Multi-hazard susceptibility assessment using Analytic Hierarchy Process: the Derwent Valley Mills UNESCO World Heritage Site case study (United Kingdom)

Luigi Guerriero[1], Mariano Di Napoli[2], Alessandro Novellino[3], Diego Di Martire[1], Concetta Rispoli[1], Kathryn Lee[3], Emma Bee[3], Anna Harrison[3], Domenico Calcaterra[1]

[1]Federico II University of Naples, Department of Earth, Environmental and Resource Sciences, Monte Sant'Angelo Campus, Naples, Italy;

[2]University of Genoa, Department of Earth, Environmental and Life Sciences, Genoa, 16132, Italy;

[3]British Geological Survey, Environmental Science Centre, Keyworth, Nottingham NG12 5GG, United Kingdom

*Correspondence to: alessn@bgs.ac.uk

Abstract: Many of the UNESCO World Heritage Sites face geological threats which could have negative effects on the value, integrity and accessibility of their heritage assets. A relevant example is the Derwent Valley Mills UNESCO World Heritage site, one of the key sites of Britain's industrial revolution of the 18th century and located along the Derwent River Valley. Individual susceptibility scenarios of natural hazards in the area like collapsible deposits, compressible ground, debris flow, landslide, running sands, shrink-swell, soluble rock and flooding (both riverine and groundwater) are available, but a comprehensive product able to support disaster mitigation measurement and land planning still does not exist. On this basis, a multi-hazard susceptibility analysis was completed with the added benefit of reducing the complexity and providing a methodological framework for multi-hazard estimation. The analysis was completed in a GIS environment through an Analytical Hierarchy Process (AHP) multicriteria decision-making process. Since the AHP method is affected by a user selection bias, a quantitative Relative significance index was derived to rank the AHP factors during the susceptibility estimation. This index suggests that flooding is the principal natural hazard for the Derwent Valley Mills UNESCO World Heritage site. The multi-hazard susceptibility map also indicates that most of the areas where the mills are located are subject to significant susceptibility to natural hazards.

Keywords: cultural heritage; Derwent Valley Mills; multi-hazard; susceptibility; England.

1. Introduction

The UNESCO's List of World Heritage Sites (WHS) in Danger encompasses several cultural and natural heritage sites that are threatened by wars, natural hazards, pollution, uncontrolled urbanization and unchecked tourist development [1-2] (https://whc.unesco.org/en/conventiontext/#Article11.4). Over the long-term, these conditions can potentially induce irremediable damage for the conservation and preservatios of the asset.

Compared to other threats, natural hazards are difficult to predict and usually underestimated [e.g. 3]. As of 2021, UNESCO considers only 3 of the 435 World Heritage Sites in the European continent in danger despite a recent analysis has associated 16% of them with high seismic hazard, 12% with very high landslide susceptibility, and 7% with high volcanic hazard [4]. As a result, there is a lack of understanding in Great Britain of the impact of natural hazards on the World Heritage List properties [5]. Multi-hazard susceptibility assessment analyses the spatial relationship between different hazards and is a key tool for WHS managers [6].

In recent decades, attention to cultural heritage protection from natural hazards has received growing interest and new methods supporting susceptibility, hazard and risk calculations have been progressively developed [7-16]. The challenge is now represented by the assessment of multi-hazards [17-19] and their potential impact [20-22].

The evaluation of multi-hazard susceptibility requires the knowledge of the interaction of multiple potentially active processes (triggering, increased-probability and catalysis/impedance) that cannot be captured by summing up a single hazard,usually evaluated indipendently within an area [21-23] . According to the type of hazard and available data, stochastic, empirical and mechanistic methods have been developed for multi-hazard susceptibility assessment [24]. Due to the lack of sufficient or reliable data [25], many authors adopt susceptibility-based approaches, where a comprehensive susceptibility scenario to multiple natural hazards is generated from the susceptibility of individual hazards [8]. That's why, in this work, we will use the terms 'hazard' and 'susceptibility' interchangeably.

On this basis, this paper analyses the British Geological Survey (BGS)'s geological and single-hazard datasets to advance the understanding of the main hazards affecting the UNESCO Derwent Valley Mills World Heritage Site (DVMWHS) (Fig. 1) in the UK through a multi-hazard susceptibility analysis. This work builds upon the geohazard assessment BGS has carried out for the UK World Heritage List sites as part of the PROTection of European cultural HEritage from GeO-hazards (PROTHEGO) project [26].

Figure 1 – a) Map showing position of the Derwent Valley Mills World Heritage Site, associated Core Area and Buffer Zone and large historic infrastructure (blue symbols). Examples of Mills and pump facility along the Derwent Valley: b) Cromford Mill, c) Leawood pump house, d) Belper East Mill. Coordinate system: British National Grid.

2. Research aim

This paper aims at providing a multi-hazard susceptibility scenario based on the Analytical Hierarchy Process for the mills located along the DVMWHS considering relevant natural hazards acting in the area such as: flooding, groundwater flooding, compressible ground, landslides, and running sands. A flowchart of the analysis we conducted is provided as Supplementary Materials (S1).

3. The Derwent Valley Mills UNESCO World Heritage site

The DVMWHS (Fig. 1) is an example of one of the key sites of Britain's industrial revolution (18^{th} century) included in the UNESCO World Heritage List in 2001 due to its international role in the birth of the modern factory system, the development of new technology for spinning cotton and the first modern industrial settlements (http://whc.unesco.org/en/list/). The DVMWHS comprises historic cotton and silk mill complexes (e.g., Belper Mills, Cromford Mills and Darley Abbey Mills), the watercourses that powered them, railways and the housing settlements erected for the mill-worker communities during the 18th and 19th centuries [27].

The Valley encompasses an approximately 24 km-long stretch of the lower course of the Derwent River valley, from Derby in the south to Matlock Bath in the north, where it almost abuts the southern boundary of the Peak District National Park. UNESCO has divided the Derwent Valley Mills World Heritage Site into a Core Area (CA) and the Buffer Zone (BZ). The Core Area is a single entity (12.3 km^2), encompassing historic buildings, features and landscapes that contribute to the universal value of the site. The Buffer Zone (43.6 km^2) represents a zone that in itself is not of outstanding universal value but that may influence the World Heritage site. The United Kingdom government, Derwent Valley Mills Partnership [28] and local councils are accountable to UNESCO for the conservation and preservation of the heritage assets within the Derwent Valley. Money have been already invested to develop plans for sustainable flood risk management over the next 50 to 100 years through the complex network of embankments of the River Derwent [29].

Geologically, the site is characterised by the presence of Quaternary alluvium, slope deposits and glacially-derived till deposits especially in the CA overlying a bedrock mostly consisting of thick interbedded mudstone, siltstone and sandstone of the Carboniferous Millstone Grit Group and Bowland High and Craven Groups (Mississippian). Due to the typical alternation of permeable and impermeable layers, such rocks are particularly prone to landslides [26].

The Derwent Valley Mills has been one of the demonstration sites of the PROTHEGO project (http://www.prothego.eu/) that analysed single hazards threatening the historic asset along the valley.

4. Materials and methods

4.1 Materials

The multi-hazard susceptibility analysis of the DVMWHS included the following natural hazards: collapsible deposits, compressible ground, debris flow, landslide, running sands, shrink-swell, soluble rock and flooding (both riverine and groundwater; Fig. 2). Data about these hazards were derived by the BGS Geosure dataset (https://www.bgs.ac.uk/datasets/geosure/) and the BGS flooding datasets (https://www.bgs.ac.uk/datasets/groundwater-flooding/). These datasets provide a score of natural hazards susceptibilities at 1:50,000 scale within the CA and the BZ using a qualitative scheme: from A (low) to E classes (high) [30]. For the purpose of our analysis, i) only natural hazards with susceptibility levels higher than B were considered thus, leaving only flooding, groundwater flooding, compressible ground, landslides and running sands, ii) susceptibility classes A to E were converted into equally-spaced numerical values ranging from 0 to 1 (i.e. susceptibility score, H_i) and iii) raster maps were derived by the available susceptibility datasets. Converted susceptibility scores (H_i) form a numerical basis for multi-hazard susceptibility estimation (see below for method).

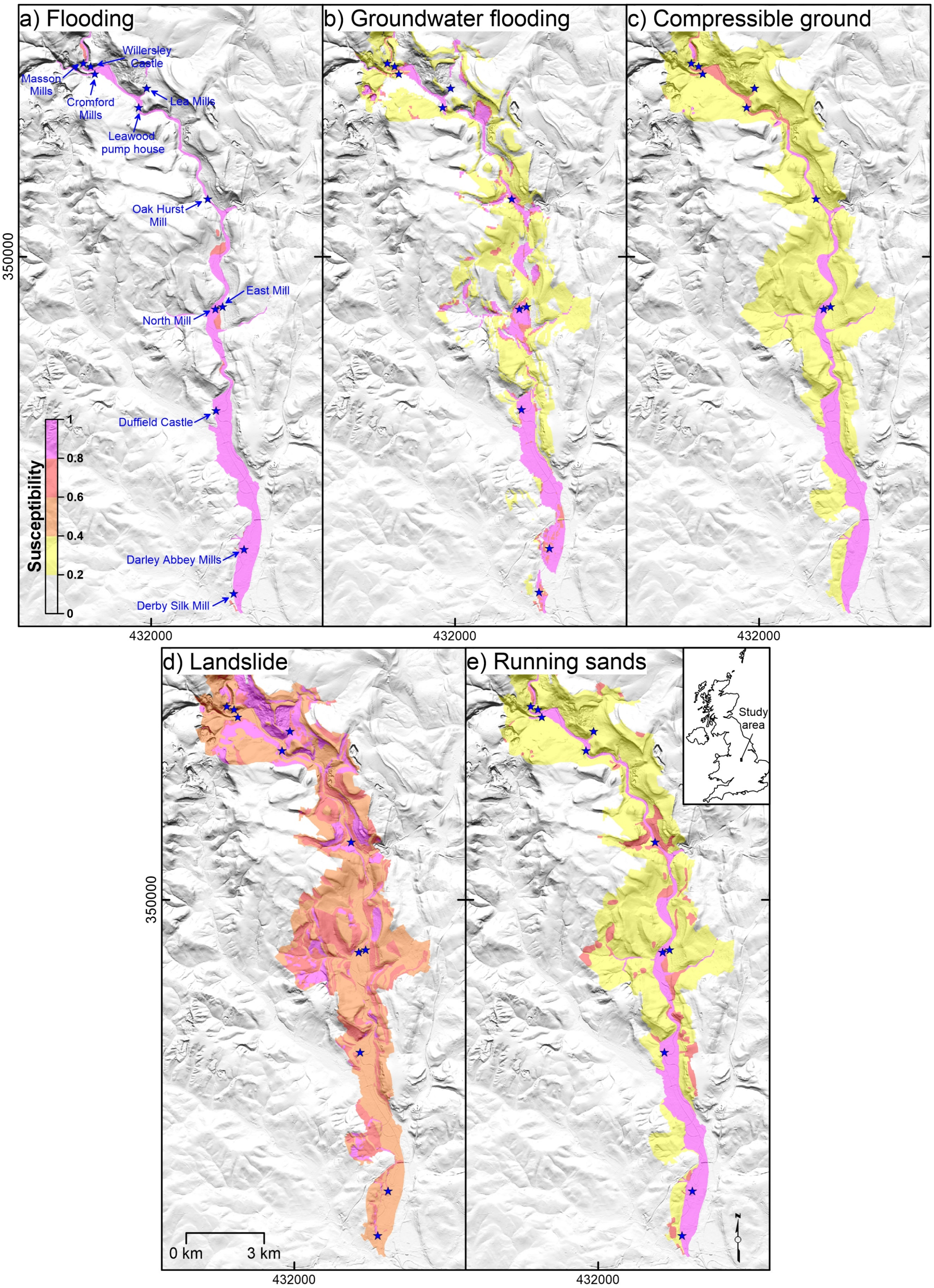

Figure 2 – Susceptibility maps of single natural hazards in the DVMWHS. The largest historic infrastructure is depicted by blue symbols. Coordinate system: British National Grid.

4.2 Multi-hazard susceptibility assessment

The multi-hazard was assessed using the Analytical Hierarchy Process (AHP) [31-32]. AHP is a semi-quantitative method where each factor (which refers to a single hazards in our case) is weighted through a pairwise relative comparison against all the other factors [33]. AHP is an expert-based methodology characterised by: i) integration of all types of information; ii) expert's knowledge and experiences are fundamental for discussion rules; iii) reached consensus, weights for each relevant factor are obtained automatically by eigenvector calculation of the comparison matrix and iv) inconsistencies can be detected using consistency index values developed in [33-34] and, eventually corrected if needed. The principal drawback of AHP is related to the subjectivity of choices, so that factors ranking may differ from one user to another. To mitigate this effect, a Relative Significance index (RSi) was firstly derived to guide the scores of the AHP factors needed for the susceptibility estimation. Since the estimation of multi-hazard susceptibility is related to the presence of historic infrastructure, the RSi index for each natural hazard (e.g. flooding, groundwater flooding etc…) is given by the sum of the susceptibility scores to a single natural hazard for each infrastructure (See Table 1 for details). For instance, RSi for flooding is the sum of susceptibility-to-flooding scores estimate at all of the considered Mills. Each hazard was then ranked according to this index and these ranks, in turn, have been used in the AHP pairwise matrices.
The multi-hazard susceptibility was estimated using a weighted sum model:

$$MH = \sum_{i=1}^{n} H_i\, W_i \qquad (1)$$

Where n is the number of considered natural hazards, H_i represents the susceptibility score to a selected individual natural hazard (from 0 to 1) and W_i is a weight representing the relative importance of that hazard (i, from 0 to 1) that modulates the contribution of each considered single-hazard susceptibility score (e.g. to flooding) to the multi-hazard susceptibility score. Weight estimation, through the AHP, was completed developing two pairwise comparison matrices. The first matrix reports the significance scores (Ss) assigned to each factor (i.e. natural hazard) on the basis of the following levels of importance defined in the literature [32]: 1 = equal, 3 = moderately, 5 = strongly, 7 = very strongly, 9 = extremely and 2, 4, 6, 8 = intermediate values. Level of importance are assigned on the basis of the relative importance between factors on the row and corresponding factors on the coloumn (See Table 2 for matrix structure and supplementary materials S2). Matrix construction is completed considering major diagonal elements with an equal level of importance (i.e. Ss =1). The second matrix uses normalized scores to derive the average weight for each natural hazard. Especially, Ss are first normalized by the total along the coloumn and subsequently averaged along the row for AHP weights estimation (See the combined matrix of Table 2 for calcaulation details and supplementary materials S2). The consistency of the AHP's weights was examined using the Consistency Ratio (CR):

$$CR = CI/RI \quad (2)$$

where RI is the Random Index and CI is the Consistency Index (CI) [35] equals to:

$$CI = \lambda_{max} - n/n-1 \quad (3)$$

where λ_{max} is the largest eigenvalue of the second matrix of order n, where n is the number of the considered natural hazards. The RI represents the consistency index of a randomly generated pairwise comparison matrix and its value depends on the number of elements being compared (i.e the size of the matrix) [35]. CR is used to check and, therefore, avoid possible inconsistencies in the pairwise matrix. When CR is > 0.1, the comparison matrix is inconsistent and should be revised [35], conversely, if CR is ≤ 0.1 the weighting coefficients are suitable. After checking the consistency of the matrix, the weighted sum model was applied to the susceptibility of each hazard into a Geographical Information System (GIS) environment to derive a multi-hazard susceptibility map of the DVMWHS at 10m resolution.

5. Results and discussion

Table 1 reports the results from the RSi analysis for the single hazard susceptibility scores over the largest historic infrastructure located in the study area (Fig. 1). Being all the mills within Quaternary fluvial deposits, i) they are located in a very high susceptibility zone to flooding and the RSi of this natural hazard is the highest in the comparison (Rank: I), ii) six mills are located either in a high susceptibility zone to groundwater flooding or compressible ground (Rank: II and III, respectively), iii) one mill is located in a very high susceptibility zone for landslide (Rank: IV) and, iv) two mills are located in a very high susceptibility zone for running sands but the overall susceptibility score for this hazard is slightly lower than that of the landslide susceptibility (Rank: V).

Based on natural hazard ranking of Table 1, a joint AHP pairwise comparison matrix, containing both Ss and normalized Ss (see numbers in pharenteses), was developed assigning a comparative score to each considered natural hazard and single hazard AHP weights were estimated (Table 2). The importance of this process along the analysed reach of the Derwent Valley has been already suggested in [36] who underlined the potential need for mitigation measurements to protect mills against riverine flooding in the light of the changing climate. The relative relevance of riverine flooding is considered strong in comparison with that of groundwater flooding and compressible ground hazards and extreme in comparison with landslides and running sands. The result is compatible with the high probability of flooding in the Environment Agency maps (https://flood-map-for-planning.service.gov.uk/).

Although landslides are widespread in the area with 44 events reported up to 2014 (https://www.bgs.ac.uk/geology-projects/landslides/national-landslide-database/), these events are located at the outer slopes of the valley so do not directly impact the key infrastructure, and are mainly represented by shallow phenomena in the Quaternary deposits or falls/topple in the bedrock especially in the northern part of the study area [26]. Finally, compressible ground (Fig. 2c) and running sands (Fig. 2e) hazard are moderate and follow the Quaternary deposits of the CA. The relative relevance of compressible ground hazard in comparison to landslides and running sands was considered equal and moderate. Landslides and running sands were considered of equal importance. Differently from previous works [37] which only provide a review of existing hazards individually, the holistic approach we have considered here allows the extraction of a ranking for prioritizing hazards and determine their magnitude compared to each other.

Table 1 – Results from RSianalysis for natural hazard ranking in each of the areas where the historic infrastructure is located. The relative significance index is the sum of all the scores for each column (hazard).

id	Historic infrastructure	Flooding	Groundwater flooding	Compressible ground	Landslide	Running sands
1	Masson Mills	1	0.6	0.6	0.4	0.6
2	Willersley Castle	0	0.2	0.2	0.4	0.2
3	Cromford Mills	1	0.6	0.6	0.4	0.6
4	Lea Mills	0	0	0.2	1	0.2
5	Leawood pump house	1	1	0.2	0.8	0.2
6	Oak Hurst Mills	1	1	1	0.6	0.6
7	North Mill	1	1	1	0.4	0.8
8	East Mill	1	1	1	0.4	0.6
9	Duffield Castle	1	1	1	0.4	1
10	Darley Abbey Mills	1	0.8	1	0.6	1
11	Derby Silk Mill	1	1	1	1	0.4
Relative Significance index (RSi)		9	8.2	7.8	6.4	6.2
Ranking		I	II	III	IV	V

Table 2 – Pairwise comparison matrix and AHP weights. Significance scores normalized by the total along the coloumn are reported in pharenteses (bold text). AHP weights for each natural hazard are astimated as the average of normalized scores along the row.

	Flooding	**Groundwater flooding**	**Compressible ground**	**Landslide**	**Running sands**	**AHP weights**
Flooding	1 **(0.616)**	5 **(0.652)**	5 **(0.625)**	9 **(0.562)**	9 **(0.562)**	**0.604**

Groundwater flooding	0.200 **(0.123)**	1 **(0.130)**	1 **(0.125)**	3 **(0.187)**	3 **(0.187)**	**0.151**
Compressible ground	0.200 **(0.123)**	1 **(0.130)**	1 **(0.125)**	2 **(0.125)**	2 **(0.125)**	**0.126**
Landslide	0.111 **(0.068)**	0.333 **(0.043)**	0.500 **(0.063)**	1 **(0.063)**	1 **(0.063)**	**0.060**
Running sands	0.111 **(0.068)**	0.333 **(0.043)**	0.500 **(0.063)**	1 **(0.063)**	1 **(0.063)**	**0.060**
Total	**1.6222**	**7.6667**	**8.0000**	**16**	**16**	

The matrix of Table 1 was used as a basis for deriving the AHP weights of the multi-hazard susceptibility assessment as average along the row of normalized significance scores. Estimated weights ranged between 0.604 of flooding hazard to 0.06 of landslide and running sands hazards. Reliability of these evaluations was suggested by a Consistency Ratio of 0.095 obtained considering a Consistency Index of 0.106 and a random index of 1.12. The multi-hazard susceptibility map for the DVMWHS is shown in Figure 4. Considering the scores assigned to individual hazards, the area with the highest susceptibility (i.e. between 0.8 and 1) is the central sector of Derwent river valley and its alluvial deposits. This susceptibility zone is much developed in comparison with zones of lower susceptibility; this is related to the weight of flooding and groundwater flooding susceptibilities, which represent the most significant hazards of the area [26]. Indeed, the area with the highest susceptibility substantially corresponds to the zone highly susceptible to these two natural hazards as well as compressible ground and running sands hazards. Considering their weights and spatial distribution, landslide hazard seems to have only a limited significance in the process. The produced map allows to include susceptibility to more than one natural hazard for the DVMWHS. The susceptibility levels are: i) Masson Mills, 0.75; ii) Willersley Castle, 0.09; iii) Cromford Mills, 0.77; iv) Lea Mills, 0.08; v) Leawood pump house, 0.82; vi) Oak Hurst Mill, 0.92; vii) East Mill, 0.91; viii) North Mill, 0.91; ix) Duffield Castle, 0.91; x) Darley Abbey Mills, 0.91; xi) Derby Silk Mill, 0.86.

Limits of these estimations are related to the limits of the method used for the analysis. A first caveat is the subjectivity in the choice of the comparative scores for individual hazards which is inevitably biased by the experience of the operator [32]. This issue was partially overcome through the introduction of the RSi to guide the ranking of the hazards. A second limit is related to the consistency of the judgment matrix that, being related to the acceptability of the results, is affected by the number of factors considered for the analysis [38]. In presence of a significant number of factors, acceptable results might be very difficult to obtain and, alternatively, multicriteria decision-making methods or machine learning methods should be considered [39-41]. Another limitation is that the AHP analysis is able to provide information about the susceptibility of an area to natural hazards, but does not consider the relationships among these hazards (e.g., flooding increasing landslides hazard or viceversa).

Despite the above-mentioned method drawbacks, AHP has many advantages that have made it one of the most widely exploited procedures in the scientific literature. The different advantages are: i) AHP provides simple and very flexible modelling; ii) it is a simple and straightforward decision-making method;

iii) any level of detail on the main focus can be listed, in this way, the overview of the main problem can be represented very easily; iv) AHP has already a very wide range of application like in planning and benefit and risk analysis and v) current computer software helps decision-makers to use AHP quickly.

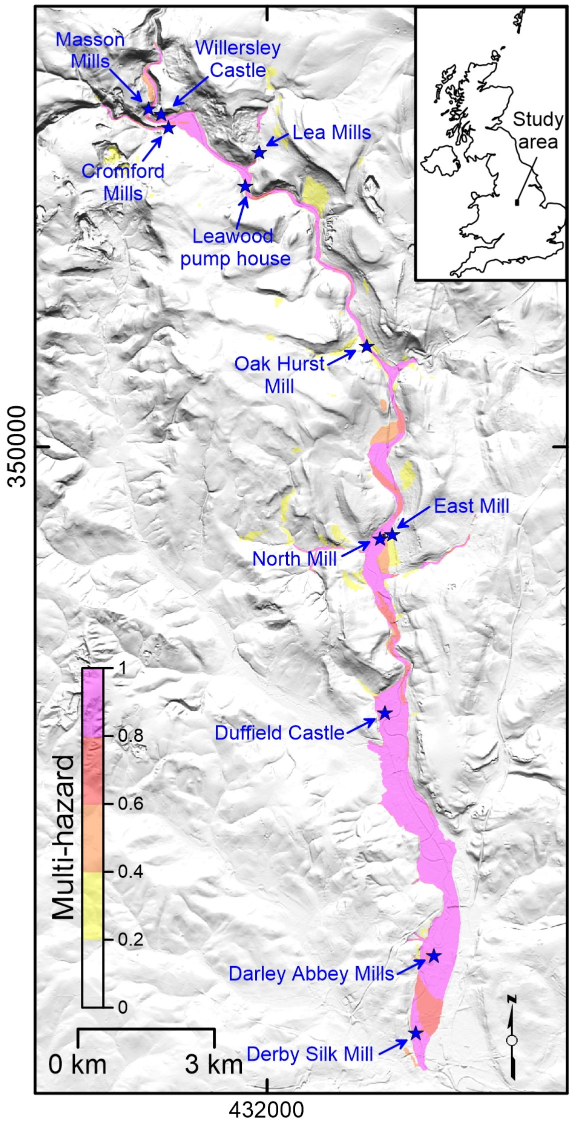

Figure 3 – Multi-hazard susceptibility map derived through the AHP method for the DVMWHS. The largest historic infrastructure is depicted by blue symbols. Coordinate system: British National Grid.

6. Conclusions

The analysis of multi-hazard susceptibility of the Derwent Valley Mills UNESCO World Heritage Site indicates that the main natural hazards for the area are, in the order: flooding, groundwater flooding, compressible ground, landslide and running sands are. Multi-hazard susceptibility mapping through a weighted sum model, parameterized using the AHP multicriteria decision-making method, suggest that the most susceptible sector of the study area is the axial sector of the valley where alluvial deposits cover the mudstone, siltstone and sandstone of the bedrock leading to favourable conditions for groundwater flooding and ground deformation phenomena like ground compression and liquefaction. The susceptibility level for the mills ranges between 0.08 of the Lea Mills and 0.92 of the Oak Hurst Mill. The resulting multi-hazard susceptibility map provides a basis for subsequent estimation of multi-hazard risk of the Derwent Valley Mills UNESCO World Heritage Site. Knowing the multi-hazard susceptibility is critical for policymakers and site managers to strengthen disaster preparedness for heritage properties in the future by building resilience and reducing general vulnerability. These types of analyses can raise awareness for local stakeholders on the urgent need for adaptation as a large number of WHS are already at risk from natural hazards under current conditions and these risks will exacerbate in this century [28] posing a serial threat to the conservation of WHSs but also can provide evidences on potentially redefining Core Areas and the Buffer Zones within UNESCO sites.

Acknowledgments

This paper was funded by the Attraction and International Mobility (AIM) projects AIM18352321 and AIM1835232. The authors thanks the Joint Programming Initiative on Cultural Heritage of the European Commission who supported PROTHEGO project (PROTection of European Cultural HEritage from GeO-hazards; https://www.prothego.eu/). The authors also would like to thank A. Farmer and D. Knight Derwent from the Derwent Valley Mills World Heritage Site for permitting us to use this site as a casestudy.

References

[1] Lollino, G., Audisio, C., 2006. UNESCO World Heritage sites in Italy affected by geological problems, specifically landslide and flood hazard. Landslides, 3, 311-321.

[2] UNESCO, 1972. Recommendation concerning the Protection at National Level, of the Cultural and Natural Heritage,”.

[3] Rispoli, C., Di Martire, D., Calcaterra, D., Cappelletti, P., Graziano S. F., Guerriero, L., 2020. Sinkholes threatening places of worship in the historic center of Naples. Journal of Cultural Heritage, 46, 3131-319.

[4] Spizzichino, D., Leoni, G.; Comerci, V., Brustia, E., Guerrieri, L., Dessì, B., Trigila, A. Iadanza, C., 2016. PROTHEGO Deliverable D.01.01: UNESCO Cultural Heritage vs Natural hazards at European scale, Version 1.0. JPI-CH Heritage Plus PROTHEGO project, Open Report, pp. 30.

[5] Howard, A. J., 2013. Managing global heritage in the face of future climate change: the importance of understanding geological and geomorphological processes and hazards. International Journal of Heritage Studies, 19, 632-658.

[6] Figueiredo, R., Romao, X., Pauperio, E. (2020). Flood risk assessment of cultural heritage at large spatial scales: Framework and application to mainland Portugal. Journal of cultural heritage, 43, 163-174.

[7] Hadjimitsis, D., Agapiou, A., Alexakis, D. and Sarris, A., 2013. Exploring natural and anthropogenic risk for cultural heritage in Cyprus using remote sensing and GIS. International Journal of Digital Earth, 6(2), 115-142.

[8] Lombardo L., Tanyas, H., Hicu, I. C., 2020. Spatial modeling of multi-hazard threat to cultural heritage sites. Engineering Geology, 277, 105776.

[9] Sevieri, G., Galasso, C., D'Ayala, D., De Jesus, R., Oreta, A., Grio, M. E. D. A., Ibabao, R., 2020. A multi-hazard risk prioritisation framework for cultural heritage assets. Natural Hazards and Earth System Sciences, 20, 1391-1414.

[10] Valagussa, A., Frattini, P., Crosta, G., Spizzichino, D., Leoni, G., Margottini, C., 2021. Multi-risk analysis on European cultural and natural UNESCO heritage sites. Natural Hazards, 105, 2659–2676.

[11] Reimann, L., Vafeidis, A. T., Brown, S., Hinkel, J., Tol, R. S., 2018. Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise. Nature communications, 9, 1-11.

[12] Guerriero, L., Ruzza, G., Guadagno, F. M., Revellino, P., 2020. Flood hazard mapping incorporating multiple probabiliy models. Journal of Hydrology, 587, 125020.

[13] Guerriero, L., Ruzza, G., Calcaterra, D., Di Martire, D., Guadagno, F. M., Revellino, P., 2020. Modelling prospective flood hazard in a changing climate, Benevento province, southern Italy. Water, 12, 2405.

[14] Di Napoli, M., Carotenuto, F., Cevasco, A., Confuorto, P., Di Martire, D., Firpo, M., Pepe, G., Raso, E., Calcaterra, D., 2020. Machine learning ensemble modelling as a tool to improve landslide susceptibility mapping reliability. Landslides, 17, 1897-1914.

[15] Novellino, A., Cesarano, M., Cappelletti, P., Di Martire, D., Di Napoli, M., Ramondini, M., Sowter, A., Calcaterra, D., 2021. Slow-moving landslide risk assessment combining Machine Learning and InSAR techniques. Catena, 203, 105317.

[16] Tufano, R., Guerriero, L., Annibali Corona, M., Bausilio, G., Di Martire, D., Nisio, S., Calcaterra, D., 2022. Anthropogenic sinkholes of the city of Naples, Italy: an update. Natural Hazards.

[17] Gill, J. C., Malamud, B. D., 2014. Reviewing and visualizing the interactions of natural hazards. Reviews of Geophisics, 52, 680-722.

[18] Pescaroli, G., Alexander, D., 2018. Understanding compound, interconnected, interacting, and cascading risks: a holistic framework. Risk Analysis, 38, 2245-2257.

[19] Terzi, S., Torresan, S., Schneiderbauer, S., Critto, A., Zebish, M., Marcomini, A., 2019. Multi-risk assessment in mountain regions: a review of modelling approaches for climate change adaptation. Journal of Environmental Management, 232, 759-771.

[20] Gill, J. C., Malamud, B. D., 2016. Hazard interactions and interaction networks (cascades) within multi-hazard methodologies. Earth System Dynamics, 7, 659-679.

[21] Kappes, M. S., Keile, M., von Elverfeldt, K., Glade, T., 2012. Challenges of analyzing multi-hazard risk: a review. Natural Hazards, 64, 1925-1958.

[22] Hewitt, K., Burton, I., 1971. Hazardousness of a place: a regional ecology of damaging events. Toronto Press, Toronto.

[23] UNEP, 1992. Agenda 21. Tech. rep., United Nations Environment Programme, http://www.un.org/ esa/dsd/agenda21/res_agenda21_07.shtml, access 03 September 2009.

[24] Tilloy, A., Malamud, B. D., Winter, H., Joly-Lugel, A., 2019. A review of quantification methodologies for multi-hazard interrelationships. Earth-Science Reviews, 196, 102881.

[25] Romão, X.; Paupério, E.; Pereira, N. A framework for the simplified risk analysis of cultural heritage assets. J. Cult. Herit. 2016, 20, 696–708.

[26] Harrison, A. M., Novellino, A., Hobbs, P. R. N., Wang, L., Bee, E., 2018. Local scale investigation and advanced modelling of the geo-hazards affecting the Derwent Valley Mills World Heritage. Case Study Site, version 1.0., Nottingham, UK, British Geological Survey, 51pp.

[27] Cigna, F., Harrison, A., Tapete, D., Lee, K., 2016. Understanding geohazards in the UNESCO WHL site of the Derwent Valley Mills (UK) using geological and remote sensing data. In: Fourth International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2016), vol. 9688, p. 96881V, International Society for Optics and Photonics.

[28] Derwent Valley Mills, 2020. Derwent Valley Mills – Management Plan 2020-2025. Available at https://democracy.derbyshire.gov.uk/documents/s3233/Derwent%20Valley%20Mills%20Management%20Plan.pdf.

[29] Managing Flood Risk – Derwent Catchment Flood Management Plan, 2010. Environment Agency summary report. Available at https://www.northyorkmoors.org.uk/discover/rivers/reports-and-resources/environment-agency-flood-management-plan-for-river-derwent.pdf [accessed on 11/2/2022]

[30] Lee, K.A.; Diaz Doce, D., eds. 2017 User Guide for the British Geological Survey GeoSure dataset. Version 8. Nottingham, UK, British Geological Survey, 14pp. (OR/17/050). Available at http://nora.nerc.ac.uk/id/eprint/518790/

[31] Skilodimou, D. H., Bathrellos, G. D., Chousianitis, K., Youssef, M. A., Pradhan, B., 2019. Multi-hazard assessment modeling via multi-criteria analysis and GIS: a case study. Environmental Earth Scieces, 78, 47.

[32] Aksha, S. K., Resler, L. M., Juran, L., Carstensen Jr., L. W., 2020. A geospatial analysis of multi-hazard risk in Dharan, Nepal. Geomatics, Natural Hazards and Risk, 11, 88-111.

[33] Saaty, T. L., 1977. A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology, 15, 234-281.

[34] Saaty, T. L., 2006. Rank from comparisons and from ratings in the analytic hierarchy/network processes. European Journal of Operational Research, 168, 557-570.

[35] Saaty, T. L., 1990. How to make a decision: The Analytic Hierarchy Process. European Journal of Operational Research, 48, 9-26.

[36] Howard, A. J., Knight, D., Coulthard, T., Hudson-Edwards, K., Kossoff, D., Malone, S., 2016. Assessing riverine threats to heritage assets posed by future climate change through a

geomorphological approach and predictive modelling in the Derwent Valley Mills WHS, UK. Journal of Cultural Heritage, 19, 387-394.

[37] Cigna, F., Tapete, D., Lee, K., 2018. Geological hazards in the UNESCO World Heritage sites of the UK: From the global to the local scale perspective. Earth-Science Reviews, 176, pp.166-194.

[38] Olson, D. L., 1988. Opportunities and limitations of AHP in multiobjective programming. Mathematical and Computer Modelling, 11, 206-209.

[39] Pourghasemi, H. R., Gayen, A., Panahi, M., Rezaie, F., Blaschke, T., 2019. Multi-hazard probability assessment and mapping in Iran. Science of The Total Environment, 692, 556-571.

[40] Pourghasemi, H. R., Kariminejad, N., Amiri, M., Edalat, M., Zarafshar, M., Blaschke, T., Cerda, A., 2020. Assessing and mapping multi-hazard risk susceptibility using a machine learning technique. Scientific Reports, 10, 3203.

[41] Rusk, J., Maharjan, A., Tiwari, P., Chen, T. K., Shneiderman, S., Turin, M., seto, K. C., 2022. Multi-hazard susceptibility and exposure assessment of the Hindu Kush Himalaya. Science of The Total Environment, 804, 150039.