are the major surface water bodies, most hydrologically transient catchment areas that are unmonitored, lacking gauges and habitat surveys, and/or not generally included in environmental restoration plans. When they are gauged, the monitoring stations are in most cases sparsely distributed and do not capture the spatial variability of flows and water cessation dynamics within the stream network. It is important that monitoring methodologies capture the spatio-temporal variability of different hydrological states and their influence on the various biophysical dynamics occurring along the stream continuum. A monitoring framework was employed in this thesis, and through various studies, selected dynamics within Mediterranean IRES were explored. The thesis presents a conceptual framework (Chapter 2) identifying the many process cascades and links that influence the variables governing the functioning of Mediterranean IRES and proposes alternative approaches to 'traditional' gauged data for the monitoring of the various complex stream dynamics. Using 30-minute interval water level and in-stream temperature readings from six dataloggers deployed in six case study areas and precipitation records from weather stations, Chapter 3 interpreted hydrological and thermal response patterns following precipitation events in catchments and sub-catchments with different drainage area size, ecohydrological and land cover typologies. The fourth chapter explored the potential of using vegetation indices (VIs) derived from visible RGB consumer-grade cameras installed on uncrewed aerial vehicles (UAVs) to analyse the relationships between streambed water presence and riparian vegetation health. The fifth chapter presents a novel ecosystem-service based assessment to provide decision makers an affordable and easy-to-use tool to prioritise and conserve Mediterranean IRES. UAVs combined with structure from motion photogrammetry techniques and GIS applications were used to extract and measure catchment and stream features that drive the provision of ecosystem services of fifteen different transient catchment areas. The findings illustrate the potential of UAVs and water level dataloggers in ameliorating the understanding of the processes occurring within Mediterranean IRES. Results show that: (1) water level response times to precipitation depend on the size of the catchment, seasonality of rain events, and land cover characteristics; (2) streambed temperature responses to precipitation episodes are influenced by the hydrological regime, were the presence groundwater springs contribute to more stable temperature variations, and the catchment land cover characteristics; (3) reflectance values from visible VIs respond to different in-stream water levels; and (4) larger catchment areas and flow regimes characterised by intermittent flows have the potential to provide more ecosystem services, whereby smaller drainage areas with predominantly urban land uses have the reduced ability to provide ecosystem services. Although Mediterranean IRES share common elements, different catchments possess diverse attributes that are fundamental in influencing the biophysical response processes. The evolution of tools capable of monitoring ecohydrological dynamics at centimetre resolutions and elevated spatio-temporal scales should pave the way for the improved identification, categorisation, and understanding of different catchment dynamics to better inform the management of Mediterranean IRES.

I would like to dedicate this thesis to my grandmother Antonia Debono and late grandfather Carmelo Debono

In-nanna u n-nannu li dejjem fi ħsiebi u li kienu fundamentali biex inkun il-persuna li jien illum

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CONTENTS LISTING

PAPERS

The following article (Chapter 2) was accepted for publication. Secondary authors also advised on the conceptual design and paper editing.

Publication

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Borg Galea A, Hannah DM, Sadler JP. **The role of uncrewed aerial vehicles (UAVs) in a biophysical ecosystem services-based assessment for Mediterranean intermitten rivers and ephemeral streams.**

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LIST OF ABBREVIATIONS

ANDWI – augmented normalized difference water index

AWEI – automated water extraction index

CLC – Corinne Land Cover

CICES – Common International Classificationo of Ecosystem Services

CMIP5 – Coupled Model Intercomparison Project phase 5

CNN – convolutional neural network

DEM – digital elevation model

DO – dissolved oxygen

DTM – digital terrain model

TEEB – The Economics of Ecosystems and Biodiversity

ENDVI – enhanced normalized difference vegetation index

ES - ecosystem services

EU – European Union

FVC - fraction of vegetation cover

GIS - geographic information systems

GLI – green leaf index

IAS - invasive alien species

IPCC - Intergovernmental Panel on Climate Change

IRBM – Integrated river basin management

IRES - intermittent rivers and ephemeral streams

ISO – International Organization for Standarization

LiDAR – Light Detection and Ranging

MEA – Millenium Ecosystem Assessment

MNDWI – modified normalized difference water index

NDRE - normalized difference red edge index

NDVI – normalized difference vegetation index

NDWI – normalized difference water index

NGRDI – normalized difference green-red index

NIR – near-infrared

RGB – red, green, blue

RGBVI – red-green-blue vegetation index

SfM - structure from motion

UAV - uncrewed aerial vehicles

VARI – visible atmospherically resistant index

VI - vegetaton index

WFD - Water Framework Directive

CHAPTER 1

INTRODUCTION

1.1 What are IRES and why are they important?

Intermittent rivers and ephemeral streams, hereafter, IRES; (Datry et al., 2014) refer to surface water bodies that experience water flow cessation or drought at some point/s along the channel. The scientific literature includes many terms that define the variety of flow regimes and intermittency for IRES, including ephemeral, episodic, temporary, intermittent, seasonal, dryland, interrupted, nonperennial, near permanent (Acuña et al., 2014a; Boulton, 2014; Chester & Robson, 2011; Thibault Datry, Bonada, et al., 2017; Davies et al., 2009; Matthews, 1988; Uys & O'Keeffe, 1997). This study follows the definition of Day (1990, p.101), who defined ephemeral streams as "rivers that run for short periods after rain has fallen high in their catchments" and Larned et al. (2008, p.4) who defined intermittent watercourses as those that "receive groundwater when the water table intersects the channel, and may also receive runoff". The transient hydrology of IRES provides habitats and refugia for diverse and unique aquatic, semi-aquatic and terrestrial flora and fauna and function as biogeochemical hotspots that retain, process and transfer carbon, nutrients and particulate matter (Skoulikidis et al., 2017a). IRES are found across the globe, comprising of more than fifty per cent of the world's river network, and are expected to increase in their distribution over the next few decades (Jaeger et al., 2014; Messager et al., 2021; Pumo et al., 2016). Many formerly permanent watercourses have already become intermittent in the past fifty years mainly due to water abstractions, climate change and alteration of land uses (Messager et al., 2021). It has been mooted that river flow regimes currently considered as permanent, will experience increased intermittency due to climate change and anthropogenic land uses (Costigan et al., 2017; Schneider et al., 2017). By 2050, in parts of Australia, Brazil, California, the Caribbean, southern Africa and in the environs of the Mediterranean Basin, flow regime shifts from perennial to intermittent are projected to occur (Döll & Schmied, 2012). According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), surface temperature is expected to rise throughout the 21 century (IPCC, 2013). Increase in the incidence and longevity of heat waves, influencing evapotranspiration rates, and the frequency and intensity of extreme precipitation events, will alter the flows in IRES, particulary in the Mediterranean region (IPCC, 2013; Loizidou et al., 2016). Flow regimes in many natural IRES are also declining and experiencing longer periods of no flows. For example in the intermittent Mediterranean stream in the Tsiknias basin, located in the central part of Lesvos Island, Greece, hydrological modelling coupled to climate change scenarios suggests an increase of dry periods and increased occurance of extreme flood and drought events (Nabih et al., 2021).

All of the above indicate the importance of preserving the ecohydrological status of IRES.Unfortunately, IRES are frequently excluded from water policy and legislation because of the difficulties in monitoring them, especially when compared to permanent rivers (Borg Galea et al., 2019; Nabih et al., 2021). For example, the European Union Water Framework Directive (WFD) (Directive 2000/60/EC), does not only ignore IRES (Datry et al., 2014), it also calls for the conservation and improvement of the ecological status of water resources and requires the characterisation of different surface water body types to identify different stream typologies that are comparable in order to define specific reference conditions (Oueslati et al., 2015). However, different assessment strategies are needed for perennial and IRES, because of their different hydrological characteristics. Even though in recent years research on IRES has increased, there is still a dearth of available information regarding the hydrological regimes of these streams (Nikolaidis et al., 2013). Furthermore, the WFD calls for the use of existing biomonitoring indices which are based on the sensitivity of taxa to the degree of nutrient enrichment to assess the health of river ecosystems. However, these 'traditional' water quality designations do not reflect the vulnerability of fauna to non-perennial flow regimes and dry periods (White et al., 2018). In addition, there is lack of baseline ecohydrological data on IRES, which limits the understanding of how these streams function and respond to flow modifications (White et al., 2018).

1.2 Defining IRES within the Mediterranean context

In the Mediterranean, IRES (hereafter, Mediterranean IRES) are the prevalent surface water bodies. Bonada & Resh (2013) defined Mediterranean rivers as those with sequential seasonal flooding and drying periods that experience annual loss of aquatic habitat connectivity including the emergence of temporary habitats during drier periods. The Mediterranean basin is considered a global hotspot of biodiversity, endemism and related ecosystem services whilst containing the highest proportion of threathened freshwater species in Europe which are among the most endangered species worldwide (Skoulikidis et al., 2017b). Mediterranean IRES are not only ecologically unique and potentially among the most susceptible to environmental damage from anthropogenic activities but are also an integral part of the socio-cultural landscape of the region (Bonada & Resh, 2013). Over the last fifty years, the Mediterranean region has already experienced a twenty per cent decrease in river run-off due to climate change and over-exploitation of water resources (Karaouzas et al., 2018). The AR5 of the IPCC identified the Mediterranean Basin as one of the most vulnerable regions of the world to climate change (IPCC, 2013). Predictions for the Mediterranean basin estimate up to thirty-five per cent of reduced rainfall and 3 – 5 °C temperature increase by 2071-2100 (Nabih et al., 2021). Surface runoff rates are expected to decrease as a result of decreases in precipitation, higher soil water retention deficits and higher potential evapotranspiration rates, contributing to reduced flow regimes in Mediterranean IRES (IPCC, 2013; Serpa et al., 2015).

The Mediterranean basin is a transitional region that is enveloped by African deserts to the south and temperate European climates to the north. The spatio-temporal variations of moisture, temperature, and rainfall patterns over the Mediterranean basin are driven by the atmospheric lows, troughs, and mid-latitude cyclones associated with the prevailing north-westerly winds originating from the North Atlantic region and sub-tropical, North African region (Şahin et al., 2015). Most areas found within the basin experience arid to semi-arid to sub-humid climates, with relatively wet and cool winters and warm, dry summers. The climatic gradient across the Mediterranean Basin is extreme, modelled by its diverse topography. The complex tectonic forces in the region, namely, the collision of the Eurasian and African plates and the strong East-West pressures to Asia Minor exerted by the Arabian plate originated the bordering cold mountainous areas of the Alps (Tierno de Figueroa et al., 2013). The Alps with annual mean temperatures that fall below zero, greatly differ to the hot African expanses where annual mean temperatures reach about 22 °C near the coast and 32.5 °C inland (Oueslati et al., 2015). The Basin includes areas with the highest annual precipitation averaging 4600mm, such as the east Adriatic coast, to the lowest annual precipitation at below 100mm in the Northern Africa region (Oueslati et al., 2015). Precipitation seasonality and variability, with periodic flooding events can be considered to be the main features of typical Mediterranean climate (Gasith & Resh, 1999). Variability in rainfall patterns is manifested with inter-annual changes in flood occurance and variations in annual rainfall patterns, whereas intra-annual seasonality is shown with spells of water surplus interspersed with periods of water scarcity (Rivaes et al., 2013).

These conditions govern the natural flow regime of many Mediterranean rivers rendering them ephemeral or intermittent at diverse spatio-temporal scales (Bonada & Resh, 2013). This transient hydrological regime is a key driver that controls the stream processes of sediment transport (Fortesa et al., 2021; Jaeger et al., 2017; Sánchez-Canales et al., 2015), the aquatic, semi-aquatic and terrestrial biota (Datry et al., 2014; Storey & Quinn, 2008), and the physicochemistry of water (Gómez et al., 2017), including organic matter (Catalán et al., 2013) and stream nitrification and denitrification rates (Arce et al., 2014). These features have resulted in distinct characteristics that can be recognized in Mediterranean IRES. For example, predictable seasonal biological variability (Bonada et al., 2007) and adaptative biological traits such as resilience and resistance (Hershkovitz & Gasith, 2013) are common attributes found in Mediterranean IRES. In the Mediterranean, there is also high level of endemism amongst freshwater biota (Cooper et al., 2013; Tierno de Figueroa et al., 2013). This can be attributed to two major palaeogeographical events. The Messinian Salinity Crises, which occured in the late Miocene, led to the dessication of the Mediterranean Sea, leading to increased salinity levels following the closure of the Strait of Gibraltar (Reyjol et al., 2006). When the connection between the Atlantic Ocean and the Mediterranean Sea was restored, circa 700,000 thousand years later, the recovering sea water levels led to the rapid flooding of several freshwater hydrological networks, leading to notable difference between the terrestrial aquatic lineages in the region (Micallef et al., 2018; Reyjol et al., 2006; Wagner et al., 2021). The subsequent event was the Quaternary Glaciation Period, where global sea level drops, connected fluvial systems, contributing to new pathways for freshwater species to travel (Wagner et al., 2021).

Apart from the climatic and physical attributes, the primary aspect that shapes the Mediterranean landscape is its long history of human occupation, spanning thousands of years and pre-historic periods. Water scarcity and its necessity for human-related activities have resulted in numerous modifications to surface water features including IRES, greatly influencing their ecohydrological functioning and the biogeography of flora and fauna (Fovet et al., 2021). Even though the Mediterranean is a water scarce region, IRES have still been somewhat underappreciated by planners and society at large. They are also among the least monitored and studied freshwater ecosystems worldwide (Skoulikidis et al., 2017c). According to Sabater et al. (2022), the often dry landscape of Mediterranean IRES and/or the catastrophic floods associated with them, contributed to the association of these features as dangerous areas that require channel alterations rather than a natural resource that need to be conserved. Flood regulation efforts and water storage requirements led to the pronounced development of impoundments in most surface water systems, from larger rivers to even the smaller streams (Grantham et al., 2013). Urbanisation, industry, touristic development and intensive agricultural practices in the Mediterranean basin have also accentuated water abstraction, either directly from surface water or through the pumping of groundwater, in some cases even leading to the hydrological transformation of perennial streams to intermittent (Benejam et al., 2010; Muñoz et al., 2018). Variations in flow regimes experienced in Mediterranean IRES lead to spatio-temporal changes to the hydrologic connectivity within the catchments, and influence the dynamics of biota, matter and energy (Merenlender & Matella, 2013).

1.3 The Maltese Islands – a case study

1.3.1 The natural environment

The Maltese Islands are an archipelago found at the central region, both latitudinally and longitudinally, within the Mediterranean Sea, comprising of three main inhabited Islands, including mainland Malta, 27 km in lenght; Gozo, 14.5 km. The word for valley in the native Maltese language is *wied*, which is of semitic origin and has connotations of the North African dry river valleys (Arabic *wadi* or *oued*) with highly seasonal flow regimes (Rolé, 2007). The surface freshwater hydrology is primarily ephemeral and driven by the climate and the Islands' geology and gemorphological topography. The annual total precipitation averages 553.1mm with mean temperatures of 18.6°C, with a mean maximum of 22.3C° and mean minimum of 14.9°C (Galdies et al., 2022). Consequently, evaportranspiration rates are high, estimated at seventy to eighty per cent of the annual precipitation, leading to low infiltration rates which occur through crack, fissures and rock porosity (Anderson, 1997). The stratigraphy of the Islands is karstic, mainly composed of limestone, with variations provided by two relatively thin strata, one of Greensand and the other Blue Clay. The latter being the only rock having a relatively impermeable lithology. Phreatic perched groundwater bodies are sustained in the Upper Coralline Limestone formation perched over the Blue Clay aquitard. Springs that form naturally from this impermeable outcrop rise to more frequent intermittent flows in the connected reaches of the watercourses. A Ghyben-Herzberg lens of freshwater floats on sea water in the Lower Coralline Limestone aquifer which is replenished by seepage from the perched aquitard and by rainfall where the impermeable blue clay is absent (Alexander, 1988).

Past tectonic activity and fluvial erosional process that were dominant during the last glacial period (Alexander, 1988; Anderson, 1997) were the main drivers towards the formation of Malta's surface water drainage network. Fault traces can be found in most ephemeral channels (Alexander, 1988). Tertiary tectonic movements formed a predominant chain of horst and graben structures running in a NE-SW direction. The stratigraphically low graben areas between the horsts, formed rift valleys, two of which forming the north and south Comino channels which are drowned under the Gozo sea channel (Alexander, 1988). The archipelago is also characterisesd by a regional dip to the northeast. The latter created a dominant influence on the drainage pattern of the Islands with high ground on western Malta and eastern Gozo and drowned fluvial valleys along the eastern coast of mainland Malta. Groundwater seepage in jointed limestone overlaying clays across fault lines led also to the formation of numerous theatre-headed valley formations (Micallef et al., 2022).

These contrasting valley formations provide different habitat settings for a wide array of aquatic, semi-aquatic and terrestrial flora and fauna. In fact, valleys provide the richest habitats in the Maltese Islands. Almost half of the 1,306 higher plant species recorded can be found within valleys (Lanfranco & Bellia, 2022). Species per unit area do not differ significantly between watercourses and outside areas, however the considerable variations in habitat types within IRES, offer significantly more abundant plant species and diverse species compositions when compared to other areas (Lanfranco & Bellia, 2022). Streams that are typically small and unsheltered, lack any riparian vegetation. Other heavily incised, gorge-like valleys such as Wied Żnuber, Wied Moqbol and Wied Babu, have typically never been agricultural and the steep sides are dominated by a natural mix of shrub and cliff-dwelling specialists such as the endemic Maltese Salt-Tree (*Salsola melitensis*), Maltese Rock-Centaury (*Cheirolophus* crassifolius) and the Maltese Sea Lavender (*Limonium melitense*) (Lanfranco & Bellia, 2022). During the wet-period, shaded valley-beds support undergrowth species usually characterised by Italian Lord-and-Ladies (*Arum italicum*), Friar's Cowl (*Arisarum vulgare*), Bear's Breeches (*Acanthus mollis*) and the Mediterranean Pellitory (*Parietaria lusitanica*) (Lanfranco & Bellia, 2022). Typical Mediterranean riparian woodland habitats are scarcely found, the most prominent located at Wied il-Luq that also hosts populations of White Poplar (*Populus alba*), whereas in another valley system, Wied il-Qlejjgħa, it also hosts White Willow (*Salix alba*) and Mediterranean Willow (*Salix pedicellata*) specimen.

Freshwater fauna are characterised by the Freshwater Crab (*Potamon fluviatile*) recorded in six different watercourses and whose limited distribution is strongly tied with the transformation of flow regimes from intermittent into ephemeral (A. Vella & Vella, 2020, 2022). The endemic Painted Frog (*Discoglossus pictus*) also inhabits streams and is the only amphibian found in the archipelago. Streams are also important corridors for numerous insects such as Odonata species (Balzan, 2012), and avifauna, were more than forty-five per cent of all four hundred and sixty-eight bird species recorded in the Islands actively use and visit streams (Fenech, 2022). In addition, nineteen out of the twenty-eight known breeding bird species in Malta, breed regularly within IRES, equating to almost seventy-five per cent of the bird species that regularly breed locally (Fenech, 2022).

1.3.2 Human influence

IRES in the Maltese Islands have also been greatly altered for human use. A walkover survey, carried out as part of the LIFE IP "Optimising the implementation of the 2nd RBMP in the Malta River Basin District (LIFE 16 IPE MT 008)" for the development of catchment-wide integrated master plans in sixteen of the largest catchment areas in Malta and Gozo, identified 202 impoundments including straight and curved dams, weirs and earth-shaped dams/fords. Most of these structures were constructed during the late 19th Century and throughout the 20th century for water harvesting, mainly for agricultural and urban use, to recharge the underlying aquifer and/or flood protection. The most prominent series of dams can be found at Wied il-Qlejjgħa, also known as Chadwick Lakes, designed by British engineer Sir Osbert Chadwick in the 19th Century for the capture and storage of rainwater. With regards to channelisation, there is stark difference between

Malta and Gozo. In Malta, numerous valleys have been built up, especially in the downstream part of the watershed area. In Gozo, towns and villages are predominantly located on top of hills and plateaux as in the past, these offered better security and views of oncoming danger from the sea. Hence, most catchments remained unbuilt and used for agricultural purposes, excluding Xlendi and Marsalforn coastal areas experiencing recent touristic development.

The development of water harvesting infrastrucure in Malta has always been considered of strategic importance for survival. Archeological evidence of rock-cut cisterns in the immediate vicinity of Ħaġar Qim and Mnajdra temples date back to the Neolithic Period (Buhagiar, 2016; Sapiano, 2008). The first reported nation-wide 'hydrological survey' was carried out in 1512 as part of a fact-finding mission by the Hospitaller Knights of Saint John before they decided to make the Islands their new home-base (Sapiano, 2008). Evidence shows that natural perched aquifer springs flowing at Għajn Tuffieħa and Ramla l-Ħamra watercourses in Gozo were used in bathing establishments during the Roman period (Buhagiar, 2016). Perched aquifer galleries are ubiquitously found in the environs of perched aquifer aquitards, with the oldest examples located in close proximity to sites of Roman and Byzantine period (Buhagiar, 2016). Perched aquifer water was tapped through well-shaft penetration and eleborate systems consisting of a series of galleries channeling spring water to specifically designated areas. Most springs are now tapped at source for potable use and agricultural irrigation purposes.This led to the reduction in the number and flow rates of springs resulting in loss of riparian habitats that depend on continuous flows (Schembri & Lanfranco, 1993).

The Second Water Catchment Management Plan for the Malta Water Catchment District 2015-2021 is a set of measures required for the achievement of the EU Water Framework Directive (WFD) (Directive 2000/60//EC). Given the small size of the Islands, the Plan integrated the entire archipelago into one water catchment district. Three watercourses, Wied il-Baħrija, Wied il-Luq and Wied il-Lunzjata in Gozo where characterised as intermittent. Recorded nutrient levels in all three streams were constantly high with nitrate levels ranging from 110-200 mg/l throughout the year (Sustianable Energy and Water Conservation Unit & Environment and Resources Authority, 2015). The potential source of nitrates is agriculture and spring water from the Perched Aquifer. Upper Coraline Limestone formation which encapsulates the Perched Aquifer, is predomnantly found in the north-western part of the Islands, which also coincide with agriculture being the predominant land-use in this region.

A major pressurse in Malta's IRES is the introduction of invasive and/or alien (IAS) floral and faunal species. The resilient Great Reed (*Arundo donax*) invaded many IRES in the Mediterranean basin and has become synonymous with the majority of watercourses within the Maltese Islands. This reed brings year-round greenary in valley landscapes, however, it contributes to localised flooding problems and species richness and diversity of native organisms is heavily hampered in invaded areas. Other plant species that are frequently encountered in Maltese streams include the Castor Oil Plant (*Ricinus communis*) especially in degraded areas, the Ballon Vine (*Cardiospermum hirsutum*) which was introduced decades ago but is becoming increasingly a rapid invader due to changes in the climate (Deidun et al., 2022) and the Acacia tree (*Aciaca spp.*) which was used in several afforestation projects carried out in 1980s. In recent years, a number of invasive and non-native fauna were also released in freshwater environments, the most notorious being the Red Swamp Crayfish

(*Procambarus clarkii*), which has been recorded in five different valleys (Deidun et al., 2018; Vella et al., 2017). Other decapods have also been released in watercourses including the Marbled Crayfish (*Procambarus virginalis*), Signal Crayfish (*Pacifastacus leniusculus*) and the Australian Redclaw (*Cherax quadricarinatus*) (Deidun et al., 2018; La Mantia et al., 2020). At Wied il-Għasel and Wied il-Qlejjgħa the freshwater terrapin species Mississippi Map Turtle (*Graptemys pseudogeographica kohni*) and the Yellow-bellied Slider (*Trachemys scripta scripta*) have also been recorded (Deidun et al., 2022).

1.4 Landscape complexity and catchment response

Even though the Maltese Islands are small, different IRES catchment areas have distinct natural characteristics that influence the ecohydrological functioning of these streams (Table 1.1). Moreover, typical of Mediterranean catchments, these have been distinctively shaped and molded by centuries of human landuse. These dynamic natural landscape variations are interspersed with the socio-cultural influences found within Mediterranean landscapes. The long history of human interaction with nature led to very few, if any, areas in the Mediterranean basin that have not been influenced by anthropogenic activity since antiquity (Conrad & Cassar, 2012). Human pressures throughout history have modified the landscape and promoted fragmentation of the natural environment, transforming ecosystems and altering hydrological response of drainage basins (De Montis et al., 2017; Garcia et al., 2017). Many human—induced changes led to intense alterations to channel-floodplain geomorphology and ecological dynamics (Jaeger et al., 2017). In many Mediterranean landscapes drained by IRES, flow is diverted or regulated through damming and surface and/or groundwater abstraction, altering flow regimes and promoting saline intrusion (Feio et al., 2014; Jaeger et al., 2017). Such alterations have drastically altered habitat conditions to the detriment of many native terrestrial, semi-aquatic and aquatic plant species, while promoting the invasion of alien and/or invasive tree species (Bunn & Arthington, 2002).

Managing and protecting such areas with intrinsic natural-anthropogenic linkages, requires a comprehensive approach that takes into consideration all the exiting variables and their relationships. Most river restoration initiatives focus on perennial systems and integrated programs focused at catchment-scale conservation of IRES are uncommon (Leigh et al., 2016). A landscape approach has been identified as useful by many researchers working with environmental management problems (Conrad & Cassar, 2012; Levia et al., 2020). This approach is especially relevant when studying Mediterranean IRES. IRES are characterised by their inherent spatio-temporal variations. Lotic, lentic and terrestrial habitat mosaics created across the river continuum by cycles of expansion and contraction, are primarily driven by flow regime and various catchment dynamics including land cover and geomorphic factors (Datry et al., 2016). Streamflow in IRES are mostly generated following a series of precipitation events over time and when certain distinct thresholds based upon the catchment's characteristics and topography are reached (Gutiérrez-Jurado et al., 2019). The complex dynamics that lead to the development of areas where flow generation occur and how these influence the integrated catchment response leading to reaches being saturated or with streamflow, needs to be investigated at appropriate scales in IRES (Gutiérrez-Jurado et al., 2019).

Conservation efforts have recently focused in maintaining ecohydrological connectivity to adjacent ecosystems so that metapopulations and ecosystem functions thrive at the landscape scale (Leigh et al., 2016). River drying adds a temporal dimension to spatial heterogeneity in IRES habitats with water cessation being a major driver of spatial variation in stream networks (Allen et al., 2020). Landscape features including geomorphological constraints govern species dispersal mechanisms with populations, communities and ecosystem processes occuring both at local and larger scales with local scale functions being influenced by processes occuring over much larger scales (Datry et al., 2017). IRES catchments support a wide range of habitats, species and populations which have interacted through out millenia and a holistic landscape approach is required to maintain functionality of Mediterranean IRES in ecological and socio-economic terms.

1.5 Thesis objectives

IRES catchments are in most cases not included in monitoring programmes and are inadequately represented in digital resources and maps amd protective legislation (Acuña et al., 2014b; Sefton et al., 2019; Vander Vorste et al., 2016). Mapping limitations derive from their size and locations and hydrological monitoring is highly challenging mainly due to the spatial variability of different stages of flow intermittence that drive the various biophysical dynamics of these streams (Beaufort et al., 2018, 2019). This, together with being highly undervalued from societies and perceived as being ecologically poor due to the periodic dryness, result in many IRES not being included in conservation and management plans (Boulton, 2014). This thesis aims to contribute to the current limitations of monitoring IRES, investigate their various ecohydrological characteristics to elucidate their complex dynamics and provide a tool for decision makers to better value and prioritise the provision of ecosystem services (ES) in Mediterranean IRES.

The thesis identifies two main challenges in Mediterranan IRES: (1) monitoring and mapping the spatio-temporal variability of flow regimes and their influence on biophysical variables, and (2) mapping and quantifying ecosystem services for integrated environmental management. 'Traditional' methods used to characterise flow regimes are problematic, for example, gauging stations are not only financially expensive, but are not ideal to capture the spatial representation of different hydrological states and how these conditions change temporally along the stream continuum. Safety concerns, lack of accessibility and capturing the temporal dimension of ecohydrological dynamics lead to field surveys and citizen science contributions not ideal to understand the complex dynamics of IRES. This deficiency of adequate monitoring tools for IRES contribute to the current limited understanding of the influence of alternating dry and wet conditions have on the ecosystem processes that provide ES in IRES (Datry et al., 2018; Koundouri et al., 2017). In addition, the understanding of the streamflow generation mechanisms that trigger flow in Mediterranean IRES catchment areas with different topologies and how these influence certain processes such as temperature responses to specific precipitation events are still unknown (Gutiérrez-Jurado et al., 2019; Somers et al., 2013). The better understanding of these dynamics is fundamental when considering that IRES are most likely to experience variations to their water flow regimes because of climate change (Dhungel, 2016), diminishing important ES such as water provisioning and irrigation and affecting the quantity and quality of habitats (Kroll et al., 2017). This highlights the need for catchment-scale monitoring approaces encompassing the diverse gradients of flow intermittency to better investigate the drivers of ecological changes in IRES (Sarremejane et al., 2021). Monitoring schemes must provide solutions to quantify the dynamic responses of biota to transient flows and the other exogenous and endogenous natural and anthropogenically-induced changes that occur in Mediterranean IRES. Apart from capturing ecohydrological data at appropriate spatio-temporal scales, such solutions need to be affordable and robust.

The specfic objectives of this thesis are to:

1. Ameliorate the understanding of the complex dynamics that drive Mediterranean IRES through the presentation of a conceptual framework that highlights the key process cascades, the various variables, and their interactions within the system.
2. Examine the thermal and hydrological responses to water level and streambed temperatures following various precipitation events within different Mediterranean IRES catchments with diverse physiographic and land use characteristics.
3. Identify the feasibility of using cost-effective and off-the-shelf Uncrewed Aerial Vehicles (UAVs) equipped with consumer-grade cameras and visibile vegetation indices (VIs) to monitor and better understand the relationships between streambed water presence and vegetation health including fraction vegetation cover (FVC) in Mediterranean IRES.
4. Develop a reliable and easy to apply ecosystem services-based biophysical assessment for ungauged Mediterranean IRES through the use of remotely-sensed images from UAVs and processed with structure-from-motion (SfM) photogrammetry techniques.

1.6 Thesis structure

Chapter 2 presents a conceptual framework compartmentalizing the natural and anthropogenic exogenous and endogenous varibales that drive Mediterranean IRES. The framework was established on a review of literature including ecology, hydrology, ecohydrology, sociohydrology, hydrogeology, and environmental management to provide a synthesis for a better understanding of the existing challenges faced when monitoring, mapping and researching Mediterrean IRES. The chapter discusses two main challenges when managing Mediterranean IRES; (1) monitoring and mapping the spatio-temporal variability of flow regimes and their influence on bio-physical variables, and (2) mapping and quantifying ecosystem services for integrated environmental management. The use of UAVs and SfM photogrammetry to improve the spatio-temporal monitoring of Mediterrean IRES is discussed and proposed. Through the use of water level dataloggers and data from local weather stations, **Chapter 3** addresses current research gaps related to the understanding of complex dynamics in Mediterranean IRES catchments. Specifically, on how in-stream water levels and temperatures respond to different precipitation events and how these responses differ between various catchments that are governed by diverse bio-physical components and land uses.

In **Chapter 4**, UAVs and SfM photogrammetric techniques were used to capture images, at detailed spatio-temporal scales, of Mediterranean IRES catchments. Collected images were processed with RGB (red, green, blue) indices to analyze vegetation health within each catchment case study site during different seasons. Various RGB indexes where compared to identify suitability and linked with water level from the catchment areas to identify linkages and patterns between vegetation chlorophyll levels and water presence within Mediterranean IRES.

Ecological functions and services provided by IRES are not fully understood (Datry et al., 2018) and thus frequently ignored or not prioritized by decision-makers and planners. In **Chapter 5** a methodology for the identification, measuring, mapping and prioritizing ES using orthophotos derived from UAVs was adapted for environmental managers working in Mediterranean IRES. The proposed and tested method included the determination of ES from selected case study catchment sites and linked with the land cover types and inferred hydrological processes. The identified features were measured and scored with criteria that reflected the environmental services and functions provided by the specific catchment attributes.

Table 1.1. Characteristics of the seventeen (17) catchments including the five (5) case study areas selected for this study and the catchments included in the LIFE IP RBMP project. All data were retreived from the LIFE IP RBMP project, except for land cover data (CLC, 2018).

Catchment Name	Drainage Area (km^2)	% Channel Observed	Total Stream Length (km)	Strahler Order at Mouth	No. of Main Tributaries (≥ 4 Strahler Order)	Average Channel Width (m)	Max. Recorded Channel Width (m)	Min. Recorded Channel Width (m)	Land Cover
Wied il-Baħrija	4	72	4	6	2	3	6	0.4	9% discontinuous urban fabric; 27% land principally occupied by agriculture; 64% sclerophyllous vegetation
Wied Blandun	3	11	3	6	2	1.6	1.6	1.6	1% continuous urban fabric; 84% discontinuous urban fabric; 2% industrial or commercial units; 12% green urban areas; 1% non-irrigated arable land
Wied Żembaq	12	30	14	6	9	2	5	1	27% discontinuous urban fabric; 15% airports; 10% mineral extraction sites; 38% land principally occupied by agriculture; 10% sclerophyllous vegetation
Wied Dalam	5	59	4	6	3	2	2	2	24% discontinuous urban fabric; 3% non-irrigated arable land; 55% land principally occupied by agriculture; 18% sclerophyllous vegetation

Il-Wied tad-Dwejra	5	79	8	6	19	3	10	1	11% discontinuous urban fabric; 2% non-irrigated arable land; 65% land principally occupied by agriculture; 22% sclerophyllous vegetation
Wied il-Għajn	6	26	3	6	2	n.d	n.d	n.d	35% discontinuous urban fabric; 1% industrial or commercial units; 1% green urban areas;6% non-irrigated arable land; 57% land principally occupied by agriculture
Wied ta' Sant' Antnin	18	28	16	7	8	7	8	5	33% discontinuous urban fabric; 5% industrial or commercial units; 7% airports; 55% land principally occupied by agriculture
Wied il-Għasel	59	67	55	8	39	5	21	0.4	58% discontinuous urban fabric; 3% industrial or commercial units; 3% mineral extraction sites; 4% sport and leisure facilities; 4% non-irrigated arable land; 13% complex cultivation patterns; 13% sclerophyllous vegetation; 2% salines
Wied tal-Ġnejna	8	21	9	6	10	6	10	1	8% discontinuous urban fabric; 63% land principally occupied by agriculture; 29% sclerophyllous vegetation
Wied ta' Ħarq Ħammiem	1	30	2	5	0	3	6	3	86% discontinuous urban fabric; 14% land principally occupied by agriculture
Wied Għomor	3	100	2	5	0	6	10	1	40%; land principally occupied by agriculture; 60% discontinuous urban fabric

Wied il-Kbir	74	73	65	8	42	7	21	1	21% discontinuous urban fabric; 4% industrial or commercial units; 3% airports; 3% mineral extraction sites; 2% sports and leisure facilities; 1% non-irrigated arable land; 9% complex cultivation patterns; 52% land principally occupied by agriculture; 1% mixed forest; 4% sclerophyllous vegetation
Mġarr	3	100	3	6	9	2	4	1	13% discontinuous urban fabric; 87% land principally occupied by agriculture
Wied il-Mistra	7	37	6	6	1	4	16	1	22% discontinuous urban fabric; 2% industrial or commercial units; 3% airports; 2% mineral extraction sites; 1% sport and leisure facilities; 1% non-irrigated arable land; 4% complex cultivation patterns; 56% land principally occupied by agriculture; 9% sclerophyllous
Wied tax-Xlendi	9	46	14	6	32	4	9	2	36% discontinuous urban fabric; 17% non-irrigated arable land; 38% land principally occupied by agriculture; 9% sclerophyllous
Wied ta' Miġra l-Ferħa	3	0	2	5	0	n.d	n.d	n.d	15% sparsely vegetated areas; 25% land principally occupied by agriculture; 60% sclerophyllous vegetation
Wied Babu	5	0	3	6	3	n.d	n.d	n.d	25% discontinuous urban fabric; 1% mineral extraction sites; 55% land principally occupied by agriculture; 19% sclerophyllous vegetation

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CHAPTER 2

MEDITERRANEAN INTERMITTENT RIVERS AND EPHEMERAL STREAMS: CHALLENGES IN MONITORING COMPLEXITY

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Abstract

In most cases, intermittent rivers and ephemeral streams (IRES) form the principal sur- face water bodies in Mediterranean regions and people are heavily dependent on them. Strong reliance on such streams results in numerous pressures, and complex relationships are formed between their various natural and anthropogenic components, which creates numerous challenges to decision-makers who require a better understanding of IRES to establish effective measures to restore ecosystem functionality and implement changes, while maintaining human well-being. In this paper, we present a conceptual framework that identifies process cascades and links to identify the variables governing Mediterranean IRES and map their complex interrelations. Climate is the main external driver, and it affects IRES through precipitation, temperature, wind action, and geomorphic factors, which in turn influence the physical and biological attributes of IRES. Monitoring challenges and knowledge gaps are presented from the conceptual framework, highlighting the need to identify solutions for the monitoring and mapping the spatio-temporal variability of flow regimes and their influence on bio-physical variables and mapping and quantifying ecosystem services for integrated environmental management. Finally, we argue that remote sensing techniques, specifically, the combined use of unmanned aerial vehicles and structure from motion photogrammetry, are key to bridging gaps in understanding and meeting the challenges of managing Mediterranean IRES.

2.1 Introduction

Temporal flows in intermittent rivers and ephemeral streams (hereafter, IRES; Datry et al., 2017; Stubbington et al., 2018) produce complex dynamics between their abiotic and biotic environments. In the Mediterranean basin, IRES are the dominant surface water bodies (Bonada & Resh, 2013; Froebrich, Nikolaidis, Prat, & García‑Roger, 2010), and people are heavily dependent upon them. Managers and planners developed numerous management measures to maximize the exploitation of their services, such as the provisioning of water and sediment (Aristi et al., 2014; Bellin, van Wesemael, Meerkerk, Vanacker, & Barbera, 2009; Bonada & Resh, 2013; Cooper, Lake, Sabater, Melack, & Sabo, 2012; Moyle, 2014). However, without prior knowledge of the complex interrelationships between the natural (e.g., hydrological regime and habitats) and human variables (e.g., chemical contamination and introduction of alien species), implementing management interventions in IRES may undermine the delivery of other equally significant environmental services.

The ability of Mediterranean IRES (hereafter, referred to as Mediterranean IRES that are found in the Mediterranean basin) to provide numerous ecosystem services (ES) is often undervalued (Stubbington et al., 2018). These transient waterways are an important resource for agriculture through the provision of irrigation and rich soils. They serve as recharge points for underlying aquifers, and if properly main- tained, they can serve as vital conduits for flood relief, especially in urbanized/populated areas. In some countries they are also valued for their provision of water and food such as through the provision of medicinal plants, herbs or provide grazing grounds for cattle (Steward, von Schiller, Tockner, Marshall, & Bunn, 2012). Mediterra- nean IRES are unique ecosystems that in some areas are biodiversity hotspots, harbouring numerous endemic species (Hershkovitz & Gasith, 2013). Flow intermittency encourages the development of complex habitats that support semi‑aquatic and terrestrial species (Datry et al., 2017). When IRES dry out numerous ecological functions are influenced including processes related to organic matter and nutrient re‑cycling (Datry, Boulton, et al., 2017). These dynamics are, however, still poorly researched (Datry, Boulton, et al., 2017).

Adequate planning and management of Mediterranean IRES necessitate a clear understanding of the links between the natural and human‑derived variables operating at different temporal and spatial scales. Due to its spatial coverage, potential for high temporal repeat rates and ability to access previously unreachable locations, remote sensing has increasingly been utilized to map and monitor river environments (e.g., Carbonneau, Fonstad, Marcus, & Dugdale, 2012; Marcus & Fonstad, 2010). Furthermore, novel remotely sensed techniques involving digital photogrammetry processing techniques such as structure from motion (SfM) combined with the use of Uncrewed Aerial Vehicles (UAVs) have opened up new opportunities for cost‑ effective, user‑friendly remote sensing with high monitoring frequency and mapping of land surfaces changes on fine spatial scales (DeBell, Anderson, Brazier, King, & Jones, 2016; Hortobágyi, Corenblit, Steiger, & Piery, 2017).

Here we produce a conceptual framework (Figure 2.1) that tries to holistically capture the dynamism of Mediterranean IRES, highlighting the key process cascades, the various variables (categorized as exoge- nous, physical and biological), and their interactions within the system. We also identify the various challenges faced in monitoring and mapping IRES. Consequently, we argue that the use of remotely sensed applications such as UAVs and SfM photogrammetry is key to capture and monitor complexity in Mediterranean IRES. Consequently, the objectives of this paper are to (i) illustrate through a conceptual dia- gram the complex interactions in Mediterranean IRES, (ii) recognize key monitoring and mapping challenges in IRES, and (iii) advance the use of UAV and SfM photogrammetry to address these challenges.

2.2 Monitoring challenges

Complexity in Mediterranean IRES is derived from the interrelation- ships between the multiple natural and human‐induced abiotic and biotic variables. These relationships acting at multiple scales (watercourse, subcatchment, and catchment) and the hierarchical influ- ences on the functioning of Mediterranean IRES operating at distant spatial and temporal scales (Munné & Prat, 2004) create numerous challenges to environmental managers. Enhanced knowledge of the different variables and their interconnections is required to establish the measures that are needed to restore sustainable function and/or implement changes in the catchment area without altering current operation. In this section, we explore and present a conceptual framework (Figure 2.1) that adopts a comprehensive view of the variables and their interactions. The conceptual framework was established on a review of literature sources concerning the ecology, hydrology, ecohydrology, sociohydrology, hydrogeology, and environmental management of transient waterways in the Mediterranean basin. The framework helps us to explore the challenges in monitoring and mapping of Mediterranean IRES (Section 2.2.2).

2.2.1 Conceptual framework representing complexity and linked process cascades

Representing all the processes that are manifested in Mediterranean IRES through a holistic diagram is merely an unrealistic feat. The con- ceptual framework diagram (Figure 2.1) represented here is guided by the need to provide a simpler and more tangible visual of the (i) multiscale phenomena that are part of the Mediterranean IRES system represented by exogenous variables and the endogenous physical and biological variables and (ii) linkages amongst natural and/or human‐derived variables influencing the system on a spatio‐temporal scale. The linkages between the different variables are colour‐coded, provid- ing a broad explanation on the type of relationship being represented. Exogenous variables, external to the catchment system, drive system changes directly influencing the endogenous physical and biological variables. Climate is the main external driver, and it varies across different latitudes and longitudes and is also influenced by humans through climate change. Climate affects IRES through four main process cascades driven by (i) precipitation patterns, types, frequency, and amounts; (ii) temperature; (iii) wind action (aeolian processes); and (iv) geomorphic factors that configure the landscape. The latter is included in the endogenous part of the diagram to reflect the shaping of landforms in different geographical locations and associated climatic zones. However, the geomorphic environment represented by geology and fluvial geomorphology is included in the physical variables section of the diagram.

2.2.2 The challenges

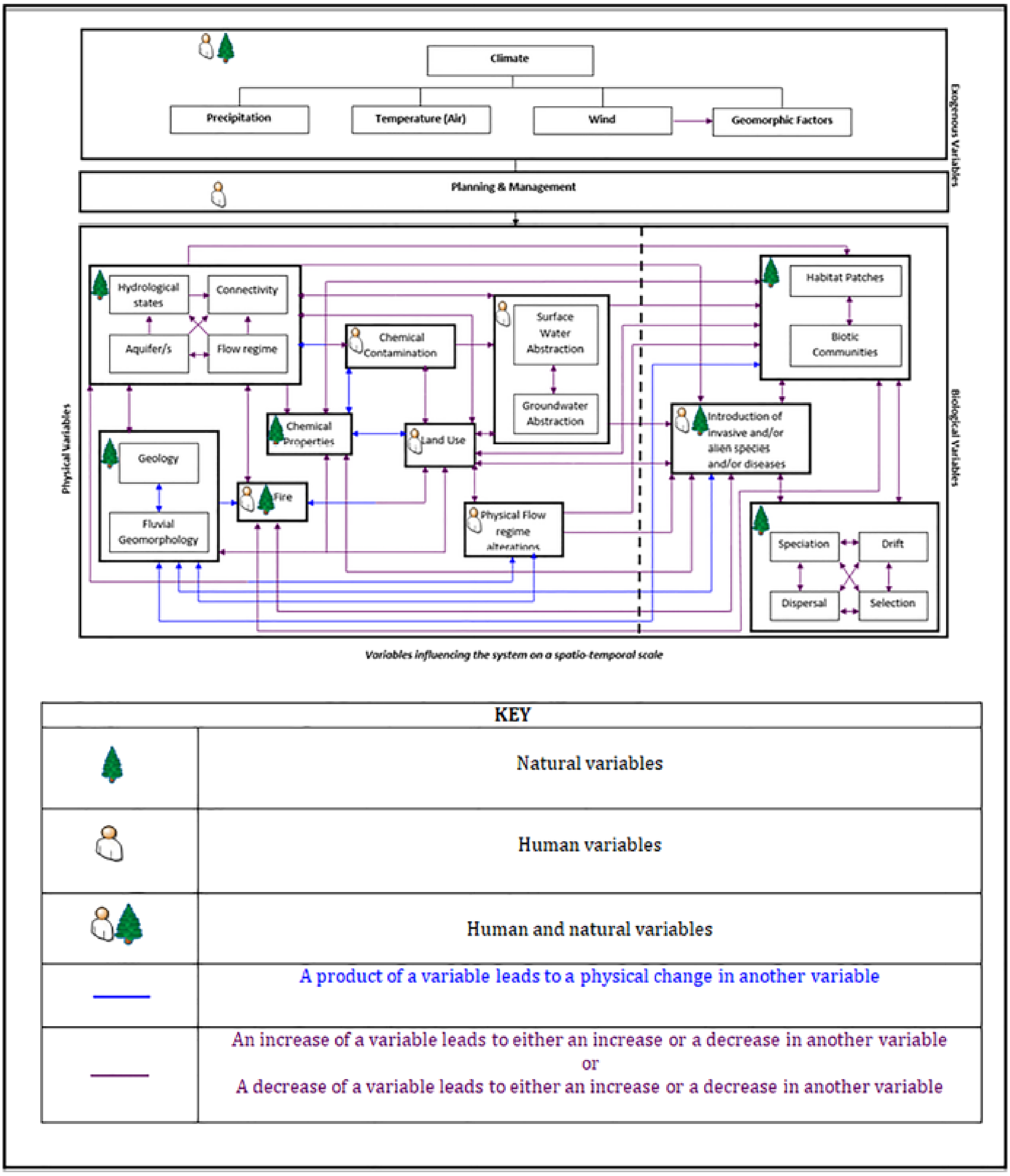
The complexity of Mediterranean IRES arises not only from the num- ber and variability of the controlling variables but also from the interactions between them. Our conceptual model shows that climate is the main driver affecting all processes through precipitation, wind action, and temperature fluctuations, which are mediated by catchment geology. Each of these variables sets in motion a series of changes which alter the characteristics and behaviour of the other natural and anthropogenic elements in the catchment area. The conceptual framework sharpens the focus on the numerous monitoring and management challenges in Mediterranean IRES. In this section the challenges and existing knowledge gaps that we believe future research should focus on are presented.

Challenge 1: Monitoring and mapping the spatio-temporal variability of flow regimes and their influence on biophysical variables

Various methods have been used to characterize the flow regime and other physical attributes of Mediterranean IRES. Gauging stations provide information about the frequency and duration of temporary flow using flow time series and facilitate a more specific definition of flow intermittency (González-Ferreras & Barquín, 2017; Snelder et al., 2013). However, most IRES catchments in the Mediterranean typically have few or no gauging stations. The installation of gauging stations is not only costly but may be prohibitive due to active geomorphological processes and restricted accessibility (Beaufort, Carreau, & Sauquet, 2019; Beaufort, Lamouroux, Pella, Datry, & Sauquet, 2018). On the ground wet and dry mapping is sometimes used to compensate the absence of gauges (Datry, Fritz, & Leigh, 2016; Turner & Richter, 2011). This method is especially useful to qualitatively describe/capture the occurrence of the different hydrological states (Costigan et al., 2017). However, this procedure demands considerable time in the field and it is impractical when mapping is to be carried out in frequent intervals and over extensive areas.

With the advent of smartphones equipped with cameras and Global Positioning Systems, the monitoring of real-time hydrological states by appropriately trained citizen scientists, has become a promising method to advance the mapping of IRES (Costigan et al., 2017). Wet and dry mapping of the spatial extent of hydrological flows by citizen scientists can be carried out over large areas and at many different sites (Turner & Richter, 2011). Citizen scientists may also be trained to collect other important ecohyrdological data such as the presence of different aquatic states, including pools or dry areas (Allen et al., 2019) that would otherwise be undectable in gauged streams (Costigan, Jaegar, Goss, Fritz, & Goebel, 2016).

Figure 2.1. Conceptual framework compartmentalizing the natural and human-induced exogenous and endogenous variables that drive Mediterranean IRES. Endogenous variables are divided into physical and biological variables. Arrows depict the links between each compartment and variables within.



Crowdwater, RIU. NET and Stream Tracker are examples of projects that crowdsource hydrological data from IRES through smartphone applications where users take geo-tagged photographs and use the app to digitally add staff gauges, eliminating the need for physical stream installations or manual measurements (Kampf et al., 2018; Prat et al., 2016). However, a prominent issue with surveying streams on foot is safety and lack of accessibility. To monitor the extent of perennial surface flow of the San Pedro River by citizen scientists, parts of the river were surveyed on horses or all‑terrain vehicles (Turner & Richter, 2011). This, however, is not feasible in all IRES. In addition, network connections may be limited in low‑income regions, hindering the accessibility and communication of data (Njue et al., 2019).

More research is required to capture and understand the variability of biophysical processes at various spatial scales that are subject to natural and human pressures (Stella et al., 2012). Data capture and monitoring methodologies must be focused on providing solutions to quantify the dynamic responses of biota to the inherent hydrological transitions and other exogenous and indogenous environmental changes in Mediterranean IRES. More- over, the geographical scope of both research and management should extend from a purely Mediterranean IRES approach, in a way that would address habitats from a biogeographical perspective, including corridor and catchment areas at various spatial scales. As advocated in Integrated River Basin Management (IRBM), a comprehensive approach of river management is needed to understand how the dif- ferent flows in energy, matter, and ecosystems operate at various scales (Carbonneau et al., 2012; Fausch et al., 2002). This would require the use of conceptual and practical tools that require the spatial quantification of a number of variables (such as dominating bio‑physical conditions and ES) and the need to address how climate change will impact on the bio‑physical conditions and how scenarios can be constructed to look at potential impacts on Mediterranean IRES communities.

Challenge 2: Mapping and quantifying ecosystem services for integrated environmental management.

The over usage of aquifer and surface waters is both an eco- nomic and political burden for Mediterranean countries (Larned et al., 2010; Nikolaidis et al., 2013). The functions provided by Mediterranean IRES continue to underline the importance of safeguarding and enhancing the services and goods provided by these systems. Considering that Mediterranean IRES play a part in peoples wellbeing, a balance needs to be struck between ensuring their proper management and meeting human needs. Arthington et al. (2014) stress that instead of aiming to reach an unachievable original environmental state, man- agement initiatives of temporary streams should be focused more on their capacity to provide numerous services to society. Mediterra- nean IRES have the potential to provide a variety of other supporting, regulating, provisioning and cultural services. However, these are mostly public goods that are not easily measured (e.g., nutrient recycling, biodiversity, sense of place, amongst others) and quantifiable in monetary terms (Gilvear et al., 2013). Historically, these services have in most cases been ignored when managing Mediterranean IRES (Boulton, 2014; Datry et al., 2017).

The availability of spatially explicit ES data at different resolutions and at catchment‑wide scale is important for managers to prioritize interventions, identify problem areas and better understand synergies and trade‑offs amongst the various ES in the system (Fu et al., 2015; Merenlender & Matella, 2013). However, most of these services are not always manifested and used within the same location or timeframes (Gilvear et al., 2013). A better understanding of what, when, and where are ecosystems services provided is cardinal to con- serve and enhance them. Even though many ES in freshwater systems are dependent on flow (Willaarts et al, 2012) a large num- ber of environmental functions in IRES extend during the dry period, providing regulating and supporting services such as erosion regulation and alleviating flooding during storm events (Datry et al., 2017; Koundouri et al., 2017). However, knowledge of the influence of alternating dry and wet conditions on the ecosystem processes that produce ES is still scarce (Datry et al., 2017; Koundouri et al., 2017). Altered flows may also be beneficial to local communities through the provision of additional/new services such as flood protection, water provisioning, and aquifer recharge to sustain rural and agricultural communities. Hence, in the absence of long-term flow data and with a desire to meet a particular set of ecological and social objectives, a recent his- torical baseline have to be used for the development of "designed" environmental flows that provide the needed ES (Acreman et al., 2014). This however necessitates a clear understanding of the relationships between flow variations and ecosystem functioning in the system.

The services provided and processes behind biogeochemical transi- tions have been discussed in the literature (Larned et al., 2010; Datry et al., 2014; Costigan et al., 2016; von Schiller et al., 2015; Arce et al., 2019). More research is needed on the benefits and activities of terrestrial biota during the dry periods and their inter- actions with aquatic species in terms of structural attributes such as soil characteristics (Arce et al., 2019), composition of vegetation and channel morphology and those primarily influencing functional attributes such as energy flow and nutrient cycling. Little is known on the impact of multiple stressors in temporary streams and their influence on ecosystem functionality (Navarro-Ortega et al., 2015). Even though Mediterranean IRES are naturally resilient to water short- age, they are particularly fragile to multiple stressors such as flow intermittency and anthropogenic pollution (Smeti et al., 2019). This is further complicated by evidence of pollutant accumulation during no flow periods (Karaouzas et al., 2018) and multivariant stressor effects, stressor interac- tions, and stressor impacts to the different environment variables along the river's continuum (Segurado et al., 2018). Furthermore, environmental managers have to deal with a constantly changing anthropogenic environment with the introduction/discovery of new pollutants. For example in Malta, 82% of samples collected from ephemeral pools in undeveloped areas between 2011 and 2013 contained levels of perchlorate which are well above the "natural" values, resulting from the only known strong source of percholate, the burning of fireworks (Pace & Vella, 2019). The impact of this contamination to the biogeochemical characteristics of IRES is still unknown.

2.3 Advancing the use of UAV and SfM photogrammetry to improve monitoring of Mediterranean IRES

The challenges presented share a common theme: the difficulty in monitoring and mapping of the spatio-temporal variability of water flows is hindering the better understanding of its impact on the biophysical variables, ES and ecological resilience of Mediterranean IRES. Water is the most essential component for ecosystem functioning (Sponseller et al., 2013; Willaarts et al., 2012) and in IRES the delivery of ES is most likely to be greatly influenced by the duration, timing, frequency and extent of the different hydrological states (Datry et al., 2017). Understanding this synergy is crucial especially in the Mediterranean where IRES are exposed to multi- ple anthropogenic stressors altering their flow regime (Skoulikidis et al., 2016). This will be further exacerbated by climate change where long-term reduction in the number of flow days and decrease in stream flow trends have already been recorded in the Mediterranean region (De Girolamo et al., 2017; Erol & Randhir, 2012; Garcia et al., 2017; Giorgi & Lionello, 2008; Moran-Tejeda et al., 2011; Nerantzaki et al., 2015; Schneider et al., 2013). Thus, an enhanced capability to monitor the spatio-temporal variation of the hydrological states in relation to other physical parameters is imperative for this understanding.

Remote sensing offers an efficient approach to monitor large areas with spatially continuous coverage of fluvial systems (Tamminga et al., 2015; Woodget et al., 2015), which cannot be achieved by traditional means. This is especially applicable in Mediterranean IRES where the transitioning between arid and wet periods form different ecohydrological conditions along the stream continuum. Advances in remote sensing platforms, sensor technology, and data processing/ analysis techniques now means that a range of fluvial metrics (e.g., channel morphology/flow state; Dietrich, 2016; Woodget et al., 2016; grain size; Carbonneau et al., 2005; Black et al., 2014; sediment load; Long & Pavelsky, 2013; Olmanson et al., 2013; depth/bathymetry, Legleiter, 2013; McKean et al., 2009; water temperature; Torgersen et al., Dugdale, 2016; and aquatic/riparian vegetation characteristics; Bertoldi et al., 2011; Flynn & Chapra, 2014) can now be assembled with relative ease. Although conventional satellite imagery and aerial photography can be costly, freely available high spatial resolution aerial photographs (Google Earth and other virtual globes) may be used to characterize hydrologic states (e.g., Legleiter, 2013) and/or map ES (Large & Gilvear, 2015). However, information is only limited to specific capture dates (Gallart et al., 2012., Gallart et al., 2016, Costigan et al., 2017) and is therefore not well-suited to site- specific studies at small scales (Tamminga et al., 2015). This is especially true in the Mediterranean, where most IRES are usually not more than a few metres wide. Use of these “conventional” remote sensing techniques has, therefore, found limited use in regions dominated by Mediterranean IRES.

Recently however, novel remotely sensed - digital photogrammetry processing techniques such as SfM, have enabled scientists to work directly with spatially explicit continuums of river data (Woodget et al., 2017). SfM photogrammetry can be applied at multiple temporal and spatial scales and at extremely detailed resolutions, allowing for novel opportunities for the under- standing of earth surface processes such as 4D (three spatial dimensions and one temporal dimension) reconstruction of landscape dynamics (Eltner et al., 2016). SfM photogrammetry develops 3D structures from 2D image sequences by automatically matching conju- gate points between scenes acquired from different angles (Fonstad et al., 2013; Woodget et al., 2015). SfM is increasingly becoming more popular amongst scientists due to its affordability and the existence of easy-to-use commercial and open source software applications that allow even nonscientists to build three-dimensional models of surface features which are subjects of scientific research (Wróżyński., 2017). SfM has been used in a vast array of ecohydrological and river management applications such as for the observation of different river stages (Duró, 2018; Niedzielsk et al., 2016), analysis of feedbacks between fluvial geomorphology and riparian vegetation (Hortobágyi et al., 2017); floodplain inundation mapping (Schumann et al., 2019) and river management and restoration (Kubota et al., 2017; Marteau et al., 2017).

The development of SfM technology has been accompanied by the emergence of UAVs, which provided scientists with cost‑effective, and user‑friendly remote sensing with high monitoring frequency and map- ping at fine spatial scales (Hortobágyi et al., 2017). Figure 2.2 provides an example of 3 cm resolution orthomosaic produced from a consumer‑grade quadcopter drone and SfM photogrammetry applica- tion of a Mediterranean ephemeral stream. To the authors' knowledge, the combined use of SfM and UAVs to investigate the spatio‑temporal variability of alternating dry and wet stages in Mediterranean IRES has not yet been adopted. However, the combination of these techniques is particularly suited to Mediterranean IRES, where the ability to respond quickly to wetting and drying events is of paramount impor- tance. Contrary to other remotely sensed applications, UAVs are not limited to specific capture dates. UAV flight missions can be carried out much more frequently, providing added solutions for the under- standing of complex processes in IRES. For example, the generation of 4D models depicting the evolution of the different hydrological states on successive dates at different spatial scales and with appropri- ate resolutions for ecohydrological monitoring would provide scien- tists with an unparalleled perspective of the spatio‑temporal dynamics of the different hydrologic states in Mediterranean IRES.

Combined with light‑weight instruments that cover the visible to thermal spectrum including multispectral or hyperspectral sensors, miniature RADAR, passive microwave radiometers, and light detection and ranging (Evaraerts, 2008), UAVs also have potential for monitoring other variables occurring along Mediterranean IRES. Although still in their infancy (in terms of their mounting on UAVs), these technologies have the potential to provide scientists with key tools to further com- prehend the influence of hydrological intermittence on other stream biophysical variables at greater resolutions and more frequent intervals (Politi et al., 2016). For example, aquatic and terrestrial habitat changes and sediment transfer in Mediterranean IRES, which are otherwise difficult to detect from the use of “conventional” remote sensing platforms, can be monitored. Many of the river remote sensing methodologies that were previously only available to conventional remote sensing platforms can now be achieved using UAV‑derived data. For example, recent studies demonstrate the maturity of UAV- mounted multispectral sensors for mapping riparian vegetation in arid regions (e.g., McCabe et al., 2017), a technique that was previously limited to airborne or satellite approaches.

Although there are currently no further peer‑reviewed examples of the use of UAV‑based multispectral sensors for the extraction of river habitat data, the authors are aware of efforts to quantify river water quality parameters (e.g., suspended sediment, algal concentrations) from such instru- ments. Similarly, although no published studies of UAV‑based river temperature monitoring currently exist, several examples using ther- mal infrared imaging are present in the grey literature (e.g., Jensen et al., 2012). The ability to acquire multispectral or thermal infrared imaging data from UAVs represents a key boon for researchers studying Mediterranean IRES where accurate data on water quality parameters (e.g., sediment yield, temperature) would fill two key data requirements.

Figure 2.2. High-resolution images of a Mediterranean ephemeral stream developed with a commercial Uncrewed Aerial Vehicles (UAV) and structure from motion (SfM) photogrammetry software compared with satellite imagery provided by ESRI that includes 15-m TerraColor imagery at small and midscales and 2.5-m SPOT imagery for the world.

	General overview of orthomosaic image developed using an UAV and SfM photogrammetry overlayed on a satellite image provided in the basemap gallery of ESRI ArcGIS v. 10.7 software package.
	Zoomed snapshot of orthomosaic image developed using an UAV and SfM photogrammetry overlayed on a satellite image provided in the basemap gallery of ESRI ArcGIS v. 10.7 software package.
	Zoomed detail of orthomosaic image developed using an UAV and SfM photogrammetry overlayed on a satellite image provided in the basemap gallery of ESRI ArcGIS v. 10.7 software package.

Orthomosiac image with a resolution of 3cm of Wied tal-Ġnejna in Malta, a Mediterranean ephemeral stream. The survey mission was planned with freeware software DroneDeploy. The aerial survey was carried out using a DJI Phantom 4 Advanced Plus quadcopter. 2D orthomosaics were created with Drone2Map (ESRI ArcGIS) application. These images are being created as part of the LIFE IP RBMP project co-financed by the European Union, in accordance with the rules of the LIFE programme under the LIFE 16 IPE/MT/008 on Optimising the implementation of the 2nd RBMP in the Malta River Basin District. The project commenced in 2018 and includes the development of Integrated Master Plans and Technical Guidelines at Catchment-Scale for Malta's IRES. The high resolution ortho-images will be used as basemaps and to map land use features along streams.

UAVs are also opening possibilities for the development of new methods and techniques not previously applicable to conventional remote sensing, which could also have benefits to the study and inte- grated management of Mediterranean IRES. For instance, surface flow velocity measurement has long been difficult to achieve using conven- tional remote sensing as velocity-sensing algorithms (e.g., particle image velocimetry or PIV; Daigle et al., 2013) require multitemporal datasets. However, the ability of drones to capture image sequences while hovering or flying slowly means that velocity mapping in river environments is now a reality (e.g., Bolognesi et al., 2017; Perks et al., 2016). Similarly, although initial experiments with UAVs necessitated lower resolution imaging sensors and was often associated with decreased image quality (due to motion blur; Sieberth et al., 2014), the increasing miniaturi- zation of camera technology coupled with enhanced gyrostabilized mounts (gimbals; Gasparovic & Jurjevic, 2017) means that in many cases, UAVs are able to provide data at even higher resolution than conventional airborne platforms. Use of SfM and UAV is also permit- ting the increase in frequency of high-resolution topographic surveys and to monitor geomorphic changes, especially in inaccessible areas such as mountain catchments (Cucchiaro et al., 2018). These advances are both well suited for Mediterranean IRES environments, where the increased spatial resolution of modern UAV sensors coupled to the ability to capture data either on an ad-hoc basis or at high temporal frequency, and to reach restricted areas, means that, even in very small Mediterranean IRES channels, observations can be obtained at an appropriate scale of reference.

The current revolution in UAV technology has substantial implica- tions for the improved monitoring and management of Mediterranean IRES. Nonetheless, there are a few disadvantages to the use of such technology. Flights are dependent on weather conditions where opti- mal operational wind speeds for most aircrafts are below a threshold of 24–32 km per hour and atmospheric moisture may damage the UAV if not adequately waterproofed (DeBell et al., 2016). As with all remote sensing-based approaches, issues of data calibration/validation remain a key impediment to their uptake. Most forms of remote sens- ing data still require some form of ground validation/calibration, and this is currently no less true for UAV/SfM approaches. Given the rapidity with which conditions change in Mediterranean IRES environments, a key challenge will be the collection of ground validation/ calibration data within the same spatio-temporal window as UAV surveys are conducted; without such data, it will be very difficult to assess the validity of UAV-derived measurements in Mediterranean IRES. Similarly, current error-assessment criteria commonly used by scientists can be difficult to apply to the "riverscape-style" continuums of data acquired using UAVs, where data quality (accuracy) is often a trade-off for greatly increased data quantity. For example, when map- ping densely vegetated areas, UAV-SfM produces point cloud data based only on the canopy surface that is visible from sky, unlike light detection and ranging data, which penetrate vegetation and tree cover and provide details of the terrain (Jayathunga et al., 2018). Researchers working with such measurements (such as calculat- ing canopy height) should therefore look to improve error-assessment approaches, making them easier to apply to these large spatio- temporal datasets. Another key concern regarding the application of UAVs in Mediterranean IRES is one of strict legislation regarding UAV flights over populated areas (Schumann et al., 2019). Because Mediterranean IRES are often highly modified environments lying close to human settlement, the use of UAV approaches may be limited either by pragmatic health and safety concerns or by legal impedi- ments to flight over population centres. It will therefore be important to seek methods to fill/interpolate data gaps induced by the inability to acquire data in urban areas, possibly through the fusion of UAV data with ground measurements and observations from "conventional" remote sensing platforms. Nonetheless, this, alongside other potential concerns should not detract from the obvious benefits that UAVs-based remote sensing (and associated techniques like SfM) bring to meeting the challenge of improved mapping and monitoring of Mediterranean IRES environments.

2.4 Conclusion

Current methods used for the monitoring and mapping of the spatio- temporal variability of flows are limiting in identifying links with the biophysical variables and provision of ES in IRES. This is further complicated by the impact of multiple human-induced stressors in Mediterranean IRES and their influence on the streams' functions and processes. With their unparalleled ability to deliver, at aborbable costs, fine spatial and temporal resolution data, whilst reaching areas which are otherwise inaccessible, SfM photogrammetry applications com- bined with UAV-based technologies are an ideal solution to better understand complexity in Mediterranean IRES. There are a number of challenges that still need to be addressed including the advancement of weatherproof UAVs, production of accurate remotely-sensed data without the need for the collection of ground-control points to validate measurements, improving error-assessment approaches in large-scale spatio-temporal datasets, and development of legal frameworks ensuring safe UAV use for both the general public and the users whilst not inhibiting scientific research. However, this paper has explained that there is great potential for exploring UAV and SfM use to monitor, better understand and manage Mediterranean IRES.

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CHAPTER 3

MEDITERRANEAN INTERMITTENT RIVERS AND EPHEMERAL STREAMS: TEMPERATURE AND WATER LEVEL RESPONSES TO PRECIPITATION EVENTS

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Abstract

Despite continued interest in flow regime variability and its influence on stream dynamics in intermittent rivers and ephemeral streams, the link between different precipitation events and its control on water presence in hydrologically transient catchments with varying land cover and biophysical characteristics, has rarely been studied. This paper presents the results from high-resolution (30-min) precipitation data and streambed temperatures collected from a fifteen-month period from six different Mediterranean intermittent and ephemeral catchments. The monitoring timeframe proved to be one of the driest periods in the studied areas in the last 50 years and most recorded rain events were small, the majority of which not exceeding 0.4mm of rainfall in a single event. As a result, a descriptive analysis approach including graphs, mean, maximum and standard deviation of 30-minute interval in-stream temperatures, water stage height and precipitation data and Pearson's correlation coefficient (r) was adopted for the results' analysis. The results demonstrate the larger studied catchments had longer water level reponse lag times to precipitation episodes. In addition, reduced water level responses to autumn rain events in rural areas indicated that the soil water retention capacity due to the limited soil moisture content during the summer period and the empty water-retention infrastructure, play an important role in governing flow presence. On the contrary, the smaller and predominantly urban catchment, resulted with the second most rapid water presence response times and the highest average streambed temperature peaks following precipitation events. Conversely, rural catchments that have groundwater spings contributing to streamflows, showed more stable temperature variations. This reseach highlights the need for the improved understanding of the intrinsic landscape and basin properties that control the spatio-temporal paterns of transient flows and thermal responses to varying rain events, especially in a changing climate.

3.1 Introduction

A wide array of variables govern the environmental condition of watercourses including, hydrology, geology, geomorphology, habitat structure, land use and water quality (Caissie, 2006). Rainfall variability, landscape characteristics and anthropogenic activities make Mediterranean intermittent rivers and ephemeral streams (hereafter, Mediterranean IRES) generate highly unpredictable and episodic flowing events. The flow regime is the key component that shapes and maintains riparian ecosystems in Mediterranean IRES (Gallart et al., 2011, 2012). The study of streamflow characteristics in IRES catchments is more complicated than perennial catchments because of irregularity of the amount, intensity and frequency of rainfall events, high evapotranspiration rates, seasonal variability between rainfall and evapotranspiration, variability in vegetation cover and physiographic features (Azarnivand et al., 2020; Berhanu et al., 2015; Borg Galea et al., 2019). In addition, in most regions, IRES are poorly gauged, leading to a dearth of data available for ecohydrological analyses required for the better understanding of the functioning of these streams (Azarnivand et al., 2020; Beaufort et al., 2018, 2019; Yu et al., 2018). In fact, the question of when, where, and why do Mediterranean IRES with diverse catchment characteristics start to flow is still not fully understood (Gutiérrez-Jurado et al., 2019). A data gap is prevalent in IRES research, where the understanding of the streamflow generation mechanisms, including the spatio-temporal variability of the hydrological processes that trigger flow is unknown (Costigan et al., 2016; Gutiérrez-Jurado et al., 2019).

There is also a paucity of research available on streambed temperature response dynamics to precipitation events in IRES. Water temperature is one of the elements that influence the environmental condition of watercourses and is a critical parameter that effects the health of freshwater ecosystems including their ecological and physicochemical processes (Morrill et al., 2005; Nelson & Palmer, 2007). Thermal dynamics in streams are highly complex. Many factors have to be considered when analysing river temperatures including atmospheric conditions, topography, stream discharge and the streambed (Caissie, 2006). Many studies already exist on water temperature variations in perennial river systems (Croghan et al., 2019; Dugdale et al., 2018; Fullerton et al., 2015) and its influence on biota (Chinnayakanahalli et al., 2011; Glover et al., 2020;) and the abiotic environment (McDowell et al., 2017; Syvitski et al., 2019). Increased stream temperature can lead to reduced dissolved oxygen (DO) limitation due to enhanced microbial activity and oxygen demand and decreased oxygen diffusion and solubility (Somers et al., 2013). Streambed temperatures govern growth, metabolism, and reproduction of aquatic biota and can be highly detrimental if it exceeds thermal limits of aquatic fauna (Somers et al., 2013). Temperature response dynamics in Mediterranean IRES are mostly driven by episodic flow events and drying and rewetting of the streambed, differing from perennial systems with prolonged and/or constant flows. Analysis of streambed temperatures in IRES, is in most cases, solely focused on the monitoring of streamflow frequency and duration (Chapin et al., 2014; Constantz et al., 2001;) and surface water – subsurface and groundwater exchanges (Constantz et al., 2002; Fakir et al., 2021; Rau et al., 2017; Ronan et al., 1998).

An understanding of temperature dynamics to diverse precipitation events during different seasons is fundamental for assessment and forecast of thermal responses to climatic variability and change (Caissie, 2006). IRES are a type of surface water body features that are mostly likely to experience variations to their hydrologic regimes because of climate change (Dhungel et al., 2016). Döll & Schmied (2012) confirm that together with water management, climate change is the main driver altering the spatial and temporal mechanisms of flow intermittency. The occurrence and intensity of extreme rainfall events are projected to intensify in many locations and global mean temperatures are anticipated to continue to rise (IPCC, 2019). In many areas there will be an increase in temperature extremes, with the increase in the frequency, duration and magnitude of hot extremes being the most predominant (IPCC, 2019). In the Mediterranean region, frequency and intensity of droughts has already increased and the highest level of warming for extreme hot days is also expected to occur (Hoegh-Guldberg O et al., 2018). Under different global warming scenarios (1.5°C, 2°C and 3°C), Marx et al. (2018) concluded that the Mediterranean region will also experience precipitation deficits, higher evapotranspiration rates and decrease in low flows. Precipitation events are expected to be less frequent and more severe (IPCC, 2013). For example, in the Maltese Islands, quantitative results from data generated from 11 Coupled Model Intercomparison Project phase 5 (CMIP5) models show that climate change will adversely affect natural freshwater supplies through increases in air temperatures, more heat extremes and fewer cold extremes, and decreases in cool season precipitation and stronger drought conditions (Galdies, 2022).

These changes are expected to affect the quantity and quality of aquatic, semi-aquatic and terrestrial habitats found in Mediterranean IRES (Kroll et al., 2017). The effects of ambient temperature increase that will have on streambed temperature and flow regimes also depend on the timing of the increase (Morrill et al., 2005). If stream water temperatures increase, especially at critical times of the year, water quality would be adversely affected, leading, for example, to shifts in aquatic biota due to prevailing anoxic conditions (Morrill et al., 2005). Different land cover also influence stream flow water temperature variations. However, little is known on the specific local and catchment-scale characteristics and their interactive influences on the magnitude and spatio-temporal patterns that cause thermal pollution in streams (Somers et al., 2013). Different soil processes such as heterotrophic respiration and biotic phenological activities may also be triggered with rising temperatures, potentially creating conditions more suitable for the expansion of non-native and/or invasive species (Acuña & Tockner, 2010; Martin et al., 2012). Hence, the better understanding of temperature responses to specific rainfall events and drying and re-wetting of the streambed is crucial to identify potential impacts to the abiotic and biotic components making up Mediterranean IRES, especially in the face of a changing climate.

The understanding of the complex dynamics generated in Mediterranean IRES catchments with diverse characteristics, from different precipitation events, and how these vary in different seasons, is crucial to conserve and manage these watercourses. This paper addresses the above-mentioned research gaps by analysing high-resolution (30 min) precipitation data and streambed temperatures collected from October 2019 till December 2020 from Mediterranean IRES found in six different catchment areas in the island of Malta. The research aims were to examine water level and streambed temperatures responses following precipitation events that occurred during the monitoring period and compare water level and temperature responses to rain events between catchments with different physiographic and land cover characteristics, to enhance our understanding of thermal and hydrologic dynamics in Mediterranean IRES.

3.2 Methodology

3.2.1 Study areas

The hydrological flows in Malta's watercourses are primarily driven by climate that is characterized by the annual total precipitation of 553.1mm and mean temperature of 18.6°C, with a mean maximum of 22.3C° and mean minimum of 14.9°C (Galdies et al., 2016; Galdies, 2022) and the karstic geomorphological topography. The Maltese Islands are mainly composed of limestone with variations provided by two thin strata, one of Greensand and one of Blue Clay, the latter being the only rock having a relatively impermeable lithology. Phreatic groundwater bodies are sustained in the Upper Coralline Limestone formation perched over the Blue Clay aquitard (SEWCU & ERA, 2015). Natural springs emerge from fractures at the edges of the perched aquifers, contributing to elongated flow periods in several watercourses, when compared to ephemeral streams that mostly experience flows only after specific precipitation events. The original horizontal structure of the strata has also been influenced by tilting and numerous fault lines that run along with two basic patterns (Anderson, 1997). In addition, throughout the Islands, flows have also been anthropogenically altered. In-stream changes include the construction of impoundments such as small dams or weirs and surface water abstraction for agricultural purposes. Some are sustained by effluents from small-scale industrial activities or seepages originating from irrigation of agricultural fields. Catchment-wide flow alterations include groundwater abstraction and water capture from private natural springs contributing to reduced flows. Field Observations were carried out in six different IRES (Table 3.1; Table 3.2; Figure 3.1) found in the island of Malta, located in the centre of the Mediterranean basin.

Table 3.1. Overview description of the Mediterranean IRES case study sites.

Case Study Site	Description
Wied Babu	Wied Babu is a coastal valley gorge which is partially inundated (ria) due to eustatic sea level rise that occured following the last ice age. The gorge was formed through a combination of rifting along the NW-SE trending Magħlaq fault and hydraulic erosion during the wetter Pleistocene period. The valley's steep and rocky sides, interspersed with numerous cliff-dwelling plant communities, offer a shaded valley-bed environment which is dominanted by numerous woody and riparian plants, including endemic specimen of high conservation value. These are however being threatened by the invasive and non-native vine *Cardiosperum grandiflorum.*

Wied Ħarq Ħammiem	The catchment area of Wied Ħarq Ħammiem is predominantly built up (Table 3.2) apart from a small (approx. 44,000 sq m) upstream area, known as Wied Mejxu, which is mostly invaded by *Arundo donax* and the downstream section of the valley, known as Wied Ħarq Ħammiem (approx. 64,000 sq m), making only eleven % of the watercourse that is not entirely urban. The mouth of the valley is disconnected from the coast by a touristic complex. A road is also separating the watercourse and the sandy coastline of Saint Georges' Bay where a sand nourishment project was carried out in 2004. The watercourse is connected to the sea via culverts passing through the hotel and underneath the road. The valley bed at Wied Ħarq Ħammiem is fairly secluded and include parcels of well structured habitats that are however interspersed with numerous IAS specimen.
Wied tal-Ġnejna	The Wied tal-Ġnejna catchment sits on two perched aquifers. Groundwater seepage gave rise to a theatre-shaped head formation in the valley (Micallef et al., 2022). The land cover is predominantly agricultural with active fields and numerous patches of recently abandoned fields. A straight concrete dam is found in the middle section of the watercourse. Many sections of the channel are occluded with dense *Arundo donax* stands.
Wied ta' Miġra l-Ferħa	Wied ta' Miġra l-Ferħa is a rural catchment, with most land cover consisting of abandoned agricultural fields and terraces. The catchment is found on Rabat/Dingli Perched Aquifer and large sections of the water channel are dominated by dense *Arundo donax* reeds.
Wied il-Luq	Wied il-Luq sub-catchment is found upstream within the largest catchment of the Maltese Islands. Numerous springs from the perched aquifer used to naturally flow and/or directed in the valley, however nowadays, only one spring is operational and is used to irrigate an orange grove that was planted in the early 20th Century. The valley has been extensively modified over the past 200 years, through the installation of reinforced dry-stone and ashlar walls, game enclosures, irrigation systems including the source of an aqueduct, and agricultural and afforrestation projects. The watercourse sustains the most prominent riparian woodland habitat in the Maltese Islands, which is also threathened by the invasion of dense *Arundo donax* stands.
Wied il-Baħrija	Wied il-Baħrija catchment is intensively cultivated. The watercourse is known to sustain extended flow periods due to the presence of springs flowing from the underlying perched aquifer. Most springs are privately-owned and used for irrigation purposes. Surface water is also pumped throughout the watercourse, including from an open second-class water reservoir this is located in an upstream part of the channel. The valley is an important habitat for the locally threatened Freshwater Crab (*Potamon fluviatile*). Most of the water channel is occluded with invasive *Arundo donax* reeds.

Table 3.2. General characteristics of the Mediterranean IRES case study sites.

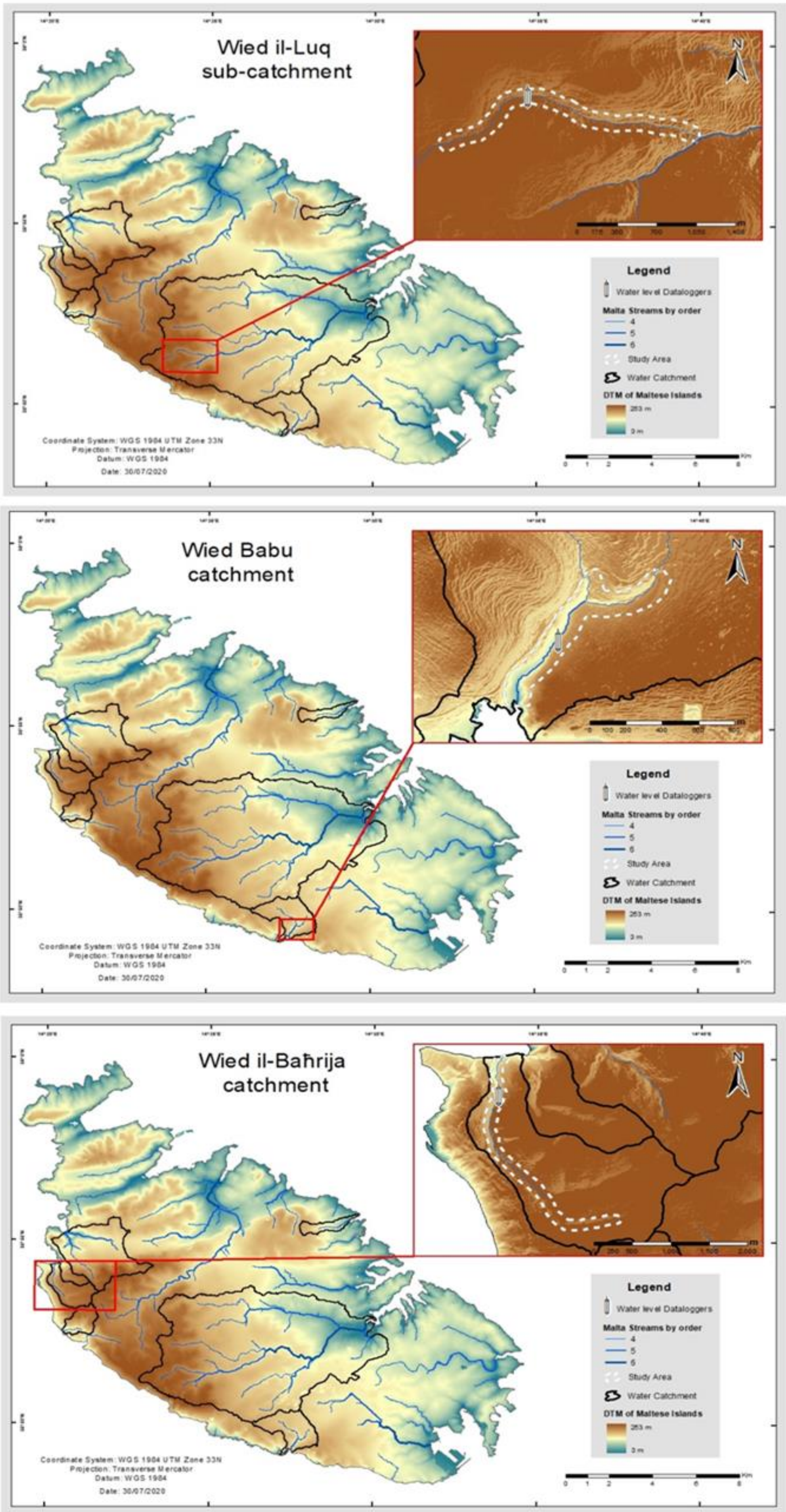
Case study site	Hydrogeology	Catchment Area (km²)	Stream order of watercourse where streambed temperature was recorded	Urban cover (%)**	Agricultural land cover (%)**	Semi-natural areas (%)*
Wied il-Luq	Rabat/Dingli Perched Aquifer	48	5	16	62	5
Wied il-Baħrija	Rabat/Dingli Perched Aquifer	2.4	6	13	41	46
Wied ta' Miġra l-Ferħa	Rabat/Dingli Perched Aquifer	1.67	5	0	38	62
Wied Babu	Ephemeral	3.38	6	26	55	19
Wied tal-Ġnejna	Rabat/Dingli and Mġarr/Wardija Perched Aquifers	5.46	6	8	63	29
Wied Ħarq Ħammiem	Ephemeral	0.95	5	86	14	0

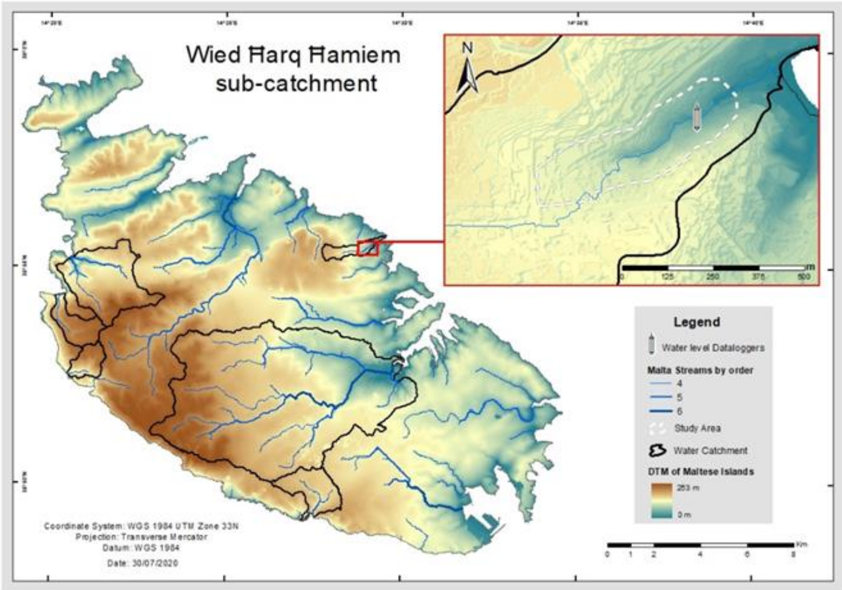
*data from Corine Land Cover 2018

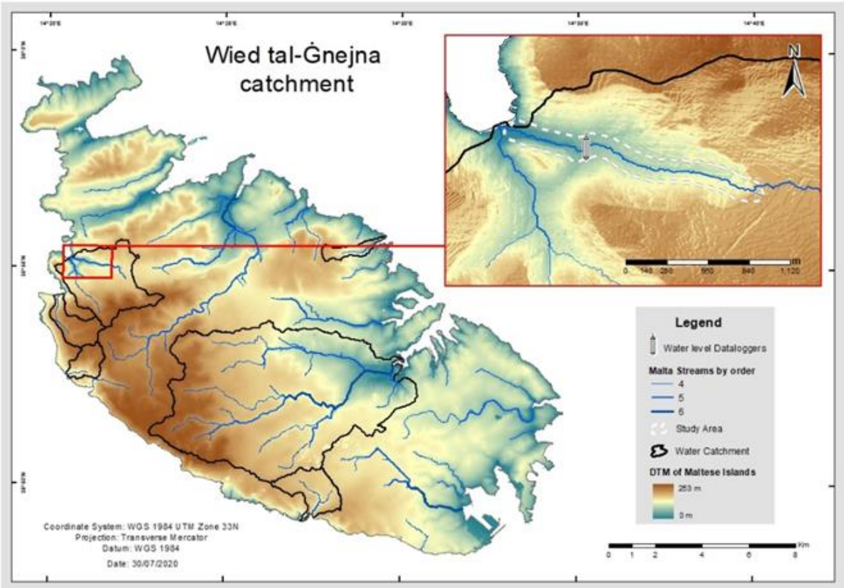
3.2.2 Data collection

Streambed temperatures (°C) and stage height data (m) were monitored using Onset HOBO U20L – 04 research-grade data loggers with a water-resistant polypropylene housing. In view of the high probability that loggers get silted or buried and/or washed away in highly turbulent systems such as IRES (Nelson & Palmer, 2007), each device was also fitted within HOBO U2X Protective Housing. In addition, they were fixed within a concrete block and tethered to an anchor point (Figure 3.2) to avoid displacement during storm events. According to the devices' technical specifications, water level accuracy varied with a typical error of 0.4 cm and maximum error of 0.8cm of water stage height. As such, water level readings <0.1cm were removed from the dataset to account for the potential logger error.

Figure 3.1. Map of the case study areas including location of the monitoring sites.




Wied Ħarq Ħamiem
sub-catchment
Legend
Water level Dataloggers
Malta Streams by order
Study Area
Water Catchment
DTM of Maltese Islands
Coordinate System: WGS 1984 UTM Zone 33N
Projection: Transverse Mercator
Datum: WGS 1984
Date: 30/07/2020


Wied tal-Ġnejna
catchment
Legend
Water level Dataloggers
Malta Streams by order
Study Area
Water Catchment
DTM of Maltese Islands
Coordinate System: WGS 1984 UTM Zone 33N
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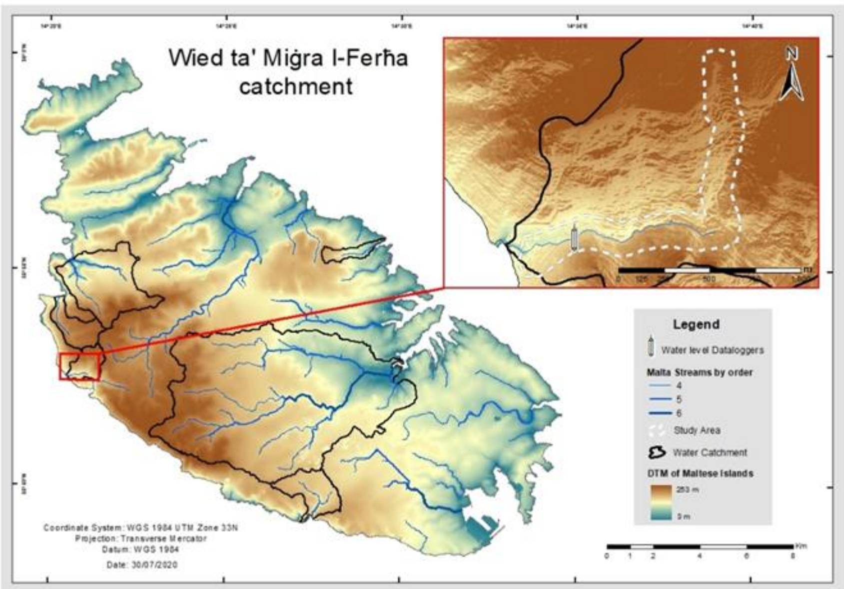
Datum: WGS 1984
Date: 30/07/2020


Wied ta' Miġra l-Ferħa
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Water level Dataloggers
Malta Streams by order
Study Area
Water Catchment
DTM of Maltese Islands
Coordinate System: WGS 1984 UTM Zone 33N
Projection: Transverse Mercator
Datum: WGS 1984
Date: 30/07/2020

Figure 3.2. Onset HOBO U20L-04 with HOBO U2X Protective Housing deployed at Wied ta' Miġra l-Ferħa case study site.

Site visits were carried out at least every two months to remove any accumulated debris and ensure that loggers were correctly functioning. The probes were programmed to make temperature and water level measurements at a 30-min sampling frequency resulting in a datalogger capacity of a maximum of 14 months determined by the chosen sampling frequency and loggers' memory capacity. One logger was deployed in each case study site (a total of six loggers). Data were uploaded in-situ by connecting the U-DTW-1 Waterproof Shuttle which in turn was connected with a laptop. For water level, the loggers recorded absolute pressure data. The Barometric Compensation Assistant tool within the HOBOware PRO version 3.7.23 application was used to compensate the recorded pressure data with atmospheric pressure collected from the Malta Airport Meteorological Office at Luqa, Malta (WMO: 16597), corrected to sea level pressure (QNH) and transposed to stream water level. Precipitation (mm) at 30-min intervals was provided by the Malta Airport Meteorological Office for three weather recording stations found outside the studied catchment areas but located in the proximity of the case study sites (Dingli, Luqa and Msida).

Data were collected from 22 October 2019 (Wied Ħarq Ħammiem, Wied il-Luq and Wied ta' Miġra l-Ferħa) and 25 October 2019 (Wied Babu, Wied il-Baħrija, Wied tal-Ġnejna) to 31 December 2020. The monitoring timeframe proved to be one of the driest periods in Malta in the last 50 years (Figure 3.4). Most precipitation events were small, the majority of which not surpassing 0.4 mm of rainfall (Figure 3.3). As a result, a descriptive analysis approach including graphs, mean, maximum and standard deviation of 30-minute interval in-stream temperatures, water stage height and precipitation data and Pearson's correlation coefficient (r) was adopted for the results' analysis. To identify whether there are linear relationships, correlation analysis was used to identify relationships between water level and in-stream temperature and lag response until highest recorded water level following precipitation. Pearson R correlation analyses the linear relationship between two continuous samples, assuming that both variables change in the same direction at a constant rate. The CORREL function in Microsoft Excel application was used carry out the statistical analysis for each sub-set values. Water level response times were quantified by adding the time from any rain event that occurred in the nearest available weather station until the highest water level result <0.1cm was detected. Temperature responses were obtained by calculating the difference in streambed temperature when the highest water level was recorded and the stream temperature during the precipitation event.

Figure 3.3. Precipitation event size histograms for the three weather stations used in this study.

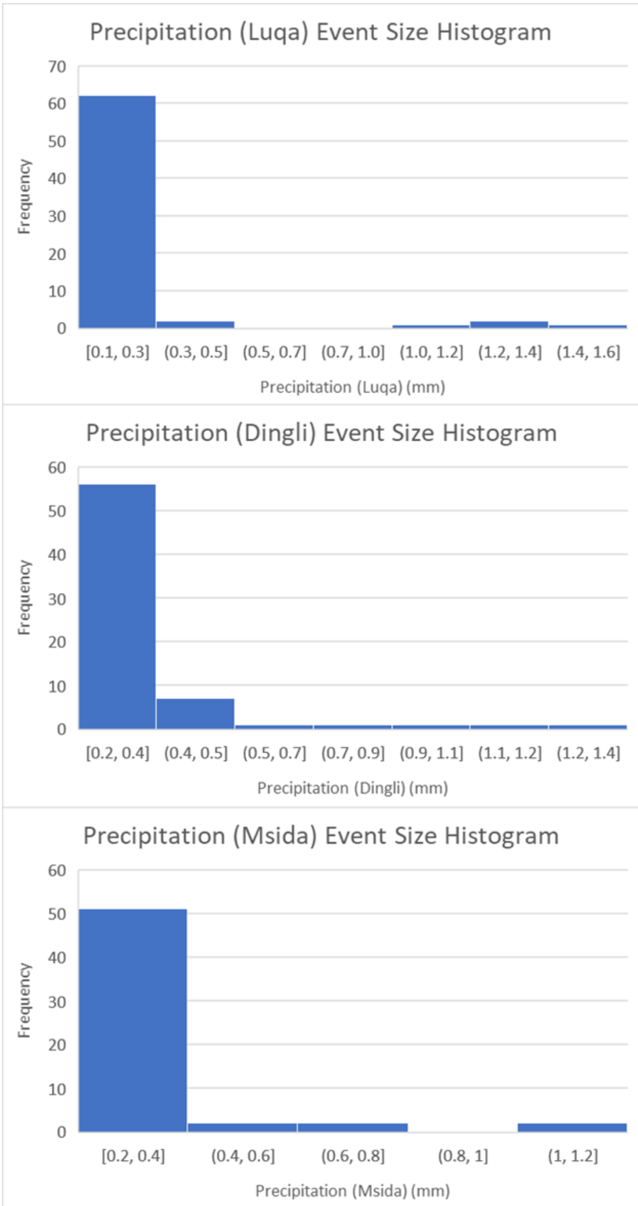
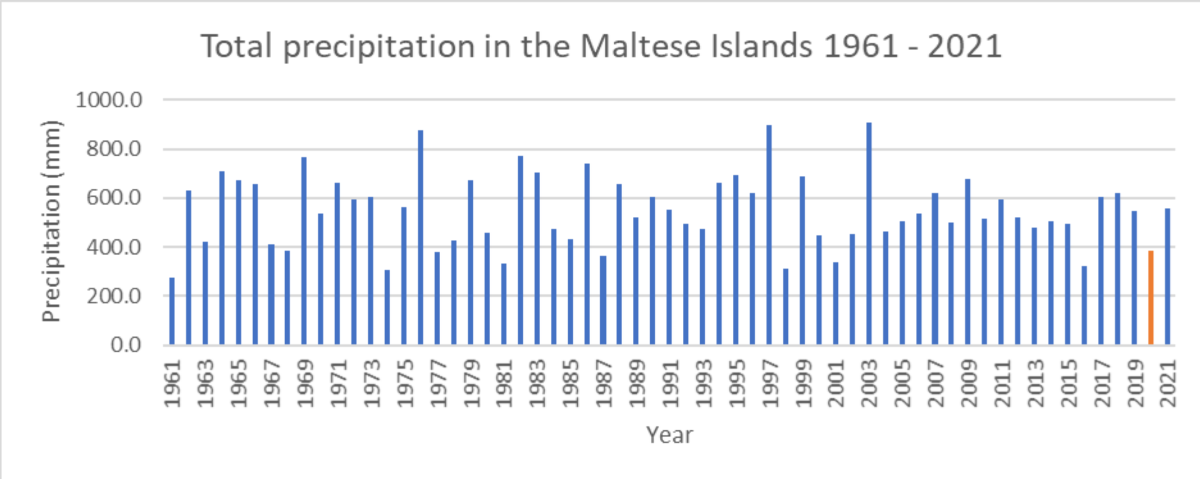


Figure 3.4. Annual precipitation total of the monitoring period in comparison with the last 50 years.



*data extracted from https://www.dwd.de/ for WMO Climate Station: 16597

3.3 Discussion and results

3.3.1 Relationship between stream level and precipitation events

3.3.1.1 Spatial patterns in stream water levels

There was considerable variability in water levels across the six case study catchments. Little water was detected during the monitoring period at Wied Babu. Only 20 water level readings registered above 0.1cm, with only 0.09% of the recordings at 30-minute interval detecting incidence of water (Table 3.3), thus with a high probability that no water flowed in the watercourse or at the location of the sensor during the study. 74% of the catchment area constitutes agricultural and semi-natural land uses which primarily include permeable surfaces. The precipitation recorded during the monitoring period of 384.4mm was well below the annual mean precipitation of 553.1mm (Galdies et al., 2016; Galdies, 2022) in the Maltese Islands. Hence, in view of being a relatively dry year, this potentially rendered the soil unsaturated for a longer period, leading to increased infiltration capability during rain events resulting in reduced surface flows accumulating along the valley bed.

Water level was recorded at one point of time or another in all the other five case study sites. Wied ta' Miġra l-Ferħa, Wied tal-Ġnejna, Wied il-Luq and Wied il-Baħrija recorded water level highs of 0.285mm, 0.159mm, 0.267mm and 0.644mm respectively. Wied Ħarq Ħammiem recorded the highest water level at 0.81mm. Wied il-Baħrija and Wied il-Luq were the two streams with the highest percentage of recordings detecting water level with 39.46 % and 27.55% respectively (Table 3.3). These sites are in fact known for the presence of perennial springs that formed naturally from impermeable blue clay outcrops in perched aquifer systems that provide extended periods with water flow following rain events. Wied il-Baħrija is, in fact, one of the few sites in the Maltese Islands that provides a habitat with perennial water flow required for the survival of the freshwater crab (*Potamon fluviatile*). This species is the largest known indigenous freshwater decapod which has a Nearly Threatened status in the IUCN Red list due to its highly fragmented population distribution (Vella & Vella, 2020). Even though having differing land uses and topographical characteristics Wied tal-Ġnejna, Wied Ħarq Ħammiem and Wied ta' Miġra l-Ferħa had similar percentages of recorded water level readings with 2.04 %, 2.08 % and 2.46 %, respectively.

Table 3.3. Percentage of water level (m) readings recorded at 30-minute intervals during the monitoring period.

Case Study site	% of water level (m) recordings (at 30minute intervals) during sensor deployment period*
Wied il-Luq	27.55%
Wied il-Baħrija	39.46%
Wied ta' Miġra l-Ferħa	2.46%
Wied Babu	0.09%
Wied tal-Ġnejna	2.04%
Wied Ħarq Ħammiem	2.08%

*Only values $\geq$ 0.1mm were considered for water presence to account for sensor error

Numerous precipitation events did not trigger water level responses in the catchments. This may be due to multiple factors. First, the weather stations used for precipitation data are all found outside the catchment boundaries, and thus, precipitation recorded may not have occurred within the case study sites. Secondly, no water level responses after rain events were more evident during the autumn months, especially in catchment areas with primarily rural land uses. Following the reduction in soil moisture content during the dry and hot summer period, the soil's water retention capacity is potentially greater, reducing the amount of surface flows reaching the watercourses. In addition, anthropogenic water-retention structures such as wells, reservoirs and dams are also empty, potentially contributing to reduced flow regime in the water channels.

3.3.1.2 Catchment responses to precipitation

Considerable variations in peak water level responses following precipitation events were noted between the catchment case study areas (Table 3.4). The shortest lag times were monitored at Wied Ħarq Ħammiem and Wied il-Baħrija with mean response times of 2.6 hrs and 2.1 hrs respectively (Table 3.4 and Figure 3.5). The predominant urban land cover and the impermeable surfaces found ubiquitously at Wied Ħarq Ħammiem catchment, may have contributed to the rapid water level responses. This case study site is also the smallest monitored catchment, and thus surface water travels in shorter distances until reaching the watercourse. On the contrary to Wied Ħarq Ħammiem, Wied il-Baħrija catchment area is mostly rural. Numerous perched aquifer springs flow into the, even though many of them are privately-owned[1] and diverted for irrigation purposes. A dam is also found upstream from the location of the deployed water level datalogger, however, the reservoir behind the dam was entirely silted during the monitoring period, and thus did not considerably influence the flow regime. The rapid water level responses following rainfall events in this catchment may be contributed to the surface water emerging from spring overflow, that also resulted in Wied il-Baħrija having the longest periods where water level was detected during the monitoring period (Table 3.4).

Table 3.4. Characteristics of water level response lag time periods (hrs).

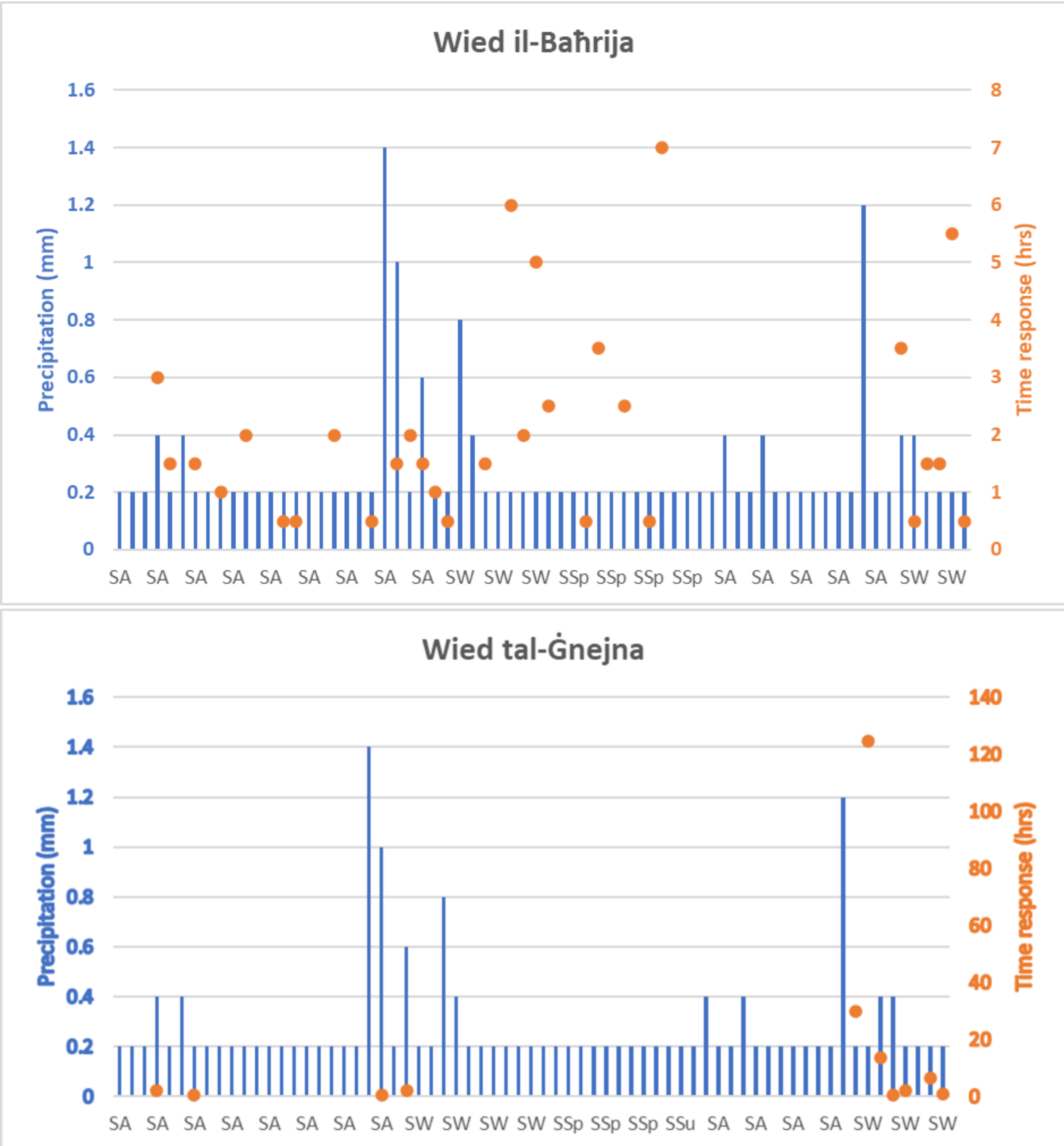
Case study site	Average maximum water level response time (hrs)	Minimum response time (hrs)	Maximum response time (hrs)	Most frequent response time (hrs)
Wied il-Luq	15.3	1	69	1.5
Wied il-Baħrija	2.1	0.5	7	0.5
Wied ta' Miġra l-Ferħa	6.8	0.5	26	1.5
Wied tal-Ġnejna	16.6	0.5	124.5	2
Wied Ħarq Ħammiem	2.6	0.5	13	2

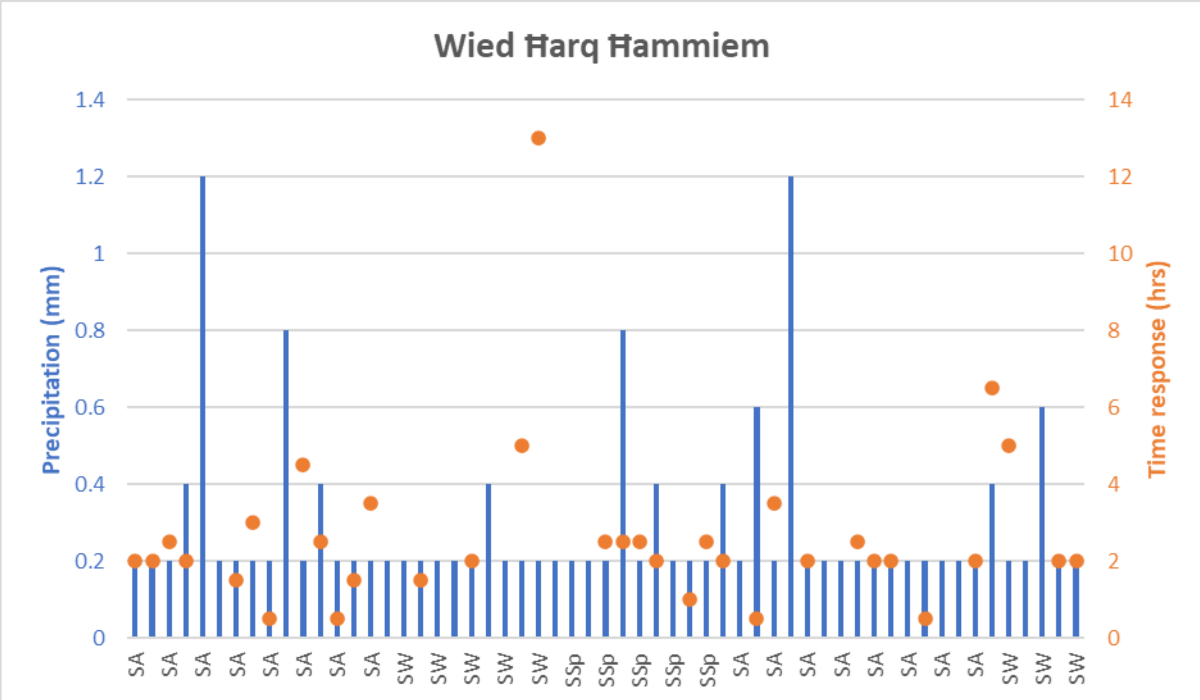
Water level responses at Wied tal-Ġnejna were only detected following 0.4mm rainfall events or greater. The response lag times in this catchment were also the longest with a mean of 16.6 hours. This may be attributed to the large size of the catchment compared to the other case study sites. However, the most frequent response time logged following rain events was still 2 hours, similar to Wied Ħarq Ħammiem. Wied tal-Ġnejna catchment is very similar to Wied il-Baħrija, in terms of the predominant rural land uses and the presence of privately-owned perched aquifer springs. In addition, the sensor was also deployed downstream from a dam that was silted up during the data collection period. However, Wied tal-Ġnejna manifested significantly different water level regime responses from Wied il-Baħrija. This can be attributed to the catchment size, Wied tal-Ġnejna catchment is double the size of Wied il-Baħrija watershed (Table 3.2), increasing the probability of surface water being drained in the soil or captured in man-made water retention facilities before reaching the watercourse. In addition, Wied tal-Ġnejna agricultural land cover is 63% compared to Wied il-Baħrija which is at 41% (Table 3.2), thus with a higher probabilty that surface water is captured for agricultural and irrigation purposes. Wied ta'

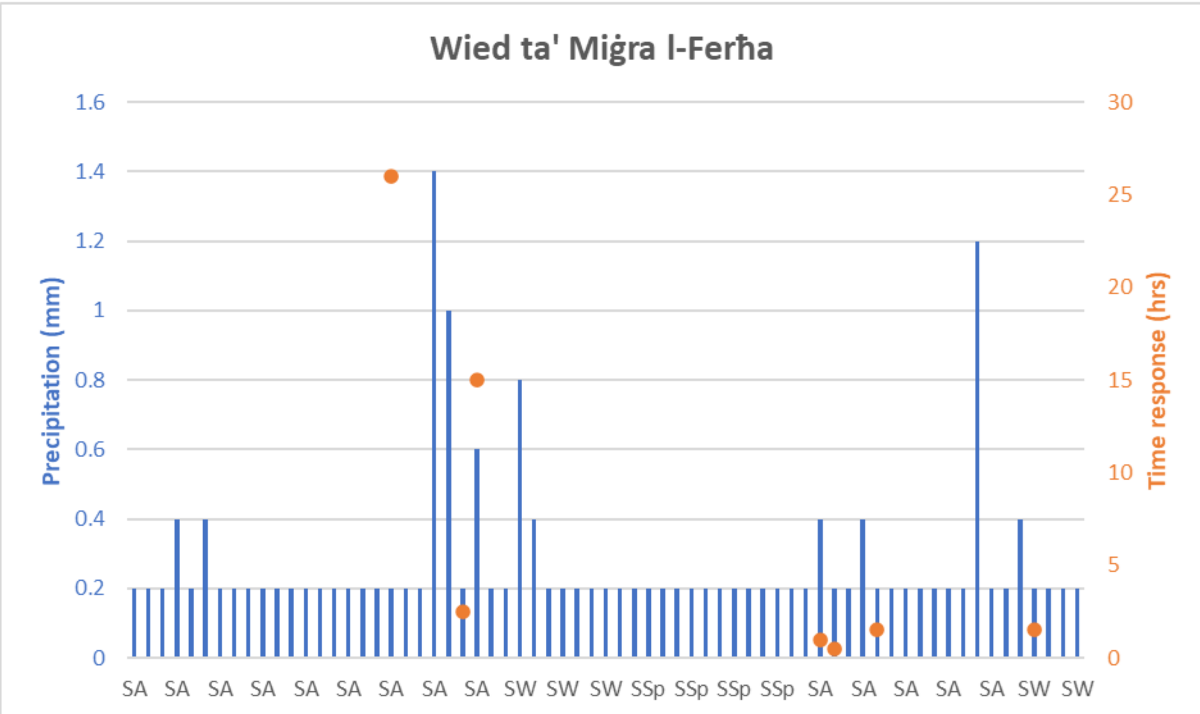
[1] Data provided by the Malta Resources Authority (MRA) in June 2022

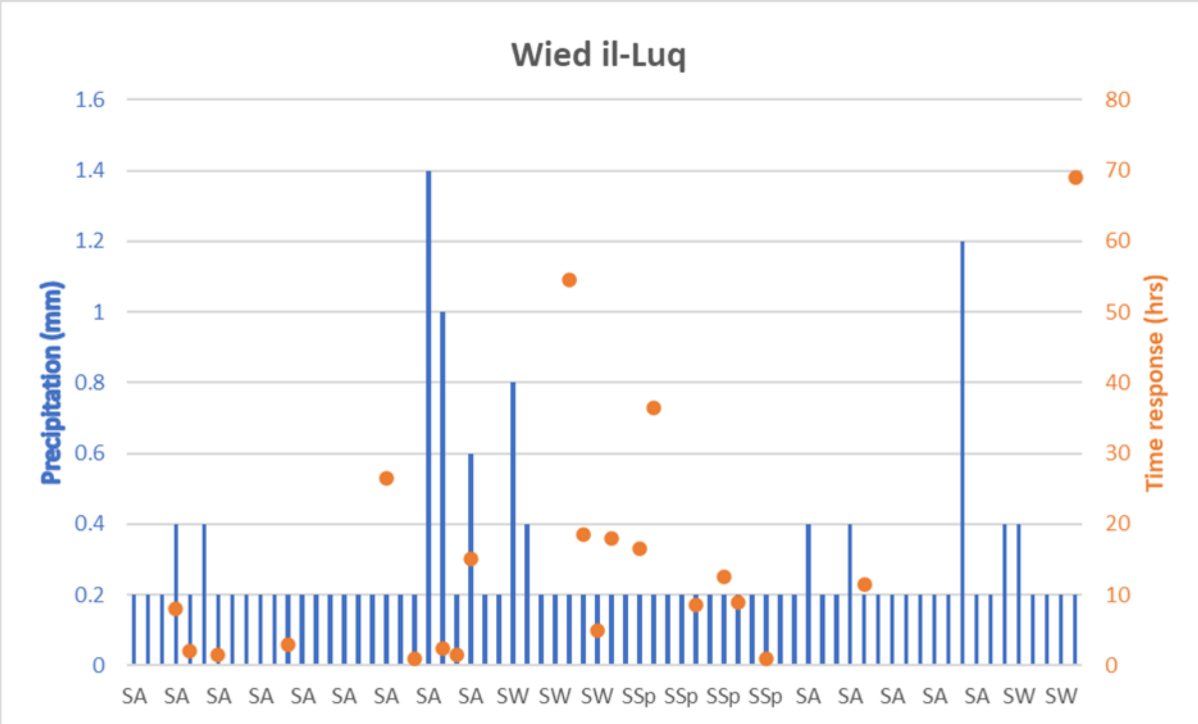
Migra l-Ferħa water level response behaved similarly to Wied tal-Ġnejna. This catchment is similar to Wied tal-Ġnejna albeit much smaller in size and with more predominant semi-natural/rural land cover compared to the agricultural land use primarily found at Wied tal-Ġnejna. The similar patterns can be noted in figure 3.5, with the main difference being that fewer water level events were recorded at Miġra l-Ferħa. Pearson's correlation results indicate that most catchments have negative relationships between precipitation and the lag time response for peak water levels, meaning that larger rain events contribute to shorter lag time responses (Table 3.5).

Figure 3.5. Response times until peak water level following the occurrence of precipitation events.




Wied Ħarq Ħammiem
Precipitation (mm)
Time response (hrs)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
14
12
10
8
6
4
2
0
SA SA SA SA SA SA SA SA SW SW SW SW SW SSp SSp SSp SSp SSp SA SA SA SA SA SA SA SA SW SW SW


Wied ta' Miġra l-Ferħa
Precipitation (mm)
Time response (hrs)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
30
25
20
15
10
5
0
SA SA SA SA SA SA SA SA SA SW SW SW SSp SSp SSp SSp SA SA SA SA SA SW SW

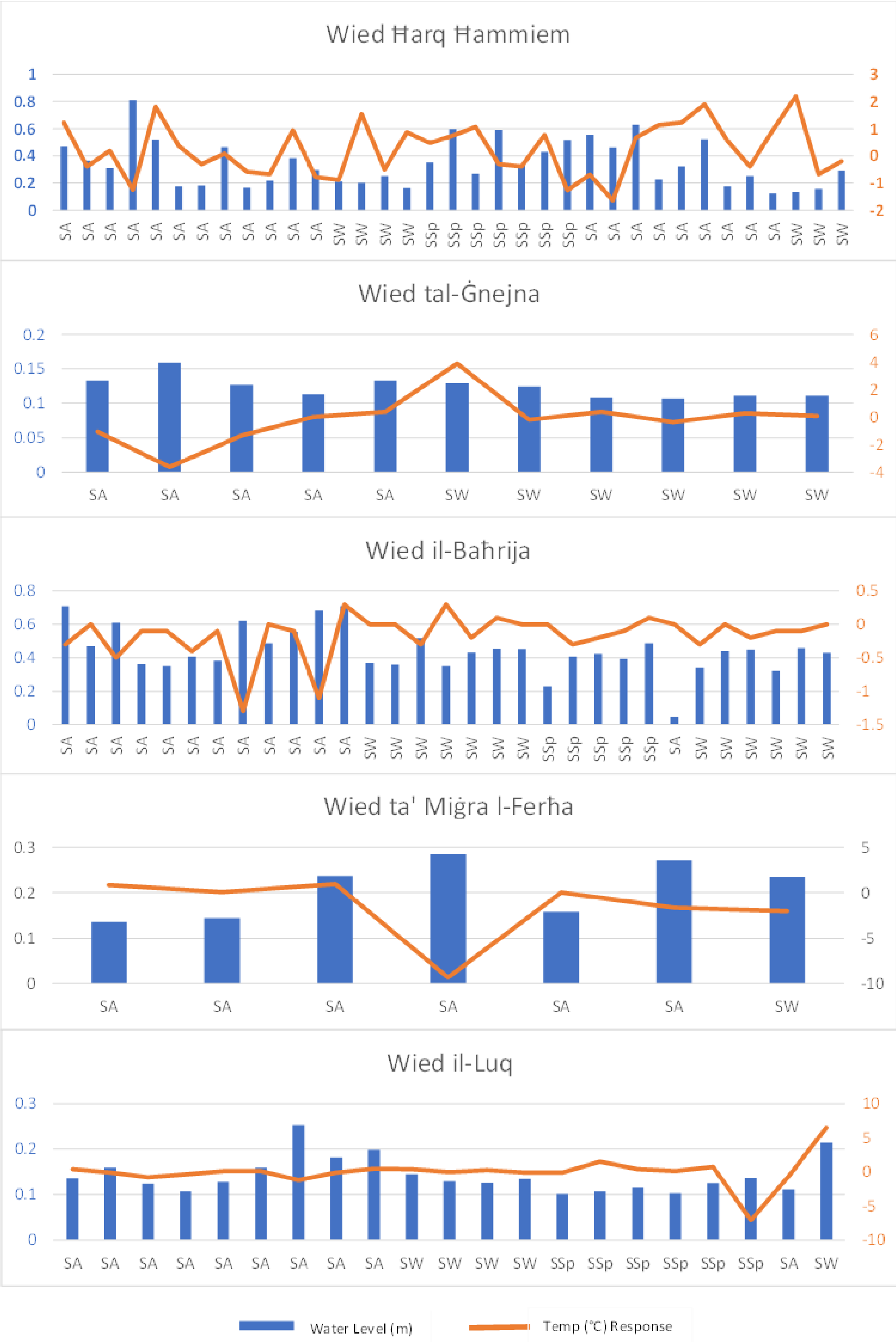


3.3.2 Relationship between in-stream temperatures and water presence

Table 3.5. Descriptive statistics of in-stream temperatures (°C).

Case Study site	Minimum recorded temperature (°C)	Maximum recorded temperature (°C)	Range (°C)	Mean (°C)	Standard Deviation (°C)
Wied il-Luq	8.18	28.85	20.67	18.09	3.21
Wied il-Baħrija	8.6	29.1	20.5	18.19	4.41
Wied ta' Miġra l-Ferħa	5.24	38.82	33.58	19.82	6.61
Wied Babu	2.73	31.88	29.15	16.83	5.29
Wied tal-Ġnejna	7.48	37.71	30.23	19.56	5.24
Wied Ħarq Ħammiem	6.57	35.97	29.4	18.53	5.99

Figure 3.6. Temperature change response at streambed peak water level following precipitation events.



Water level dataloggers were deployed in shaded areas at Wied il-Luq, Wied il-Baħrija and Wied Babu, whereas at Wied ta' Miġra l-Ferħa and Wied tal-Ġnejna, the loggers where stationed in more exposed surfaces. The positioning of the sensors may have contributed to the recorded temperatures as the overall mean values at Wied ta' Miġra l-Ferħa and Wied tal-Ġnejna are higher than the other case study sites. Wied il-Baħrija and Wied il-Luq case study sites have the lowest statistical dispersion of stream temperature values throughout the monitoring period. Both sites have the lowest stream temperature ranges and lowest standard deviation (Table 3.5). This may be attributed to the prolonged periods of detected water presence in both streams which may have also influenced the temperature values as both sites have the highest recorded minimum temperature levels. Conversely, the lowest minimum temperatures were recorded from Wied Babu, where nearly no water level data was logged during the monitoring period. This may be attributed to the steep sides and deep gorge morphology and dense riparian vegetation along the valley-bed providing shade and cooler micro-climatic conditions.

Following precipitation, the temperature response at peak valley bed water level had an average of 0.23 °C (Table 3.6) with Wied Ħarq Ħammiem, a predominantly urban catchment (Table 3.2), showing the highest response from all the case study areas with considerable temperature response peaks when compared to the other sites (figure 3.6). Urban stream water temperatures are highly variable and subject to short-term peaks and throughs during high-intensity rainfall events (Croghan et al., 2019). Greater developed surface areas should in fact contribute to higher baseflow temperatures in watercourses (Somers et al., 2013). The upstream hydrological connections to impervious surfaces and stormwater infrastructure such as culverts and the increased incident solar radiation due to limited vegetation and canopy cover may have contributed to the higher streambed temperature responses at Wied Ħarq Ħammiem. In addition, rapid heat-transfer between precipitation and surfaces with a low specific heat-capacity such as the typically dark colour used for the infrastructure, can heat quickly and reach higher than normal temperatures, exceeding air temperature on warm days (Berdahl & Bretz, 1997; Croghan et al., 2019).

Table 3.6. Characteristics of streambed temperature response following precipitation events.

Case Study site	Temperature change response (°C)		
	Mean	Min.	Max.
Wied il-Luq	0.02	-7.09	6.48
Wied il-Baħrija	-0.16	-1.3	0.3
Wied ta' Miġra l-Ferħa	-1.57	-9.29	0.95
Wied tal-Ġnejna	-0.13	-3.62	3.9
Wied Ħarq Ħammiem	0.23	-1.63	2.19

Compared to the distinct temperature pulses recorded at Wied Ħarq Ħammiem, temperature variations following precipitation events at peak water level were much more stable in the other catchment case study sites. Webb et al. (2003) found out that short-term stream temperature was more influenced by water discharge and air temperature was more impactful on stream temperature over more extended periods. This can explain the minimal temperature change responses recorded at Wied il-Luq and Wied il-Baħrija as both streams showed longer periods of water level readings. Wied il-Baħrija has strong linkages with groundwater springlines and the associated aquifer discharges whereas at Wied il-Luq the intermittent flow of water is known to occur from a broken spring water collection pipe that was formerly part of the water collection system of the Wignacourt Aqueduct sytem that was constructed by the Hospitaller Order of Saint John administration in the 17th Century to deliver water to the capital city of Malta. Surface water flows originate from a perched aquifer spring known as Ta' Sala. The spring water is primarily used for the irrigation of an orange grove planted in the early 20th century and the overflow water is then re-directed into the valley bed. Groundwater seepage into streams is known to moderate stream temperatures by providing relatively cool input in summer and warm input in winter, creating local thermal and climate refugia for aquatic biota (Kaandorp et al., 2019). In both Wied il-Baħrija and Wied il-Luq, the monitored seasonal mean temperature responses provided a moderate water temperate affect. At Wied il-Baħrija these stood at -0.3 in autumn, -0.06 in winter and -0.1 in spring and at Wied il-Luq, the average temperature variations resulted in -0.17 in autumn, 0.14 in winter and -0.73 in spring. The lowest mean temperature responses were recorded at Wied ta' Miġra l-Ferħa. The water level readings did not indicate intermittent water level responses, however, this does not preclude potential upstream aquifer seepage as geologically, the catchment sits on the Rabat/Dingli perched aquifer. However, the dense riparian cover dominanted by *Arundo donax* reeds may be the main contributer to the lowering of temperature levels of the surface waters. At Wied tal-Ġnejna, temperature variations were also relatively stable, with a decrease in temperatures trend during autumn events, and an increase in temperature trend following winter precipitation events.

Pearson's correlation results indicate that both positive and negative associations between water level (m) and stream temperature (°C) values exist (Table 3.7). The strongest negative relationship was found at Wied il-Baħrija indicating that the higher the water level the lower the recorded temperatures. High water levels at Wied il-Baħrija were potentially sustained from groundwater springs, resulting in lower water temperatures. A negative association was also noted at Wied tal-Ġnejna and Wied il-Luq, the latter also probably resulting from cooler water originating from a perched aquifer spring. The strongest positive correlation was noted at Wied Babu, followed by Wied ta' Miġra l-Ferħa and Wied Ħarq Ħammiem. The positive relationship at the latter is potentially linked with the rapid heat transfer capabilities of the mainly urban surfaces of the catchment whereas the fewer water level readings recorded at Wied ta' Miġra l-Ferħa and Wied Babu during the monitoring period may have contributed to the positive relationship result.

Table 3.7. Pearson *R* correlations for in-stream water levels temperatures and precipitation and lag time respones of highest water level readings.

Case Study site	**Pearson correlations**	
	water level (m) & stream temperature (°C)	**precipitation (mm) & lag time response following highest water level recorded (hrs)**
Wied il-Luq	-0.094	-0.169
Wied il-Baħrija	-0.524	-0.067
Wied ta' Miġra l-Ferħa	0.285	0.223
Wied Babu	0.432	n/a
Wied tal-Ġnejna	-0.158	-0.277
Wied Ħarq Ħammiem	0.218	-0.052

3.4 Study limitations

Data collection was carried out during one of the driest years in the Maltese Islands with the annual precipitation total of 384.4mm well below the annual mean of 553.1mm (Galdies et al., 2016). Furthermore, most rainfall events were diminutive, the majortity of which not exceeding 0.4mm of total precipitation and not longer than 30 minutes. Streamflow may generate in response to a single rain event but in other catchments, flow might be triggered following a series of precipitation events (Gutiérrez-Jurado et al., 2019) and thus, the limited variability of precipitation events during this study's monitoring period made it difficult to analyse, in more detail, thresholds that generate water presence along the streambed. A multi-year monitoring period would be ideal to enhance the possibilities of capturing more varied rain events and provide added temporal data variability. Moreover, the degree to which IRES respond to radiative and climatic forcing is also heavily dependent on land use and topographical composition of the catchment area, and is thus highly dynamic, complex and multi-faceted (Dugdale et al., 2018; Durfee et al., 2021; Laizé & Hannah, 2010). Water presence in IRES typically exhibits highly spatial variability within catchments due to the intrinsic catchment land cover and geomorphic characterteristics and thus, single point data collection stations are not enough to portray spatial explicitness. More sampling locations are required to capture water presence and streambed temperature responses to precipitation events and provide an improved understanding of both the longitudinal and lateral stream dynamics. In addition, the six dataloggers used in this study were deployed in varying conditions. The availability of more loggers would allow better analysis and comparison of results of data points within different environments including stream location and between shaded and unshaded areas, amongst others. Better precipitation data coverage, including specific catchment weather data would also be more respresentative of the potential rain events influencing the studied IRES. For example, Weather Radar precipitation data can be used to yield high temporal and spatial resolution that can quantify catchment-scale precipitation accurately and contribute for the analysis of precipitation processes that drive water temperature fluxes and flow regimes during single rain events (Croghan et al., 2019).

3.5 Conclusions and further research needs

By using 30-minute water-level and stream temperature readings spanning thirteen consecutive months from six different Mediterranean IRES found in Malta and precipitation records from three weather stations, this paper interprets hydrological and thermal response patterns following precipitation events in catchments with varying environmental and land cover characteristics. The study highlights links between water presence and temperature responses to precipitation and basin characteristics including the presence of perched aquifer surface water springs, land cover typologies and catchment size. In general, larger catchments had longer water level reponse lag times to precipitation episodes. Reduced water level responses to autumn rain events in rural areas indicated that the soil water retention capacity due to the reduced soil moisture content during the summer period and the empty water-retention infrastructure play an important role in governing flow presence in the studied streams. Whereas the smaller and predominantly urban catchment case study site, had the second most rapid water presence response times. This urban catchment, also showcased the highest average stream temperature peaks following rain events. On the contrary, the predominantly rural case study areas, that also have perched aquifer spring water contributions, manifested more stable temperature variations due to the spring water cooling effect in summer and warming influence in winter. Also, the lowest mean temperature responses were recorded at Wied ta' Miġra l-Ferħa, where the water stage height readings did not indicate the presence of spring water contributions, but the dense riparian cover dominanted by stands of *Arundo donax* reeds may led to the decreases in temperatures.

This study highlighted several critical areas for future research on the hydrological and thermal responses of Mediteranean IRES. The specific characteristics within catchment areas are fundamental in influencing the response processes of IRES. The study and categorisation of streamflow generation mechanisms, i.e the when, where and how flows respond to different precipitation episodes is crucial for better management responses, especially in response to climate change. More research need to focus on the specific local and catchment-scale variables and interactions on the magnitude and spatio-temporal patterns that cause hydrological and thermal variations in IRES (Somers et al., 2013). A better understanding of the landscape factors and basin properties that control spatio-temporal patterns of flow and thermal processes is needed. Additional focus should also be given to spring-fed intermittent watercourses. Intermittent groundwater dominated IRES are not only potentially more climate resilient than ephemeral streams with flows dependant only on precipitation, but also create a mosaic of additional habitats and thermal refugia for aquatic species (Kaandorp et al., 2019). Monitoring regimes must include data collection points from spring sources and a dense stream gauge/sensor network to better identify the influence of spring water on regime flows, hydrological states and thermal responses at high spatio-temporal dimensions.

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CHAPTER 4

MEDITERRANEAN INTERMITTENT RIVERS AND EPHEMERAL STREAMS: THE ROLE OF UNCREWED AERIAL VEHICLES (UAVs) IN DETERMINING RIPARIAN VEGETATION CONDITION

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Abstract

Current limitations in monitoring transient flow regimes that characterise Mediterranean IRES, limit the understanding of how hydrology influences riparian habitats along the stream continuum at various temporal scales. Monitoring solutions such as Uncrewed Aerial Vehicles (UAVs) combined with structure from motion (SfM) photogrammetry and Vegetation Indices (VIs) derived from visible images, have already been proved to be successful for the mapping of diverse vegetation types in different environments. However, the use of such applications to study the spatio-temporal variability of alternating dry and wet conditions in Mediterranean IRES does not appear to have been tested in a field setting. This study investigates the feasibility of four different RGB VIs to monitor and better understand links between in-stream water presence and vegetation condition. Statistical analysis demonstrated links between visible VI mean reflectance values with different streambed water level (m) categories. Reflectance values also showed seasonal trends where RGB VI values where highest when images were mapped during the winter period, alluding to good vegetation health. However, when reflectance values were compared with cumulative rain events, RGB VI values were low when images were captured in periods followed by the highest occurrence of rain events since the previous September. Inconsistent results confirmed the need for further research on the potential applicability of RGB VIs to monitor vegetation responses to streambed water presence and precipitation events including the categorisation of different catchment characteristics and landscape configurations and comparison with RGB VI reflectance values to better understand the results obtained from these indices.

4.1 Introduction

Intermittent and ephemeral streams (IRES) compose more than half of the earth's surface water networks. In the Mediterranean basin they are prevalent due to limited precipitation which is further exacerbated by the changing climate and intensive land uses (Skoulikidis et al., 2017). Understanding the impact of dynamic hydrological flows on the biophysical characteristics, and the influence of socio-economic activities in Mediterranean IRES is fundamental for the development of policy, and implementation of adapt management strategies (Borg Galea et al., 2019). Quantifying the temporal and spatially explicit variability of flow cessation is paramount for the understanding the anthropogenic impacts of climate change, water abstraction and flow regulation (Messager et al., 2021). IRES are in fact a surface water body type with the highest probability to experience altered hydrological regimes due to climate change (Dhungel, et al., 2016). The Mediterranean is expected to experience more frequent droughts and aridity, intensification of heavy rainfall and increased seasonality of precipitation, water availability and streamflow (Ali et al., 2022). Hence, understanding the response of aquatic, semi-aquatic and terrestrial habitats to changing climatic conditions and drying and wetting states in IRES is crucial.

There is a dearth of tools available to monitor the response of riparian corridors to dry and wet conditions of IRES, limiting the development of research in these streams (Moidu et al., 2021; Sarremejane et al., 2021). This accentuates the necessity for catchment-scale monitoring approaches encompassing the various gradients of flow intermittency to better investigate the drivers of ecological changes in IRES (Sarremejane et al., 2021). Current limitations in monitoring the spatio-temporal variability of flow regimes is hindering the understanding of the influence of hydrology on biota and abiotic features, their links with the provision of ecosystem services and the resilience of Mediterranean IRES (Acuña et al., 2020). Monitoring schemes must provide solutions to quantify the dynamic responses of biota to temporal hydrological variations and the other exogenous and endogenous natural and anthropogenically-induced changes that occur in Mediterranean IRES (Borg Galea et al., 2019). In addition, apart from being able to capture ecohydrological data at frequent intervals and over larger scales, such tools and schemes need to be cost-effective and reliable.

During recent decades, remote sensing techniques, such as satellite imagery and aircraft surveys, have emerged that capture spatially explicit data at a higher resolution and with frequent monitoring potential (Caruso et al., 2019; Woodget et al., 2017). However, to date, satellite images such as Sentinel-2 are limited to 10m resolutions and with a maximum revisit rate of sixteen days. Aircraft surveys can be planned more flexibly, but involve highly expensive and cumbersome organisation efforts to apply (Matese et al., 2015). Technological advancements and greater affordability of Uncrewed Aerial Vehicles (UAVs) combined with the recent development of Structure from Motion (SfM) photogrammetry techniques, provide novel opportunities for studying dynamic environmental changes in any given location (Lussem et al., 2018). In contrast to satellite imagery, UAVs can provide images even on cloudy days by taking images below cloud cover and offer the possibility to map smaller areas at very high resolutions (Marcial-Pablo et al., 2019). This is ideal to monitor Mediterranean

IRES with narrow riparian corridors, including lower-order streams that are ≤ 5 metres wide or with limited or no accesibility such as deep gorge dry valleys. Even though satelite imagery, such as Sentinel-2 imagery, can be super-resolved up to 2.5m resolutions through radiometric normalization and super-resolution network techniques, UAV imagery can achieve centimeter accuracy resolutions (Latte & Lejeune, 2020). In fact, results from UAV imagery have already demonstrated the ability to identify small-scale hydrological and habitat features that are important for the analysis of ecohydrological connectivity in IRES (Spence & Mengistu, 2016; Yang et al., 2019). Flow intermittence in Mediterranean IRES develops alternating "terrestrial" and "aquatic" phases along the river continuum, contributing to a complex mosiac of habitats types and ecological refugia for flora and fauna. These shifting habitat mosaics do not only vary spatially, but the extent, spatial arrangement and connectivity constantly change, following cycles of expansion and contraction (Datry et al., 2017; Larned et al., 2010). This means that ecosystem protection, restoration and management at the catchment, sub-catchment or even riparian habitat scale in Mediterranean IRES, does not only necessitate more accurate and detailed orthomosaics and Digital Elevation Models (DEMs), but also the capture of images at higher temporal resolution. This can be provided by UAVs, especially following their recent developments and upgrades that enable the acquisition of imagery data in a more rapid, flexible, convenient and efficient manner (Dash et al., 2018; Grau et al., 2021).

Accurately estimating the spatio-temporal expansion and contraction of habitat mosaics in Mediterranean IRES is key to providing better insights on the processes, especially the flow regime, that drive these dynamics. Flow alterations caused by human actions including climate change, construction of water-retention infrastructure such as reservoirs and weirs, surface and ground water abstraction for irrigation, water diversion, increase of impermeable surface and channelization contribute to vegetation and ecological change risks strongly associated with increasing magnitude of flow alteration (Tzoraki et al., 2016). Spectral indices obtained by satellite remote sensing have been widely used to understand phenological response and classification of vegetation types (Motohka et al., 2010). Many consumer-grade UAVs are versatile and can be equipped with a variety of miniaturized instruments such as near-infrared (NIR) cameras and thermal sensors (Caruso et al., 2019; Micieli et al., 2022). In various applications these have, in fact, replaced traditional measurement methods in biomass and fraction of vegetation coverage (FVC) detection due the high spatial resolution, high positioning accuracy, ease of use and decrease in costs (Agapiou, 2020; Guo et al., 2021). Both RGB and NIR cameras can be used to capture images and derive vegetation indices (VIs). These indices are mathematical combinations of visible and near infrared (NIR) spectral bands in the electromagnetic spectrum that can be used to quantify vegetation cover and health through the provision of data on chlorophyll concentration levels (Bendig et al., 2015; Tóth, 2018).

VIs have been widely used for agricultural applications including estimations of plant health (DadrasJavan et al., 2019), biomass monitoring (Bendig et al., 2015; Marín et al., 2020) , crop biophysical properties including phenology, yield and growth patterns (Marino & Alvino, 2021; Sakamoto et al., 2011; Tunca et al., 2018; Wahab et al., 2018; Yeom et al., 2019), nitrogen status (Benincasa et al., 2018; Muñoz-Huerta et al., 2013; Viña et al., 2011), amongst others. The majority of VIs require data from non-visible spectral bands (e.g., the NIR band). The most regularly used VI is the normalized difference vegetation index (NDVI) which uses multispectral information based on the difference between the maximum absorption of radiation *R* as a result of chlorophyll pigments and the maximum reflectance in NIR spectral region a a result of leaf cellular structure (Tucker, 1979). However, affordable and light-weight off-the-shelf consumer UAVs equipped with sensors capable of capturing invisible spectral bands are still rare in comparison to their 'conventional' RGB counterparts. Modification kits with sensors enabling consumer UAVs to capture near-infrared images exist but their cost and the likely violation of the drone's factory warranty after modification remain issues limiting their adoption (H. Zhao & Lee, 2020). Similarly, while pre-existing 'plug-and-play' multispectral drone sensors do exist (eg. MicaSense Altum, Sentera 6X), these sensors are often beyond the funds and expertise of riparian management organisations working in IRES. Hence, the acquisition of images in the visible bands (RGB) due to the easy access of consumer-grade high resolution cameras at low prices, weight and with instant mobility make these tools a more attractive choice for vegetation mapping (Xue & Su, 2017; H. Zhao & Lee, 2020).

The use of visible VIs from high resolution aerial photos proved to be successful for the mapping of diverse vegetation types in different environments including wetlands (Zhou et al., 2021), alpine ecosystems (Ide & Oguma, 2013), arctic valleys (H. B. Anderson et al., 2016; Parmentier et al., 2021), and desert where extracting vegetation coverage with at least 90% accuracy was achieved (Arnon et al., 2007; Ding et al., 2022). However, the combined use of UAVs and VIs derived from visible RGB to investigate the spatio-temporal variability of alternating dry and wet dynamics in Mediterranean IRES does not appear to have been trialled in a field setting. We argue that analysing high-resolution data with the use of affordable remotely sensed equipment will provide better understanding of the habitat responses towards the transient flows that characterise IRES. In this study, various VIs reflectance ranges derived from RGB data captured from UAVs are compared with precipitation data and water level readings collected from *in-situ* dataloggers in five different Mediterranean IRES case study sites. The objective of this research is to identify the feasibility of using cost-effective and off-the shelf UAVs, equipped with consumer-grade cameras and visible VIs to monitor and better understand links between in-stream water presence and vegetation health including FVC in Mediterranean IRES. Specifically: (i) explore VI RGB reflectance value trends with different water level and precipitation dynamics; and (ii) compare the performance of four different RGB VIs through the analysis of timeseries normalized mean reflectance values.

4.2 Methodology

4.2.1 Study areas

The study areas are five IRES reaches found in the island of Malta, located in the central Mediterranean basin (Table 4.1). Climate is the main driver of hydrological flows in Malta's surface water streams. The annual total precipitation of 553.1mm and mean temperature of 18.6°C, with a mean maximum of 22.3C° and mean minimum of 14.9°C, makes the islands relatively hot and dry (Galdies et al., 2016; Galdies, 2022). Flows are also determined by the islands' karstic geomorphology which is primarily made up of limestone with variations provided by two thin strata, one of Greensand and one of Blue Clay, the latter being the only rock having a relatively impermeable lithology. Phreatic perched groundwater bodies are sustained in the Upper Coralline Limestone formation perched over the Blue Clay aquitard (SEWCU & ERA, 2015). The original horizontal structure of the strata has also been influenced by a general West-East tilt and numerous fault lines that run along with two basic patterns, those trending NE-SW which dominate and those tending NW-SE (Anderson, 1997; Schembri, 1993). In addition, throughout the islands, flows have also been anthropogenically altered through the construction of impoundments such as small dams or weirs and/or are also sustained by effluents from small-scale industrial activities.

Table 4.1. General characteristics of the Mediterranean IRES case study sites.

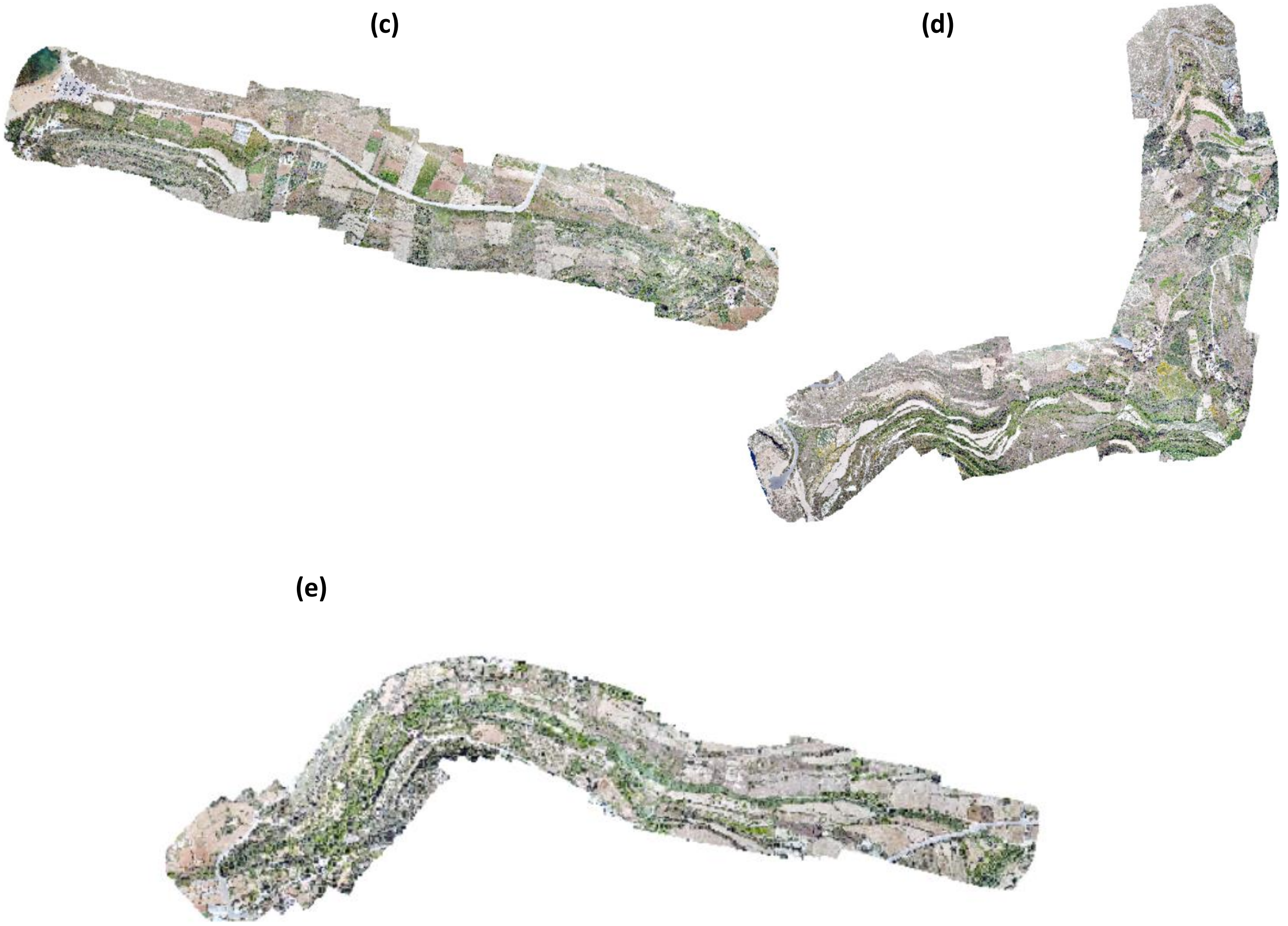
Case study site	**Hydrogeology**	**Catchment Area (km²)**	**Stream order of watercourse where streambed water level was recorded**	**Urban cover (%)***	**Agricultural land cover (%)***	**Semi-natural areas (%)***
Wied il-Luq	Rabat/Dingli Perched Aquifer	48	5	16	62	5
Wied il-Baħrija	Rabat/Dingli Perched Aquifer	2.4	6	13	41	46
Wied ta' Miġra l-Ferħa	Rabat/Dingli Perched Aquifer	1.67	5	0	38	62
Wied tal-Ġnejna	Rabat/Dingli and Mġarr/Wardija Perched Aquifers	5.46	6	8	63	29
Wied Ħarq Ħammiem	Ephemeral	0.95	5	86	14	0

*estimated from Corine Land Cover 2018

4.2.2 Remotely sensed data

Table 4.2. Mediterranean IRES case study sites.

Image	Case Study Site	Resolution at UAV launching home-point	Capture Dates (RGB only)	Capture Dates (RGB + NIR)
a	Wied il-Baħrija	3cm	20190524; 20190615;20200323; 20200523; 20201216	n/a
b	Wied Ħarq Ħammiem	3cm	20190511;20190601;20190707; 20200216;20200410	20201217
c	Wied tal-Ġnejna	3cm	20190511;20190607;20190707; 20191102; 20200209;20200410;	20201217
d	Wied ta' Miġra l-Ferħa	3cm	20190531;20201213;20200412; 20200531	20201223
e	Wied il-Luq	3cm	20190517;20190601;20191102; 20200409;20200524	20200816

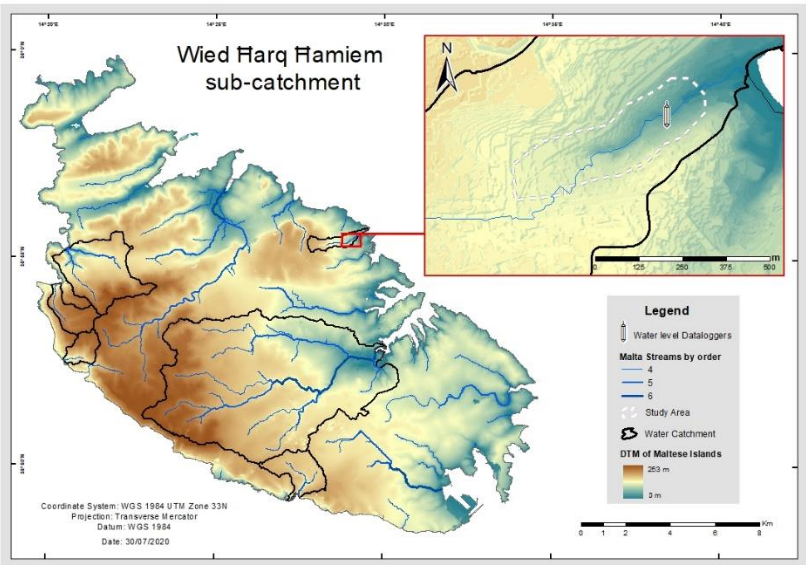


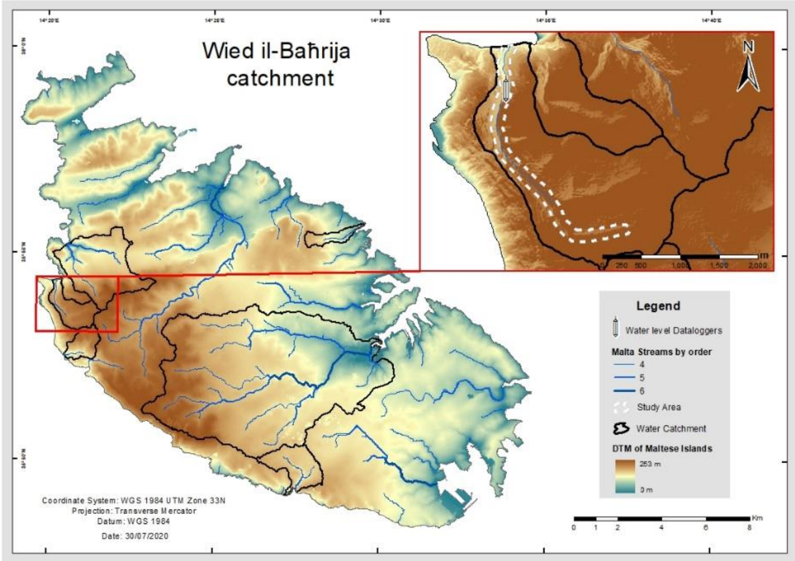
High resolution optical imagery of the study areas was collected using DJI Phantom 4 Advanced, DJI Mavic 2 Pro and DJI RTK 210v2 quadcopters (Table 4.2). These UAVs are capable of autonomous waypoint flight following a pre-planned route, which was created with the DJI Pilot mission flight software for the DJI RTK 210v2, DroneDeploy freeware application for the DJI Phantom 4 Advanced, and Sentera FieldAgent for DJI Mavic 2 Pro. A Sentera AGX710 multispectral camera was installed on the DJI RTK 210v2. The camera can acquire both RGB and NIR images, simultaneously, at 12.3MP, and therefore able to collect data from different spectral bands: blue (446nm), green (548nm), red (650nm), red edge (720nm), NIR (840nm). The camera was bundled with an irradiance sensor to record light conditions in the same spectral bands as the multispectral sensor ISO (International Organization for Standardization) value and exposure time was set to automatic. With regards the DJI Phantom 4 Advanced and DJI Mavic 2 Pro, RGB images were taken by the quadcopters' factory-installed 20MP cameras. The DJI Mavic 2 Pro was also used to capture NIR images, using a 1.2MP Sentera NDVI Single Sensor.

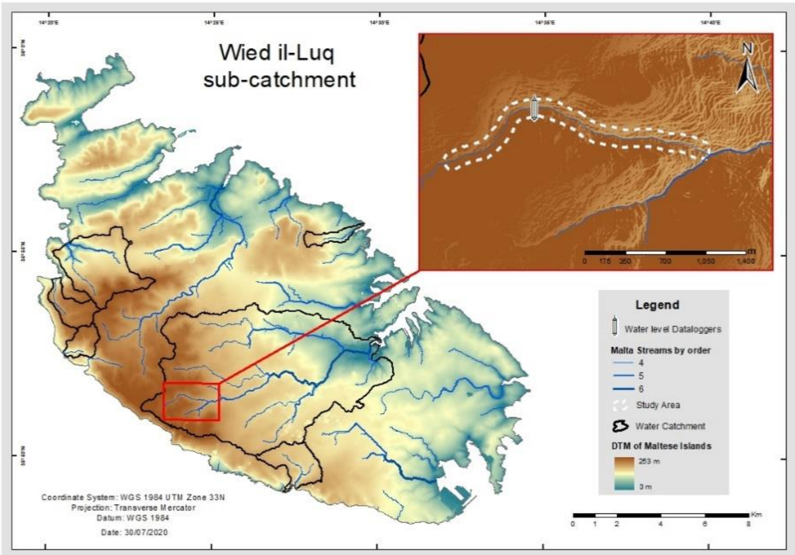
4.2.3 Data collected in-situ

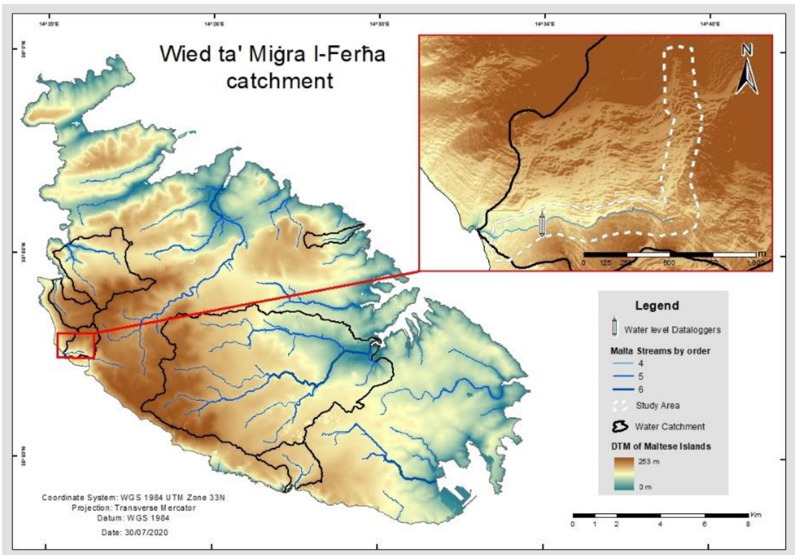
Water level data (m) was collected using Onset HOBO U20L – 04 water level loggers. Data was collected from 22 October 2019 (Wied Ħarq Ħammiem, Wied il-Luq and Wied ta' Miġra l-Ferħa) and 25 October 2019 (Wied il-Baħrija, Wied tal-Ġnejna) to 31 December 2020. In view of the likelihood that loggers become silted or buried and/or washed away in highly turbulent IRES systems (Nelson & Palmer, 2007), each device was also fitted within HOBO U2X Protective Housing. In addition, they were fixed within a concrete block and tethered to an anchor point to avoid displacement during storm events. According to the devices' technical specifications, water level accuracy varied with a typical error of 0.4 cm and maximum error of 0.8cm of water stage height. As a result of the potential logger error water level readings <0.1m were taken as indicating no water was present.

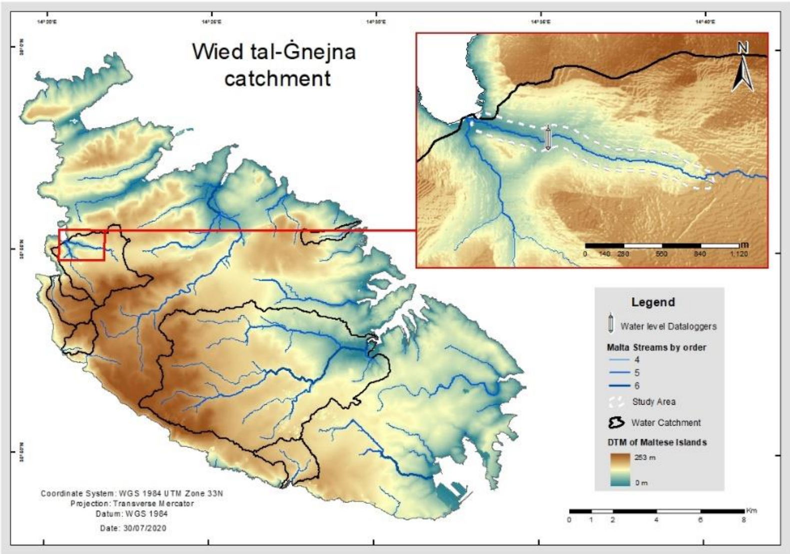
Figure 4.1. Maps of the case study areas including location of the monitoring sites.




Wied il-Baħrija
catchment
Legend
Water level Dataloggers
Malta Streams by order
Study Area
Water Catchment
DTM of Maltese Islands
Coordinate System: WGS 1984 UTM Zone 33N
Projection: Transverse Mercator
Datum: WGS 1984
Date: 30/07/2020


Wied il-Luq
sub-catchment
Legend
Water level Dataloggers
Malta Streams by order
Study Area
Water Catchment
DTM of Maltese Islands
Coordinate System: WGS 1984 UTM Zone 33N
Projection: Transverse Mercator
Datum: WGS 1984
Date: 30/07/2020


Wied ta' Miġra l-Ferħa
catchment
Legend
Water level Dataloggers
Malta Streams by order
Study Area
Water Catchment
DTM of Maltese Islands
Coordinate System: WGS 1984 UTM Zone 33N
Projection: Transverse Mercator
Datum: WGS 1984
Date: 30/07/2020



Site visits were carried out at least every two months to remove any accumulated debris and ensure that loggers were correctly functioning. The probes were programmed to take water level measurements at a 30-min sampling frequency. One logger was deployed in each case study site (a total of five loggers). The loggers recorded absolute pressure data. The Barometric Compensation Assistant tool within the HOBOware PRO version 3.7.23 application was used to compensate the recorded pressure data with atmospheric pressure collected from the Malta Airport Meteorological Office at Luqa, Malta, corrected to sea level pressure (QNH) and transposed to stream water level. Precipitation (mm) at 30-min intervals was provided by the Malta Airport Meteorological Office for two weather recording stations found in the proximity of the case study sites (Dingli and Msida).

4.2.4 Processing of RGB and NIR images

The captured photographs were processed for the generation of VI data (Table 4.3) and images (4.2; 4.17-4.45). The UAV images were mapped with sufficient overlap to produce SfM-based photogrammetric orthoimages. The 2D orthomosaics were produced with the ArcGIS Drone2Map application[2]. Using ESRI ArcMap 10.8.2, the watercourses were clipped from the produced images. To perform visible and non-visible VIs on each pixel of the RGB and NIR orthomosaics, a custom software application (PIXAM) was designed using Visual Studio 2015 and C# .Net 4.5. The developed software has tools to superimpose both RGB and NIR orthoimages with identical georeferencing to obtain pixels values from each image. This georeferencing process was fundamental to achieve same pixels in three-dimensional space required to obtain accurate measurements. Once the images have been rigorously processed to assure correct georeferencing, these were superimposed

[2] https://www.esri.com/en-us/arcgis/products/arcgis-drone2map/overview

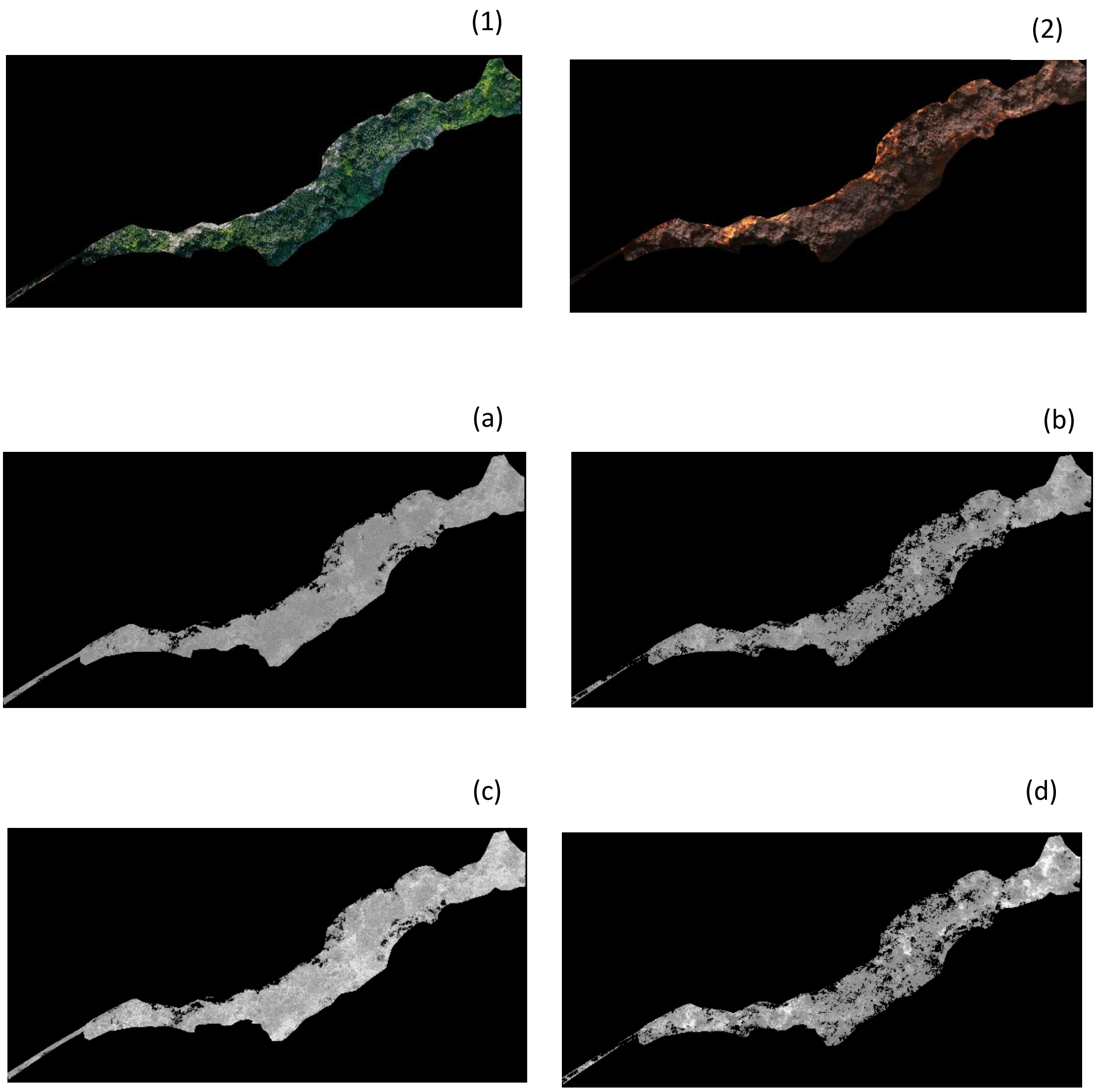
to obtain the required VI-processed pixels. A resultant image was then displayed visualizing the vegetation on the landscape in black and white, were a 0 to 1 index represents the FVC of the pixel and anything under 0 is set to the minimum value (1) in each RGB value. Initial black pixels were represented as NaN and did not represent a valid pixel. The following VIs were applied to all RGB images (Table 4.3): (1) Visible atmospherically resistant index, (2) Green leaf index, (3) Red-green-blue vegetation index, and (4) Normalized difference green-red index, whereas the following VIs were applied for the NIR images: (5) Normalized difference vegetation index; (6) Enhanced normalized difference vegetation index; (7) Normalized difference red edge index. These indices explore in different ways the visible bands (red-green-blue) and the invisible red and near-infrared bands. The outcomes were then analysed and compared with precipitation and water level data to identify linkages and trends. A descriptive analysis approach including graphs, mean, standard deviation (SD) and coefficient of variation (CV) was adopted to compare the four visible VI indices and to analyse against hydrometeorological parameters. Statistical differences between normalized means of the visible VIs reflectance values and three in-stream water level (m) categories (zero, low ($\leq$ 0.15m), and high (> 0.15m)) exhibited within the five case study sites were examined using a non-parametric one-way analysis of variance Kruskal-Wallis Test.

Table 4.3. Vegetation Indices used in this study.

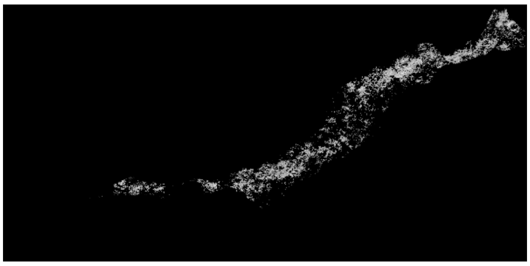
Vegetation Index	Name	Equation	Reference
VARI	Visible Atmospherically Resistant Index	(GREEN – RED) / (GREEN + RED – BLUE)	(Gitelson et al., 2002)
GLI	Green Leaf Index	(2*GREEN – RED – BLUE) / (2*GREEN + RED + BLUE)	(Louhaichi et al., 2001)
RGBVI	Red-Green-Blue Vegetation Index	(GREEN*RED) – (RED*BLUE) / (GREEN*GREEN) + (RED*BLUE)	(Bendig et al., 2015)
NGRDI	Normalized Difference Green-Red Index	(GREEN – RED) / (GREEN + RED)	(Tucker, 1979)
NDVI	Normalized Difference Vegetation Index	(NIR-RED)/ (NIR+RED)	(Rouse, Jr. et al., 1976)
ENDVI	Enhanced Normalized Difference Vegetation Index	(NIR+GREEN) - (2*BLUE) /	(Susantoro et al., 2018)

		(NIR+GREEN) + (2*BLUE)	
NDRE	Normalized Difference Red Edge Index	(NIR-RED) / (NIR+RED)	(Barnes et al., 2000)

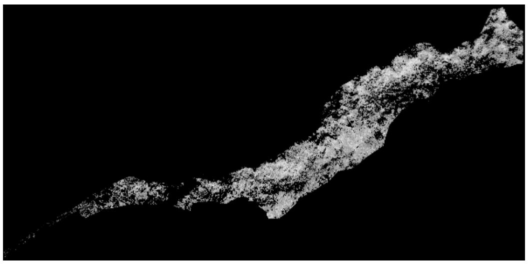
Figure 4.2. Examples of vegetation indices data applied in the red-green-blue (RGB) and NIR orthophotos (20201217) of Harq Hammiem case study site. (a) Green leaf index, (b) Normalized difference green-red index, (c) Red-green-blue vegetation index, (d) Visible atmospherically resistant index, (e) Normalized difference vegetation index, (f) Enhanced normalized difference vegetation index, (g) Normalized difference red edge index. All VI images produced in this research are found in the Appendix section of this paper.



(e)



(f)



4.3 Results

4.3.1 Vegetation indices

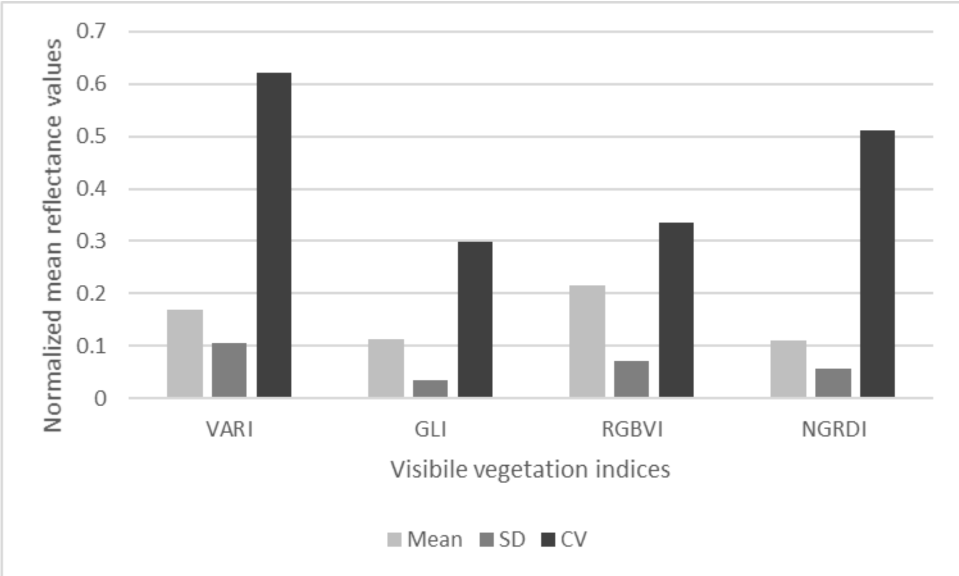
The results from the visible VIs from orthophotos captured for each case study at different dates during the monitoring period spanning from November 2019 and December 2020 are shown in the appendix section of this paper. Vegetated areas are emphasised with light grayscale tones, while non-vegetated land cover with the darkest tones of grey.

As shown in Figures 4.17 - 4.41, in general, all VIs were able to detect and highlight vegetation along the riparian corridors. From the images it was observed that in many cases, the visible atmospherically resistant index provided the worst performance with regards to vegetation detection. This can be most prominantly seen in Ħarq Ħammiem and Miġra l-Ferħa case study sites where in Figures 4.25 - 4.30 and 4.37 - 4.41 sparsely and non-vegetated areas are not clearly defined when compared to the other VI results. From a temporal perspective, the images captured in December at Ġnejna, Ħarq Ħammiem and Miġra l-Ferħa (Figures 4.24, 4.30 and 4.41), it was observed that lighter grayscale tones in all VIs, are the most prominent, indicating increased FVC (fraction of vegetation coverage) when compared to other months. At Wied tal-Ġnejna and Wied il-Luq, the November images (Figures 4.21 and 4.33) illustrated the areas with most darker grayscale tones, whereas at Wied ta' Ħarq Ħammiem , this pattern was identified in the July result (Figure 4.27) , whereas at Wied ta' Miġra l-Ferħa, the February image (Figure 4.38) showed the least light greyscale tones.

From visual interpretation of the results, the RGB VIs can provide a good account for FVC and local of vegetated areas. However, results are not accurate, anthopogenic structures such as buildings are not always well-defined (Figure 4.37-4.31), and sparsely or non-vegetated areas such as bare rock surfaces, including lower garrigue habitats, and soil, are depicted as vegetated such as Figures 4.25 – 4.30. Figure 4.3 depicts the mean, standard deviation and coefficient of variation for the normalized mean of the four RGB VI indices values. The normalized mean reflectance values for the entire timeseries showed identical means for green leaf index and normalized difference green-red index with 0.11, whilst both the visible atmospherically resistant index and the red-green-blue vegetation index had higher averages standing at

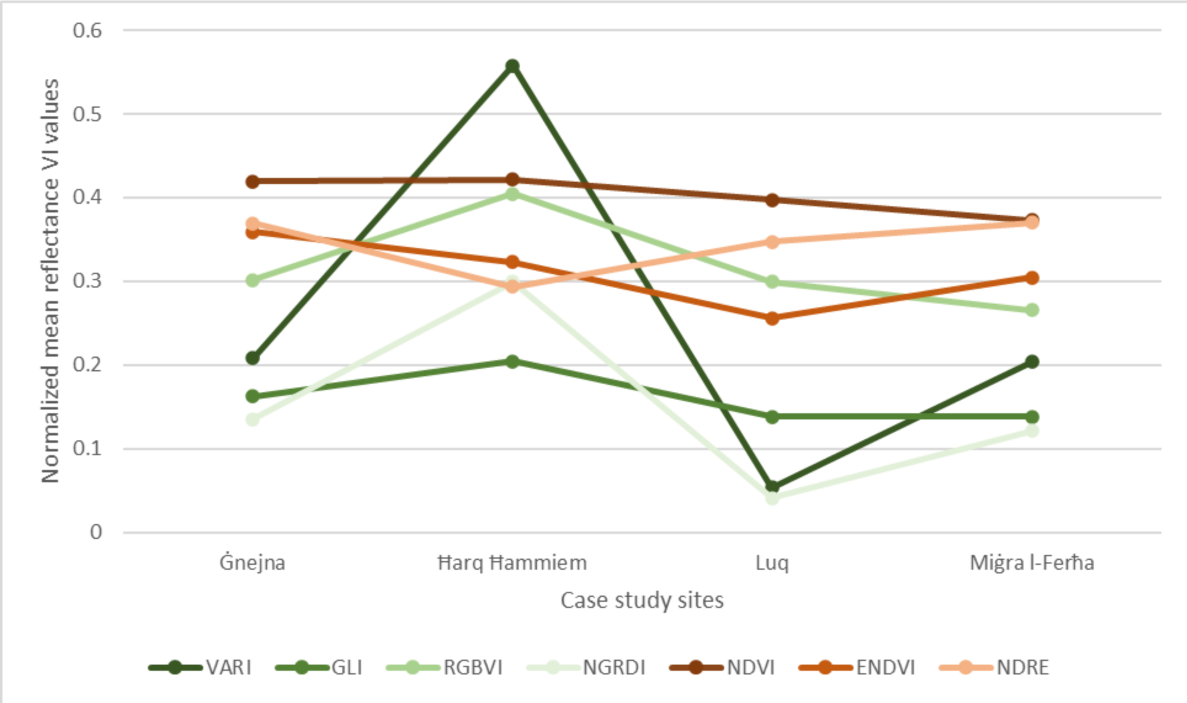
0.17 and 0.21 respectively. The standard deviation and the coefficient of variation for all visibile indices was low indicating that reflectance values were clustered in the vicinity of the mean.

Figure 4.3. Bar graph showing mean, standard deviation (SD) and coefficient of variation (CV) for the normalized mean RGB VI indices values.



Non-visible VIs processed from NIR images captured in December 2020 from single flights from Wied il-Ġnejna, Wied Ħarq Ħammiem and Wied ta' Miġra l-Ferha, and August 2020 from Wied il-Luq were plotted against RGB VIs (Figure 4.4). The mean reflectance values from NIR images were generally higher than the visible VI values, with the exclusion of the VARI and RGBVI results gathered from Wied ta' Ħarq Ħammiem. In the next section a comparison of the VI results and the recorded water level and precipitation data is provided.

Figure 4.4. Normalized mean reflectance values of RGB VIs: Green leaf index; Normalized difference green-red index; Red-green-blue vegetation index; Visible atmospherically resistant index, and NIR VIs: Normalized difference vegetation index; Enhanced normalized difference vegetation index; Normalized difference red edge index. Captured from Wied tal-Ġnejna, Wied ta' Ħarq Ħammiem, Wied il-Luq and Wied ta' Miġra l-Ferħa case study sites.



4.3.2 *Comparing Vegetation Indices and recorded hydrometeorological metrics*

Figures 4.5 – 4.8 depict the average ranges of the visible RGB VIs against the mean monthly in-stream water level (mm) in each case study site. Different spatial trends of reflectance values within each studied area are minimal, indicating that according to the visible reflectance value results, any changes in FVC and vegetation health is ubiquitous within the entire Mediterranean IRES reaches at the point in time the areas where mapped with the UAVs. All RGB VIs manifested similar trends for each site, showing that visible atmospherically resistant index, green leaf index, red-green-blue vegetation index and normalized green-red index provided very similar results for each studied IRES. At Wied il-Baħrija all the RGB VI reflectance values where stable and did not show significant changes when in-stream water level was recorded or not. However, Wied tal-Ġnejna, Wied il-Luq and Wied ta' Miġra l-Ferħa showed that higher monthly water level averages resulted in higher reflectance values, whereby lower or no monthly water level detection led to lower refectance values, indicating a potential relationship between water presence and FVC and vegetation health. This was further substantiated by the boxplot in Figure 4.9. The monthly averages of water level data collected during the RGB captured dates in all case study sites were classified into three ranges, zero (no water level, i.e. <0.1m), low ($\leq$ 0.15m) and high (> 0.15m), and plotted against the normalized mean visible RGB reflectance values, clearly indicating a lower reflectance value mean under zero flow conditions. This was further substantiated with a Kruskal-Wallis test (H-value 9.83 and p-value 0.007), also comparing the normalized RGB VI means against the three water level categories, that showed significant differences in indices values in at least one water level category.

Figure 4.5. Normalized Mean RGB Visible atmospherically resistant index (VARI) range within different sections in each case study site and mean monthly in-stream water level (mm).

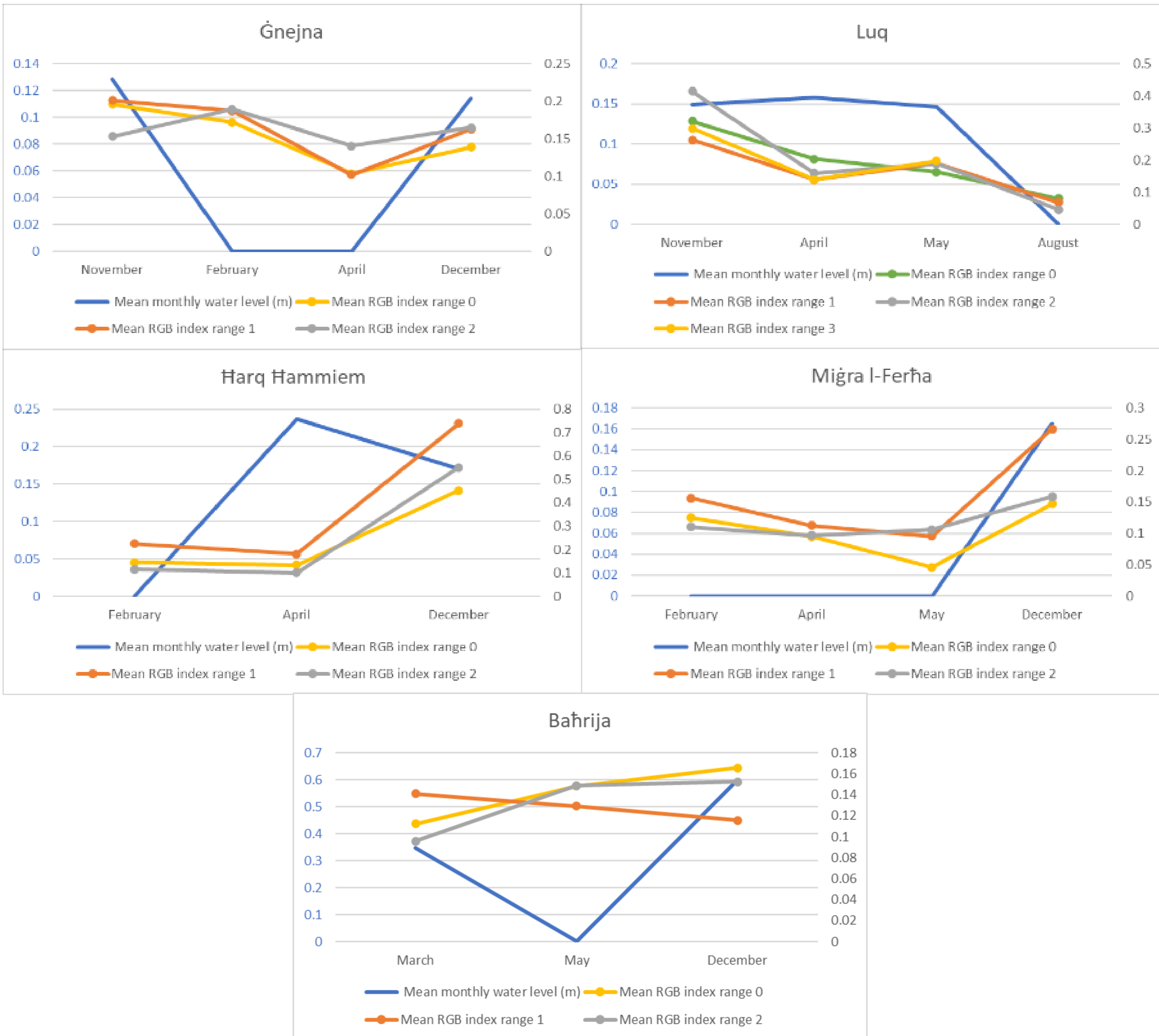
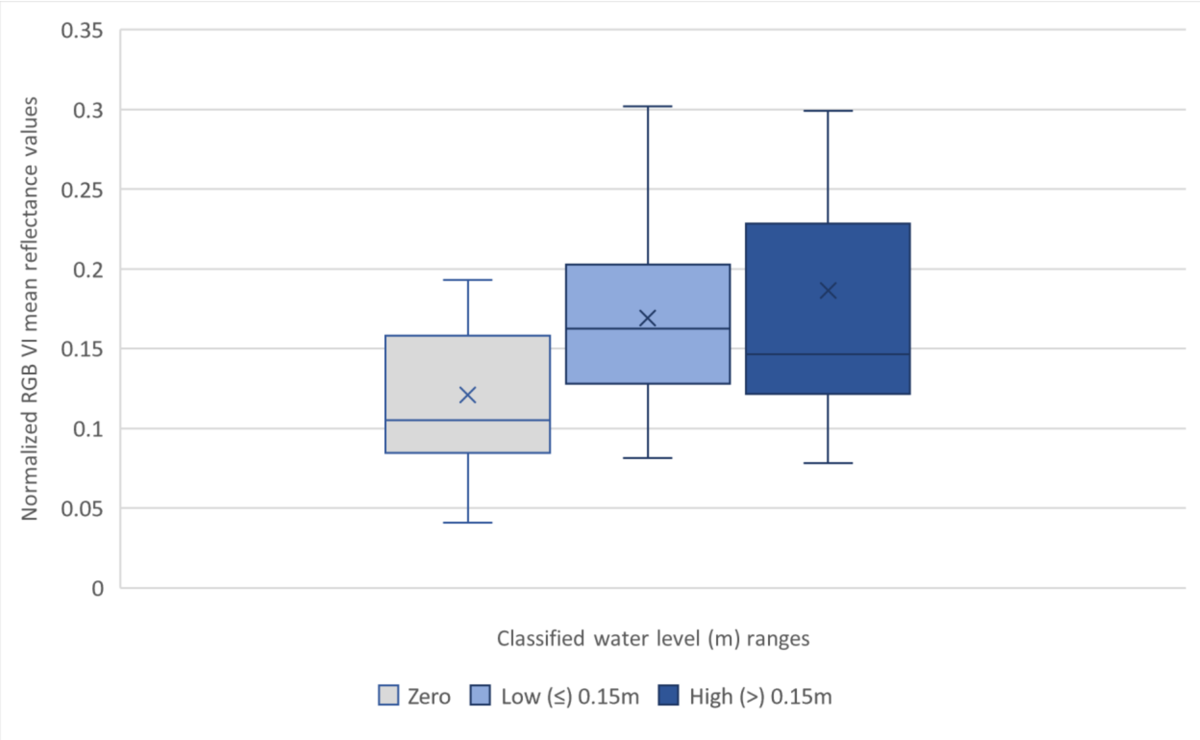


Figure 4.6. Normalized Mean RGB Green leaf index (GLI) range within different sections in each case study site and mean monthly in-stream water level (mm).

Figure 4.7. Normalized Mean RGB Red-Green-Blue Vegetation Index (RGBVI) range within different sections in each case study site and mean monthly in-stream water level (mm).

Figure 4.8. Normalized Mean RGB Normalized difference green-red index range (NGRDI) within different sections in each case study site and mean monthly in-stream water level (mm).

Figure 4.9. Boxplot graph showing normalized mean and standard deviation of reflectance values for visible atmospherically resistant index; green leaf index; red-green-blue vegetation index; and normalized difference green-red index range classified by water level ranges (zero, low (≤0.15m) , and high (> 0.15m)) occurring in all case study sites.



Figures 4.10 – 4.13 compare mean RGB VI reflectance values with total monthly precipitation (mm) recorded from weather stations in the vicinity of the case study sites. At Wied Ħarq Ħammiem and Wied ta Miġra l-Ferħa all RGB VI results indicate low visible VIs reflectance ranges when low or no precipitation readings where recorded and comparatively high reflectance values when rainfall events occurred. These sites are characterised by an ephemeral hydrological regime (Chapter 3) where flow is dependent on particular precipitation events and these VI results indicate increased vegetation greeness responses following rain events. In the other case study sites, comparatively higher RGB VIs reflectance values were also noted during dry months when no precipitation occured, for instance, in July at Wied tal-Ġnejna, May at Wied il-Luq and June at Wied il-Baħrija. Figures 4.10 – 4.13 only take in to account mean precipitation occured within the month that mapping took place, disregarding the potential latent affect of previous rain events on vegetation. Figure 4.14 depicts the mean reflectance value indices applied for the visibile VIs plotted against the total precipitation (mm) since September prior to the RGB image capture dates. The results show that the mean reflectance values are lowest when total accumulated precipitation is higher.

Figure 4.10. Normalized Mean RGB Visible atmospherically resistant index (VARI) range and total monthly precipitation (mm).

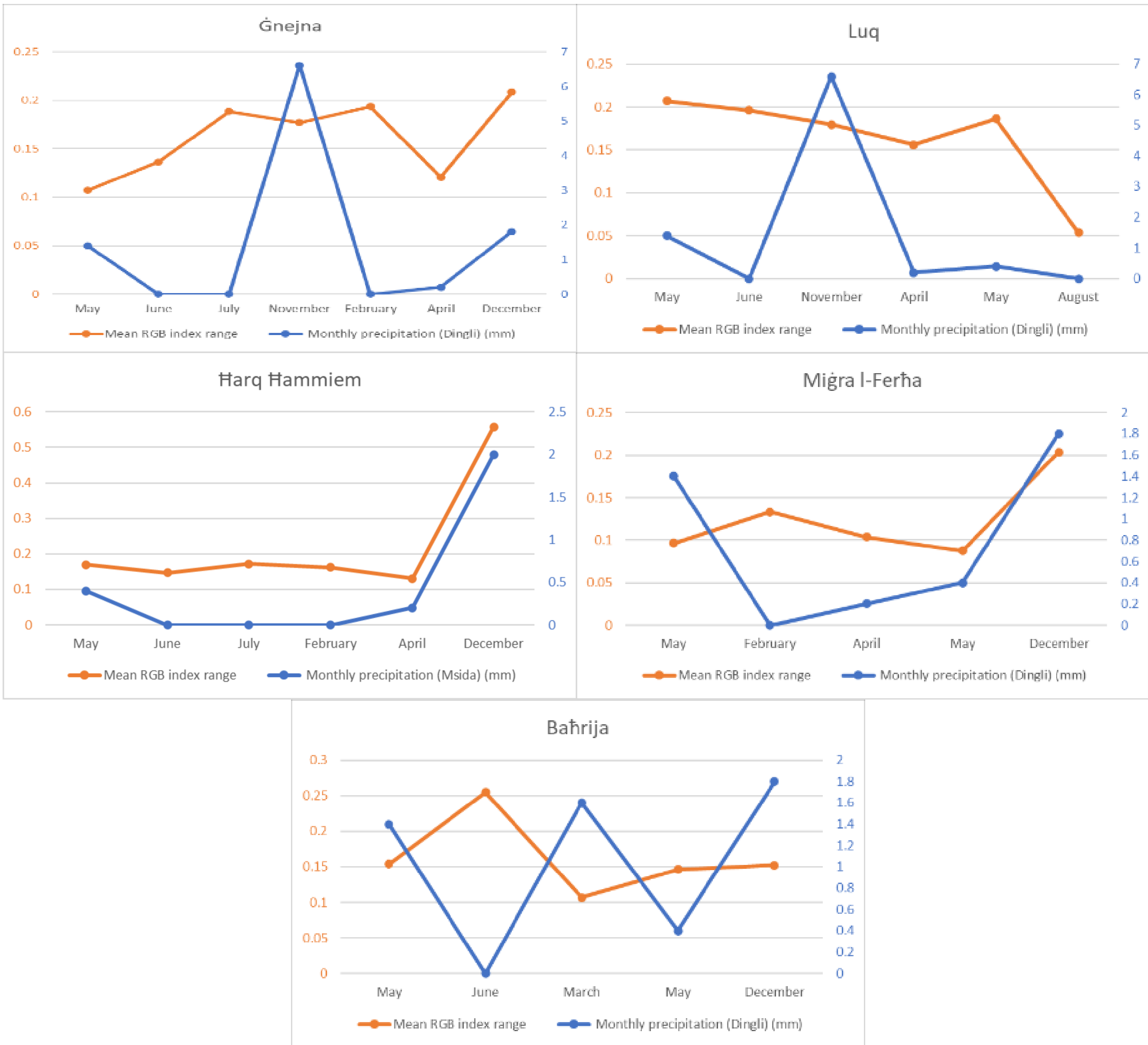


Figure 4.11. Normalized Mean RGB Green leaf index (GLI) range and total monthly precipitation (mm).

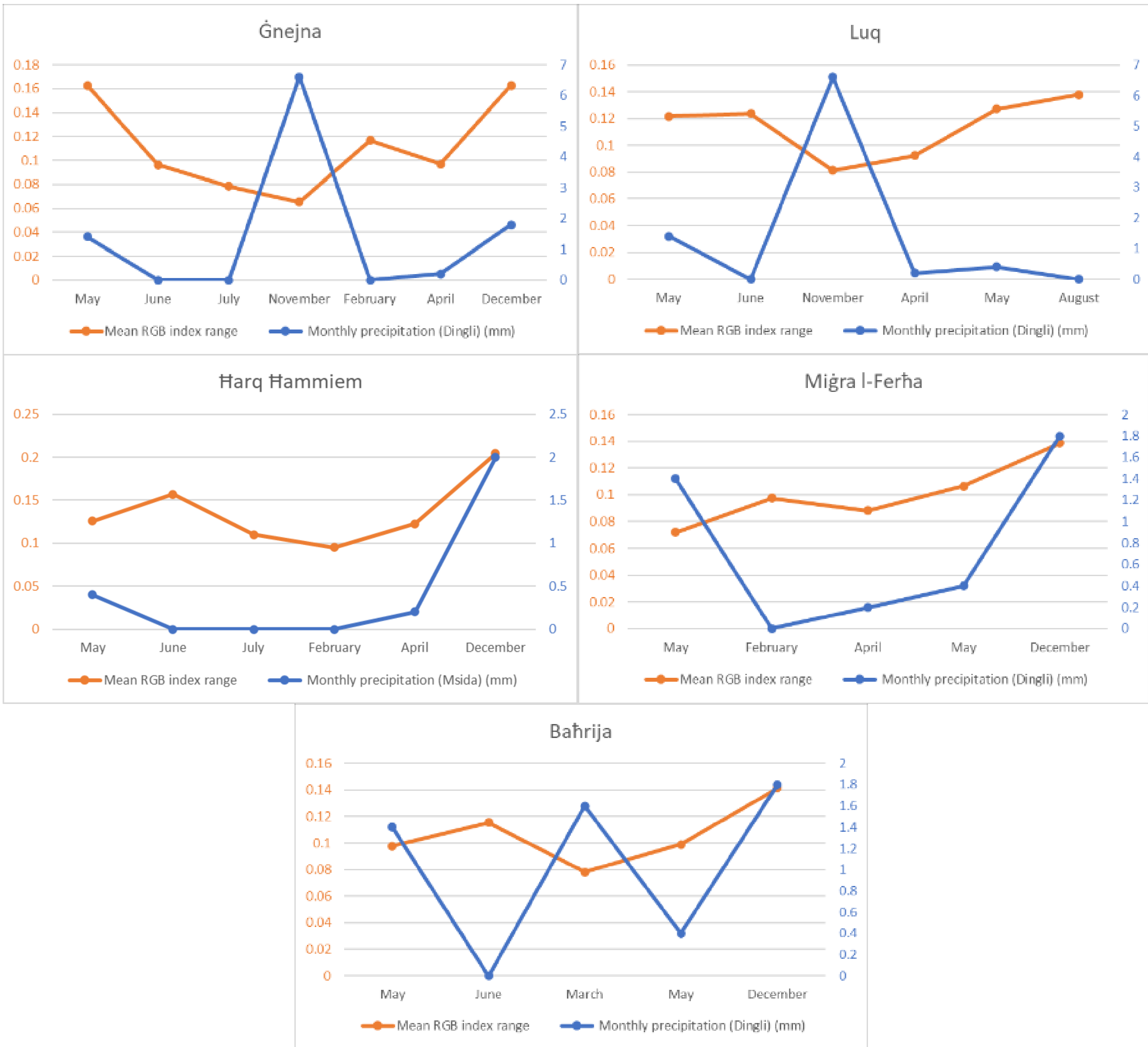
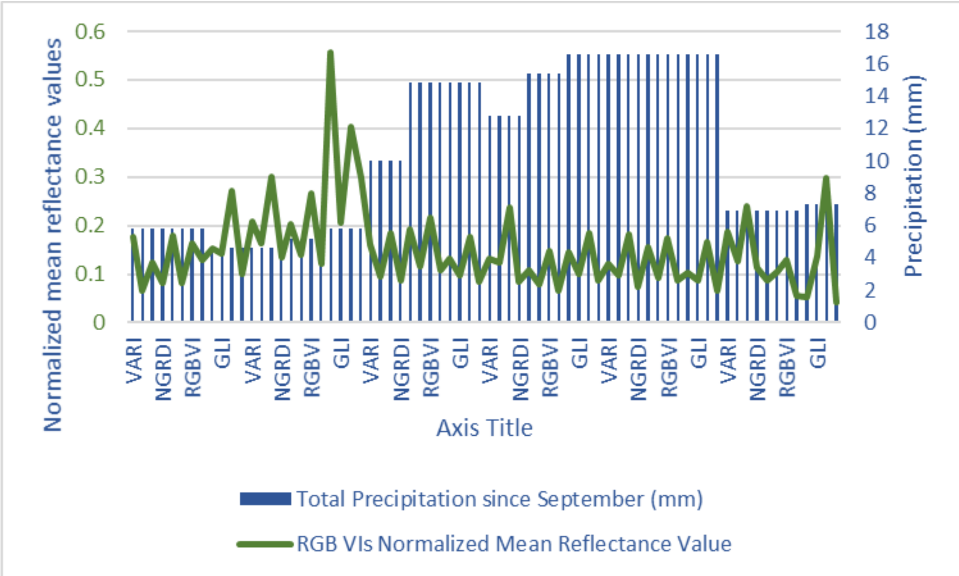


Figure 4.12. Normalized Mean RGB Red-Green-Blue Vegetation Index (RGBVI) range and total monthly precipitation (mm).

Figure 4.13. Normalized Mean RGB Normalized difference green-red index range (NGRDI) and total monthly precipitation (mm).

Figure 4.14. Plot showing the mean reflectance value indices applied in the visible spectrum: Green leaf index, Normalized difference green-red index, Red-green-blue vegetation index, Visible atmospherically resistant index plotted against total precipitation (mm) since September prior to the RGB image capture dates.



A comparison of the visibile RGB VIs reflectance values was made for the different seasons and annual quarters monitored during this study (Figures 4.15 – 4.16). Low standard deviation and coefficient of variation values indicated that reflectance values are clustered in the vicinity of the mean for all RGB VIs. For all the RGB VIs, the mean reflectance values were highest (close to 1) in the images captured during the winter period, averaging at 0.18 compared to 0.12 in autumn, 0.14 in summer and 0.12 in spring. Vegetation detection using solely visible spectral data is based on the fact that the green vegetation have larger green indices than other land cover objects in the normalized RGB colour space (Alex et al., 2017; Marcial-Pablo et al., 2019; W. Yang et al., 2015). This may infer that compared to other seasons, vegetation greenness and FVC is in fact, greater during the wetter months.

Figure 4.15. Recorded normalized mean reflectance values for visible RGB Vegetation indices during different seasons.

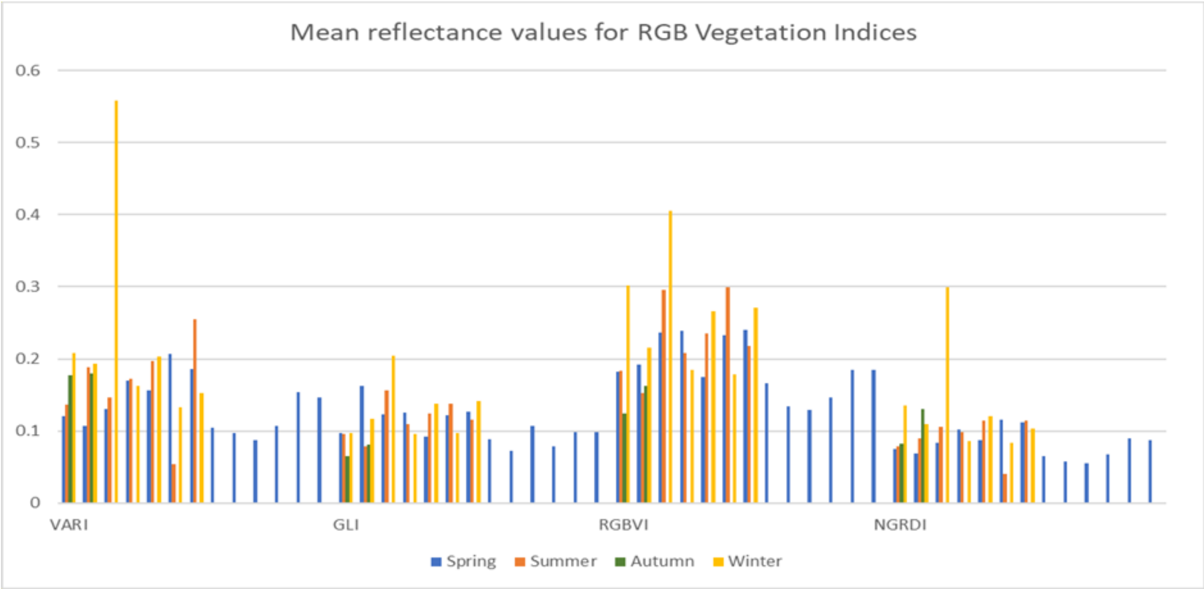
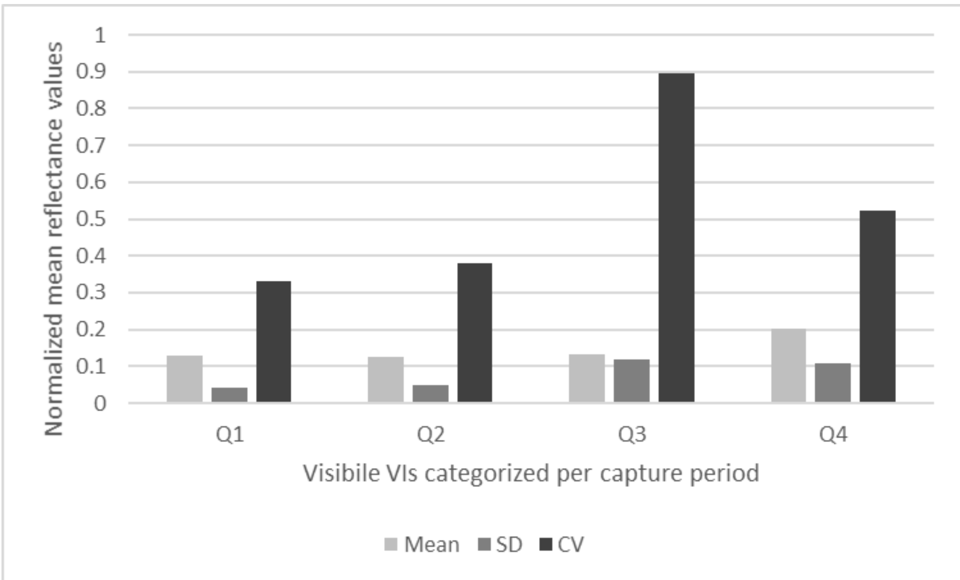


Figure 4.16. Normalized mean, standardized deviation (SD) and coefficient of variation (CV) for all RGB VI values compared per annual quarters.



4.4 Discussion and future applications

In this study various visible-light VIs captured from UAVs are compared with precipitation data from weather stations found in the vicinity of the case study areas and water stage height readings collected from in-situ dataloggers in five different Mediterranean IRES case study sites. The main objective of this research was to analyse the viability of using cost-effective and off-the-shelf UAVs and consumer-grade RGB cameras, the use of SfM photogrammetric techniques to produce high-resolution orthomosaics and the adoption of visible VI's to monitor riparian vegetation health and FVC responses to in-stream water presence in Mediterranean IRES. The reflectance values result from the different RGB VIs were considerably similar and consistent for each case study site with VARI having the most spreadout values relative to the mean, indicating that such index may be the least reliable. When RGB indices data was analysed with hydrometeorological parameters, results indicated that imagery captured during no flow periods contributed to lower mean reflectance values as seen in boxplot (Figure 4.9) and Kruskal-Wallis test indicating considerable variations in reflectance values between different water level categories (zero (no water level, i.e. <0.1m), low ($\leq$ 0.15m) and high (> 0.15m)). However, inconsistencies were still noted within different case study sites. For example when analysing the plots for each case study sites depicting the normalized mean reflectance values against in-stream water level and precipitation (Figures 4.5 – 4.8 and 4.10 – 4.13), Wied ta' Miġra l-Ferħa was the only site with higher reflectance values when precipitation and water level was recorded within the same month when image capturing occured and with lower reflectance results when no or low precipitation and water level data was monitored. This relationship was only noted with stage height data at Wied tal-Ġnejna and Wied il-Luq and with precipitation data only at Wied Ħarq Ħammiem. Different trends in RGB mean reflectance values was also noted when compared during different year periods. Indices values were lower in periods when total accumulated precipitation was higher (Figure 4.9) indicating that the latent influence of previous rain events was not reflected in the RGB imagery. However, for the four RGB VIs, resulted in highest reflectance values during the wetter months, indicating that compared to other seasons, vegetation health and FVC was enhanced. The difference between these results potentially show that vegetation health and extent is not solely based on precipitation, but is also dependant on other variables dependant on seasonality.

This inconsistency in the results can be attributed to two main factors: (i) the reliability, effectiveness, and accuracy of visible RGB VIs in monitoring riparian vegetation health, and (ii) the diverse conditions and intrinsic characteristics of each Mediterranean IRES catchment or sub-catchment that impose different ecohydrological responses to varying hydrometeorological events. Three different RGB cameras where used to capture the images in this study and differences in the sensitivity of the cameras to capture in specific wavelengths can lead to the significant dispersal of reflectance values (Agapiou, 2020). Other factors that influences the VI results is flying day time and year period as it affects the sun light angle, weather conditions and atmospheric transference (Woodget et al., 2017; W. Yang et al., 2015). Therefore, the comparison analysis adopted in this study is based on the changes and trends of the despersal values during different annual periods and hydrometeorological metrics, namely in-stream stage height and precipitation data collected from weather stations in the proximity of the case study sites. In view that only one waterlevel datalogger was deployed in each studied IRES reach, the orthomosaics were also divided into sections (three sections for Wied Ħarq Ħammiem, Wied ta' Miġra l-Ferħa, Wied il-Baħrija, Wied tal-Ġnejna and four sections for Wied il-Luq) to identify any different spatial trends in the reflectance values within each case study site. Differences within the sites were minimal indicating that according to the visible reflectance value results, any changes in FVC and vegetation health is ubiquitous within the entire stream reaches at the point in time the areas where mapped (Figures 4.5 – 4.8). However, variations in the reflectance values when compared to water level and precipitation may also be attributed to the intrinsic catchment characteristics. For instance, Wied il-Baħrija is dominated by dense *Arundo donax* stands, that in this particular valley, the leaves of the reeds remain mostly green throughout the year, due to the intermittent flow regime fed by perched aquifer springs. This may have contributed to the higher reflectance values during the drier periods. At Wied Ħarq Ħammiem, low reflectance values resulted in April 2020, when a high monthly mean water level was recorded. This may be due to the particular hydrological characteristics of the stream. The land use of Wied Ħarq Ħammiem catchment is predominantly urban (Table 4.1), characterised with impermeable surfaces, that potentially exacerbate hydrological flow rates resulting in flashy runoff responses following specific precipitation events (Chapter 3). This ephemeral behaviour may limit the soil and plant absorption characteristics leading to reduced immediate phenological and vegetation growth responses.

4.4.1 *Capturing diverse spatio-temporal conditions in Mediterranean IRES to understand vegetation responses to hydrometeorological events*

As previously discussed in this paper, the use of VIs from high resolution aerial photos has already been tested and demonstrated effective in different landcapes (e.g. H. B. Anderson et al., 2016; Bendig et al., 2015; Ide & Oguma, 2013; Parmentier et al., 2021; Possoch et al., 2016; Yeom et al., 2019). However, the combined used of SfM, UAVs and visibile VIs to investigate vegetation health in Mediterrean IRES has not yet been adopted. RGB VIs have already been used in environments dominanted by limited or fragmented vegetation such as the arctic and alpine ecosystems and deserts (Arnon et al., 2007; Ding et al., 2022). Mediterranean IRES reaches characterised by dispersed vegetation do exist, especially during the dry period or else in lower-order smaller streams with physical conditions that limit the growth for abundant vegetation. However, as seen from this study, the landscape characteristics of different Mediterraean IRES catchments vary greatly. Some Mediterranean IRES reaches are densely vegetated, including for example, the Mediterranean riparian woodland habitat that is also protected under Annex I of the Habitats Directive (Council Directive 92/43/EEC – code 92A0 and 92C0) whilst other streams may include sparsely vegetated pockets. The varying colours and background composition of riparian corridors will greatly influence the quality of VI results (W. Yang et al., 2015). This neccessitates further research on the potential applicability of the combined use of UAVs and visible VIs to monitor vegetation health and FVC in Mediterranean IRES. Different landscape mosiacs that are characteristic of Mediterranean IRES reaches must be studied further and categorised to identify similar colour patterns that are more easily identifiable, analysed and statistically compared with the RGB VIs. In addition, in view that the Mediterranean IRES landscape mosiac change in a cycle of terrestrial-aquatic habitat conditions caused by the periodic drying and rewetting creating different landscape characteristics throughout the year (Vorste et al., 2020), multiple surveys and image statistical comparisons across the wetting and drying cycles are required.

The advancement in these monitoring methods will provide managers and decision-makers working in Mediterranean IRES, the tools to better understand vegetation and habitat responses towards different hydrometeorological events. This is especially important in a changing climatic environment and in catchments influenced by anthropogenically altered land uses. In this study, *in-situ* monitoring of water level data was carried out by the deployment of one water level datalogger in each catchment or sub-catchment case study site. This limited the undertanding of the different hydrological states that are typical of IRES environments which will vary along the riverbed continuum (Gallart et al., 2011). Nowadays, UAVs can be used to accurately track rapid landscape transformations in a spatially-explicit manner that can also be integrated within more detailed monitoring at long-term sites (Vivoni et al., 2014). In river hydrological assessments, UAVs together with SfM photogrammeric techniques can be used to carry out topographic surveys and 3D models at centimeter level precision (C. S. Zhao et al., 2017). In addition, numerous spectral surface water detection indices exist including the normalized difference water index (NDWI) (McFeeters, 1996), the modified NDWI; MNDWI (Xu, 2006) and the automated water extraction index (AWEI) (Feyisa et al., 2014). However, these are still not reliable and prone to misclassification errors due to water features with similar patterns to non-water structures and dissimilarity of reflectance properties of water pixels under specific conditions, such as muddy waters. Recently developed indices, for instance, the augmented normalized difference water index (ANDWI) (Rad et al., 2021) use the expanded spectral ranges provided by satellite images which do not offer the higher pixel resolutions and temporal frequency that can be provided by UAVs and required to monitor Mediterranean IRES.

Figure 4.17. Vegetation indices results in the RGB orthophoto (a) dated 20190524 of the Baħrija case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

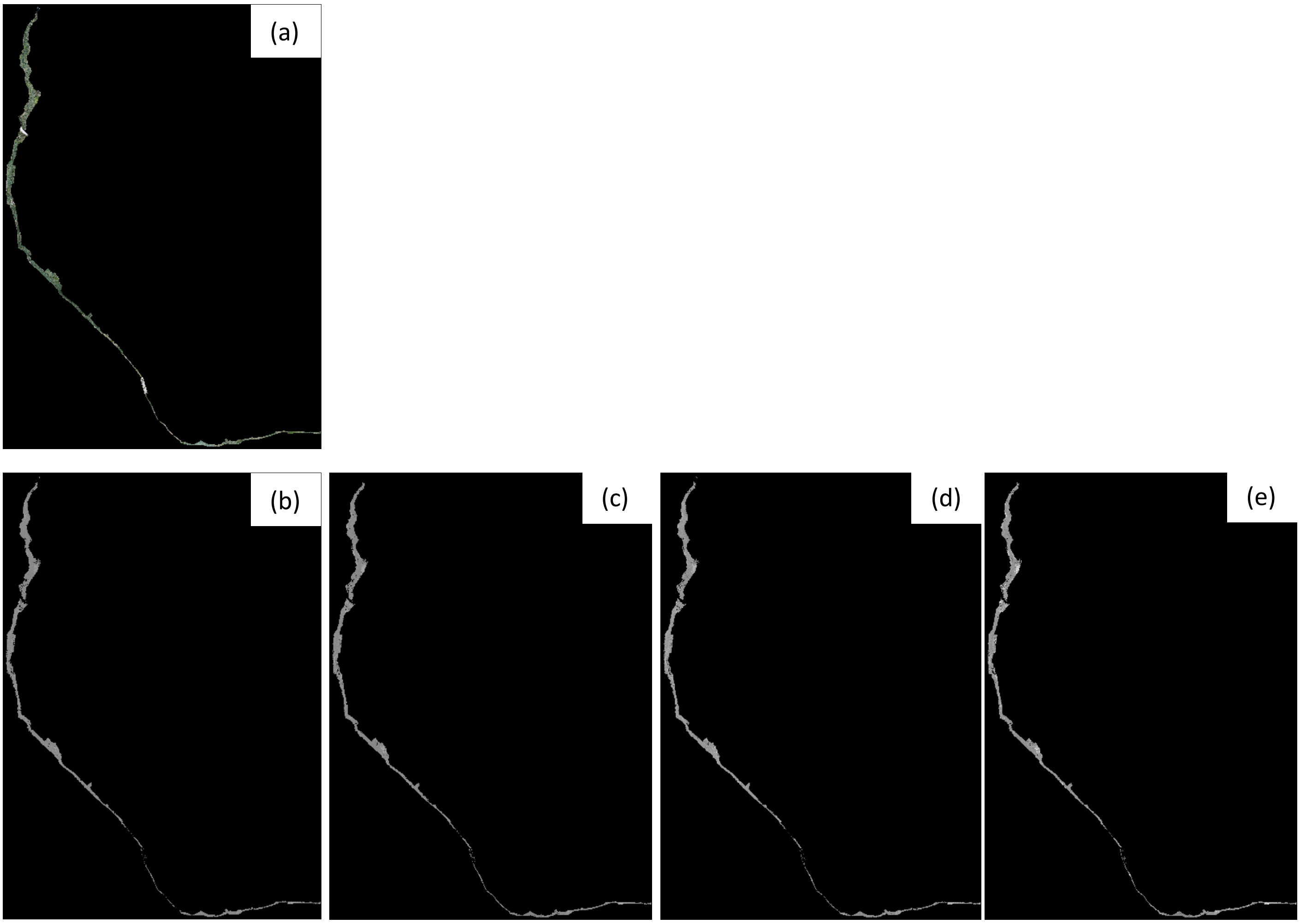


Figure 4.18. Vegetation indices results in the RGB orthophoto (a) dated 20190511 of the Ġnejna case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

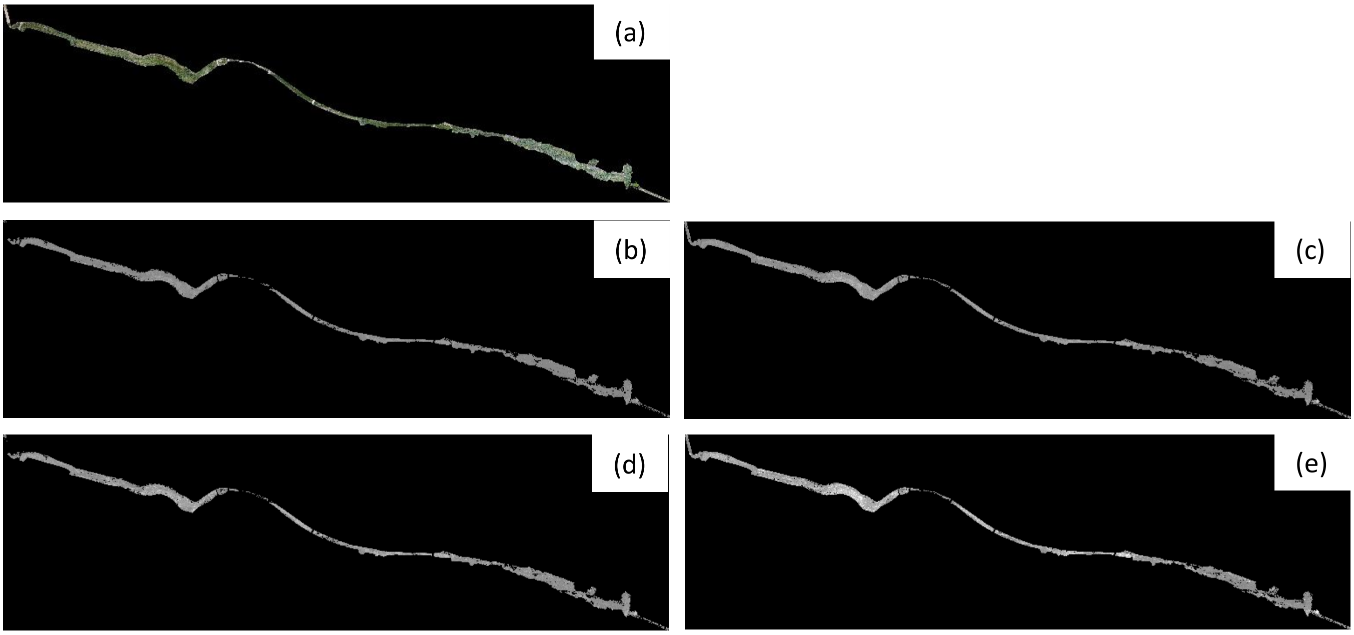


Figure 4.19. Vegetation indices results in the RGB orthophoto (a) dated 20190607 of the Ġnejna case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

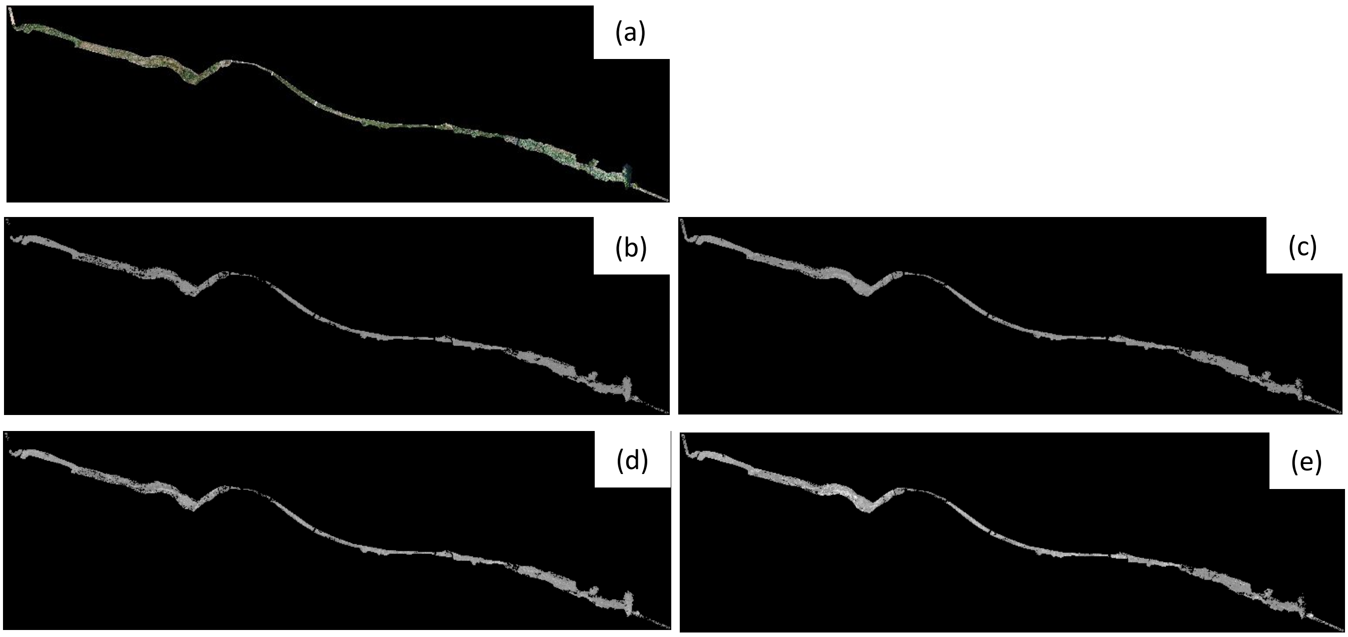


Figure 4.20. Vegetation indices results in the RGB orthophoto (a) dated 20190707 of the Ġnejna case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

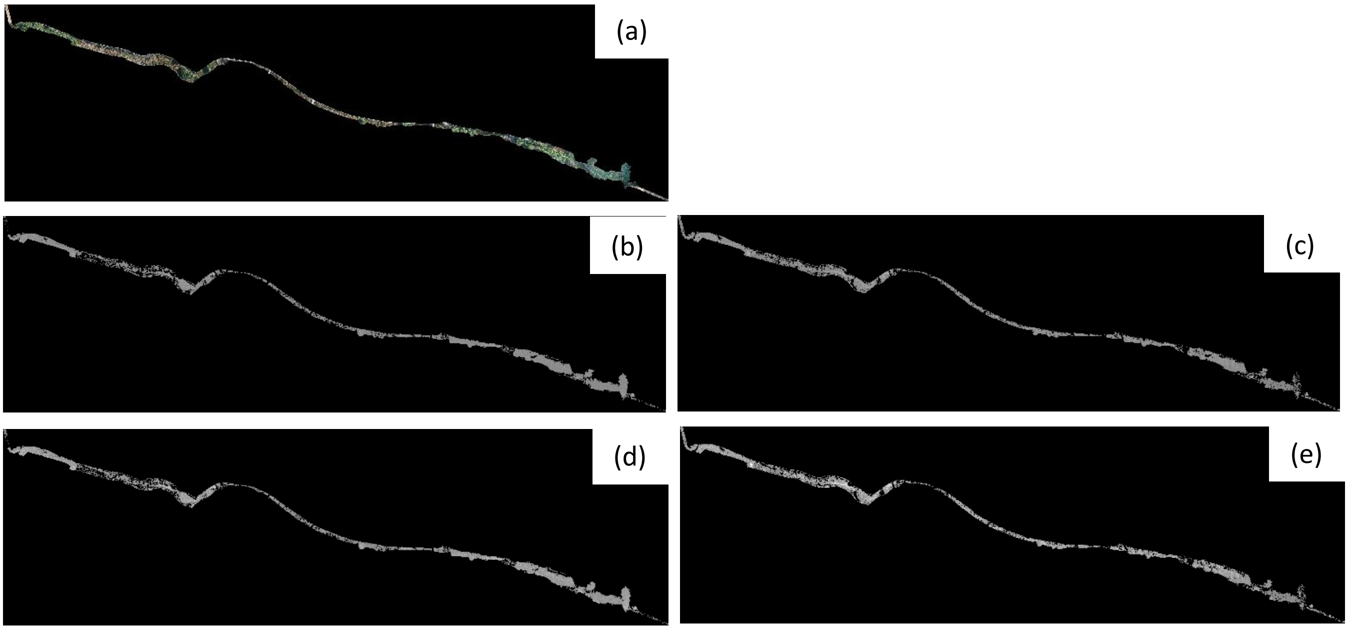


Figure 4.21. Vegetation indices results in the RGB orthophoto (a) dated 20191102 of the Ġnejna case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

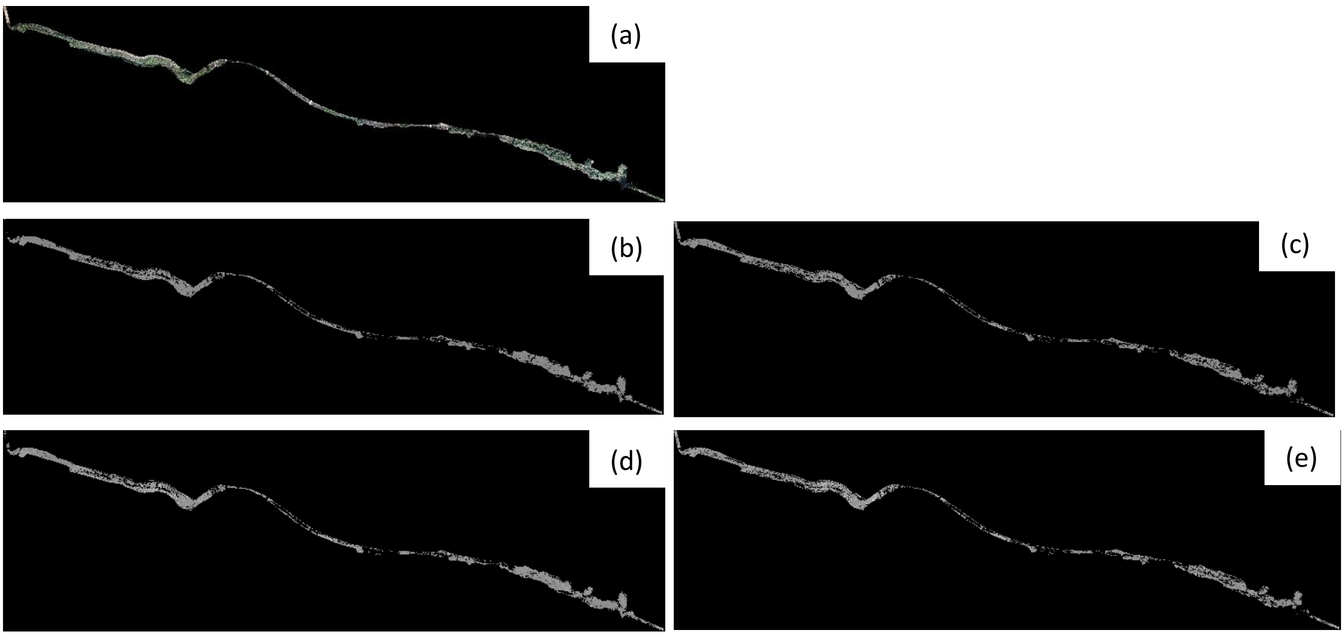


Figure 4.22. Vegetation indices results in the RGB orthophoto (a) dated 20200209 of the Ġnejna case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

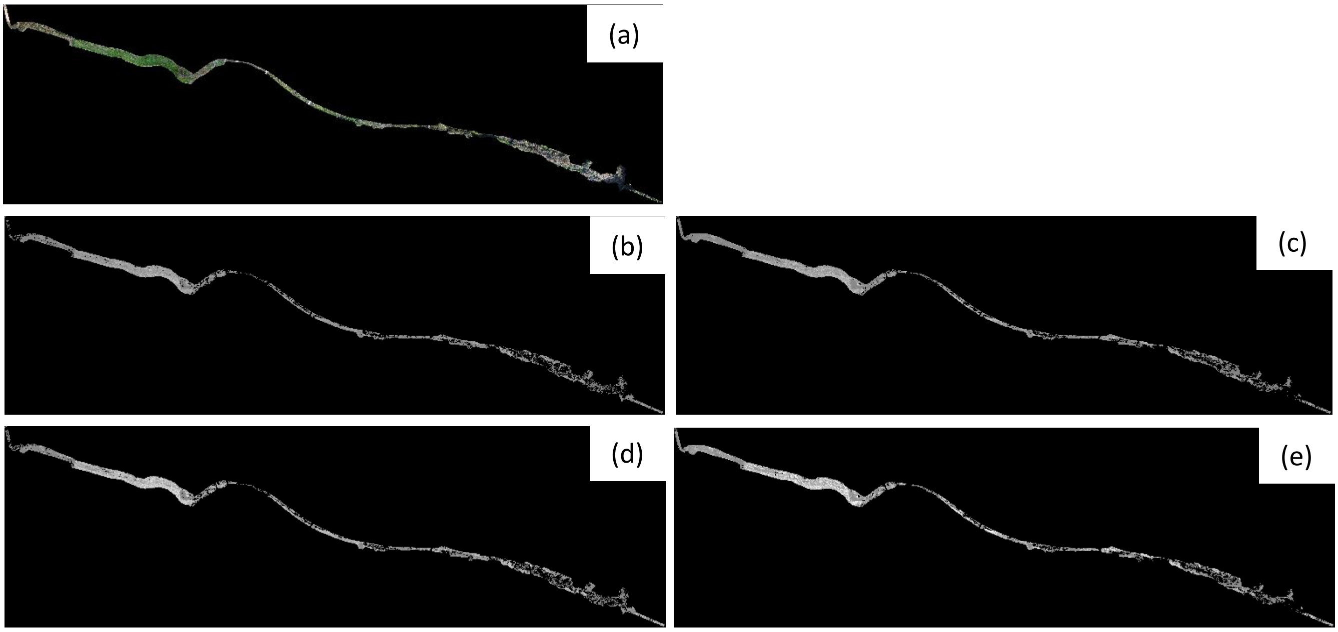


Figure 4.23. Vegetation indices results in the RGB orthophoto (a) dated 20200410 of the Ġnejna case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

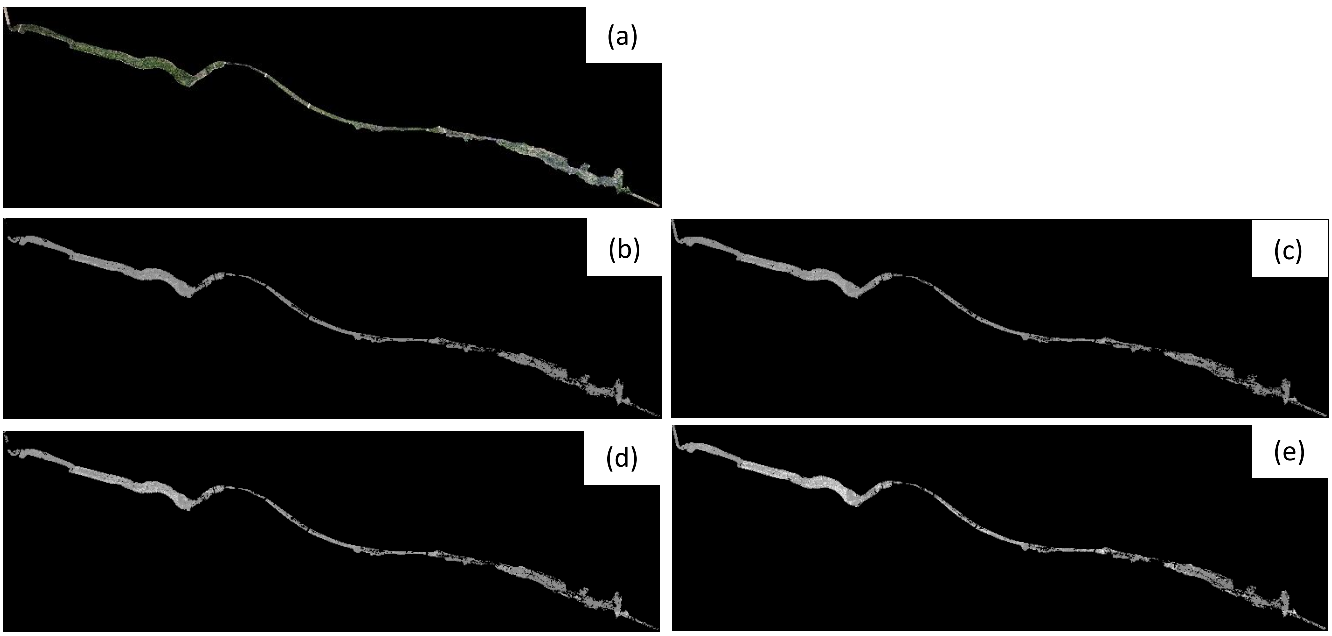


Figure 4.24. Vegetation indices results in the RGB orthophoto (a) dated 20201217 of the Ġnejna case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

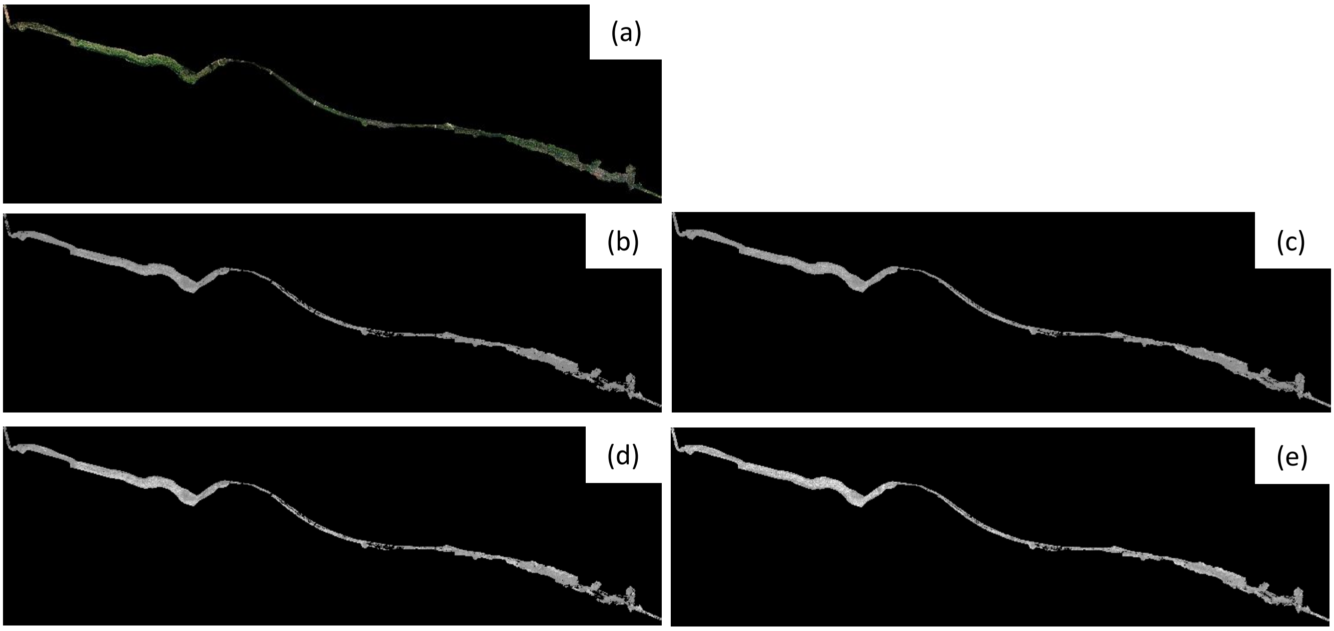


Figure 4.25. Vegetation indices results in the RGB orthophoto (a) dated 20190511 of the Harq Hammiem case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

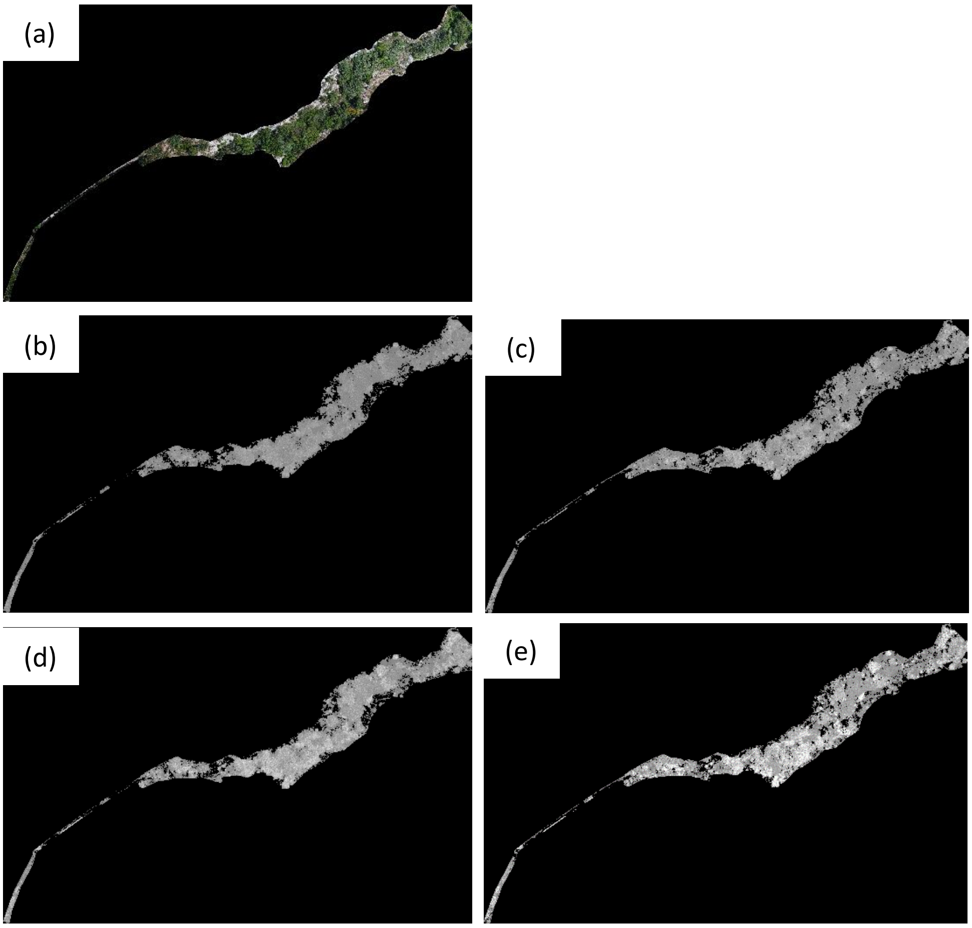


Figure 4.26. Vegetation indices results in the RGB orthophoto (a) dated 20190601 of the Harq Hammiem case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

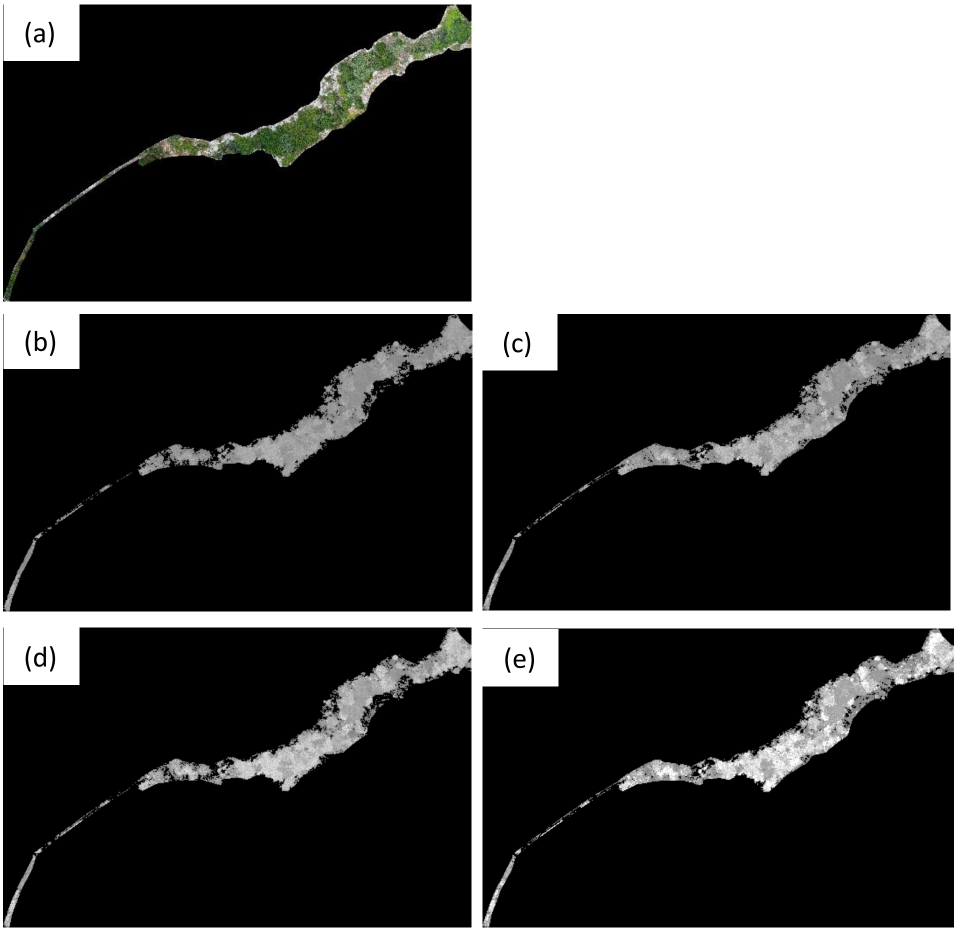


Figure 4.27. Vegetation indices results in the RGB orthophoto (a) dated 20190707 of the Harq Hammiem case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

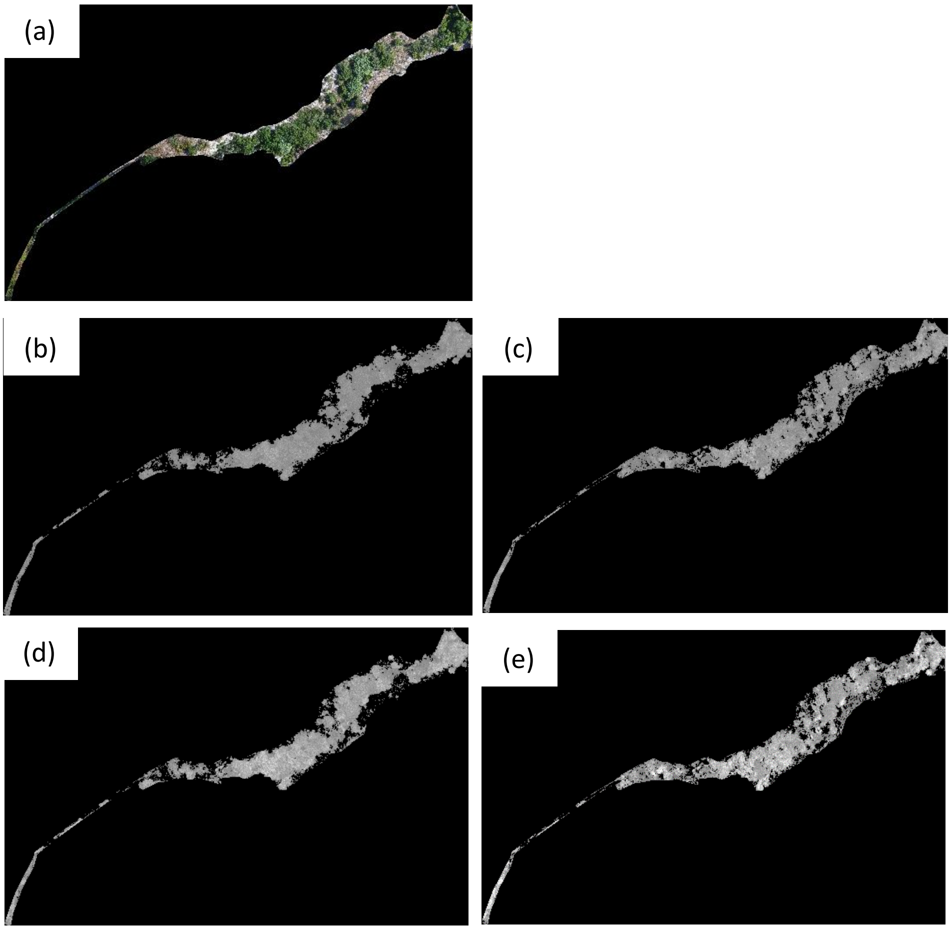


Figure 4.28. Vegetation indices results in the RGB orthophoto (a) dated 20200216 of the Harq Hammiem case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

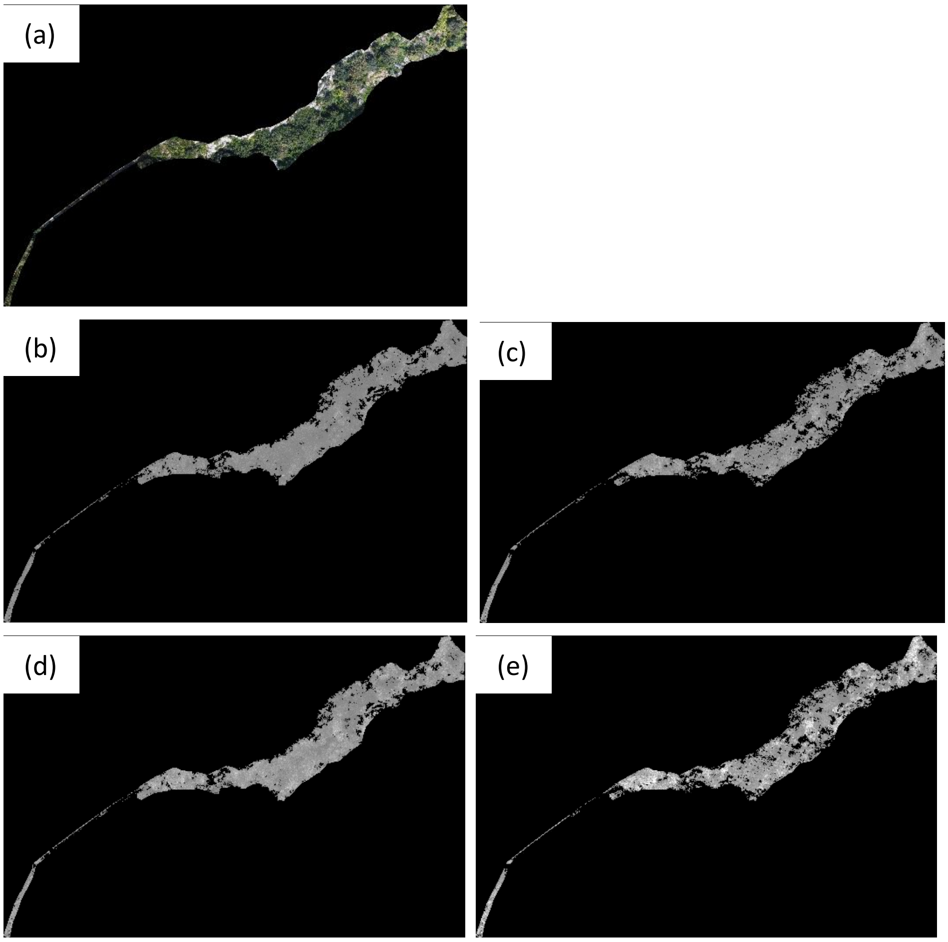


Figure 4.29. Vegetation indices results in the RGB orthophoto (a) dated 20200410 of the Harq Hammiem case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

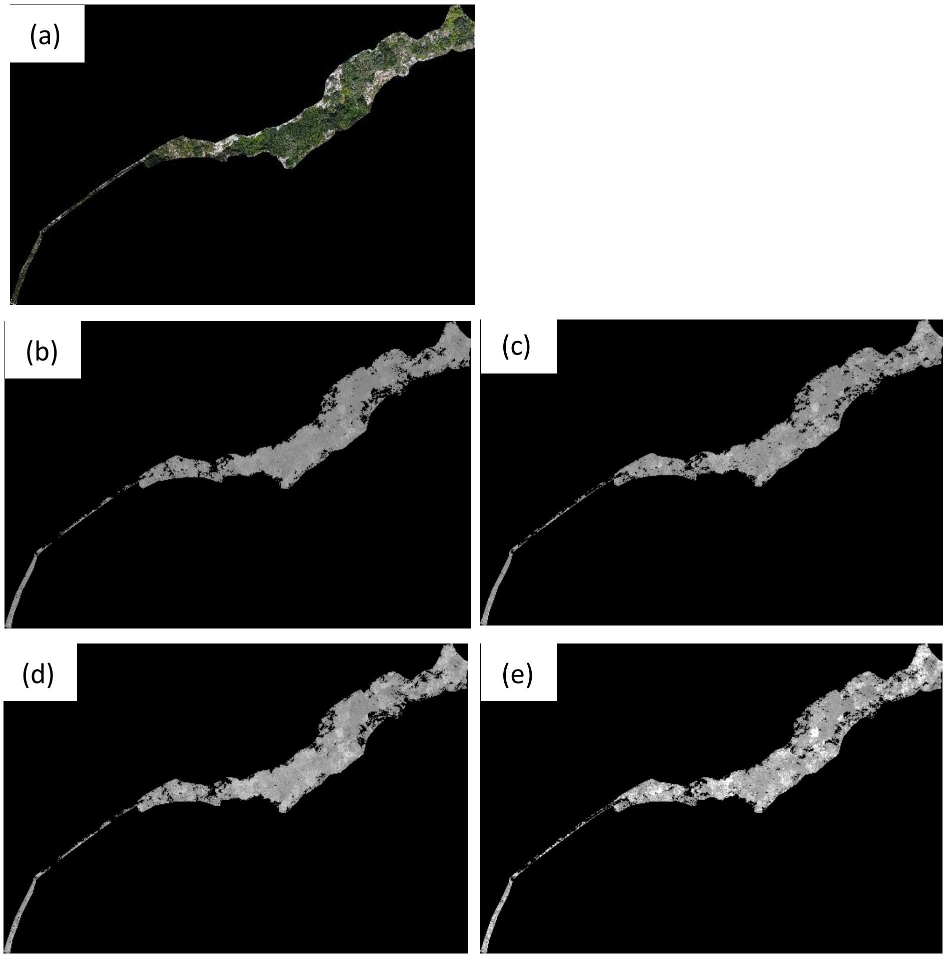


Figure 4.30. Vegetation indices results in the RGB orthophoto (a) dated 20201217 of the Harq Hammiem case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

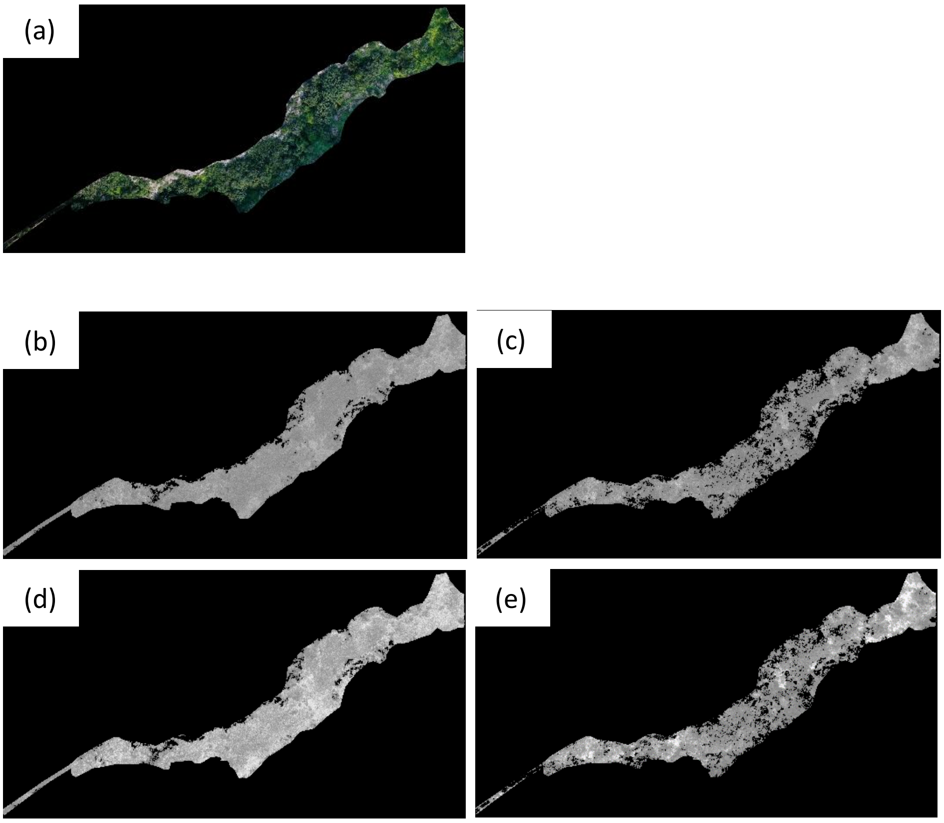


Figure 4.31. Vegetation indices results in the RGB orthophoto (a) dated 20190517 of the Luq case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

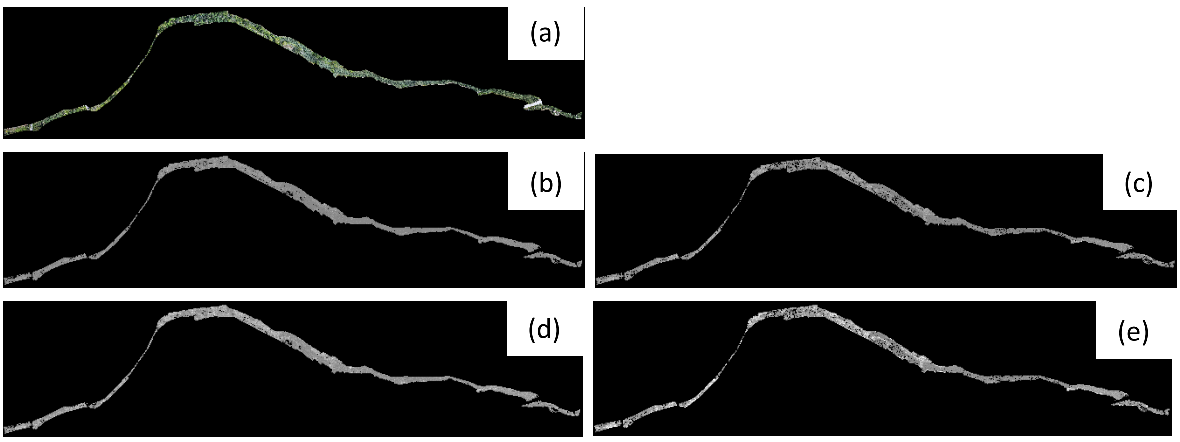


Figure 4.32. Vegetation indices results in the RGB orthophoto (a) dated 20190601 of the Luq case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

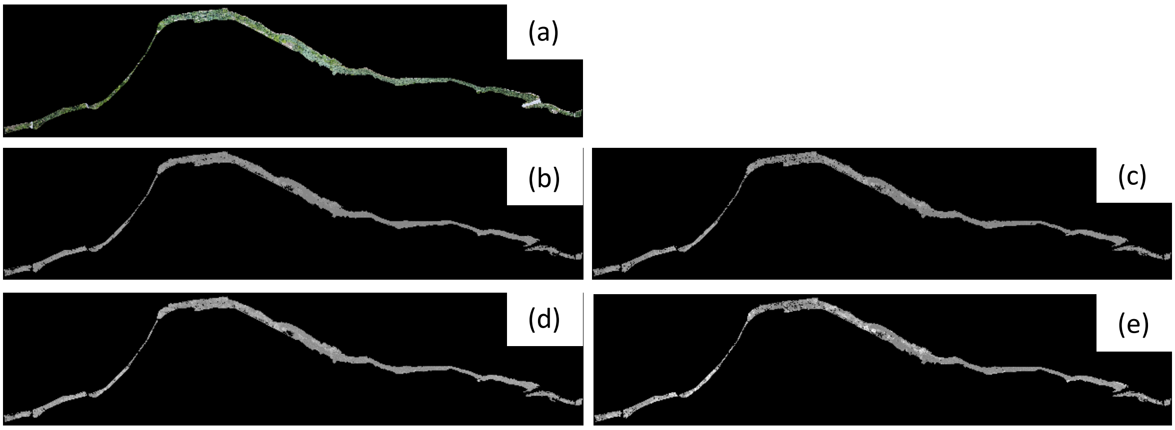


Figure 4.33. Vegetation indices results in the RGB orthophoto (a) dated 20191102 of the Luq case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

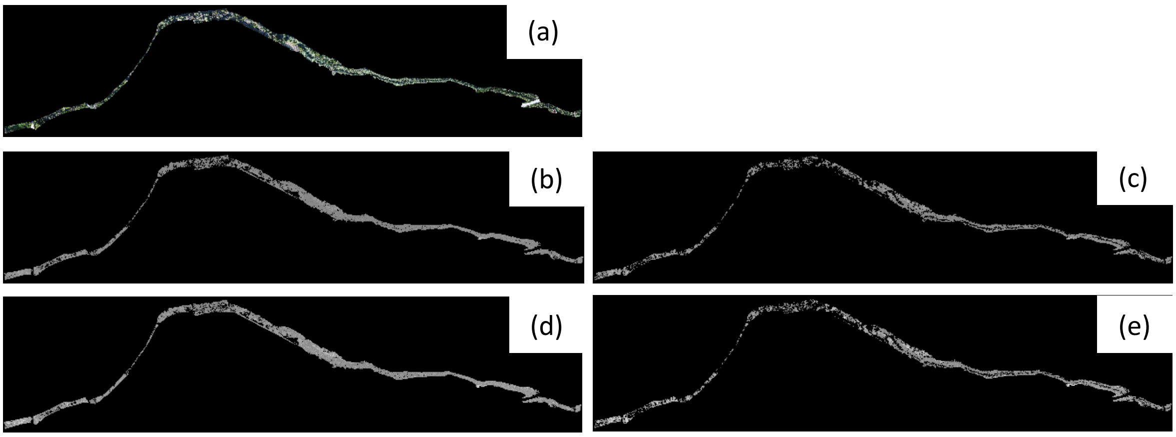


Figure 4.34. Vegetation indices results in the RGB orthophoto (a) dated 20200409 of the Luq case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

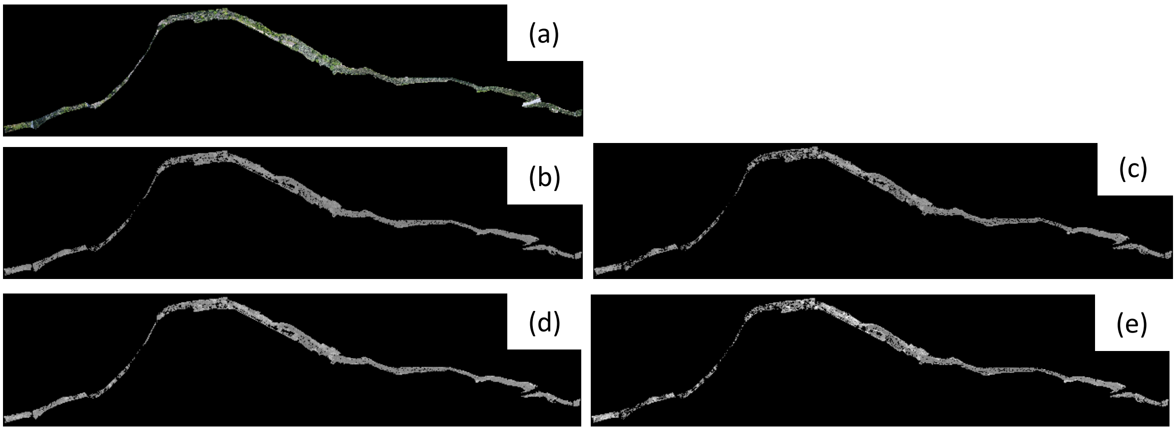


Figure 4.35. Vegetation indices results in the RGB orthophoto (a) dated 20200524 of the Luq case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

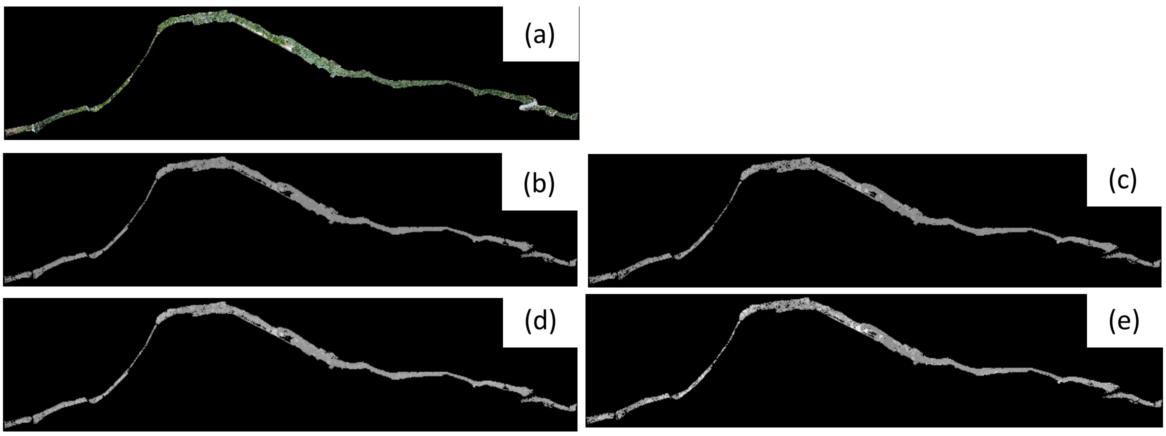


Figure 4.36. Vegetation indices results in the RGB orthophoto (a) dated 20200816 of the Luq case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

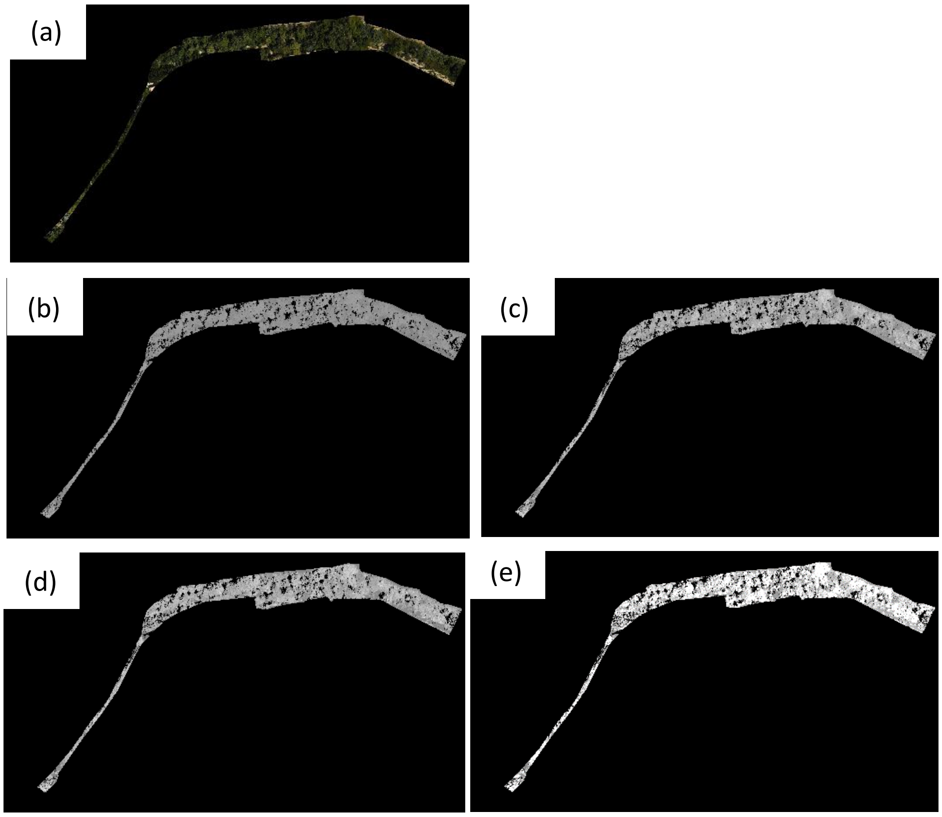


Figure 4.37. Vegetation indices results in the RGB orthophoto (a) dated 20190531 of the Miġra l-Ferħa case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

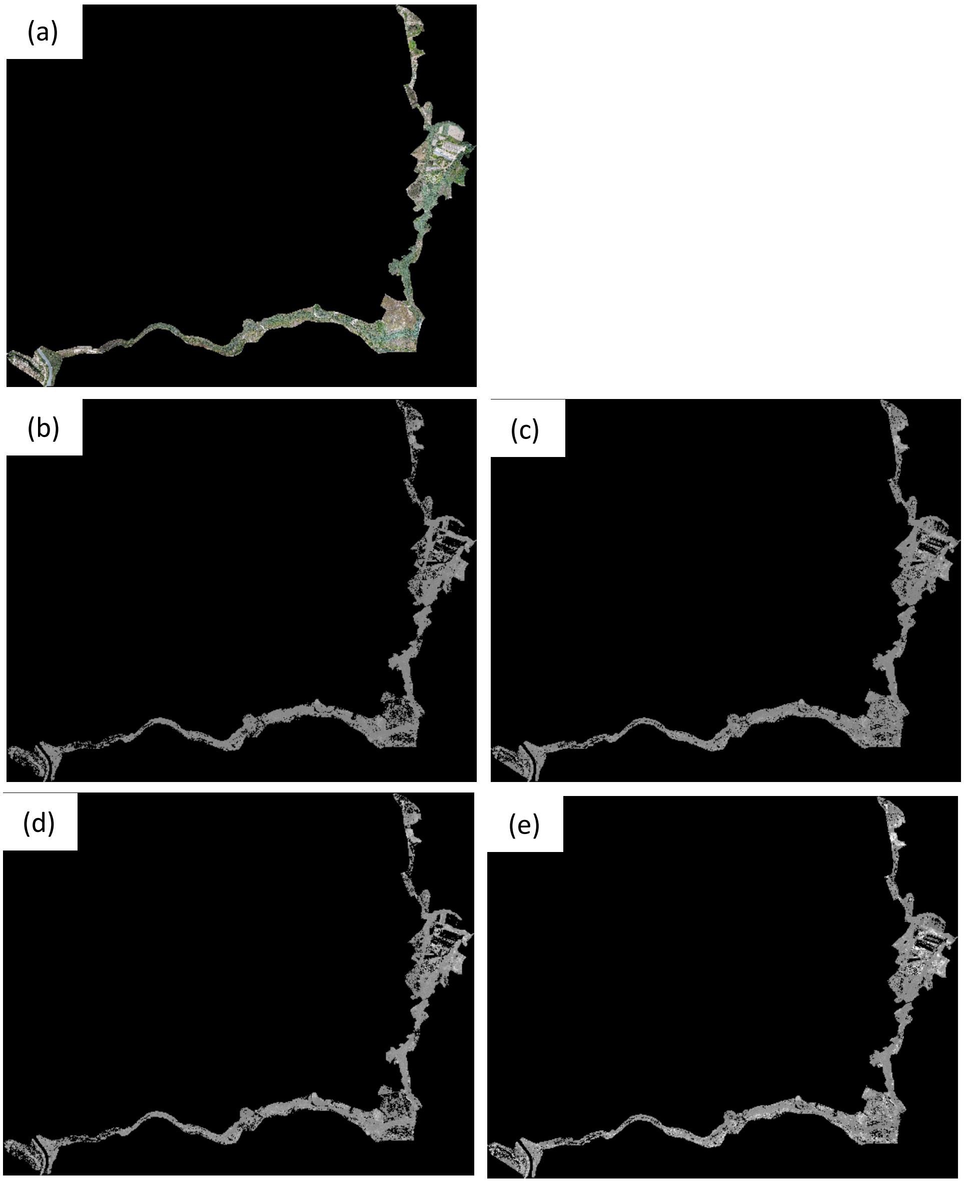


Figure 4.38. Vegetation indices results in the RGB orthophoto (a) dated 20200213 of the Miġra l-Ferħa case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

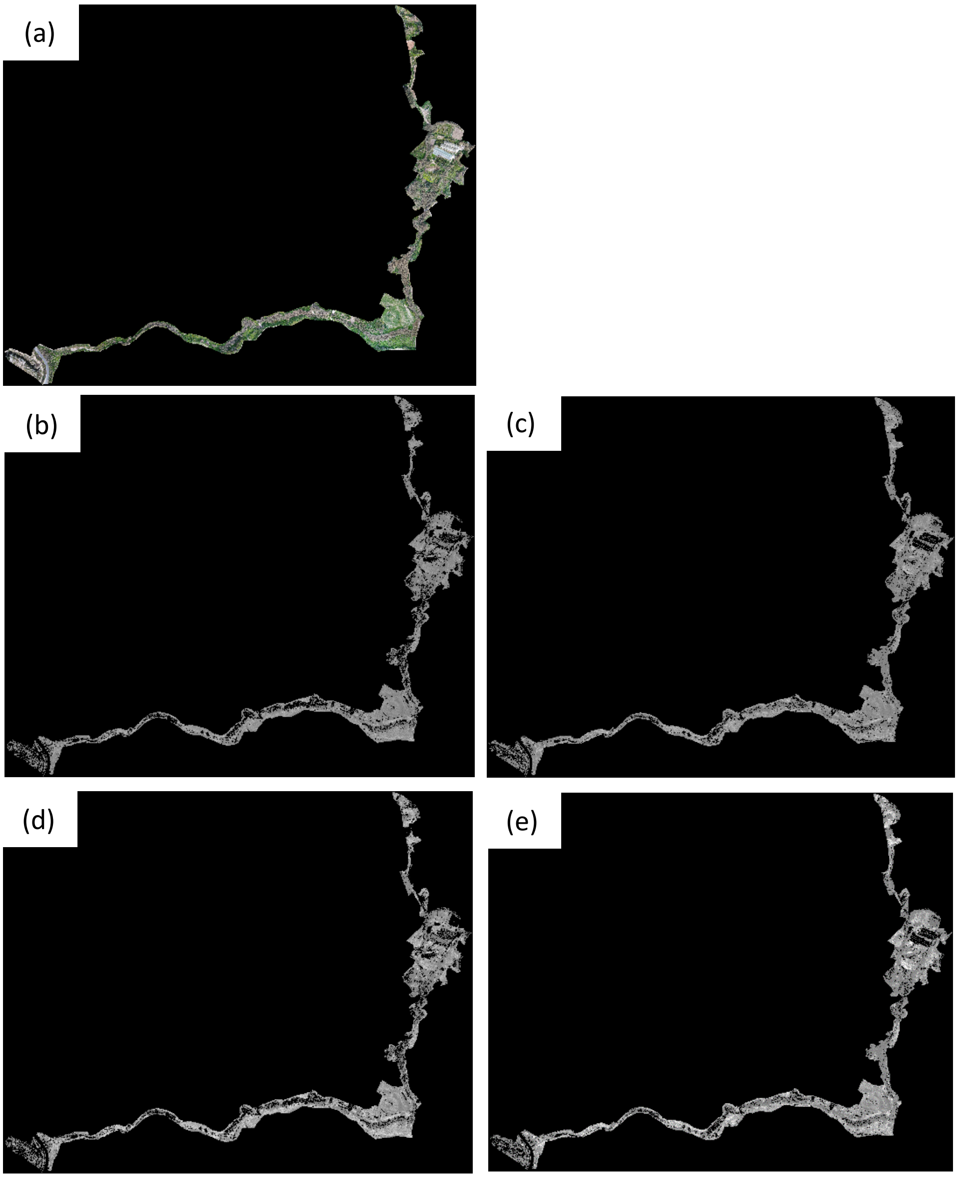


Figure 4.39. Vegetation indices results in the RGB orthophoto (a) dated 20200412 of the Miġra l-Ferħa case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

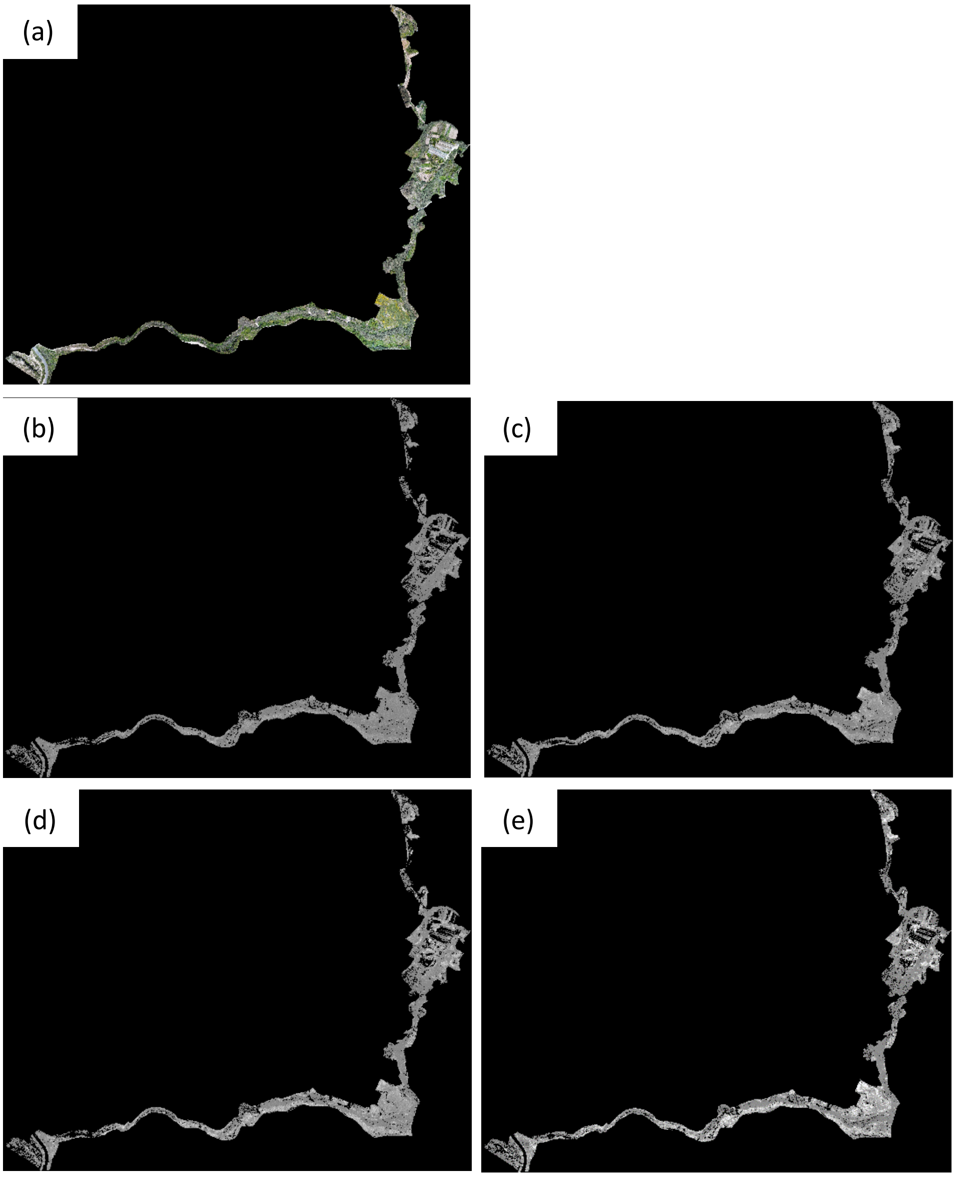


Figure 4.40. Vegetation indices results in the RGB orthophoto (a) dated 20200531 of the Miġra l-Ferħa case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

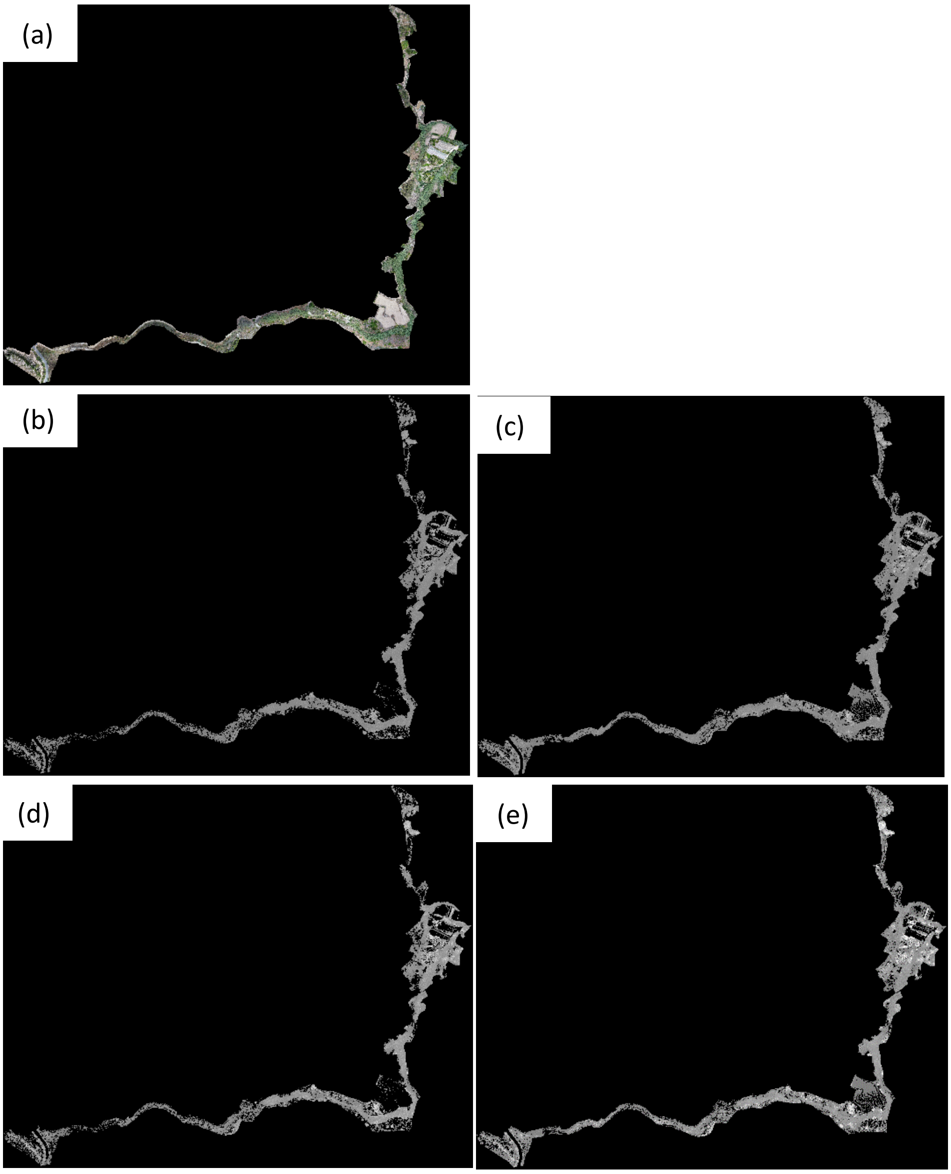


Figure 4.41. Vegetation indices results in the RGB orthophoto (a) dated 20201213 of the Miġra l-Ferħa case study, (b) green leaf index, (c) normalized difference green-red index, (d) red-green-blue vegetation index, (e) visible atmospherically resistant index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

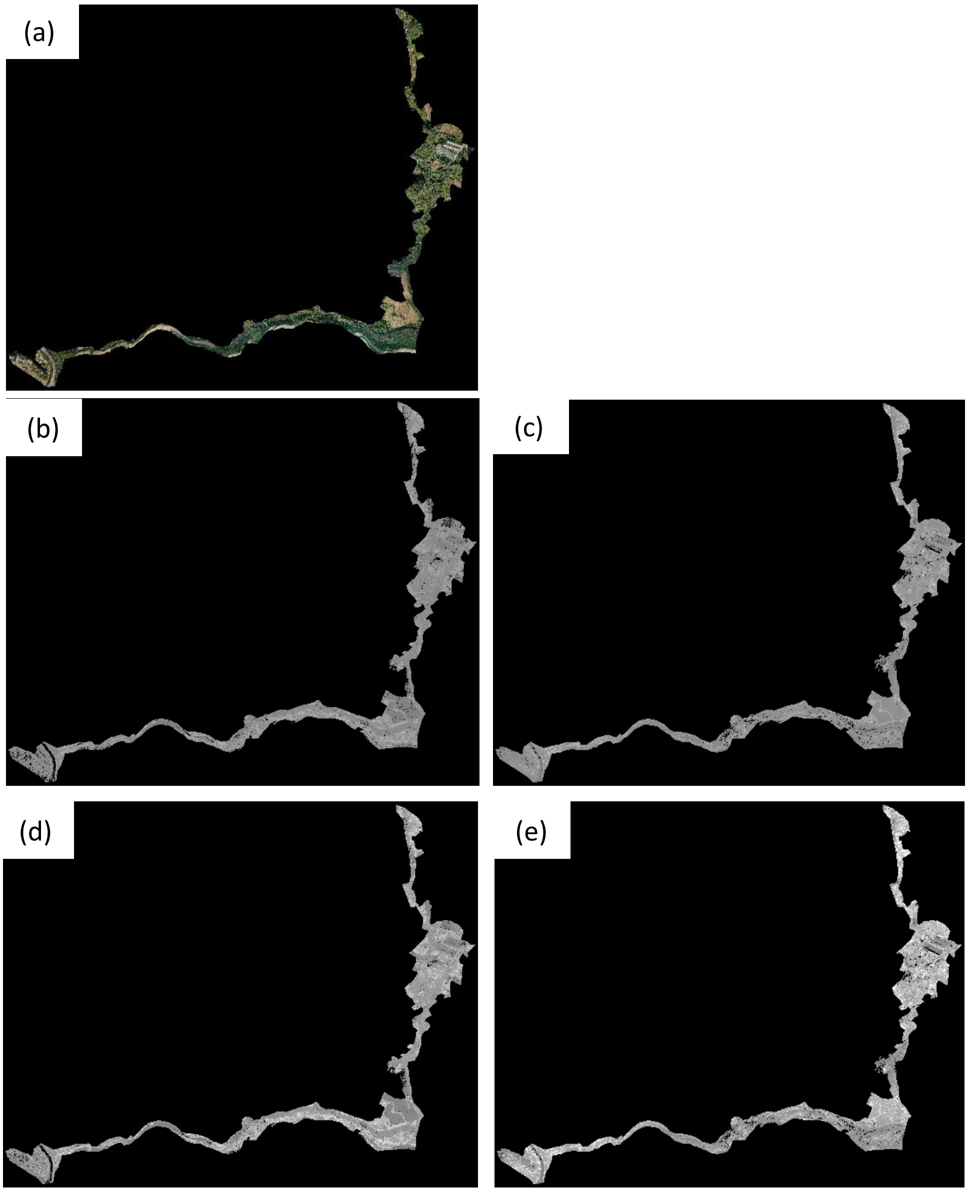


Figure 4.42. Vegetation indices results in the NIR orthophoto (a) dated 20201217 of the Ġnejna case study, (b) enhanced normalized difference vegetation index, (c) normalized difference red edge index, (d) normalized difference vegetation index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

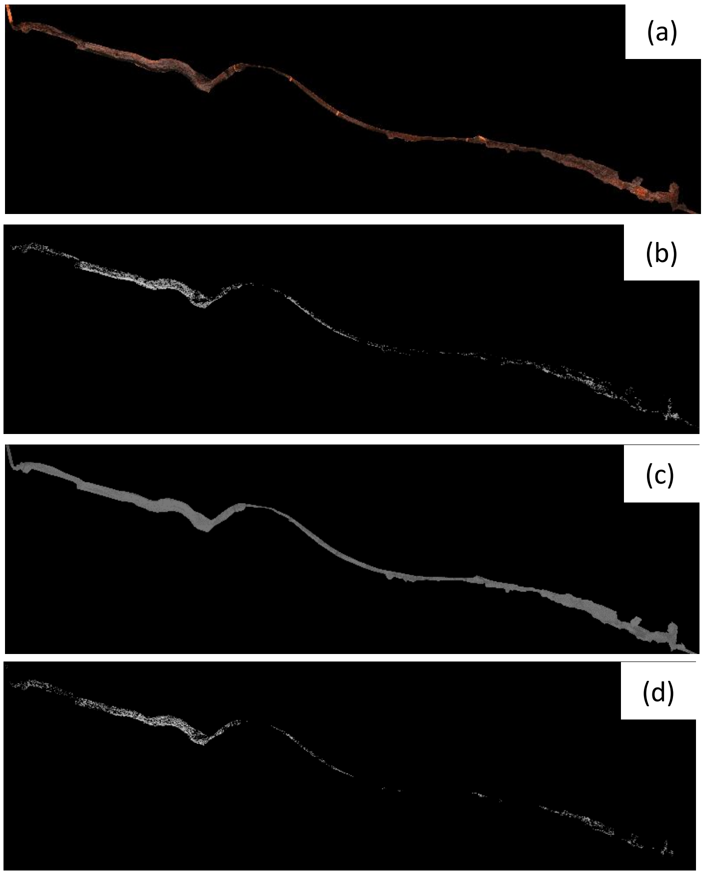


Figure 4.43. Vegetation indices results in the NIR orthophoto (a) dated 20201217 of the Harq Hammiem case study, (b) enhanced normalized difference vegetation index, (c) normalized difference red edge index, (d) normalized difference vegetation index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

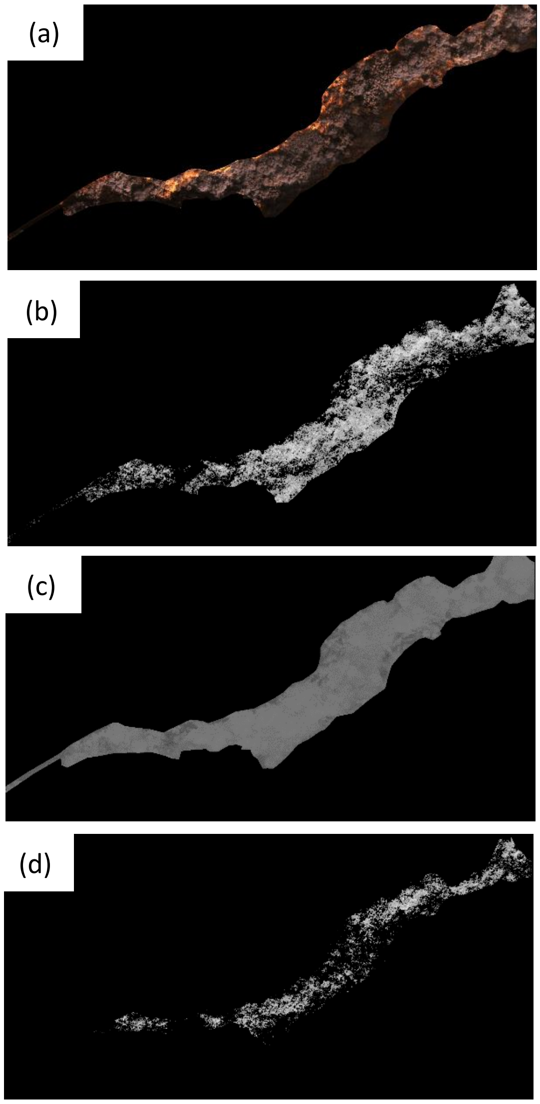


Figure 4.44. Vegetation indices results in the NIR orthophoto (a) dated 20200816 of the Luq case study, (b) enhanced normalized difference vegetation index, (c) normalized difference red edge index, (d) normalized difference vegetation index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.

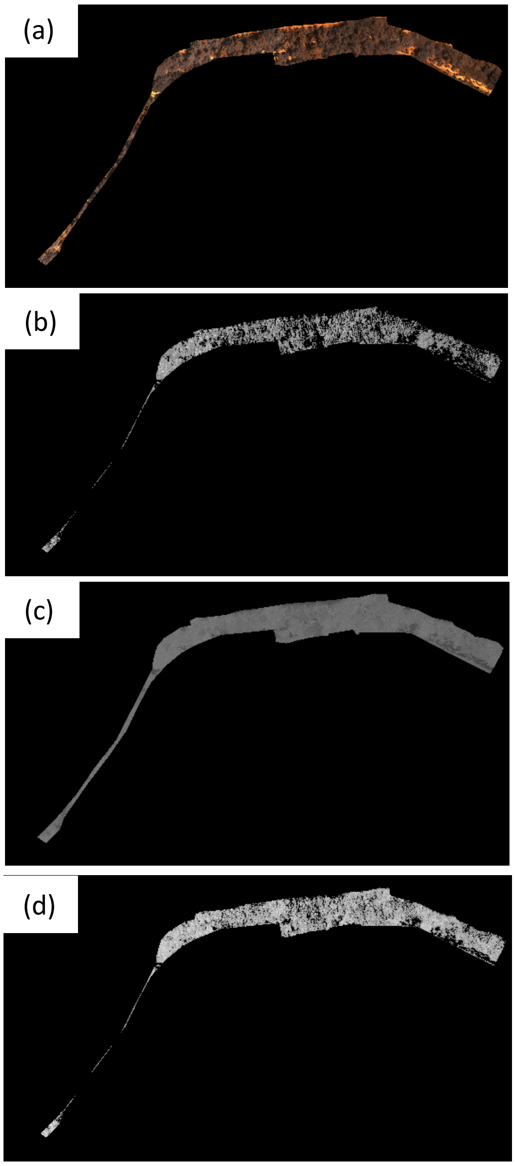
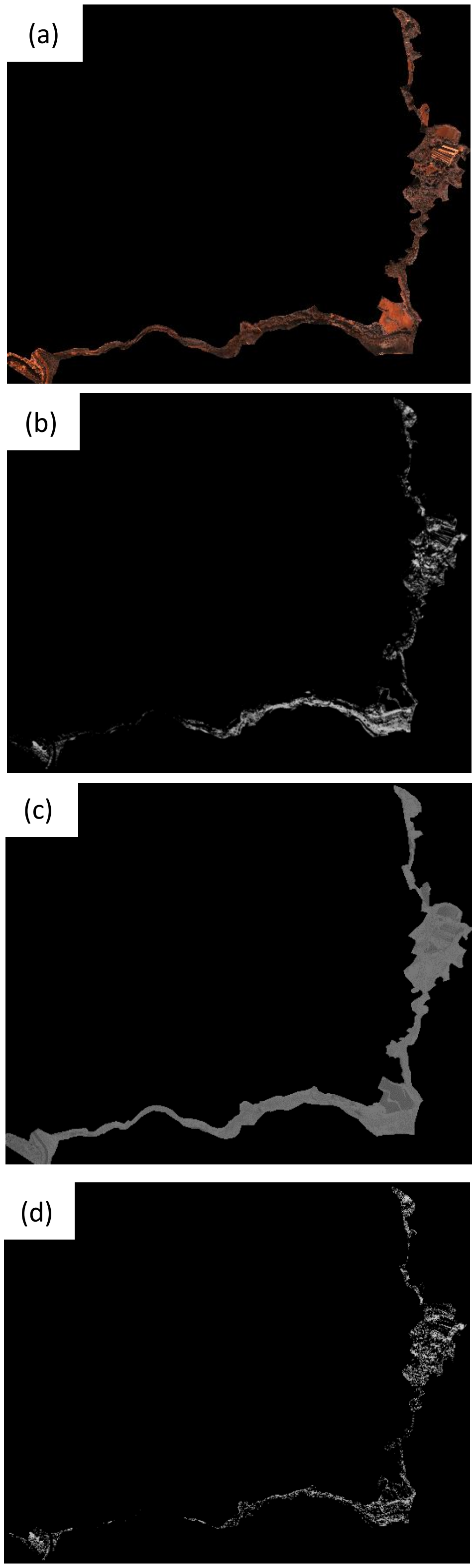


Figure 4.45. Vegetation indices results in the NIR orthophoto (a) dated 20201223 of the Miġra l-Ferħa case study, (b) enhanced normalized difference vegetation index, (c) normalized difference red edge index, (d) normalized difference vegetation index. Vegetated areas are highlighted with the light grayscale tone while non-vegetated areas with the darkest tone of grey.



4.5 Conclusion

In this paper, cost-effective and off-the-shelf UAVs, in conjunction with consumer-grade RGB cameras, and water-level dataloggers deployed in five Mediterranean IRES case study sites, were used to study the relationships between streambed water presence and riparian vegetation health. Specifically, the aims of this paper are to compare the performance of four different RGB VIs; explore responses of visible VI reflectance values against water level and precipitation data within different Mediterranean IRES catchments; and propose methods to improve the reliability and robustness of RGB VI applications to monitor vegetation against varying hydrometeorological dynamics within Mediterranean IRES environments. The results from the different RGB VIs were similar for all studied sites. This was shown by the similar averages and timeseries trends, with VARI having the most spreadout values relative to the mean, indicating that this index may be the least robust. Reflectance values were also spatially consistent within the entire case study sites, with no major differences in different sections of the captured images, when compared with the full extent of the studied reaches. When the visibile indices were analysed with water level and precipitation data, the varying catchment topologies, including vegetation type and land cover, indicated potential influences on the reflectance range results. Statistical analysis showed links between the RGB VI mean reflectance values with different streambed water levels. Reflectance values also portrayed seasonal dynamics. RGB VI values where highest when images were captured during the winter period, inferring that vegetation health is greater. However, when reflectance values were compared with cumulitive precipitation events, VI values were low when images were captured in periods followed by the highest incidence of rain events since the previous September. The robustness of visible VI's and the diverse intrinsic conditions that characterise different Mediterranean IRES catchments can be attributed to the inconsistency of the achieved results. Further research is required on the potential applicability of RGB VIs to monitor the spatio-temporal responses of riparian vegetation health and extent in Mediterranean IRES. Different catchment characteristics and landscape configurations must be categorized and statistically compared with RGB VI values to better understand the results obtained from these VIs. The development of these affordable tools show promise to ameliorate the knowledge on the ecohydrological dynamics of Mediterranean IRES, at centimetre resolutions and high spatio-temporal rates, and especially in response to human pressures and a changing climate.

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CHAPTER 5

THE ROLE OF UNCREWED AERIAL VEHICLES (UAVs) IN A BIOPHYSICAL ECOSYSTEM SERVICES-BASED ASSESSMENT FOR MEDITERRANEAN INTERMITTENT RIVERS AND EPHEMERAL STREAMS

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Abstract

In most cases, Mediterranean IRES are not included in monitoring and conservation schemes. This can be attributed to the poor understanding of their ecohydrological functions, monetary costs required for their management and general perception by society that these are second class systems when compared with perennial rivers. In this study, a novel ecosystem-based assessment is presented and tested in a number of Mediterranean IRES catchments. The identification and scoring of ecosystem services in IRES is fundamental towards enhanced recognition of these systems and prioritization of management strategies. The assessment is specifically aimed for ungauged stream networks as commonly the case in the Mediterranean. Uncrewed Aerial Vehicles (UAVs) combinded with Structure from Motion (SfM) photogrammetry, ground-truthed data and Geographic Information Systems (GIS) applications were used to map and quantify selected IRES attributes that contribute to the flow of ecosystem services. Fifteen catchment and stream attribute features and seventeen ecosystem services (five provisioning, six regulating, three supporting and four cultural) were used in this analysis. The results of the assessment showed that the highest ranked catchments had the largest drainage networks and included geomorphic conditions suitable for intermittent flow regimes, whereas urban catchments with smaller drainage networks scored the least. The use of UAVs together with SfM photogrammetry applications proved to be affordable, user-friendly and effective in capturing ES indicators in Mediterranean IRES with centimetre-accurate resolutions.

5.1 Introduction

Mediterranean intermittent rivers and ephemeral streams (hereafter, referred to as Mediterranean IRES that are found in the Mediterranean basin) experience flow cessation and commonly, the partial or complete loss of flows and/or standing surface waters (Datry et al., 2017; Gallart et al., 2012). Even though in the Mediterranean, IRES are the dominant surface water features and water management is historically focused towards maximizing resiliency to natural water scarcity (Grantham et al., 2013), IRES have been generally ignored for environmental monitoring regimes and restoration programmes, and are the least studied freshwater ecosystems worldwide (Datry et al., 2018; Grantham et al., 2013; Skoulikidis et al., 2017a; Stubbington et al., 2018a). This mismanagement of IRES is contributing to serious ecosystem degradation leading to negative impacts to societies that are dependant on them (Acuña et al., 2014a). The lack of recognition can be attributed to poor understanding of their extent and ecohydrological functions, monetary costs for their conservation and management, and a general perception by society that such systems are not important due to the paucity of surface waters and periodic no flows that promoted the underestimation of their environmental and socio-economic values (Acuña et al., 2014a, 2017; Skoulikidis et al., 2017; Stubbington et al., 2018). The valueing of IRES by society is also highly dependant on the hydrological regime including the flow and non-flow periods, seasons, particular stakeholder groups, geographical origin and socio-cultural context (Jorda-Capdevila et al., 2021).

IRES generally lack legal recognition and hence, are not protected on the same level as perennial rivers (Acuña et al., 2014a). In the European Union (EU), IRES may not meet the threshold for classification as a water body, depending on the identification methods adopted in a particular region (Munné & Prat, 2004). For example, Malta applied alternative means to characterise surface waters as the physical descriptors set by the EU Water Framework Directive (WFD) were deemed insufficient to characterise local inland surface water bodies which are dominated by transient water dynamics. The 2nd Water Catchment Management Plan for the Malta Water Catchment District 2015 – 2021 adopted the "hydrological regime" as the single defining criterion to characterise the Islands' watercourses (SEWCU & ERA, 2015). In view of the absence of flow data, empirical information was primarily used to classify watercourses. With this approach, only three stream reaches, with a total lenght of 3.3km from an approximate 376km of surface water drainage network found in the Maltese Archipelago were classified as "temporary", and legally obligated for WFD monitoring and reporting. Novel and easy-to-adopt approaches and assessment tools are needed to better inform decision-makers on how IRES functions translate to improved human well-being.

Over recent decades, there has been an increased recognition of society's dependency upon natural habitat complexity and ecological functions to sustain human well-being (Boulton et al., 2016). The concept of ecosystem services (ES) is widely recognised as having potential for understanding the relationships between ecosystems and society. ES are most commonly classified into four broad categories: provisioning, regulating, supporting, and recreational/cultural services (MEA, 2005). Following the Millenium Ecosystem Assessment (MEA, 2005), The Economics of Ecosystems and Biodiversity (TEEB,

2010) report and the Common International Classification of Ecosystem Services (CICES) (Haines-Young & Potschin, 2012), the adoption of the ES approach increased exponentially in environmental planning and policy (Reyjol et al., 2014). In fact, ES assessment tools are frequently used in environmental management to define and prioiritize conservation actions (e.g. Hou et al., 2018; Katada et al., 2017; Tiemann & Ring, 2022; Willaarts et al., 2012). The anthropocentric ideology of the ES approach in environmental planning, that focuses on the benefits that humans obtain from ecosystems and their functions (MEA, 2005), has the potential to provide decision-makers working in Mediterranean environments, a better understanding on the key societal benefits provided by IRES and in turn prioritise their management and protection. Recent studies showcased in detail the environmental and socio-economic values that IRES provide to society (Koundouri et al., 2017; Vorste et al., 2020). For example, in the Mediterranean, IRES are highly valuable in agricultural landscapes were Kaletová et al. (2019) identified at least ten potential ES benefits for crop production and animal husbandry attributable to IRES, namely; surface water, ground water, nutrition for animals, nutrients and organic matter, pollination, soil fertility, genetic diversity, parasitoids, research approach and soil water-air regime.

The understanding of the relationships between the transient hydrological regime and ecosystem structure and function in Mediterranean IRES is still limited (Acuña et al., 2014b; Muñoz et al., 2018). This can principally be attributed to the difficulties encountered when monitoring and mapping Mediterranean IRES at adequate spatio-temporal scales to capture the water flow and aquatic states (Gallart et al., 2011) dynamics and their influence on the biophysical variables along the hydrologically temporary stream continuum (Borg Galea et al., 2019). In fact, many IRES are unmapped and ungauged or when gauged, stations are usually sparsely distributed and do not capture the spatial extent of the various hydrological states, ranging from connected flows, unconnected pools and dry periods (Costigan et al., 2017). Hence any ES assessment methodology in Mediterranean IRES needs to take into consideration the absence of viable long-term hydrological datasets whilst still encompassing the heterogeneity, connectivity and dynamism of the catchment at appropriate spatio-temporal scales (Large & Gilvear, 2015).

In recent years, remote sensing techniques, most notably, satellite data have emerged that capture spatially explicit data at high spatial resolution and with regular monitoring potential (Caruso et al., 2019; Woodget et al., 2017). Remote sensing is especially useful when catchment-scale approaches are required (Large & Gilvear, 2015). However, extractible information is limited by spatial and temporal resolutions (Latte & Lajeune, 2020). Information is only limited to specific capture dates and the limited resolutions hinder data analysis, especially in the Mediterranean, where most IRES and headwater streams are frequently only a few metres wide (Borg Galea et al., 2019; Costigan et al., 2017; Gallart et al., 2016). In this paper we argue that the use of novel remotely-sensed technologies involving structure-from-motion (SfM) photogrammetry combined with the use of uncrewed aerial vehicles (UAVs) such as quadcopter drones, have the potential for cost-effective, user-friendly mapping of ES indicators in IRES with elevated temporal frequency on fine spatial scales (Borg Galea et al., 2019). Imagery from UAVs have already been deployed to map small-scale ecohydrological and biophysical features in IRES (Spence & Mengistu, 2016; Yang et al., 2019). This study presents and tests a methodology for catchment-scale Mediterranean IRES ES assessment. The assessment is aimed for stream networks that are ungauged and/or have limited timeseries of ecohydrological data as commonly the case in the Mediterranean (Kastridis et al., 2020). The method uses remotely sensed images from UAVs and processed with SfM photogrammetry techniques to produce high resolution orthophotos combined with ground-truthed data. Specifically, the objectives were to 1) devise a robust and easy to apply ES assessment tool to enable the prioritisation of conservation and restoration measures in Mediterranean IRES and 2) illustrate the tool's effectiveness by applying it to multiple catchments with different ecohydrological conditions.

5.2 Methodology

The methodological steps used in this paper were adapted from Keele et al. (2019) and Large & Gilvear (2015) and uses a "patch-dominated" river corridor approach where a landscape-scale framework is adopted for the better understanding of the discontinuous ecological patterns along river networks. In the proposed Mediterranean IRES ES assessment, this approach was translated to capture, as much as possible, the various conditions found in the stream networks that result due to dynamic and temporary flow patterns in Mediterranean IRES. While Keele et al. (2019) and Large & Gilvear (2015) used Google Earth, a virtual-globe imaging platform, to observe and measure riverscape features, in this study, a framework using UAVs, SfM photogrammetry techniques and GIS applications was adopted to measure and quantify ES delivered from various Mediterranean IRES catchments. The method comprises three basic steps. The first stage involves the identification of applicable catchment-scale and reach (source to mouth) scale features that determine the type and level of ES. The second step included the identification of methods using geographic information system (GIS) applications from the remotely sensed UAV and ground-truthed data at appropriate scales. Finally, the development of a protocol for the assigning of Mediterranean IRES features to individual ES and an evaluation matrix for scoring the provided ES.

5.2.1 Determination of ES provided by Mediterranean IRES and linking with measurable IRES features

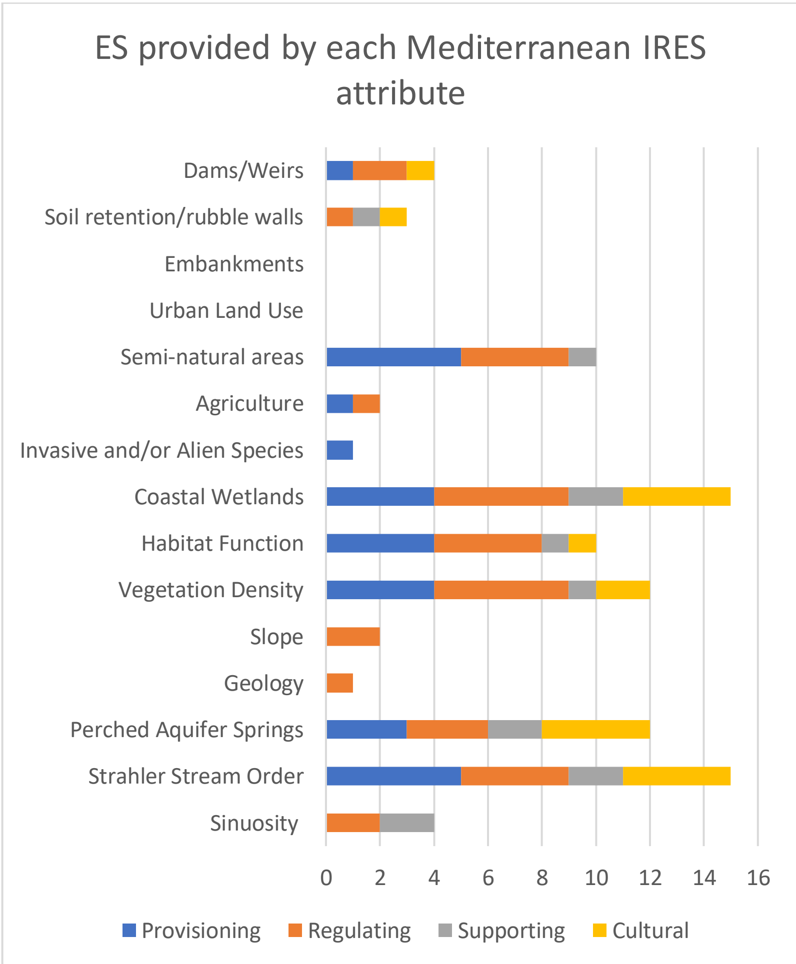
Linking ecosystem function to human well-being is a complicated endeavour due to the limited understanding of the mechanisms and dynamics that provide ES in many natural ecosystems (Ringold et al., 2013). This is more evident in Mediterranean IRES where the influence of transient flows on many ecosystem functions that provide ES is still undetermined (Koundouri et al., 2017). Koundouri et al. (2017) provided a comprehensive list of potential ES available at landscape-level by IRES that result from the various hydrological states of flowing, non-flowing (pools) and dry phases of the flow regime. In addition, Pastor et al. (2022) identified 109 indicators to assess and measure ES from IRES. Given that one of the main objectives of this paper is to provide an ES assessment for ungauged or poorly gauged catchments, a conservative approach was adopted for the selected ES of Mediterranean IRES, where the focus was to identify those ES that can be effectively measured through UAV, ground-truthing and GIS applications, without the strict requirement for timeseries data.

Table 5.1. ES determined from Mediterranean IRES attributes visible from orthophotos derived from UAVs, and their division into Provisioning, Regulating, Supporting and Cultural ES categories. (Adapted from Keele et al. (2019); Large & Gilvear (2015) and Koundouri et al. (2017)).

Ecosystem Services	Sinuosity	No. of tributaries	Perched aquifer	Geology	Slope	Vegetation cover	Habitat function	Coastal wetlands	Invasive and/or	Agriculture	Semi-natural areas	Urban land uses	Embankments	Soil	Dams/weirs	**No. of features**
Provisioning																
Food		■	■			■	■	■		■	■					7
Fibre and fuel		■	■			■	■	■	■		■					7
Fresh water		■	■								■				■	4
Biochemical		■				■	■	■			■					5
Genetic Materials		■				■	■	■			■					5
Regulating																
Climate regulation		■	■			■	■	■			■					6
Water regulation (hydrological flows)		■	■	■		■		■			■				■	7
Water purification and waste treatment		■	■		■	■	■	■			■					7
Erosion regulation	■					■	■	■		■	■			■		7
Natural hazard regulation	■	■			■	■	■	■							■	7
Supporting																
Soil formation	■															1
Nutrient cycling		■	■					■								3
Biodiversity	■	■	■			■	■	■			■			■		8
Cultural																
Spiritual and inspirational		■	■					■								3

Recreational		■	■					■								3
Aesthetic		■	■			■		■						■	■	6
Educational		■	■			■	■	■								5
Number of services provided by feature	4	15	12	1	2	12	10	15	1	2	10	0	0	3	4	

Figure 5.1. Total provisioning, regulating, supporting and cultural ES provided by each identified Mediterranean IRES attribute/feature.



The MEA-based ES categorisation of provisioning, regulating, supporting and cultural was used for the selected seventeen ES provided by Mediterranean IRES (Table 5.1 & Figure 5.1). Sixteen of the ES derived from IRES were identified by Koundouri et al. (2017), whilst in this study, 'biodiversity', was also added under the *supporting* ES category. Biodiversity supports ecosystem functions not only through the quantity of species present in a community, but also through their interactions and specific characteristics (Smeti et al., 2019). Even though, biodiversity in Mediterranean IRES is lower than in perennial rivers (Skoulikidis et al., 2017), it is fundamental to consider biodiversity in the context of species richness in addition to habitat structure and processes when trying to understand the links between biodiversity and ecosystem functioning and in turn, the provision of ES (Smeti et al., 2019).

Fifteen features contributing to the provisioning of ES in Mediterranean IRES where identified and described in Tables 5.2 and 3. These were kept to a minimum to simplify the data capture and analysis process as much as possible and to minimize duplication, whereby more than one attribute account for a single IRES function that might potentially produce a bias towards ES supported by those specific catchment features (Large & Gilvear, 2015). Twelve of the selected features can be measured from the UAV derived images whereas the other features are determined from ancillary non-remotely sensed data (Table 5.4). In view of the assumed dearth of temporal hydrological data and the spatio-temporal variability of duration, frequency, timing and magnitude of each of the potential hydrological phases in IRES (Gallart et al., 2011), other attributes that provide an indication of the flow regime pattern of the studied case study areas where included in the ES assessment. These include non-remotely-sensed information but easily available datasets, such as 'geology', and the presence privately-owned 'perched aquifer springs'. These attributes were included to provide additional information on the probable flow regime pattern of the studied catchment. In the Mediterranean, the temporary hydrological regime with particular seasonal, inter-annual and spatial heterogeneity (Bonada & Resh, 2013) is governed by the highly temporal climate variations, with predominantly low precipitation during summer (Skoulikidis et al., 2017). Together with climate, the interaction between catchment characteristics such as topography, geology and vegetation also contribute to the flow regimes (Costigan et al., 2017). Hence, baseline geophysical attributes such as geology and other 'natural' additional sources of surface water flows are important indicators for ES provisioning in Mediterranean IRES. Another non-UAV derived feature included the methodology is 'habitat function' where ground-truthed surveys (see Section 2.2) were carried out along the entire stream (with $\geq$ 4 Strahler stream order) network to map and classify (average of unfavourable prospects, good prospects, or excellent prospects) the habitat mosaic arrangement and capability to sustain species, populations and diversity of flora and fauna. In table 5.2, the theoretical linkages between the Mediterranean IRES attributes, inferred driving processes and potential ES are described for all the fifteen features used in the proposed ES assessment tool.

5.2.2 Extraction of Mediterranean IRES features from the remotely sensed and survey data

Data capture was carried out as part of the RBMP LIFE Project (LIFE 16 IPE MT OO8) throughout 2019 and 2020. The project involved the filling of information gaps on Malta's main IRES catchments through the collection of datasets and field surveys. Surveys involved the capture of remotely-sensed images through the use UAVs and ground-truthed field data. High resolution images were collected using quadcopters DJI Phantom 4 Advanced and DJI Mavic 2 Pro. These UAVs are capable of autonomous waypoint flight following a pre-planned route, which was created with DroneDeploy freeware application for the DJI Phantom 4 Advanced and Sentera FieldAgent for DJI Mavic 2 Pro. The images were taken by the quadcopters' factory-installed 20MP cameras. For the ground-truthing, an adapted field survey method was designed, based on widely used habitat and hydro-morphological assessments (González del Tánago & García de Jalón, 2011; Rinaldi et al., 2015; Stubbington et al., 2018b; CNR-ISA Water Research Intitute, 2008). The boundary of the detailed survey areas was reach-based from source to mouth of the catchments, in addition to a 50m buffer delineated on either side of the water channels.

Table 5.3 presents a summary of the steps for the measurement of the twelve Mediterranean IRES features extracted from the remotely-sensed UAV imagery. The images were captured with sufficient overlap to produce SfM-based photogrammetric orthophotos. The 2D orthomosaics and Digital Terrain Models (DTM) were produced through a photogrammetric point cloud analysis with ESRI ArcGIS Drone2Map application. ESRI ArcMap 10.6.1 was the GIS application used to analyse and measure the ES features from the captured UAV images. For example,

Table 5.2. Linkage between Mediterranean IRES features or land cover types, inferred hydrological processes and characteristics, natural ecosystem functions and ES delivered including positive and negative feedback (Adapted from Keele et al. (2019); Large & Gilvear (2015)and Koundouri et al. (2017)).

Catchment feature/attributes	Inferred hydrological processes and characteristics	Natural Ecosystem functions	ES Positive Feedback	ES Negative Feedback
Sinuosity	Outer bank erosion; temporary pool formation; longer path length; riffle formation; reduced slope; hydrologic connectivity	Flow attenuation, hydraulic diversity; channel dynamism; refugia;	Erosion regulation; natural hazard regulation; soil formation; biodiversity	
No. of tributaries (Strahler stream order)	Sediment and water supply; biotic and nutrient transfer; hydrologic connectivity	Hydraulic diversity; channel dynamism; habitat creation	Food; fibre and fuel; fresh water; biochemical; genetic materials; climate regulation; water regulation; water purification and waste treatment; natural	

			hazard regulation; nutrient cycling; biodiversity; spiritual and inspirational; recreational; aesthetic; educational	
Perched aquifer springs	Intermittent sediment and water supply; biotic and nutrient transfer; decreased water temperature	Hydraulic diversity; channel dynamism; habitat creation	Food; fibre and fuel; fresh water; climate regulation; water regulation; water purification and waste treatment; nutrient cycling; biodiversity; spiritual and inspirational; recreational; aesthetic; educational	
Geology	Potential for groundwater recharge/discharge and occurrence of natural perched aquifer springs	Hydraulic diversity; channel dynamism; habitat creation	Food; fibre and fuel; fresh water; climate regulation; water regulation; water purification and waste treatment; nutrient cycling; biodiversity; spiritual and inspirational; recreational; aesthetic; educational	
Slope	Low slopes reduce energy gradient for transfer of water, sediment and nutrients, promoting storage and biogeochemical processing, reworking of sediment in active reaches	Habitat diversity; channel dynamism; habitat creation; sediment storage; habitat	Water purification and waste treatment; natural hazard regulation	

		heterogeneity; increased wetted perimeter		
Vegetation cover	Substrate stabilisation; enhanced hydraulic roughness; shading; allochthonous leaf litter and woody debris input	Habitat creation and hydraulic diversity; cooling of water; food source; refugia	Food; fibre and fuel; biochemical; genetic materials; water purification and waste treatment; erosion regulation; biodiversity; educational	
Habitat function	Substrate stabilisation; enhanced hydraulic roughness; shading; allochthonous leaf litter and woody debris input	Habitat creation and hydraulic diversity; cooling of water; food source; refugia	Food; fibre and fuel; biochemical; genetic materials; water purification and waste treatment; erosion regulation; biodiversity; educational	
Coastal wetlands	Aquatic and semi-aquatic habits; plant and animal succession processes; sites for nutrient storage and transformation; sediment deposition	Carbon sequestration; phosphorous uptake and denitrification; habitat heterogeneity; flow attenuation; refugia	Food; fibre and fuel; biochemical; genetic materials; water purification and waste treatment; natural hazard regulation; nutrient cycling; biodiversity; spiritual and inspirational; recreational; aesthetic; educational	
Invasive and/or alien plant species	Shading; soil/sediment stabilisation; allochthonous leaf litter and woody debris input; enhanced hydraulic roughness	Fragmentation of native habitats; displacement of native flora and	Fibre and fuel	Flood; ecological fragmentation; deterioration of water quality

		fauna; water quality; increase in the susceptibility of riparian corridors to fire		and reduced quantity
Agriculture	Potential for increased runoff response; enhanced fine sediment input; water quality deterioration	Loss of natural land cover; hydrologic alteration; natural biodiversity and cultivar biodiversity	Food; erosion regulation; biodiversity	Monoculture
Semi-natural areas	Enhanced sediment input	Plant and animal succession processes	Biodiversity	First succession opportunistic species
Urban Land Use	Potential for increased runoff response; water quality deterioration	Loss of natural land cover; hydrological alteration	None	Flood; ecological fragmentation
Embankments	Elimination of flood inundation	Loss of natural land cover; hydrologic alteration	None	Ecological fragmentation
Soil Retention/Rubble Walls	Reduced flood inundation; reduced sediment input	Hydrologic alteration; habitat creation	Erosion regulation; biodiversity; aesthetic	
Dams/Weirs	Increased residence time of stormwater; associated deposition of sediment from suspension; increased groundwater infiltration; increased water temperature	Hydrologic alteration; changes in habitat composition; changes in	Water regulation; natural hazard regulation; aesthetic	Ecological fragmentation; altered sediment transfer

		sediment transfer		

for the stream order the Strahler method was used. Order 1-4 were excluded as their significance is limited for the scope of this study. Stream order was extracted from the DTMs. DTMs derived from UAVs have been proven to not only reduce working costs, minimize the danger of mapping inaccessible or dangerous areas, with adequate efficacy, but also provide adequate accuracies (Polat et al., 2017). In another example, slope was calculated as percentage rise through the 'Slope' tool from the ARC Toolbox option in ArcMap. Other attributes such as vegetation cover, invasive and/or alien species, the type of embankments, presence of soil retention walls and dams or weirs were remotely mapped with the UAV-derived orthomosaics and ground-truthed through the field surveys.

Table 5.3. Mediterranean IRES features, and measurement methods determined from UAV. (Adapted from Keele et al. (2019) and Large & Gilvear (2015)).

IRES features/attributes	Observable evidence from UAV data	Delineation and measurement of IRES feature/attributes
Sinuosity	Stream with bends	2D images from UAV
Strahler stream order	Classification of streams	Formation of drainage networks from DTMs/2D images from UAV
Slope	DTM derived from SfM photogrammetry processed UAV images	2D images from UAV
Vegetation cover	Total area of separately green coloured patches	Estimate percentage area of separately green coloured patched (ground-truthed with LIFE IP RBMP data)
Coastal wetlands	Darker tones in coastal areas	Map (polygon feature) and calculate percentage area of darker, non-textured vegetation in coastal areas
Invasive and/or alien species	Visible evidence from high resolution orthophotos captured by an UAV and processed through a SfM photogrammetry process	Map (polygon feature) and calculate percentage area of uniform patches of vegetation and individual trees identified from high resolution and high magnification (ground-truthed with LIFE IP RBMP data)

Agriculture	Presence of field patterns with uniform vegetation/soil colour	Map (polygon feature) and calculate percentage area (Corine dataset)
Semi-natural areas	Presence of field patterns (less distinctive) with no uniform vegetation/soil colour (abandoned agricultural fields) and other green areas including sclerophyllous vegetation	Map (polygon feature) and calculate percentage area (Corine dataset)
Urban Land Use	Uniform areas of settlement, including single buildings	Map (polygon feature) and calculate percentage area (Corine dataset)
Embankments	Narrow linear, clearly artificial (concrete) features paralleling channel	Map (polyline feature) and calculate length (ground-truthed with LIFE IP RBMP data)
Soil Retention/Rubble Walls	Rubble wall structures paralleling channel	Map (polyline feature) and calculate length (ground-truthed with LIFE IP RBMP data)
Dams/Weirs	Narrow straight features, or narrow arched features or wide masonry 'humps' cross-cutting channel and obstructing the watercourse	Number of dams/weirs (ground-truthed with LIFE IP RBMP data)

Table 5.4. Additional Mediterranean IRES features determined from non-UAV data.

IRE features/attributes	Non-UAV data source
Perched aquifer springs	Map with location of privately-owned springs (Energy and Water Agency) and knowledge from local experts
Geology	Geology map (Planning Authority)
Habitat function	Field survey data (LIFE IP RBMP) and calculate percentage area of habitat mosaics function with "excellent prospects", "good prospects" and "average and unfavourable prospects"

5.2.3 Scoring system for the individual IRES features and prioritisation of provided ES from Mediterranean IRES catchments

The data extracted from GIS analysis were inputted in Microsoft Excel and Mediterranean IRES indices were calculated with the mathematical tools available. Similar to Large & Gilvear's (2015) scoring matrix, the system used in our ES assessment is integer-based whereby 0 meant 'absent' or of virtually no value to ES provision and 3 refers to 'optimal' or near the maximum possible potential for ES provisioning (Table 5.5). Equal weighting was applied for all the identified ES as their value is dependent on preference and societal characteristics where these are provided. A weighting for each ES attribute was however calculated with accordance to the number of potential ES provided for each particular feature. For example, sinuosity contributes to the provisioning of four ES (Table 5.1), thus the attributed scoring for sinuosity was multiplied by the percentage value of the same attribute for each case study site. The advantage of this type of scoring system is its adaptability to different geographical and socio-economic circumstances. Different types of ES are valued differently as both the spatial and/or temporal scale of the analysis varies (Reyjol et al., 2014). Even in the Mediterranean, diverse societies differ in their valuing and their demands/requirements for ES. Hence, the weighting across all fifteen ES can be modified in different areas/regions in the Mediterranean based on societal decisions and biogeographical conditions.

Table 5.5. Rules relating to attributing Mediterranean IRES features/attributes or land cover types at catchment scale to potential ecosystem service score.

IRES features/attributes	**Score**			
	0	**1**	**2**	**3**
Sinuosity	Straight (1:1)	Sinuous (<1.5)	Highly sinuous (1.5 – 2.5)	Tortuous (<2.5)
Strahler stream order	≤4	5	6	≥7
Perched Aquifer Springs[3]	0	≥1	≥ 5	≥10
Geology	N/A	Globigerina Limestone or Lower Globigerina Limestone	Upper Coralline Limestone	Blue Clay
Slope (% rise)	≥50%	≥150%	≥300%	≥500%
Vegetation Cover	≤4%	≤10%	≤15%	>15%
Habitat function	≥ 50% "average or unfavourable prospects"	≥ 30% "good prospects"	≥ 50% "good prospects"	≥20% "excellent prospects"
Coastal Wetlands	Absent-trace (>5%)	Low (6-25%)	Medium (26-50%)	High (>50%)
Invasive and/or Alien Species	High (≥10%)	Medium (9-5%)	Low (4-2%)	Absent-trace (≤1%)
Agriculture	Absent-trace (>5%)	Low (6-25%)	Medium (26-50%)	High (>50%)
Semi-natural areas	Absent-trace (>5%)	Low (6-25%)	Medium (26-50%)	High (>50%)
Urban Land Use	Absent-trace (>5%)	Low (6-25%)	Medium (26-50%)	High (>50%)

[3] Registered private natural springs provide by Malta Resources Authority (MRA) in July 2022

Embankments	Fully embanked on both sides	Discontinuous but extensive	Locally present	Absent
Soil Retention/Rubble Walls	Absent	Locally present	Discontinuous but extensive	Fully continuous on both sides
Dams/Weirs	≥16	6-15	1-5	0

5.3 Case studies and results

The ES assessment was tested in fifteen IRES catchment areas located in the island of Malta, located in the central Mediterranean basin (Figure 5.2, Table 5.6). Malta is the third most densely populated country in the EU with 1,867 persons per square kilometres, contrasting with the second largest island in the archipelgo, Gozo with 486 persons (NSO, 2019). Similar to most Mediterranean IRES, climate is the main driver of flow regimes in the Islands' surface water channels. The annual total precipitation of 553.1mm and mean temperature of 18.6°C, with a mean maximum of 22.3C° and mean minimum of 14.9°C makes the archipelago relatively hot and dry (Galdies et al., 2016; Galdies, 2022). The hydrological regime is also determined by the Islands' karstic geomorphology which is primarily made up of limestone with variations provided by two thin strata, one of Greensand and one of Blue Clay, the latter being the only rock having a relatively impermeable lithology. Phreatic perched groundwater bodies are sustained in the Upper Coralline Limestone formation perched over the Blue Clay aquitard (SEWCU & ERA, 2015). The original horizontal structure of the strata has also been influenced by a general West-East tilt and numerous fault lines that run along with two basic patterns, those trending NE-SW which dominate and those tending NW-SE (Anderson, 1997; Schembri, 1993). In addition, throughout the islands, flows have also been anthropogenically altered through the construction of impoundments such as small dams or weirs and/or are also sustained by effluents from small-scale industrial activities. The selected drainage basins make up 68% of the archipelago's surface area and have varying characteristics that affectively represent the islands' landscape topologies. Three catchments, il-Wied tad-Dwejra, Wied ta' l-Imġarr and Wied tax-Xlendi, are located in Gozo, whereby the other twelve case study sites are found within the mainland, Malta. Wied il-Għasel and Wied il-Kbir have the largest catchments, covering a surface area of 59km² and 74km² respectively, and have the highest Strahler stream order (8), whilst Wied ta' Ħarq Ħammiem is the smallest, with a drainage reach of 1km² and stream order of 5. The land use of Wied Blandun, Wied Għomor and Wied ta' Ħarq Ħammiem is predominantly urban and Wied il-Baħrija is the most 'rural' with 64% of its catchment classified as 'sclerophyllous vegetation' (CLC, 2018). Conversely, agriculture is the primary land use in Wied Dalam, il-Wied tad-Dwejra, Wied il-Għajn, Wied ta Sant' Antnin, Wied tal-Ġnejna, Wied il-Kbir, Wied ta' l-Imġarr and Wied il-Mistra.

Figure 5.3 depicts the weighted score for the ES attributes for each case study site and table 5.7 presents the final ranked scores of the ES assessment. Il-Wied tad-Dwejra in Gozo, Wied il-Kbir and Wied il-Għasel and received the highest scores whilst Wied il-Għajn and Wied Ħarq Ħammiem catchments acquired the lowest ES provisioning ranking. Being the largest catchments, Wied il-Kbir and Wied il-Għasel obtained high scores with regards to their physical attributes, such as stream order, which is directly related to these sites' drainage surface area. From a geomorphic perspective, both catchments include areas where the impermeable blue clay layer is found, leading to the formatIion of natural perched aquifer springs that contribute to intermittent surface flows. In fact, in Wied il-Għasel, there were 42 registered springs and in Wied il-Kbir there were 19 (MRA, 2022). In comparison, Wied il-Baħrija was the third catchment with the highest amount of registered perched aquifer springs with 7 (MRA, 2022). Conversely, Il-Wied tad-Dwejra obtained high scores mainly due to its ecological characteristics. The catchment ranked third with regards to vegetation cover in the riparian area with 19.19% and scored first with the highest percentage of its habitat with excellent prospects for habitat function, standing at 27.44% of the case study site's stream reach. This catchment also ranked with the lowest surface area where invasive and non-native plant species were found and the third lowest with surface area characterised as urban (CLC, 2018).

Wied Ħarq Ħammiem ranked the second-lowest. In view of its small size, compared to the other case study sites, the catchment received low scores in the geophysical attributes with the lowest slope percentage rise and lowest stream order (5). In addition, this stream network is found within an urban conurbation, with 56% of its land cover classified as urban (CLC, 2018). Wied il-Għajn, is also one of the smaller catchments with a drainage area of 6km². This drainage network is highly framented, with only 3.98% vegetation cover along the riparian zone. From a geomorphic point of view, this catchment scored low with regards to slope percenentage rise and geology, where the absence of the impermeable blue clay formation, means that no additional 'natural' spring water flows that contribute to the transient hydrological regime of this watershed.

Figure 5.2. Location of the fifteen case study catchment areas and stream network for the biophysical ES-based assessment for Mediterranean IRES.

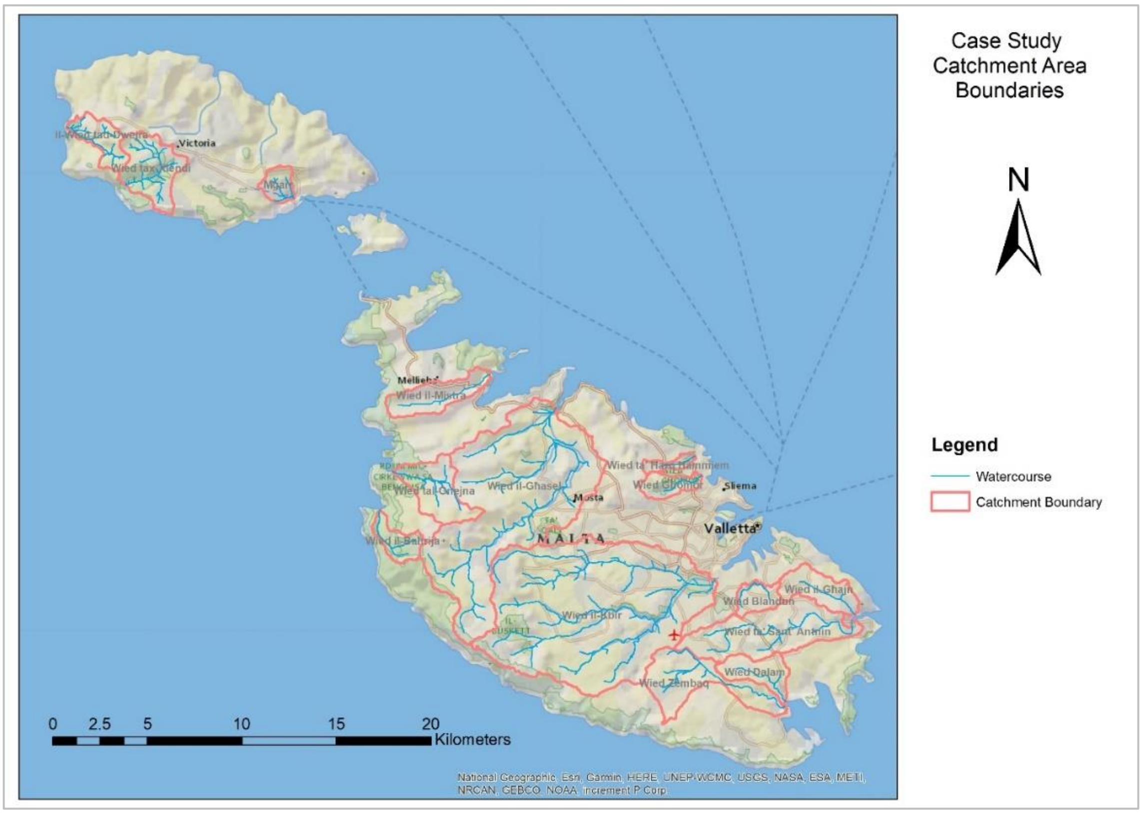


Table 5.6. Characteristics of the fifteen catchments areas selected for this study. All data were retrieved from the LIFE IP RBMP project, except for land cover data (CLC, 2018).

Catchment Name	Drainage Area (km²)	% Channel Observed	Total Stream Length (km)	Strahler Order at Mouth	No. of Main Tributaries (≥ 4 Strahler Order)	Average Channel Width (m)	Max. Recorded Channel Width (m)	Min. Recorded Channel Width (m)	Land Cover
Wied il-Baħrija	4	72	4	6	2	3	6	0.4	9% discontinuous urban fabric; 27% land principally occupied by agriculture; 64% sclerophyllous vegetation
Wied Blandun	3	11	3	6	2	1.6	1.6	1.6	1% continuous urban fabric; 84% discontinuous urban fabric; 2% industrial or commercial units; 12% green urban areas; 1% non-irrigated arable land
Wied Żembaq	12	30	14	6	9	2	5	1	27% discontinuous urban fabric; 15% airports; 10% mineral extraction sites; 38% land principally occupied by agriculture; 10% sclerophyllous vegetation

Wied Dalam	5	59	4	6	3	2	2	2	24% discontinuous urban fabric; 3% non-irrigated arable land; 55% land principally occupied by agriculture; 18% sclerophyllous vegetation
Il-Wied tad-Dwejra	5	79	8	6	19	3	10	1	11% discontinuous urban fabric; 2% non-irrigated arable land; 65% land principally occupied by agriculture; 22% sclerophyllous vegetation
Wied il-Għajn	6	26	3	6	2	n.d	n.d	n.d	35% discontinuous urban fabric; 1% industrial or commercial units; 1% green urban areas;6% non-irrigated arable land; 57% land principally occupied by agriculture
Wied ta' Sant' Antnin	18	28	16	7	8	7	8	5	33% discontinuous urban fabric; 5% industrial or commercial units; 7% airports; 55% land principally occupied by agriculture

Wied il-Għasel	59	67	55	8	39	5	21	0.4	58% discontinuous urban fabric; 3% industrial or commercial units; 3% mineral extraction sites; 4% sport and leisure facilities; 4% non-irrigated arable land; 13% complex cultivation patterns; 13% sclerophyllous vegetation; 2% salines
Wied tal-Ġnejna	8	21	9	6	10	6	10	1	8% discontinuous urban fabric; 63% land principally occupied by agriculture; 29% sclerophyllous vegetation
Wied ta' Ħarq Ħammiem	1	30	2	5	0	3	6	3	86% discontinuous urban fabric; 14% land principally occupied by agriculture
Wied Għomor	3	100	2	5	0	6	10	1	40%; land principally occupied by agriculture; 60% discontinuous urban fabric
Wied il-Kbir	74	73	65	8	42	7	21	1	21% discontinuous urban fabric; 4% industrial or commercial units; 3% airports; 3% mineral extraction sites; 2% sports and leisure facilities; 1% non-

									irrigated arable land; 9% complex cultivation patterns; 52% land principally occupied by agriculture; 1% mixed forest; 4% sclerophyllous vegetation
Mġarr	3	100	3	6	9	2	4	1	13% discontinuous urban fabric; 87% land principally occupied by agriculture
Wied il-Mistra	7	37	6	6	1	4	16	1	22% discontinuous urban fabric; 2% industrial or commercial units; 3% airports; 2% mineral extraction sites; 1% sport and leisure facilities; 1% non-irrigated arable land; 4% complex cultivation patterns; 56% land principally occupied by agriculture; 9% sclerophyllous
Wied tax-Xlendi	9	46	14	6	32	4	9	2	36% discontinuous urban fabric; 17% non-irrigated arable land; 38% land principally occupied by agriculture; 9% sclerophyllous

Figure 5.3. Plot showing total assessment weighted scores for each ES attribute in the fifteen Mediterranean IRES catchment area case study sites.

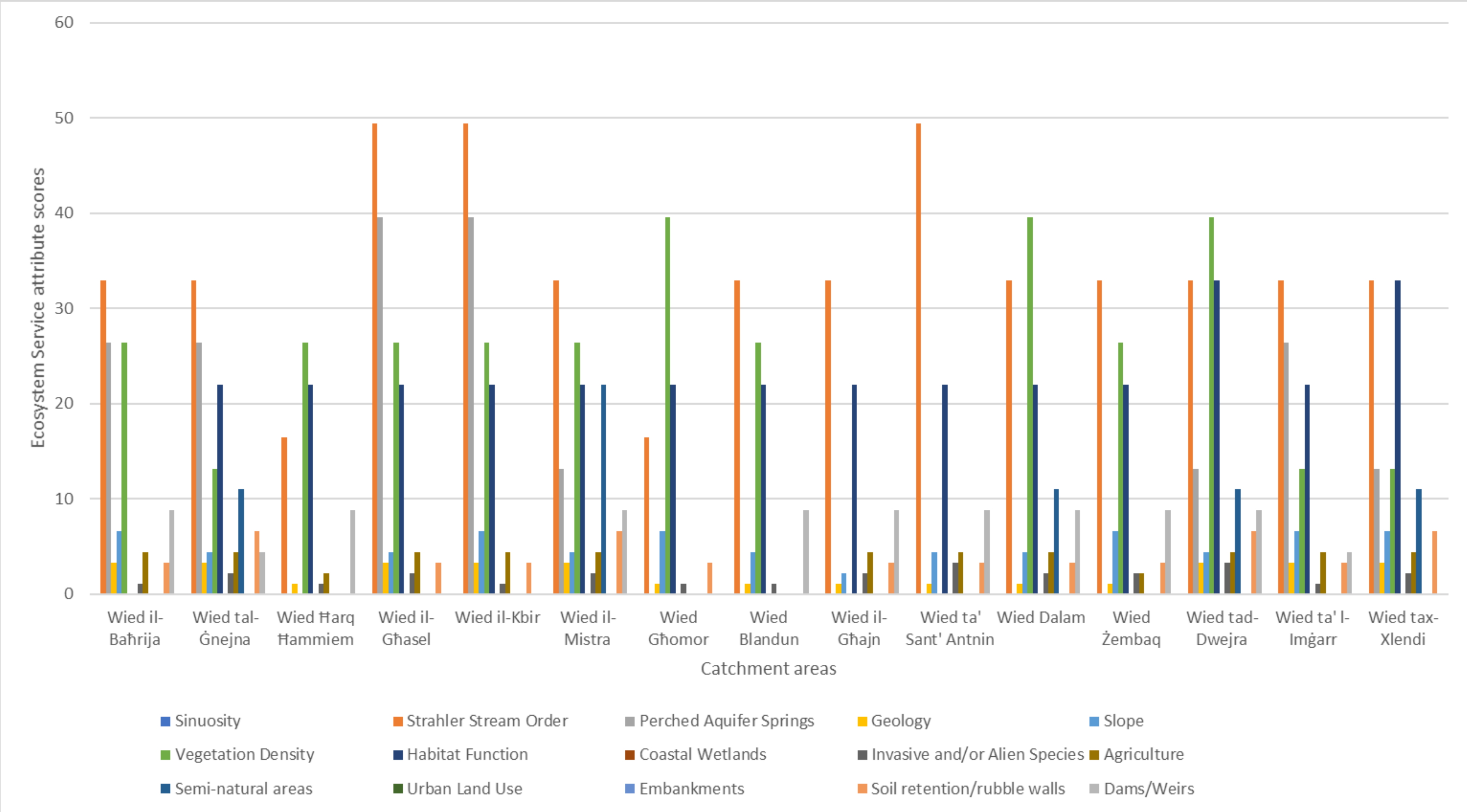


Table 5.7. Final results and ranking of the Mediterranean IRES ES-based assessment.

Case study site	Final ranking
Wied tad-Dwejra	160
Wied il-Kbir	156
Wied il-Għasel	155
Wied il-Mistra	146
Wied tal-Ġnejna	131
Wied Dalam	130
Wied tax-Xlendi	126
Wied ta' l-Imġarr	118
Wied il-Baħrija	113
Wied Żembaq	105
Wied ta' Sant' Antnin	97
Wied Blandun	97
Wied Għomor	90
Wied Ħarq Ħammiem	78
Wied il-Għajn	77

5.4 Discussion

5.4.1 Challenges and opportunities

The approach proposed in this paper aimed to provide an effective and simple to operate ES assessment tool in Mediterranean IRES catchment areas. The identification and scoring of ES in IRES is be an important step towards enhanced recognition of these important features in Mediterranean landscapes, leading to potentially better protection and conservation. The assessment is specifically aimed for stream networks without or limited baseline temporal ecohydrological datasets. Hence, assumptions were made on other features that indicate the flow regime patterns in the case study sites. In the studied catchments areas, the features 'geology' and 'perched aquifer springs' provide an indication of whether the flow is ephemeral, hence primarily driven by specific precipitation events and hydrological continuity is limited to a period of time, usually ranging from days to weeks, or intermittent, whereby the presence of springs that form naturally from specific geomorphic features, contribute to more frequent surface flows in the connected reaches of the watercourses. However, these attributes are only indicative of the flow regime dynamics in the catchment area which vary between floods, flow, connected pools, isolated pools, humid riverbed and dry riverbed (Gallart et al., 2011). The ES assessment presented in this paper, provides only a general indication on the freshwater availability of the catchment. For example, flow conditions in IRES may provide several ES such as swimming, irrigation, and drinking water, but these are not available when streams are dry and pumping water for irrigation is not optimal/advisable during connected pool phases (Kaletova et al., 2021). Thus, when using this ES assessment, the availability of key water-related ES that are driven by the spatio-temporal water flow conditions along the entire stream continuum in Mediterranean IRES, are not fully considered.

In the selected case study sites, the ES assessment was applied for the entire catchment areas and the ranking represents the cumulative ecosystem service benefit value. This approach is ideal to capture as much as possible landscape heterogeneity of biophysical variables and ecosystem functions contributing to the provision of ES (Fausch et al., 2002). de Groot et al. (2010) presented a cascade conceptual approach were ES are based on ecosystem functions which are in turn dependant on biophysical variables. In river networks, the varying biophysical structures and processes along the river continuum, render the delivery of ES spatially bound by the extent of the providing ecosystem, which is intrinsically unspecific (Vermaat et al., 2016). This is especially true in IRES, which are characterised by dynamic shifting habitat mosiacs governed by trainsient flows, whose extent and connectivity regularly varies across catchment areas in response to climatic and geophysical dynamics (Vorste et al., 2020). For example, the flows of matter and energy, which influence biogeochemical processes and ecosystem functioning, change with alternating dry and wet periods and depending on their location (von Schiller et al., 2017). Accounting for delivery of ES at tributary junctions (Large & Gilvear, 2015), and/or sub-catchment scales is ideal to account for and compare different contributions of ES in diverse sections of the drainge network. Such an approach would also be useful for environmental managers to identify ES hotspots in specific reaches within catchment areas that require special protection or conservation actions.

The ranking of biophysical attributes contributing to ES can provide a robust baseline for decision-makers to prioritise conservation actions. However, the ES assessment presented in this study, does not incorporate social preferences or societal needs for ES. The combination of biophysical and social dimensions through the inclusion of stakeholders in ES assessment methodology can potentially provide an additional perspective and add value to expert knowledge, provide higher levels of legitimacy of decisions, contribute to more resilient communities, add acceptance levels to implementation actions and compliance with applied measures (Menzel & Teng, 2010). On the other hand, participatory approaches may include additional financial costs and elongated timeframes going against one of the main scope of our Mediterranean IRES ES assessment, that is, to provide an easy to use tool for environmental managers (Menzel & Teng, 2010).

5.4.2 Applicability of UAVs

The use of light-weight consumer-grade UAVs in the application of the ES Assessment proved to be a cost-effective and efficient tool to capture orthoimagery for the extraction and mapping of biophysical characteristics of Mediterranean IRES. A total of 80km (lenght) of watercources were mapped in an 18 month field campaign. This timeframe does not include the post-processing stage (SfM photogrammetric transformation of images into orthophotos and DEMs) of the captured images which required extensive processing timeframes and adequate hardware facilities. Studies have shown that UAV DEM accuracy have the potential to be competitive with airborne high accuracy Light Detection and Ranging (LiDAR) survey data (Leitão, 2016). Conversely, Coveney & Roberts (2017), when comparing UAV only DEMs with DEMs orthorectified with external GNSS ground-target ground control point (GCP) coordinates, elevation differences ranged up to 5.82m, and 95% of errors were $\leq$5.03m. Even though such results may provide little value for precise modelling of environmental processes that are dependant upon elevation, however, these can be sufficient for baseline ES assessment excercises. Nonetheless, the use of at least one ground control point for every 6 hectares of surface area will achieve good orthoimage and DEMs accuracies from UAV derived imagery and potentially increase the robustness of the ES assessment methodology (Coveney & Roberts, 2017).

The use of the off-the-shelf consumer-grade digital cameras to acquire IRES imagery resulted in the development of very-high resolution data (3cm) captured at 100m altitude from the drone deployment home point. Presently, UAVs have also the ability to carry other instruments including systems that cover the visible to thermal spectrum, multi or hyperspectral capability, low-cost Inertial Navigation Systems (INS), miniature RADAR, pasive microwave radiometers, and LiDARs (Evaraerts, 2008, Rhee et al., 2018). Recent advancements in sensor development are improving the UAVs capabilities at a nearly identical level of observational capacity as when using other remotely-sensed technologies including manned aircraft and satellite (Rhee et al., 2018). The incorporation of non-visibile spectrum imagery with UAVs would facilitate the acquisition of vegetation fraction cover and health, more detailed delineation of fluvial landforms and water presence detection, thus improving the spatial recognition of different aquatic states along the streams (Keele et al., 2019; Large & Gilvear, 2015; Marcial-Pablo et al., 2019; Micieli et al., 2022; Van Looy et al., 2019). The inclusion of these non-visibile data capture applications would provide added robustness, improved mapping techniques and a better understanding of the ecosystem functioning in Mediterranean IRES, thus ameliorating the ES assessment.

5.5 Conclusion

Fifteen hydrologically transient catchment areas were assessed with a novel ecosystem-based assessment aimed for Mediterranean IRES. The highest ranked catchments had the larger drainage areas and include geomorphic conditions suitable for intermittent flow regimes, whereas smaller catchment areas with predominant urban land cover scored the least. The assessment is based on the properties of features and land use types, and their links with the potential provision of riverscape ES (Keele et al., 2019; Large & Gilvear, 2015). The methodology considers the absence of ecohydrological data availability at sufficient spatio-temporal scales that is commonly encountered in Mediterranean IRES. The use of UAVs combined with SfM photogrammetric techniques and GIS applications to extract, measure, and quantify these inherent attributes at catchment and reach scales was tested in the selected case study areas. A variety of methods were presented for the measuring and quantifying of IRES features that contribute to the provisioning of particular ES. The objective of this low-cost and easy to apply method is to facilitate decision-makers to prioritise and effectively conserve the frequently unmonitored and unmanaged Mediterranean IRES. This paper uses current understanding of IRES ecosystem functioning and provisioning of ES (Koundouri et al., 2017; Pastor et al., 2022). Links were established with the identified 17 ES between 15 IRES features and land cover types, and natural ecosystem functions. The rule-based ES scoring approach for Mediterranean IRES was applied at catchment and reach (from source to mouth) scale to showcase the tool's applicability across hydrologically transient drainage networks with different characteristics, including dimensions and land uses.

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CHAPTER 6

GENERAL DISCUSSION

Driven by the difficulties experienced by environmental managers in accessing applications and methodologies that effectively capture the spatio-temporal variability of biophysical variables within Mediterranean intermittent rivers and ephemeral streams (IRES), this thesis had the broad objective of identifying appropriate and new tools and methods to ameliorate the understanding and expand knowledge on the various processes that drive hydrologically transient stream networks. Implementing methodologies that included the use of water level dataloggers and Uncrewed Aerial Vehicles (UAVs) equipped with consumer-grade RGB cameras combined, with structure from motion (SfM) photogrammetry and vegetation indices (VIs) derived from the visible spectrum, the selected stream and catchment attributes and dynamics were studied within various Mediterranean IRES watersheds characterised by different land cover typologies and ecohydrological dynamics. The thesis specifically explored the water presence and temperature responses to precipitation events, analyses the suitability of visible VIs in capturing vegetation health and cover in response to varying in-stream water level conditions and specific rain events and proposed a novel ecosystem services (ES)-based assessment to provide decision makers with a robust, easy-to-use, and affordable tool to prioritize and conserve Mediterranean IRES. Adding to existing research in IRES and addressing selected knowledge gaps, the specific objectives of this thesis were to:

1. Improve the understanding of the complex dynamics that drive Mediterranean IRES.
2. Analyse the thermal and hydrological responses to water presence and streambed temperatures following various precipitation events in catchments with varying intrinsic characteristics.
3. Identify the feasibility of using cost-effective, off-the-shelf equipment to monitor and assess vegetation health condition in response to water presence at high pixel resolutions.
4. Develop a reliable and easy to apply ES-based biophysical assessment for ungauged Mediterranean IRES.

This final chapter draws together the key findings from empirical studies (Chapters 3-5) and discusses the knowledge gaps highlighted in Chapter 2 that are addressed in this thesis. Practical implications of the results, tools and methodologies used and general limitations that have arisen from this study area are also discussed.

6.1 Key findings

A summary of the key findings and their practical/applied implications are listed in table 6.1. The conceptual framework diagram (Figure 2.1) compartmentalizing the natural and anthropogenically-induced exogenous and endogenous variables that govern Mediterranean IRES presented in Chapter 2 highlighted the various knowledge gaps within these systems that are difficult to capture and assess with current methods and tools. Traditional monitoring approaches in IRES fail to properly consider the biophysical dynamics that occur in response to different aquatic states along the entire stream network occurring at varying periods (Gallart et al., 2012). In view of their unmatched ability to deliver at affordable costs, fine spatial and temporal resolution data, whilst reaching areas which are otherwise physically inaccessible, UAV-based technologies combined with SfM photogrammetry techniques are proposed as a solution to better understand complexity in Mediterranean IRES. These applications together with the deployment of water level data loggers, were used to assess the potential of VIs derived from RGB imagery to monitor vegetation health and fraction of vegetation cover (FVC) responses to in-stream water incidence. The mean reflectance values from the four tested VIs: visible atmospherically resistant index (VARI); green leaf index (GLI); red-green-blue vegetation index (RGBVI); and normalized difference green-red index range (NGRDI) were similar for the five studied Mediterranean IRES catchments. When compared with water stage height and precipitation data, RGB VI results were influenced by the different intrinsic catchment characteristics, including vegetation typologies and land use. Statistical analysis showed links between the visible VI reflectance values with different streambed water levels. Reflectance values demonstrated contrasting seasonal dynamics, were higher values (close to 1) resulted during the winter period, inferring the vegetation condition is greater during the wetter months. However, when compared with images that were captured in dates that had the most cumulative rain events since the previous September, reflectance values were low (close to 0), potentially indicating reduced vegetation health.

Table 6.1. Summary of the key findings and their practical implications to IRES in the Mediterranean and beyond.

Key findings	**Implications**
Catchment dimensions influence the water presence lag times following precipitation events	Prioritising the protection and conservation of larger catchments in assessment strategies.
Streambed water level responses following precipitation events are influenced by seasonality.	Elongated drought periods will potentially exacerbate the reduction of flow generation in IRES. Increasing management focus on improving hydrological connectivity at catchment scale.
Streambed water level responses following precipitation events are influenced by land cover.	Focus on improving hydrological connectivity at catchment scale and reduce impermeable surfaces in urban-dominated drainage areas.
Catchment land cover condition streambed thermal responses.	Focus on the implementation of green and blue infrastructure such as Sustainable Drainage Systems (SuDS) and Nature-based solutions (NBS) to promote 'natural' catchment functioning.
Groundwater discharges moderate in-stream thermal dynamics.	Prioritising the protection and conservation of catchments with intermittent flows fed by groundwater springs.
Mean reflectance value results from different visible VIs showed links with streambed water presence and seasonality.	Visible VIs have potential to be used for estimating vegetation health and FVC in Mediterranean IRES. Future studies must focus on determining different catchment

	characteristics and landscape configurations and compare with RGB VI values.
Catchment dimension and intermittent flow regimes due to groundwater discharges influence the potential provision of ecosystem services.	Prioritising the protection and conservation of catchments with intermittent flows fed by groundwater springs and larger drainage area networks.
Urban catchment areas have the least potential in providing ecosystem services.	Focus on improving the ecohydrological and biophysical functioning of urban stream features that contribute to ecosystem service provisioning.
Development of a novel, easy-to-use, ecosystem service-based biophysical assessment applicable for ungauged Mediterranean IRES catchments.	Potential increase in the assessment of ungauged Mediterranean IRES to prioritise and ameliorate conservation efforts.

UAVs, SfM photogrammetry and geographic information systems (GIS) applications were also used to measure stream and catchment attributes that contribute to the provision of ES in Mediterranean IRES. These measurements fed an ES-based biophysical assessment adapted from Keele et al. (2019) and Large & Gilvear, (2015). The new developed methodology specifically targets Mediterranean IRES and considers the low ecohydrological data availability at sufficient spatio-temporal scales that is commonly the case in transient stream networks (Callow & Boggs, 2013). The assessment was tested in fifteen Mediterranean IRES catchments comprising 68% of Malta's surface area. Larger catchments that include geomorphic conditions that contribute to intermittent flows were ranked the highest whereby smaller watersheds with predominantly urban land cover were ranked the lowest.

Water level dataloggers were used to monitor water stage height data (m) and streambed temperatures (°C) in six of the IRES catchments with different drainage basin dimensions, flow regime and land cover properties. These data were analysed with precipitation records from three weather stations to study surface water generation mechanisms and thermal responses to rain events in different catchments. Findings indicate that the dimensions of drainage basins greatly influence response lag times to precipitation events with larger catchments having longer response rates than smaller ones. Seasonality and land cover are also important variables influencing water level response and in-stream temperature dynamics to rain events. Longer water presence lag times were recorded in rural catchments due to the increased water retention capacity of soils and the presence of empty water-retention infrastructure following months of scarce precipitation. The highest average stream temperature peaks were recorded in an urban ephemeral catchment whilst a catchment with densely vegetated riparian areas resulted with the lowest mean temperature response to rain events. Stable streambed temperature responses were recorded in catchments with intermittent flows driven by groundwater springs due to the spring water cooling affect in summer and warming influence in winter.

6.2 Findings implications and future research

6.2.1 Contributions to the challenges in monitoring complexity

The conceptual diagram presented in Chapter 2 synthesizes the exogenous variables that influence the various natural and human-induced processes within Mediterranean IRES catchments. Even though the diagram is a simplified illustration of the dynamics that occur within hydrologically transient catchments, the complex interrelationships between the various stream features are clearly displayed. Climate is the principal component the drives all variables in Mediterranean IRES through precipitation, aeolian processes and temperature dynamics which are mediated by catchment geology. Each of these components sets in motion a series of processes that influence the functioning and behaviour of all catchment elements. This exercise led to the identification of two main challenges regarding the management of Mediterranean IRES.

The **first challenge** described the difficulties in monitoring and mapping the spatio-temporal variability of flow regimes and their influence on biophysical variables. Frequently used methods such as gauging stations, wet and dry mapping and remotely-sensed data from satellites or crewed aircrafts have serious limitations in capturing, at moderate costs, high-resolution information at the required spatial and temporal dimensions to effectively map catchment dynamics driven by flows that experience periodic cessation (Borg Galea et al., 2019; Costigan et al., 2016, 2017). In this thesis, digital SfM photogrammetry processed centimetre-accurate images, derived from UAVs with RGB cameras, were used to measure, at affordable costs, several stream features that contribute to the provisioning of ES including sinuosity, drainage area networks, stream order and slope percentage rise (Chapter 5). In combination with water level dataloggers, these were also used to identify the feasibility of visible VI data to monitor vegetation health and extent within riparian areas (Chapter 4).

Even though patterns were identified between RGB VIs and different water level categories, inconsistent results were also presented with reflectance values being highest when images were captured during the winter period, inferring that vegetation health is greater. However, when reflectance values were compared with cumulative precipitation events, VI values were low when images were taken during periods following a higher occurrence of rain events since the previous September. This inconsistency questions the robustness of VIs derived from RGB imagery to monitor riparian vegetation health in IRES. Since the use of UAV technology in river management is relatively new and practically absent in transient catchments, more research is required to test the applicability of these VIs in Mediterranean IRES. Different IRES catchment characteristics and landscape configurations must be categorized and statistically compared with RGB VI reflectance values to improve the understanding of the links between VI results and vegetation condition. These studies must be performed with UAV-derived data due to the higher spatial resolution, lower flight altitudes above ground level, and reduced influence from atmospheric and solar conditions (that have a major influence on VI results) when compared with satellite imagery. In fact, studies have already shown notable differences in VI results of same landscapes when comparing remotely-sensed images derived from UAV and satellite platforms (e.g. Mangewa et al., 2022; Matese et al., 2015; Messina et al., 2020). Different UAV models and RGB cameras must also be tested to detect differences in the sensitivity of the cameras to capture specific wavelengths that can lead to the significant dispersal of reflectance values

(Agapiou, 2020). Furthermore, other conditions that potentially impact VI results including flying day time and year period, need to be taken into consideration as these have an impact on the sun light angle, weather conditions and atmospheric transference (Woodget et al., 2017; Yang et al., 2015).

Six water level dataloggers with automatic data collection capabilities and designed to be left in the field to collect data over long periods of time, were deployed in six different Mediterranean IRES catchment and sub-catchments. Apart from water stage height data (m), streambed temperature (°C) was also monitored. In Chapter 3, water level and in-stream temperature responses to all rain events measured from three weather stations found in the vicinity of the studied catchments from October 2019 till December 2020, were analysed. With 30-minute sampling frequency and very limited maintenance requirements, these tools proved efficient in identifying various water presence and thermal responses to rain events. In order to ameliorate the knowledge on streamflow generation mechanisms within IRES, and how flow regimes respond to different precipitation occurrences, future studies using such tools must include a denser sensor network to better capture the various hydrological states (Gallart et al., 2011) that form in IRES. This is also important to measure thermal variations within different stream reaches under varying conditions, including for example, the sources of groundwater springs, to better analyse the influence of spring water temperatures on stream functions.

The **second challenge** identified from the conceptual framework exercise was the need to improve our knowledge on how dry and wet conditions drive stream processes that provide ES in Mediterranean IRES. Whilst Chapter 3 and 4 provide methodologies and studies using relatively recently developed tools that contribute to the understanding of the response mechanisms of biophysical parameters to precipitation and 'natural' groundwater sources, Chapter 5 explored the role of UAVs and SfM photogrammetry in measuring stream and catchment attributes that contribute to the flow of ES. This was done through the development of a novel ES assessment for Mediterranean IRES that are typically ungauged or poorly monitored (Costigan et al., 2017). Other physical catchment attributes that indicate between ephemeral or intermittent flow regime patterns were included in the assessment such as geology and the presence of natural groundwater springs. However, these still do not accurately portray the spatio-temporal flow-regime dynamics along the river continuum that influence biophysical variables contributing to ES provision. The exploration of spectral surface water detection indices such as the normalized difference water index (NDWI) (McFeeters, 1996), the modified NDWI; MNDWI (Xu, 2006) and the automated water extraction index (AWEI) (Feyisa et al., 2014) can improve the mapping of aquatic states. However, these are still not reliable, are prone to misclassification errors and are no longer practical in high-resolution multispectral images due to insufficient spectral information (Chen et al., 2020; Rad et al., 2021). Recently, a new frontier in deep learning techniques such as convolutional neural networks (CNNs), have shown promising feature representation capability for remotely sensed images (Cheng et al., 2017). Using a sequence of feed-forward layers, CNN is made by neurons that have learnable weights and biases, were high resolution images are used as inputs which allow the encoding of certain properties and extraction of low-level features such as lines, edges and corners including the subsampling of layers that make the features resilient against distortion and noise (Kadhim & Abed, 2020). Surface water body mapping with machine learning and CNN techniques have already proven effective (e.g., Chen et al., 2020; Guo et al., 2020; Huang et al., 2015) and their application in Mediterranean IRES have to be explored to account for the classification errors presented by water spectral indices and improve the identification of high-resolution surface water features along the stream continuum.

6.2.2 Considerations for Climate Change

The methods and results observed in this thesis have implications on climate change impacts observed and forecasted on surface water bodies in the Mediterranean. Even though IRES make up more than 50% of the world's surface water bodies and are expected to increase due to human stressors and climate change, they are still highly unrepresented in policies and legal protection mechanisms and are still mostly unmapped, ungauged and unmonitored (Acuña et al., 2014; Gutiérrez-Jurado et al., 2019). This thesis presents a monitoring framework that uses recently developed tools that have the potential to solve the problem of the inadequate and/or absence of timeseries ecohydrological data at high spatio-temporal rates found in IRES systems. The framework includes affordable tools such as UAVs and water level data loggers that are easy to use and require limited training. These applications have the capability of monitoring, at high resolutions, the dynamics behind streamflow cessation, drying and re-wetting and episodic surface flows and their influence on physicochemical and ecological variables within different catchments. These capabilities should advance the development and expansion of appropriate monitoring frameworks and conservation efforts within different IRES catchments in the Mediterranean and beyond.

Climate is the main external variable that commands flow regime in Mediterranean IRES (Borg Galea et al., 2019). Understanding the mechanisms that generate streamflow in Mediterranean IRES and how these respond the different precipitation events that vary in magnitude and distribution is important to predict flow regime variations caused by climate change. The 6th Assessment Report of the IPCC predict that more than half of global rivers will experience periodic drying, and increased frequency and intensity of droughts may cause perennial rivers to become intermittent, and IRES to disappear (Parmesan et al., 2022). In the Mediterranean, river runoff and low flow are expected to decrease mostly due to reduced precipitation (Ali et al., 2022). This thesis has highlighted the important influence of the intrinsic catchment characteristics that have on streambed water presence, where drainage area dimensions, land uses and added flows from perched aquifer springs influenced water level response lag times (Somers et al., 2013). Water is an important component in ecosystem functioning and is a fundamental ES, especially in typically drought-prone areas where Mediterranean IRES are found. Furthermore, different flow phases have a distinct impact on the ES flow to society, where during no or low water flow periods, ES provision is highly altered or non-existent (Koundouri et al., 2017). More research needs to focus on the specific local and catchment-scale variables, especially land cover typologies, and how these correlates with different precipitation events.

Life in all aquatic ecosystems, including IRES is influenced by the water's physicochemical parameters such as dissolved oxygen (DO), light, pH, salinity and temperature (Gómez et al., 2017). The latter parameter studied in Chapter 3, also showed links with catchment typologies, where following rain episodes, urban catchments displayed the highest average thermal peaks, whereby rural catchments with groundwater discharges, showed more constant temperature changes, and catchments with denser vegetation coverage resulted with the lowest mean temperatures. Improving our understanding on how groundwater springs and vegetation cover condition surface water variations and how these, in turn are influenced by the transient flow regime, should provide better guidance to environmental managers in implementing solutions for more resilient ecosystems, especially when surface water temperatures are predicted to increase due to climate change (Ali et al., 2022).

6.3 Conclusion

This final chapter has discussed pertinent findings from this thesis. Deliberations on the findings' implications to IRES research and climate change considerations were also made. Collectively these results highlight the influence of intrinsic catchment characteristics of different Mediterranean IRES towards stream water presence mechanisms, thermal dynamics, and the performance of visible VIs in quantifying vegetation condition. In addition, a novel ES-based biophysical assessment was developed to provide decision-makers a robust, practical, and affordable tool to assess Mediterranean IRES with limited empirical ecohydrological datasets. Even though in recent years there was an increased research interest in IRES, numerous data gaps are still prevalent with regards to generation of streamflow and the influence of transient hydrological regimes on the various ecological and physical variables within IRES. The tools employed in this research have shown that these can be applied in Mediterranean IRES and can provide environmental managers with improved options to capture and understand catchment and stream dynamics.

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