A Multi-Hazard Platform for Cultural Heritage at Risk: The STORM Risk Assessment and Management Tool

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Abstract. In response to the adverse effects of natural hazards and climate change threats on cultural heritage, a methodology of risk assessment and management was developed and applied to five pilot sites: the Historical Centre of Rethymno in Greece, the Mellor Heritage Project in the United Kingdom, the Roman Ruins of Tróia in Portugal, the Baths of Diocletian in Italy, and the Ancient City of Ephesus in Turkey. According to the methodology, a practical and easy-to-use tool was implemented to help the end-users in managing the impacts of natural hazards and climate change on their cultural heritage sites. The tool comprises three major phases: Site Hazard Assessment, Risk Assessment, and Risk Management Strategies. It assists site managers and experts to identify sudden- and slow-onset natural hazards and climate change threats and to assess their corresponding risks to different areas of the pilot sites. The tool is linked to a web-GIS service, which is capable of providing hazard and risk information and maps for each pilot site. The module Risk Management Strategies enables the user to define risk treatment strategies and associated measures in response to each hazard. Overall, the tool facilitates a shared understanding of the risk data and maps among the multiple stakeholders engaged in the protection of cultural heritage sites to enable a more effective decision-making process.

1. Introduction
In respect to the protection of cultural heritage from natural hazards, two different trends can be recognised: structural risk assessment of historic fabrics (e.g. [1]), and the overall process of risk assessment and management for cultural heritage (e.g. [2]; [3]; [4]). National and international projects have also been dedicated to the subject, such as Climate for Culture (2009-2014) and NOAH’S ARK ‘Global Climate Change Impact on Built Heritage and Cultural Landscape’ (2001-2007) with a specific focus on the impacts of climate change on materials and structures of cultural heritage.

In the STORM project (Safeguarding Cultural Heritage through Technical and Organisational Resources Management), a methodology of risk assessment and management for cultural heritage properties has been developed in response to the adverse effects of natural hazards, including climate change influences. The proposed methodology was applied to the five STORM pilot sites: the Historical Centre of Rethymno in Greece, the Mellor Heritage Project in the United Kingdom,
the Roman Ruins of Tróia in Portugal, the Baths of Diocletian in Italy, and the Ancient City of Ephesus in Turkey. Natural hazards and threats affecting each pilot site have been identified, analysed, and subsequently, mapped in the GIS environment. Risk components (i.e. hazard, exposure, and vulnerability) incorporated into a risk index to measure the level of risks. According to the STORM risk map concept, relative risk maps have been generated to share a common understanding of the risks at the pilot sites among the risk management team, including the site managers and other stakeholders.

The output of the pilot sites risk assessment further supports the decision-making process to determine risk treatment strategies. Moreover, the procedure of the risk assessment provided a clear perception of the risk elements for each pilot site to develop a site-specific risk reduction plan through various options including hazard mitigation and coping capacity building. The three main pillars of the risk treatment framework involve risk prevention and mitigation (including adaptation to climate change), risk preparedness and emergency response, and recovery plan. Furthermore, to ensure rapid intervention in case of emergency and to limit further damage, a broad array of first aid actions for a variety of cultural heritage typologies is included.

This paper mainly focuses on a Risk Assessment and Management (RA&M) tool that has been implemented based on the methodology developed in the STORM project. The tool facilitates a shared understanding of the risk data and maps among the multiple stakeholders engaged in the protection of cultural heritage sites to enable a more effective decision-making process.

2. STORM multi-hazard context

One of the main challenges in the STORM project was a large number of natural hazards while considering climate change influences. Thus, the analysis and prioritization of hazards and threats affecting the pilot sites played a key role in framing the initial steps of the risk assessment. Besides the common classification of hazards, to adequately address the short- and long-term effects of natural hazards and threats on heritage sites, the hazards are further categorized according to the speed of onset (Figure 1). Accordingly, sudden-onset hazards (e.g. earthquakes, storms, and floods) and slow-onset hazards (e.g. wetting-drying cycles and wind-driven rain) were integrated into the hazard assessment procedure. Future alterations due to climate change, such as projected changes in hydro-meteorological events (e.g. change of precipitation and heat waves), were also addressed in the assessment procedure.

![Classification of natural (or socio-natural) hazards that may affect cultural heritage](image-url)

**Figure 1.** Classification of natural (or socio-natural) hazards that may affect cultural heritage [5]
3. STORM Risk Assessment and Management Tool

The STORM Risk Assessment and Management RA&M tool has been implemented according to the Risk Assessment and Management Methodology developed in the STORM project [6]. The tool enables the site managers and experts to identify and analyse natural hazards affecting a heritage site, assess the value of areas of the site, analyse the vulnerability of the site, measure the level of risks in different areas of the site, and finally determine site-specific strategies to mitigate the risk associated with each hazard.

The RA&M tool is composed of three main modules that enable the STORM’s risk assessment and management methodology to be implemented in a systematic and understandable way. The main components of the RA&M tool, as shown in Figure 2, are as follows:

- Site Hazard Assessment
- Risk Assessment
- Risk Management Strategies

![Figure 2. STORM Risk Assessment and Management tool: main components and their interrelations](image)

The Site Hazard Assessment module is comprised of a Hazard Identification step and a Hazard Analysis step. The Hazard Identification step allows the user to quantify the relevance of each hazard (whether sudden-onset or slow-onset) to the pilot site. The Hazard Analysis step enables the computation of an overall ranking according to a set of ranking factors [5] defined in the methodology (to be rated from ‘very low’ (1) to ‘very high’ (5)) in order to identify the hazards of interest (Figure 3).

The Risk Assessment module provides a more thorough assessment for different areas of each pilot site. In this module, the user can add any number of areas to the site and then create a risk assessment for each of those areas. The Risk Assessment module is composed of the following steps: Hazard Analysis, Exposure Analysis, Susceptibility Analysis, Coping & Adaptive Capacity Analysis, Risk Identification, and Risk Analysis. Each of those steps conforms with the same defined steps of the Risk Assessment methodology [6]. Overall, the following three components of risk are analysed in this step:

- Hazard: sudden-onset hazards (e.g. storms, flooding, wildfires) and slow-onset hazards (e.g. change in freeze-thaw events, heat waves, and prolonged wet/dry periods) were incorporated in the assessment procedure;
- Exposure: movable and immovable heritage assets and their associated values were considered as elements at risk; and
Vulnerability: a vulnerability assessment method was developed to evaluate the susceptibility of the pilot sites to damage according to their structural and material characteristics. Furthermore, adaptive and coping capacities of the management system were taken into account.

According to the above risk components, the level of risk corresponding to a specific hazard and characteristics of an area of a site is determined (Figure 3). Finally, the Risk Management Strategies module categorizes each site’s area per level of priority concerning a specific hazard. The prioritisation is based on the output of the Risk Assessment module. In this step, users have the possibility to prioritise items, which have been defined for each area in the STORM platform, according to their values and sensitivity to different hazards. The tool enables the user to define risk treatment strategies and associated measures in response to each hazard. Figure 4 shows an example of risk treatment strategies and their associated measures for the earthquake hazard. The strategies involve risk prevention and mitigation including adaptation to climate change, risk preparedness and emergency response, and recovery plan.

Each page of the tool is supplied with an Informational tab that provides the user with the required information, such as definitions, assessment indicators, and rating scales, to facilitate conducting the assessment steps. Apart from the semi-quantitative and qualitative ranking scales, a colour coding system is also applied in the assessment process to better illustrate the priority levels.

Technically, front-end development of the tool involves a collaborative effort between multiple STORM partners. The task is mainly split into defining the workflow and user interaction through the production of a mock-up solution and coding work. The tool is developed as a web interface, served from the STORM main platform. The users will mainly be domain experts and site managers, and the interface should be as user-friendly as possible. One of the main features of this tool is its ability to cover the risk assessment and management for multiple pilot sites - presently Tróia (Portugal), Mellor (England), Diocletian Baths (Italy), Rethymno (Greece) and Ephesus (Turkey) - and a number of separate areas and items for each site. This is achieved with the clear and systematic functionalities for the different workflows.

Overall, the STORM RA&M tool has been developed to provide the targeted stakeholders, heritage conservators, risk experts, and the trusts of the pilot sites with a user-friendly instrument to manage the risks of natural hazards and climate change. The tool will provide a shared understanding of the risk data and assessment processes among the multiple stakeholders engaged in the protection of cultural heritage sites to facilitate decision-making processes. In the context of the STORM project, the tool provides some other components of the STORM platform with the necessary data, for instance, GIS services to generate and update hazard and risk maps for each pilot site.
Figure 3. An example of the home page on the Risk Assessment and Management tool

Figure 4. An example of the Risk Management Strategies webpage
4. Web-GIS services for proactive risk management
Several web-based GIS services have been developed to support the STORM project, aiming to successfully address all geographical information management, processing and visualization requirements. In particular, the web-GIS services are able to manage geospatial data to support risk assessment analysis (and modelling), monitoring and situational awareness processes. The core functions of the STORM web-GIS services operate on a client-server architecture. The architectural schema of the STORM web-GIS infrastructure is formed by a set of free and open-source components; GeoServer [7], an open-source web map server, connected to a PostGIS [8] geodatabase for storing spatial information, and OpenLayers [9] web mapping client API, for visualizing geographical information on a dynamic and interactive web map interface. GeoServer is a free and open-source solution of a web-mapping server that can provide access to geographical information through web services that openly support documented standards and protocols [10]. OpenLayers is also a free and open-source, JavaScript based, web mapping (programming) library for designing dynamic and interactive web maps, assisting in the development of rich web-based GIS applications [11].

Corresponding spatial information is stored on the server in the form of raster or vector data types, which act as static GIS layers in the corresponding web map services; however, dynamic spatial information is also supported by the web-GIS services and stored in a PostGIS geodatabase for addressing specific needs, i.e. monitoring and situational awareness processes.

The STORM web-GIS services, besides spatial information management, are able to provide visualization of geographical information in an efficient and illustrative manner, currently related to the surrounding areas of the STORM cultural heritage pilot sites. In particular, this information includes sensor node locations (installed and deployed on-site), specific site areas and item locations that need to be monitored, topographical information (elevation, aspect, slope) of the wider area, as well as geological and hydrolithological information available from local, regional, national and other available EU open sources. Most importantly, the web-GIS services are able to support the functionality of other services and tools of the STORM platform, such as the RA&M tool, the Surveillance and Monitoring and the Quick Damage Assessment services, thus providing associated information as thematic map layers through the STORM dashboard. As such, STORM platform users are provided with accurate situational awareness services and are able to effectively and timely manage and monitor critical situation events, their evolution and potential effects.

As already noted, the STORM Risk Assessment and Management process for generating and updating hazard and risk maps for cultural heritage monuments and sites is based on the processing of geographic information and the analysis of their spatial association. The semi-quantitative analysis of the identified hazards provide each pilot site with the evaluation of the associated severity, exposure (heritage values) and vulnerability (susceptibility and coping and adaptive capacity), and allow an estimate of the overall risk for the pilot site. Web-GIS services mainly support the visualization of hazard-related data sets, e.g., landscape topography and geology, together with the corresponding outcomes of the spatial analyses that provide direct images (maps) of the hazards and their associated risks. Therefore, cultural heritage operators, planners and decision-makers are offered with services able to assist them to efficiently plan hazard and risk mitigation actions.

Regarding the situational awareness web-GIS service, simple events in the STORM context represent a critical situation image of a heritage asset-at-risk by processing physical phenomena and damages or human activities. The corresponding web-GIS service was developed to support spatial (overlay) analysis of these data layers for understanding the scope, complexity, and severity of critical situations, enabling the identification of affected heritage assets and structures while assessing their potential damage. This will assist in prioritising mitigation, restoration or recovery actions. The respective web-GIS map services are incorporated to the STORM platform in order to visualize critical situation events and associated hazards severity as corresponding "situational picture" maps. An example of the STORM platform utilizing the situational awareness web-GIS service is illustrated in Figure 5.
5. Conclusion
The systematic procedure of assessment and management in the RA&M tool provides a clear perception of the risk elements necessary to develop a site-specific risk reduction plan through avoiding or reducing the identified hazards, reducing the structural or material susceptibility, promoting coping and adaptive capacities, and increasing the effectiveness of emergency response using the situational awareness web-GIS service. The risk assessment further assists the decision-making process by providing the necessary information to understand which area and hazard corresponding to the identified risks need treatment strategies and on which level.

The RA&M tool was developed to provide a shared understanding of hazard and risk among the multiple stakeholders engaged in the protection of the pilot sites, and to facilitate the decision-making process in determining risk reduction measures for the different areas of each site. Accordingly, risk prevention/mitigation, emergency response and recovery strategies can be developed to address the different hazards and risks. Linking the risk assessment tool and Web-GIS service provides spatial (overlay) analysis of hazard, vulnerability, and risk to build situational awareness maps corresponding to different hazards and areas of each pilot site.

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