



A multi-hazard historical catalogue for the city-island-state of Malta (Central Mediterranean)

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Abstract

The city-island-state of Malta is traditionally viewed as a low-hazard country with the lack of a long historical catalogue of extreme events and their impacts acting as an obstacle to formulating evidence-based policies of disaster risk reduction. In this paper, we present the first multi-hazard historical catalogue for Malta which extends from the Miocene to 2019 CE. Drawing on over 3500 documents and points of reference, including historical documentary data, official records and social media posts, we identify at least 1550 hazard events which collectively have caused the loss of at least 662 lives. Recognising that historical materials relating to Malta are complicated by the presence of a strong temporal bias, we establish a four-point reliability indicator and apply this to each of the 1065 recordings, with the result that some 79% show a high degree of reliability. For an island state where there are significant gaps in the knowledge and understanding of the environmental extremes and their impacts over time, this paper addresses and fills these gaps in order to inform the development of public-facing and evidence-based policies of disaster risk reduction in Malta.

Keywords Malta · Environmental hazards · Historical catalogue · Disaster risk reduction

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1 Introduction

Islands have been long-represented as having high levels of exposure to environmental extremes owing to the complex interplay of a variety of factors (Pelling and Uitto 2001; Méheux et al. 2007; Wisner and Gaillard 2009). Recent research has found that this is particularly apparent for advanced, independent and heavily urbanised island states, such as the city-island-state¹ of Malta (Main et al. 2021). There is some research which has considered the hazardous history of economically more advanced islands and archipelagos where hazards occur frequently and/or where there are frequent reminders of the hazardousness of the place. Examples include work in: Iceland, Sicily and the Canarian and Azorean archipelagos (e.g. Barbano and Rigano 2001; Gaspar et al. 2015; Galindo et al. 2020; Chester et al. 2022). It is only relatively recently that the complex exposure and hazard history of city-island-states has, however, been considered. Here extreme natural events may be relatively infrequent, but the impacts are highly significant given the state's level of economic and physical development with even modest events having severe financial consequences as a measured proportion of GDP (e.g. Main et al. 2018; Agius et al. 2020).

1.1 Malta

The city-island-state of Malta, also known as the Maltese Islands, is a small, European Union (EU), archipelagic island state comprising three principal islands: Malta (246 km²); Gozo (67 km²); and Comino (2.7 km²) (Schembri 2019; Main et al. 2021). Located in the central Mediterranean (Fig. 1) some 90 km south of Sicily, Malta is one of the most densely populated countries in the world with a resident population of over 0.5 million people and total density of 1,628 persons per km² (National Statistics Office 2020).

Lying in a north-west–south-east direction in the Sicily Channel, Malta is situated approximately 200 km south of the convergence boundary between the Eurasian and African tectonic plates, with smaller, though no less active, major faults including the Hyblean-Malta Escarpment, those comprising the Sicily Channel Rift Zone and the Pantelleria Rift surrounding the islands at a distance of between approximately 80–150 km (Fig. 1; Catalano et al. 2008; Baldassini and Di Stefano 2017; Galea 2019). The city-island-state is dissected by two systems of faults: predominantly north-east–south-west trending faults, such as the inactive Great Fault, and those trending north-west–south-east that include the Maghlaq Fault off Malta's south-west littoral (Villani et al. 2018; Gauci and Scerri 2019). The stratigraphy of Malta comprises a five-layered sequence of sub-horizontal Oligocene–Miocene carbonate sediments and clays (Pedley et al. 2002; Scerri 2019; Chatzimpaloglou et al. 2020). These are, from youngest to oldest: Upper Coralline Limestone; Greensand; Blue Clay; Globigerina Limestone and Lower Coralline Limestone. The tectonics and geology of the archipelago contribute to a varied suite of landforms that include:

¹ The concept of the city-island-state recognises the complex multi-scalar interconnectivity between 'city' and 'state' and the multiple ways in which they are embedded in 'islandness' when considering advanced sovereign islands in the context of urbanisation. Other terms, such as island city states, city island, and island cities (e.g. Baldacchino 2014; Grydehøj 2014, 2015) have previously been used in studying urbanisation, city forms and processes on islands. As a city-island-state, Malta functions and operates not just as a city and city-state with, amongst other factors, a significant urban area relative to the size of the state as a whole, but also as a city-state with the characteristics of an island-state (see Main et al. 2021 for a detailed discussion of this concept).

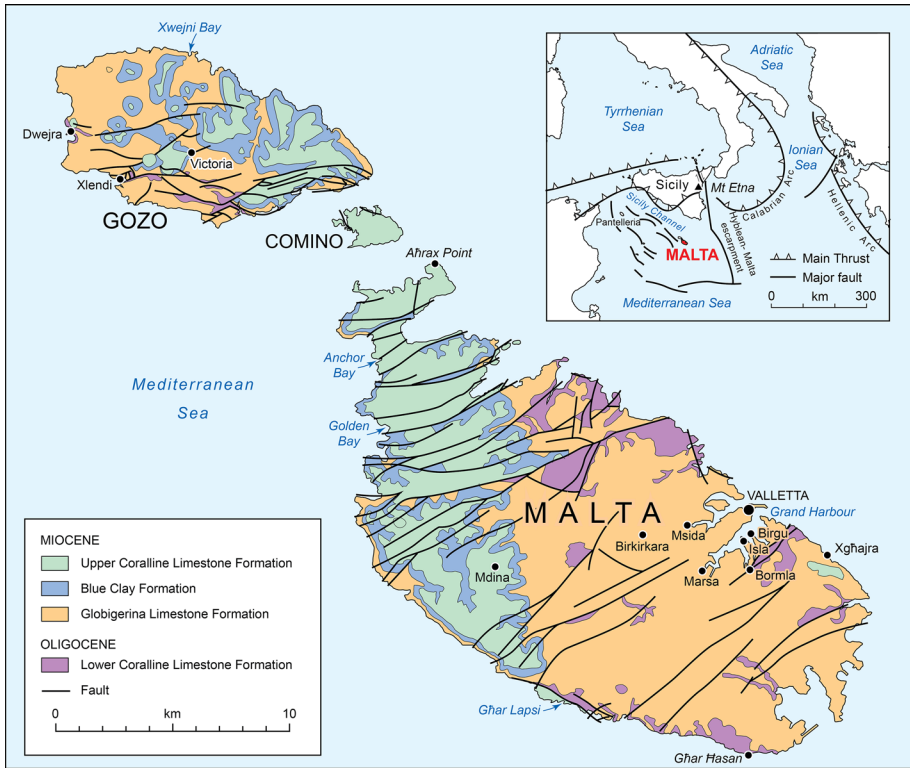


Fig. 1 The geological and tectonic structure and setting of Malta. Adapted after Oil Exploration Directorate (1993) and Main (2019)

limestone plateaux; high cliffs; drowned coastlines (*rias*); drowned and erosional shorelines; highly incised former river valleys (*widien*), up to several kilometres long and tens of metres deep, and a 14-km-long horst-and-graben sequence extending north-north-west from the Great Fault (Alexander 1988; Furlani et al. 2017, 2021; Gauci and Scerri 2019; Gauci and Schembri 2019a). Malta’s climate is typical of the semi-arid Mediterranean, with hot dry summers and warm wet winters. Some 85% of annual rainfall (c. 530 mm) falls between October–March and mean monthly temperatures range from 12 °C in January to 26 °C in July (Galdies 2011; Schembri 2019).

In spite of this complex setting and physical geography, Malta has been traditionally viewed as a low-hazard country, not considered disaster prone and sometimes styled as the “safest place on Earth” (Camilleri 2011; Appleby-Arnold et al. 2018). Originating from an international disaster risk index, the *World Risk Index*, it has been argued that such viewpoints may potentially engender a false sense of security amongst the population (Main et al. 2018). Amongst critiques of indices such as these, it has been pointed out that such assessments are based on inadequately researched and incomplete historical catalogues of damaging events (Main et al. 2018). The *Sendai Framework for Disaster Risk Reduction 2015–2030* identifies, not only the importance of an integrated multi-hazard approach to disaster risk reduction (DRR), but also the requirement for knowledge, and the sharing of knowledge, on extreme events that have impacted a location throughout its history to better

identify disaster risk and inform and shape policies of sustainable development within the context of DRR (United Nations 2015). In their work reviewing the international rankings of Malta in terms of hazard exposure, Main et al. (2018) identify a lack of long historical records of extreme events and their impacts, which is currently acting as one of the principal obstacles to the formulation of detailed hazard assessments and evidence-based policies of DRR in this densely populated nation. Existing policies are limited, with their principal focus being on hazards associated with pluvial storm flooding.

In Malta the literature on hazards is dominated, either by the reporting and cataloguing of discrete events such as earthquakes (e.g. Abela 1969; Galea 2007; Agius et al. 2020), dolines (e.g. Calleja 2010a, b) or pluvial storm flooding (Malta Resources Authority 2013) or is focused on the evidence for extreme events in the past: their causes; processes of initiation and their impacts.² This has included work on past tsunamis (Biolchi et al. 2016; Causon Deguara and Gauci 2017; Mottershead et al. 2018) and geomorphological phenomena including landslides, rockfall, sea-arch collapses and dolines (Mantovani et al. 2013; Prampolini et al. 2018; Satariano and Gauci 2019; Devoto et al. 2021). There are also instances of hazard assessments for singular Maltese hazards including earthquakes (e.g. D'Amico et al. 2015; Panzera et al. 2015), tsunamis (e.g. Sørensen et al. 2012; Basili et al. 2018; Mueller et al. 2020), coastal hazards (e.g. Soldati et al. 2015, 2019a, b; Micallef et al. 2018; Rizzo et al. 2020, 2022; Mantovani et al. 2021) and flooding (e.g. Paindelli et al. 2021). However, these are not always solely focused on Malta. Elsewhere, Selmi et al. (2022) conducted a degradation risk assessment of 27 geosites across the city-island-state to various anthropogenic and natural threats, finding that the threat from climate change and related environmental threats is very acute. Recent research has not only criticised the catalogue of, and policies associated with, pluvial storm flooding, but has also highlighted that Malta is exposed to a much wider range of environmental extremes than has been commonly supposed (Jones 2018; Main et al. 2018; Main 2019). Following major events, such as severe storms (e.g. 28 February 2019), significant coastal erosion (e.g. 8 March 2017) and local or regional earthquakes (e.g. 7 July 2003), attention to Malta's hazardous history is renewed, but this soon fades from public consciousness.

In this paper and accompanying supplementary material (Table S1) we publish Malta's first multi-hazard historical catalogue in which geophysical, geomorphological and meteorological extremes are recorded, identified and in some cases inferred, from the Miocene epoch (c. 23-c. 25 Ma) to 2019 CE. We adopt the two-part definition of "multi-hazard" of the UN Office for Disaster Risk Reduction (UNDRR n.d.) in which the term refers to: (1) the selection of multiple major hazards that a country faces, and (2) the specific contexts where hazardous events may occur simultaneously, as cascades, cumulatively or concurrently over time accounting for the potential interrelated effects. In so doing we aim to address significant gaps in knowledge and understanding on environmental extremes and their impacts on Malta from geological times until the present day.

² In their paper, Sangster et al. (2018) identify that the reporting and cataloguing of geophysical, hydrological and meteorological extremes, their impacts and societal responses has grown rapidly in recent decades while highlighting that such growth and evolution has occurred, and continues to evolve, independently. They argue that this poses challenges to multi-hazard historical analysis for a given place. Such analysis, they demonstrate, can and should make considerable value and contributions to multi-hazard assessment.

2 Methodology

Works exploring the hazardous history of diverse places have drawn upon a range of historical data which have included: maps; pictorial sources; government and non-governmental archives; newspapers of record; diaries; correspondence; parish records; oral histories; military archives; and early scientific publications and communications (e.g. Branca and Del Carlo 2004; Macdonald et al. 2010; Riede 2014). In the case of Malta, however, the availability of historical data is complicated by strong temporal bias.

Documents relating to the history of Malta date mainly from after the time of the arrival of the Order of St. John of Jerusalem (Knights of St. John) in 1530 and there is a marked absence of documents from the time of Islamic occupation (870–1090 CE). Texts relating to the early years of the British occupation were destroyed in the 1870s while a large quantity of pre-1500 texts were either destroyed or removed from Gozo by the invading Turks in 1551 (Galea 2007; Main 2019). With the exception of early texts which provide some rudimentary data on natural phenomena, newspapers from the second half of the nineteenth century provide what is considered the best source of information regarding past environmental extremes. For the texts that have survived from the period of the Knights of St. John and later, there is a predominance of pre-1846 materials in the collections of contemporary literate individuals within the archives of the: Cathedral and Inquisition; Order of Malta; Religious Orders and University of Malta. Some of the texts which survived the destruction of the 1870s are housed in the National Archives at Rabat (Malta).

In spite of such unavoidable limitations, in constructing the first multi-hazard historical catalogue a range of historical documentary data, official records and social media posts have been examined covering over 3500 documents and media (Main 2019, pp. 68–74). These include: contemporary newspapers of record, including the *Times of Malta* and its sister paper the *Sunday Times of Malta*, alongside the *Malta Herald*, *Malta Today*, *Malta Independent*, *Daily Malta Chronicle* and international newspapers of record such as *The Times* of London; texts of learned and literate individuals comprising diaries, letters and personal correspondence; previous scholarly and official reports and listings, including major works by Abela (1969), Galea (2007), Calleja (2010a, b), the Malta Resources Authority (2013) and Agius et al. (2020) and photographs and maps archived by the University of Malta, National Library and National Archives of Malta. Digitised versions of these sources have also been consulted.

While the use of these data has proved fruitful in constructing this multi-hazard historical catalogue, there are some limitations. First, there is a low sensitivity to small-scale events both within the contemporary newspapers of record, with their focus skewed on “news of the day” and in “event-oriented” stories, and records left by individuals (Raška et al. 2014). This is particularly apparent in accounts of earthquakes in the pre-1995 period when the first digital seismograph, enabling more accurate recording and archiving of data, was installed (Galea 2007; Agius et al. 2020); several seismometers, including a Milne-Shaw horizontal pendulum seismograph that was thrown out of alignment by the 18 September 1923 earthquake, have existed since the beginning of the twentieth century with the network today consisting of eight broadband seismometers (Galea et al. 2021). In exploring media archives, several search terms were used to identify historic hazardous events. These included: storm, quake, tremor, earth-movement, shake, flood, gale, landslide, rockfall, temperature and snow. Terms such as rain, precipitation and wind were discounted because they produced records of forecasts or overall observations, not known and recorded events. Finally, media reports often present a spatio-temporally scattered account of past events,

a limitation particularly notable for geomorphological extreme events. For example, it is commonplace for events to be recorded within historical texts if and when they were of such significance that they caused threats to human life, property and/or infrastructure. It is because of factors such as these that we recognise that some gaps remain in our catalogue.

2.1 Reliability indicator

In assembling and presenting our multi-hazard catalogue a four-point reliability scale (Table 1) has been used, which is adapted from Maramai et al. (2014). In the case of this catalogue, this is particularly important because firm supporting data for events may not exist and/or some elements (e.g. date, magnitude, locations affected) may remain either unknown or questionable. As this is the first catalogue of its type for Malta, all events that have been identified within the records are included, but the reliability indicator has been added to demonstrate the dependability of each of the 1,065 recordings. Illustrated in Fig. 2, it is clear that the overall reliability of the catalogue is strong, with the majority of entries being definite (28%; $n=295$) or confirmed (52%; $n=549$). Within the catalogue, it is important to distinguish between a record and a(n) event(s): a record represents the original data source (e.g. a newspaper article, diary extract, photograph or video), while an event is what is being described within the record. There is clearly, therefore, the possibility that more than one environmental extreme may be described within a recording and these have thus been counted separately within the catalogue.

3 The catalogue

Drawing upon the range of data discussed above, we have compiled the first multi-hazard historical catalogue for Malta describing events which range in occurrence from the Miocene to 28 February 2019 (Table S1). In total, 1550 events have been identified which have caused at least 662 human fatalities; while only a minimum count based on available evidence, it is important to identify that the majority of these fatalities were from a single event in the 1550s (Sect. 3.1). Recognising the definition of multi-hazard (Sect. 1.1), our catalogue considers both the multiple natural hazards facing Malta and the hazardous events that may occur simultaneously, as cascades, cumulatively or concurrently (Pescaroli and Alexander 2015); where such latter events are associated with recordings of differing reliability, this is identified within our catalogue. This work demonstrates that, in contrast to the opinion that Malta is a low-hazard country, there is not one district in the city-island-state that has not been exposed to at least one of the environmental extreme events (Table 2). Before demonstrating the variety of environmental extremes and their impacts over time (Sect. 3.1), several findings arising from our work are important to discuss: small total count considering length of the catalogue; reliability resulting from temporal bias and nature of records; identification of spatial patterns and triggering processes; and the compound and cascading effects from climate change.

Although total counts may seem small, four factors need to be emphasised. First, it is “only because of the probabilistic nature of extreme events impacting vulnerable people that [the island state] has not been more severely affected in recent years” (Main et al. 2018, p. 131). Second, rapid and ongoing expansion of the urban footprint, including significant coastal development with over 35% of Malta’s littoral classified as urban in 2017 (up from 5% in 1990), is making areas and their increasing population more exposed and vulnerable

Table 1 The four-point ranking scale used in the historical catalogue

Rank	Description	Explanation	<i>n</i>
4	Definite event	Corroborated by multiple sources or historical texts. Sources are reliable and trustworthy	293
3	Confirmed event	The event is confirmed by (a) reliable source(s), but an element of the event remains questionable or unknown	549
2	Probable event	Recognised as an event within the catalogue, but more data are required to confirm occurrence and impact	212
1	Questionable event	Based on inference, modelling or physical data only. This may be questionable	11

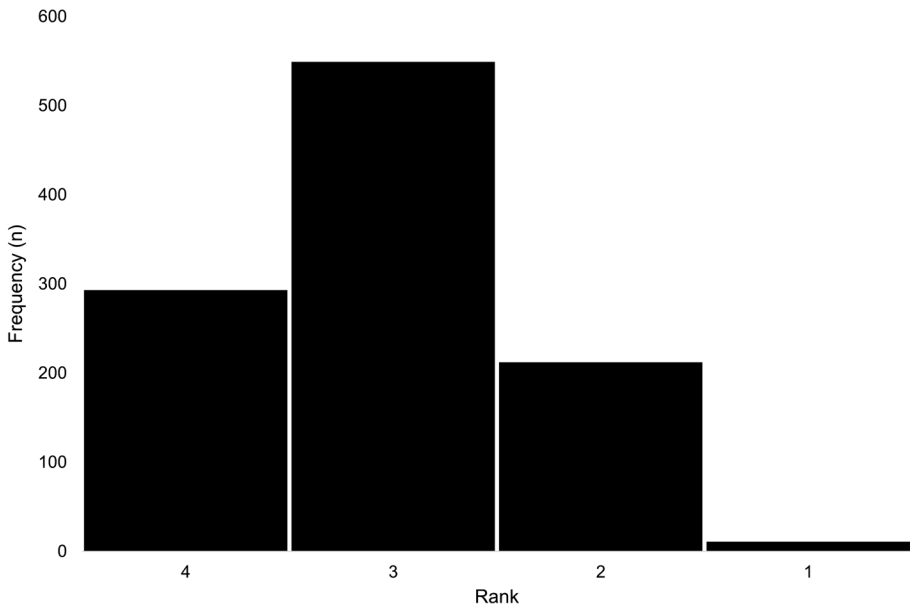


Fig. 2 Histogram of catalogue reliability scores (see Table 1 for rank descriptions)

than they were in the past (Schembri 2003; Vella et al. 2005; Ciarlò 2017; Main et al. 2021). Third, it is highly probable given the nature of the evidence discussed in Sect. 2 and below that other events may still remain unrecorded. Finally, the total count recorded is the minimum number of hazardous events that can be identified. For example, the record of the 1657–March 1658 earthquakes merely identifies: “a series of earthquakes”. Recognising that “a series” constitutes more than 1 event, this and similar events have been totalled at 2 in this catalogue.

The overall reliability within our multi-hazard historical catalogue is strong with the majority of records having a reliability of 3 or 4 (Sect. 2.1). Related to this, four key findings may be identified: (1) over 60% of meteorological extremes have a reliability of 4, compared with, respectively, 10% and 50% for geophysical and geomorphological; (2) the majority of geophysical extremes have a reliability of 3 (64%), followed by 2 (24%); (3) the records relating to geomorphological extremes show a greater spread of reliability; and (4) over 90% of records with a ranking of 1 represent geophysical extremes of which earthquakes and tsunamis are dominant. These findings are the result of the temporal bias within, and nature of, the records used to compile the catalogue. This is most clearly seen in the context of tsunamis for which records of impact on the island state are complex. In the case of tsunamis dating from geological times, debate over their generation, origin of erosional features and deposits found along low-lying coasts has been intense (Carroll et al. 2012; Causon Deguara and Gauci 2017; Tappin 2018; Fig. 3a, b). In contrast, where written records, models and maps exist, it is possible to make inferences about the ways in which historic tsunamis impacted the islands. Combining these data with existing Mediterranean tsunami catalogues (e.g. Tinti et al. 2004; Maramai et al. 2014), it has been possible to infer that tsunamis in c. 8000 years BP, 21 July 365 CE, 4 February 1169 and 20 February 1743, impacted the coastline of the archipelago (Pareschi et al. 2006; Pararas-Carayannis 2011; Biolchi et al. 2016; Mottershead et al. 2018; Main 2019). Conversely, the

Table 2 The hazard exposure of Malta by district and recorded occurrences within the historical catalogue

	<i>n</i>	Gozo and Comino	Northern	Northern Harbour	Western	Southern Harbour	South-eastern
Earthquake	717	✓	✓	✓	✓	✓	✓
Tsunami	16	✓	✓	✓		✓	✓
Tsunami/Seiche	2	✓	✓	✓		✓	✓
Volcanic Ash	11	✓	✓	✓	✓	✓	✓
Volcanic Eruption	1	✓	✓				
Ground Collapse	66	✓	✓		✓		✓
Coastal Erosion	9	✓	✓	✓	✓	✓	✓
Mass Movement	87	✓	✓		✓	✓	✓
Seiche	22		✓	✓			✓
Waterspout	18	✓	✓	✓		✓	✓
Tornado	6			✓	✓		✓
Whirlwind	5			✓		✓	✓
Tornado/Whirlwind	1		✓		✓		
Medicane	4	✓	✓	✓	✓	✓	✓
Strong Winds	95	✓	✓	✓	✓	✓	✓
Storm	171	✓	✓	✓	✓	✓	✓
Extreme Temperatures	65	✓	✓	✓	✓	✓	✓
Hailstorm	48	✓	✓	✓	✓	✓	✓
Snowfall	10		✓		✓		
Dust/Sandstorm	9	✓	✓	✓	✓	✓	✓
Flooding	163	✓	✓	✓	✓	✓	✓
Drought	24	✓	✓		✓		✓

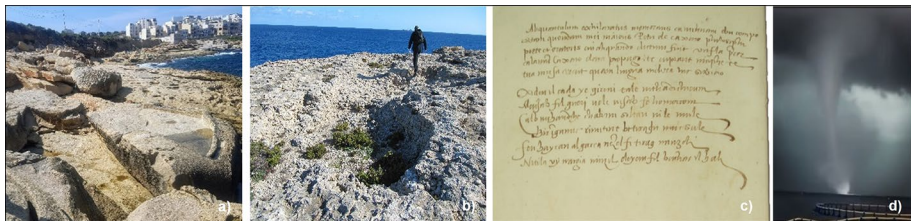


Fig. 3 Example historical records of Malta’s hazardous history: **a** boulder deposits at Xghajra possibly emplaced by an extreme wave event, photograph by R. Gauci; **b** erosional socket at Ahrax Point possibly emplaced by an extreme wave event, photograph by G. Main; **c** the *Il-Kantilena* poem believed to have been written pre-1485 about a ground collapse event, image by H. de Guettelet (Wikimedia Commons CC Attribution-Share Alike 3.0); **d** video of tornadic waterspout on 10 November 2017, New.Info.Hoje YouTube channel (<https://www.youtube.com/watch?v=Yj6zE-McnMw>)

use of historical texts in relation to meteorological and geomorphological phenomena must be treated with caution as they often lack a temporal framework required for event identification and inclusion within the catalogue. An example of this is information within the first literary text written in the Maltese language, *Il-Kantilena* (Fig. 3c) by Pietru Caxaro sometime pre-1485, yet not recorded until December 1533–May 1563. The poem is widely considered to refer to the collapse of a homeowner’s property by ground subsidence due to

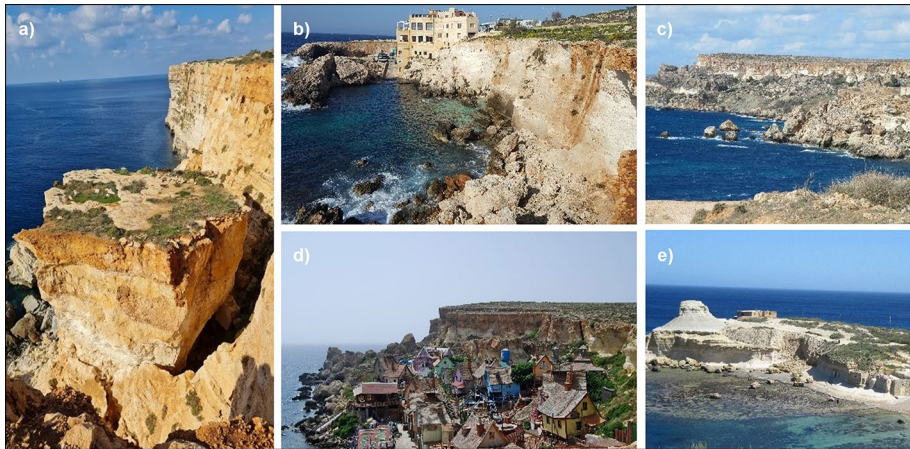


Fig. 4 Mass movement phenomena along the coastline: **a** rockfall at Għar Hasan, photograph by R. Gauci; **b** rockfall at Għar Lapsi, photograph by R. Gauci; **c** block sliding and rockfall at Golden Bay, photograph by G. Main; **d** block sliding above Popeye Village, Anchor Bay, photograph by F. König (Wikimedia Commons, GNU Free Documentation Licence Version 1.2); **e** rockfall at Xwejini Bay, photograph by G. Main

the unstable geological foundations (Gauci and Schembri 2019b), but its attribution and true meaning may be debated (Main 2019, p. 74). In marked contrast, events with a high reliability and that occurred post-1850, and more notably after 2000, are ones in which there are multiple records in newspapers, and/or other printed sources and on social media (Fig. 3d; Alexander 2014; Main 2019); this may be considered, at least in part, to be a reflection of the digital revolution since c. 1980 through which multiple and varied sources of historical and contemporary data are available (Srinivasan et al. 2009; Clarke 2012; Alexander 2014; Kaplan 2015).

Examining the catalogue enables identification of the spatial patterns and triggering processes of environmental extremes which have impacted the archipelago. This is most clearly seen in the context of geomorphological events which are triggered by local *in-situ* geological and tectonic forces. For example, forms of mass movement (e.g. rockfall, lateral spreads, block-slides) are common along extensive areas of the north Malta and east Gozo coasts and are directly associated with the geological setting, generally, and the north-east–south-west trending faults more particularly (e.g. Fig. 4; Devoto et al. 2012, 2021; Prampolini et al. 2018; Soldati et al. 2019a, b). Although there are instances of rockfalls and landslips inland within our catalogue, these are largely the consequence of erosion and collapse of fissures within the Globigerina Limestone formation and historic bastion defences with some successful mitigation measures being installed to protect heavily visited historic sites such as Mdina (Bonnici et al. 2008; Gigli et al. 2012). Similarly, ground collapse is largely associated with such *in-situ* processes with Calleja and others identifying the importance of bedrock geology and faulting (Pedley 1974; Calleja 2010a, b; Soldati et al. 2013). Across these geomorphic hazards, the Blue Clay lithology is a key factor owing to its relative “plasticity” (Mantovani et al. 2013). As Malta witnesses the ongoing and rapid expansion of the urban footprint on to areas associated with this lithology, coupled with other anthropogenic land-use changes, it is possible that the occurrence of such extremes may accelerate and begin to impact previously uninhabited areas (e.g. Gutiérrez et al. 2014).

In contrast, the geophysical and meteorological extremes recorded in this catalogue, triggered by *ex-situ* tectonic and atmospheric processes, are more challenging to identify in terms of their spatial patterns. Some spatial patterns may, however, be identified. First, while our historical catalogue demonstrates that all areas of Malta are exposed to earthquakes due to the regional and local tectonic setting, the “soft” Blue Clay lithology is a key factor in three-way harmonic interaction and seismic site amplification, with the western half of Malta, Comino, and the island of Gozo having the greatest potential to amplify seismic ground motion (Pace et al. 2011; Panzera et al. 2013; Vella et al. 2013; Farrugia et al. 2015, 2021). Building height and structure also play a localised role (e.g. Grech 2002, 2006; Agius et al. 2016). Second, by nature of the archipelago’s geography extreme wave events and seiches are more likely to have an impact along the low-lying northern and eastern coasts and bays of the archipelago with significant threats to land use and critical infrastructure (Main 2019, p. 109–122; Mueller et al. 2020). As these areas continue to become commodified and increasingly more urban, the risk from future events increases in significance. This is particularly apparent during the summer months owing to the influx of vulnerable tourists, with 1.7 million people visiting between April and September 2019, and with research showing little interaction and collaboration between policy-level stakeholders considering DRR in Malta’s tourism industry (Morrison 2013; Main 2019; Kennedy et al. 2020; Malta Tourism Authority 2020). The competent authorities concerned with DRR in Malta have installed a series of enhanced sea-level gauges around parts of the coastline with the aim of providing an early warning to the authorities and local communities in the event of a tsunami (Gauci 2021). The threat posed by pluvial flooding meanwhile is largely concentrated in low-lying areas and is associated with *widien* (Sect. 1.1; Malta Resources Authority 2013; Main et al. 2018, p. 845). As development has continued to encroach across these areas since 1964 (i.e. following independence from British rule), it has been suggested that Malta experiences “flooding by design” (Schembri 2010). Since the time of the Knights of St. John and recognising the physical, economic and environmental threat posed by flooding, several legislative mitigation measures have been established. Recently these include the €52 million National Flood Relief Project that adopted a multi-catchment approach across five flood-prone areas with extensive hard infrastructure benefitting c. 4500 properties (AIG Malta 2017; Main 2019, p. 208–211).

Climate change is a serious global concern with the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2021) identifying the Mediterranean region as an area that by mid-century will see an increase in drought, aridity, temperature extremes, increase in extreme weather events and rises in mean and extreme sea levels. Many of the environmental extremes identified within our catalogue may be linked to the cascading effects of climate change. For example, increasing incidences of extreme weather with possible resultant increases in, for example, flooding and coastal erosion particularly in areas where Blue Clay crops out at sea level (Ciarlò 2017). Climate change is expected to have significant impacts across Malta including: flooding of coastal areas due to sea-level rise and increasing storminess; drought stress on agriculture and water supplies and extreme weather events with impacts on coasts (including geosites), structures, infrastructure, crops and subsequently human health (Ciarlò 2017; Selmi et al. 2022). In the case of the latter, Attard (2015) has found significant impacts are likely on the transport network, critical port and other structures along the coast, all of which contribute significantly to the national economy and play an important role in future national development. Moreover, the predicted 0.34–0.63 m rise in local sea-level

by 2100 (IPCC/NASA 2021), together with increases in episodes of extreme weather, pose a serious threat to the coastal populations.

3.1 Selected event descriptions

Of the events identified within our catalogue, we select seven across geophysical, geomorphological and meteorological categories to demonstrate both the variety of environmental extremes and some of the challenges inherent within the data. The selection includes the event that caused the most fatalities, the largest seismic catastrophe, a record-breaking rainfall episode, one of the most explosive Etnean eruptions in the twenty-first century with recorded ash fall on Malta, the most intense Mediterranean cyclonic storm to have impacted Malta directly, and coastal erosion which has international significance.

3.1.1 23 September 1551 (or 1555/1556)

Occurring on 23 September in either 1551, 1555 or 1556 (sources differ but many believe that it occurred during 1555 or 1556 during the tenure of Grand Master Fra' Claude de la Sengle), the Grand Harbour was hit by an EF-3 (McDonald 2002) tornadic waterspout with winds gusting 218–233 km h⁻¹. The tornado began its life as a waterspout in the Harbour before moving inland causing extensive damage to settlements believed to include Isla, Birgu and the Forts of St. Elmo and St. Michael, the foundation stone of Valletta not being laid until 1566. In addition to the damage to settlements, four galleys of the Knights of St. John were destroyed. At least 600 people were killed and it is not known either how many were Maltese, Knights, or how many may have recovered from their injuries (Anon 2017a).

3.1.2 11 January 1693

The earthquake of 11 January 1693 was arguably one of the largest catastrophes in Malta's hazardous history. With an epicentre in Sicily, a magnitude of 7.4 and recorded EMS-98 intensities in Malta of VII-VIII, the earthquake caused widespread damage across the island state with reports focusing on the impact felt in the major settlements of the time, notably: Valletta; Birgu; Bormla; Isla; Mdina and Victoria (Abela 1969; Barbano and Rigano 2001; Galea 2007; Main et al. 2018). The earthquake triggered rockfalls in some hillside and cliff areas, notably on Gozo, with a Mt³+2.3 and intensity V⁴ (Sieberg-Ambraseys scale) tsunamis recorded along the low-lying coasts and in the fishing village of Xlendi (Tinti et al. 2004; Camilleri 2006; Biolchi et al. 2016).

Following the earthquake, a special commission was instituted by the Knights of St. John to carry out a detailed study of the impacts from the earthquake and found that within

³ The tsunami magnitude (Mt) is a number used to compare sizes of tsunamis generated by different earthquakes. Analogous to earthquake magnitude, it quantifiably conveys information about the strength of the source rather than effects of the waves; Murty and Loomis (1980) introduced a magnitude scale suitable for tsunamis generated by earthquakes based on the initial potential energy of a tsunami (Tinti et al. 2004; USGS n.d.).

⁴ Estimates of the intensity of this tsunami differ, with Mottershead et al. (2018), for example, suggesting an intensity of K₀I-III for the event, a figure they consider to be congruent with the available evidence on Malta. For consistency, this work uses the intensity scale and data reported on the Sieberg-Ambraseys scale and as detailed in the tsunami catalogue of Tinti et al. (2004).

the capital, Valletta, “there was not one house that did not need some repair”, with some having to be demolished (Galea 2007, p. 732). Damage was particularly apparent to ecclesiastical infrastructure and around one-third of the houses across Malta were razed to the ground as people fled from their homes and slept outside, in shelters, underground or on board ships (Shower 1693; Main et al. 2018). Some contemporary reports suggest that the earthquake was correlated with an eruption of Mount Etna (Sicily) during which “the whole Top of the Mountain appeared all in Flames” (Shower 1693, p. 14). These reports are not, however, supported by historical catalogues and records of Etnean eruptions during this period (Branca and Del Carlo 2004; Branca et al. 2015).

3.1.3 3–23 October 1951

Events in October 1951 included a record-breaking monthly rainfall of 584.32 mm, with 1951 remaining the wettest year on record. On 3 October a waterspout c. 8 miles off the Grand Harbour was the first sign of instability, followed by the first pluvial storm on 4 October that left almost every house along Valley Road in Msida ankle-knee (0.6–0.9 m) deep in water, two people died and extensive damage was caused to fields, crops and transport infrastructure (Anon 1951a, b, c). It would take almost 24 h to pump water out of homes with many fields remaining underwater throughout October. Overnight on 14–15 October, the storms returned causing extensive damage across the islands with houses flooded and others collapsing due to the wind and rain. Some people had narrow escapes from injury and death when farm buildings collapsed in Gozo (Anon 1951d).

Further storms on 17 October left three people dead and eight injured, c. 120 buildings collapsed or were badly damaged, with some homes in Birkirkara and Msida standing in 1.2 m of water. Upon seeing the waters rising, many residents in Msida self-evacuated to homes of friends or neighbours higher up the valley. Two days later, basements and cellars were flooded, with hailstones—some reported with a diameter of 40 mm—adding to building damage; ship schedules providing much needed food and public water supplies were also impacted (Anon 1951e, f). The final storms on 22–23 October flooded houses in Msida and Marsa with over 1.2 m of water with some buildings collapsing in Valletta and Birkirkara (Anon 1951g).

3.1.4 5 September 1980

In the mid-afternoon of 5 September, Golden Bay, a popular sandy beach resort on the north-west coast of Malta, was crowded with hundreds of bathers. At around 14:45 LT (GMT + 1), the lowermost section of the northern side of the Ghajn Tuffieħa headland broke off in a large rockfall into the Bay (Anon 1980a, b). Contemporary reports recorded the occurrence of an earthquake during the event, but it is uncertain whether this was the cause, whether the rockfall was merely a response to geomorphological processes or whether seismic activity acted as a triggering or enhancing mechanism. Only three people were injured when rocks fell 80–100 m from their paddleboat and the most serious injuries were a punctured lung, broken bones and superficial head injuries (Anon 1980a, b).

Despite feelings of fear and alarm, reports of panic may be considered journalistic licence given the accepted definition of the latter within hazard studies (der Heide 2004, p. 342). Although many people were frightened and alarmed, with many rushing inland fearing a large wave, they still acted rationally and quickly in rescuing the injured and

searching for any other injured victims (Anon 1980a, b). In 2015, one of the officials who witnessed this event recalled in the *Times of Malta*: “When I saw the cliff coming down, we got on a speedboat and shot off. Boulders tumbled down on to each other, spewing rocks across the bay. I thought I’d be looking for bodies. It was a miracle that nobody got killed. It was unbelievable. The paddleboat [on which three people were injured] looked like it had been bombarded” (Carabott 2015).

3.1.5 27 October 2002

The eruption of Mount Etna that began on 27 October 2002 and finally ceased on 28 January 2003 was one of the most explosive events of the last few centuries with eruption columns up to 7 km a.s.l. (Andronico et al. 2005). While this eruption would be dwarfed by the repeated paroxysms of Etna in 2021, the ash during this most recent eruption did not fall on Malta, instead passing a few kilometres to the east. In comparison ash from the 2002 eruption was recorded as falling on Malta on 27 October and was described as having “coated the country in an insidious film of black dust [... resulting in] homes and cars being covered in soot” (Zammit 2002). Although the flanks of the volcano are visible from Malta, the local press reported general confusion and several conspiracy theories regarding the source of the “soot”. These included: the principal power station; the waste dump; the hospital chimney; local hotels; a passing ship; and a passing warplane (Zammit 2002). A higher magnitude event and an appropriate wind direction could close Malta’s international airport with a devastating effect on the tourist and wider economies (Azzopardi et al. 2013; Main 2019; Main et al. 2021).

3.1.6 7 November 2014

A peculiar feature of the Mediterranean Sea is the formation of low-pressure cyclonic systems which are known as medicanes (Romero and Emanuel 2013; Cavicchia et al. 2014). One of the most widely reported instances of medicane impact was Medicane Qendresa that made landfall at around 16:30 LT on 7 November 2014, with wind speeds of up to 154 km h⁻¹ and c. 3 m high waves in the Sicily Channel (Masters 2014).

Damage and disruption from this event was extensive with contemporary accounts focused on the damage that resulted from winds inland. Fortunately there were no reports of injuries or fatalities. Much damage and disruption was caused to the transport network, with roads blocked, flights and inter-island ferry services suspended and, in one instance, road tailbacks of up to 4–5 km. Low-lying streets were flooded; cars, walls and in some instances houses were damaged; trees were uprooted across Malta and large areas experienced blackouts as electricity poles were blown down (Martin 2014; Muscat 2014). While some drivers and individuals uploaded photos and videos of the disruption and coastal scenes to social media, notably from Gozo (e.g. Fig. 5; Muscat 2014), unfortunately, and rather surprisingly, few records could be found of damage to coastal critical infrastructure (Main 2019).

3.1.7 8 March 2017

Recognised internationally as one of *the* images of Gozo, if not the whole island state, *It-Tieqa tad Dwejra* (i.e. The Window of Dwejra or The Azure Window) was a 30 m high sea-stack and arch on the north-west coast of Gozo believed to have formed between 1866 and

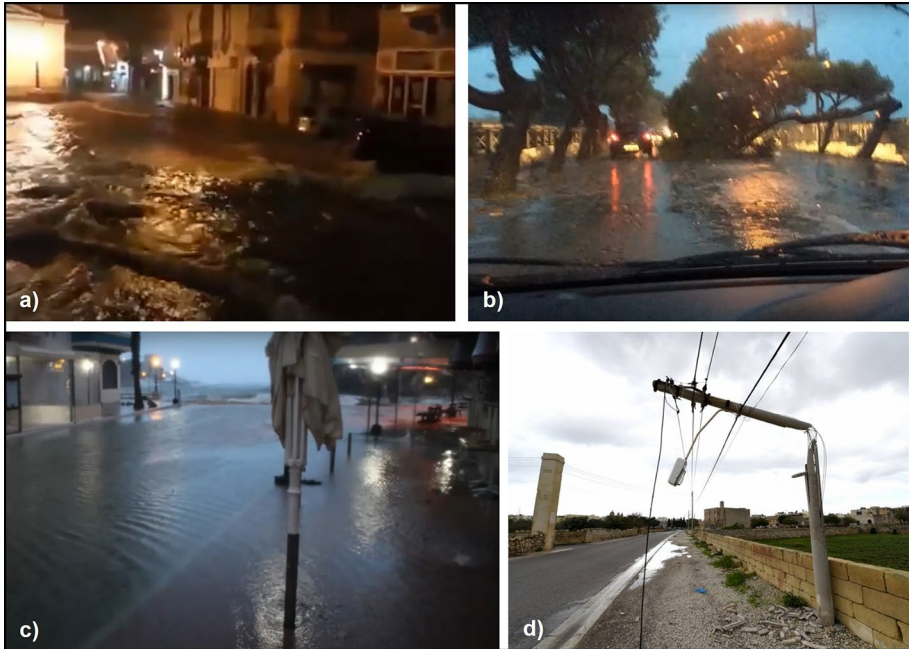


Fig. 5 Recorded impacts from Medicane Qendresa: **a** video of flooding in Birkirkara, posted on Facebook by R Zampa and re-posted by *Malta Today* (Anon 2014); **b** Downed trees narrowly missing cars, image by Malta Roads Traffic Updates; **c** video of flooding in Xlendi posted by A Muscat (https://www.youtube.com/watch?v=7W_6KEZ3RQ4); **d** Damage electricity pylons, image from slideshow compiled by R Attard for Anon (2014)



Fig. 6 The Azure Window, Dwejra: **a** August 2006, photograph by G. Bowman (Wikimedia Commons CC Attribution 2.0 Generic); **b** 26 February 2017, photograph by G. Main; **c** June 2017, photograph by A. Hepworth and reproduced with permission

1879 (Carabott 2017; Satariano and Gauci 2019; Fig. 6). Featuring in major blockbuster movies and television series such as *Game of Thrones* and *Clash of the Titans*, the arch extended 60 m into the Mediterranean. Significant erosion over the preceding three decades, and particularly between 2010 and 2017, had weakened the arch with up to 90% of the lower rock formed from Lower Coralline Limestone collapsing during previous storms (Gatt 2013; Carabott 2017). During the storm of 7–9 March 2017, strong north-westerly winds reached speeds of c. 72 km h^{-1} off Gozo's north-west coast generating wave heights of up to 3 m and these factors combined to cause the arch to collapse (Galea et al. 2018).

At 09:32:11 LT on 8 March and to the surprise of local people and scientists, the stack collapsed with a “loud whoomph” into the sea below, with scientists estimating that c. 38 million kg of rock was involved (Anon 2017b; Caruana 2017; Galea et al. 2018). Following a report by Gatt (2013) fines were levied and fences and later security officers were hired to protect the arch from continued erosion from tourist foot-fall and tourists from the dangers posed by the rapidly eroding arch (Satariano and Gauci 2019). Fortunately, with the exception of the two recently hired security officers and a local resident watching the storm, the area was devoid of visitors. Despite its recent date, there is no video or photographic record of this event.

4 Catalogue significance

As the first multi-hazard historical catalogue for the city-island-state of Malta, this work constitutes a significant advance in understanding of the variety of environmental extremes and their impacts on Malta over time with resultant implications for DRR.

While we combine, synthesise and update as appropriate catalogues and listings of geophysical extremes from the literature and official sources (e.g. Abela 1969; Ventura and Galea 1993; Branca and Del Carlo 2004; Azzopardi et al. 2013; Maramai et al. 2014; Agius et al. 2020), our most significant contribution is in the recording of meteorological and geomorphological extreme events. For instance, the *Preliminary Flood Risk Assessment* (Malta Resources Authority 2013) provides an indication of flood events over a 33-year period (1979–2012) in so doing identifying 27 flood events from newspaper reports. By comparison, and within the same period, we record the occurrence of 63 events (129% increase), further extending the flooding record back to the early 1900s (Main 2019, p. 196). Similarly, the work of Galdies (2011) provides a detailed overview of various climate-related statistics between 1951 and 2010 including consideration of: precipitation, thunderstorms, hail, fog and wind direction. While this is a key work for the quantitative and statistical consideration of meteorological phenomena and extremes, it fails to provide qualitative descriptors of impacts from, or details about, individual extreme events such as those provided by our catalogue. In addition our consideration of interdisciplinary extreme event-related data is, we maintain, a feature in successful DRR policies (Martinez et al. 2018; see below). Other works (e.g. Bowen-Jones et al. 1961; Micallef 1999; Sapiano et al. 2008) refer to, and provide some descriptions of, events such as flooding, snowfall and drought and it is from these accounts that our research has been developed. In the context of geomorphological extremes, while collapse features have been dated and mapped (e.g. Calleja 2010a, b) and further coastal hazard assessments have been published (e.g. Soldati et al., 2019a, b; Mantovani et al. 2021), individual events and those triggered by other environmental extremes such as flooding have often gone unrecorded. For example, the Malta Resources Authority (2013) does not identify ground collapse as a cascading hazard from the violent storm and flooding of 24–25 October 2010 (Calleja 2010a, b; Pescaroli and Alexander 2015). Consequently, our work adds weight to recent findings that Malta is exposed to a much wider range of extreme environmental events than is commonly supposed (Jones 2018; Main et al. 2018; Main 2019).

Alongside advancing understanding of the variety of environmental extremes and their impacts, our work enables attempts to be made in order to understand the temporal variability of events and their recordings. Figure 7a illustrates temporal variability of sample events from the 1500s to 2019 further indicating increase in total population. From this

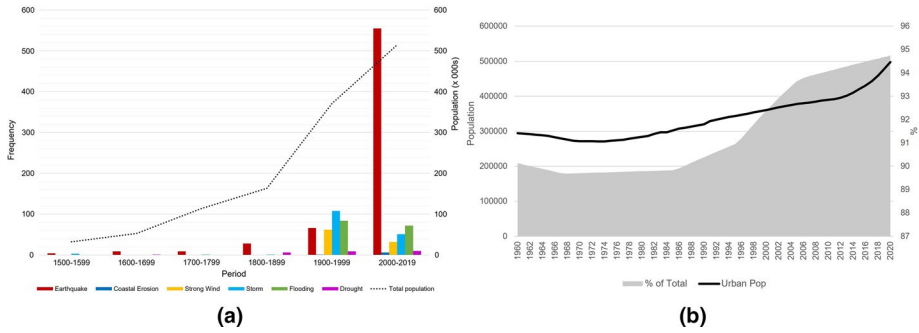


Fig. 7 **a** Variability of earthquakes, coastal erosion, strong winds, storm, flooding and drought over time against total enumerated population; **b** urban population of the city-island-state as a total and percentage of total population between 1960 and 2020. Population data is from national census data, Malta Blue Books (nso.gov.mt) and the World Bank

and Table S1, some temporal patterns may be identified. First, the occurrence of precipitation-related extreme events follows the trend identified within the climate data for Malta (Galdies 2011) in occurring between September and May. There are at least 17 events, however, that fall outside of this pattern, taking place over the summer months between June–August. For example, on 4 June 2007 57.6 mm of rain was recorded (approx. 72 times greater than the June average) causing localised inundation across flood-prone and low-lying areas with many homes and businesses being impacted, and people having to be rescued from their vehicles. Fortunately, no injuries or major damage was reported (Testa 2007). Illustrating the localised nature of flooding and heavy downpours, the *Times of Malta* carried a report which stated that: “at one point, Msida Valley was clear of rainwater but as [Civil Protection Department personnel] approached Birkirkara, they saw a wave of water rushing down towards them resulting from a heavy downpour” (Testa 2007, p. 17). Second, the increased incidence of earthquakes is less to do with increasing seismicity in the Mediterranean and area immediately surrounding the city-island-state, but more to do with the increasing availability and digital recording of such events (Galea et al. 2021), although it is not always possible to determine felt versus non-felt earthquakes within the data presented in the current study. Third, the increase in coastal erosion may be due to an increase overall in extreme weather (Ciarlò 2017) and/or an increase in the reporting of such events due to its enhanced impact on the expanding urban population since 1960 (Fig. 7b) especially in coastal areas.

Through our presentation of a holistic and multi-hazard historical catalogue, our work provides a comprehensive and detailed point from which to establish and inform the development of public-facing and evidence-based policies of DRR in Malta. As has been identified in this paper, a lack of long historical records has previously acted as an obstacle to the construction of detailed hazard and risk assessments (Main et al. 2018). Within their review of Malta’s NRA, the European Commission (2016) and Main (2019, p. 281–284) further identified a number of recommendations for the future including a requirement for a national disaster database and the importance and need to recognise and include multi-hazards, complex crises and cross-border risks. For Malta such cross-border environmental risks include *inter alia*: earthquakes; volcanic ash fall; medicanes; and drought. By providing the first detailed picture of such multi-hazard environmental threats and their impacts for the city-island-state over time this work will, it is hoped, inform future NRA cycles.

There is a recognition within the Maltese authorities' risk reduction and management strategy of the need for knowledge and awareness of, and research into, the hazards, threats and risks facing Malta (European Commission 2016, p. 43). This is also recognised internationally by the *Sendai Framework* (Sect. 1.1; United Nations 2015). In compiling this work we are, not only disseminating results and data on Malta's environmental hazards and threats, but are also simultaneously attempting to demystify Malta's low-hazard history and styling as the "safest place on Earth" (Camilleri 2011; Appleby-Arnold et al. 2018), which have resulted from previously published incomplete and inadequately researched historical catalogues. Additionally, there is a need for communication about non-classified parts of the over 1,000-page NRA to enhance public knowledge and awareness of potential hazards, threats and actions of preparedness (European Commission 2016), a finding which is shared by Main (2019, p. 284).

5 Conclusion

The city-island-state of Malta has traditionally been viewed as a low-hazard, advanced and independent archipelagic island state in the central Mediterranean with a complex setting and physical geography. This view is due in part to a lack of long historical records of environmental extremes and their impacts on Malta, a situation which has created difficulties in formulating detailed hazard assessments and evidence-based policies of DRR for this densely populated city-island-state. Islands such as Malta have long been overlooked given the infrequency of damaging events, yet in the future, impacts from such events may be highly significant given the rate of continued economic development and growth in the population at risk.

In this paper and accompanying supplementary material, we have compiled over 3,500 documents and points of reference and have established the first multi-hazard historical catalogue for Malta. In so doing, we have identified at least 1,550 hazardous events that have claimed at least 662 lives and which have encompassed geophysical, geomorphological and meteorological extremes. This represents a significant advance in understanding the timing, frequency and impact of extreme natural events on Malta. Such events include: local, regional and distal earthquakes; putative effects of volcanic eruptions; coastal erosion; tornadoes; medicanes; sand-storms; flooding; and drought. The majority of these events are considered reliable with 79% having a reliability of 3 (confirmed) or 4 (definite), while only 1% are considered questionable. Additional work in this area is required, notably in identifying any events that are still absent from the record. Recognising the continuing economic and physical transformations of the city-island-state, it is further critical to model the impacts of past events on contemporary Malta in order to inform the development of evidence-based policies and practices of disaster risk reduction, all of which are key recommendations and objectives of Malta's risk reduction and management strategy.

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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