Journal of Cultural Heritage 55 (2022) 339–345

Contents lists available at ScienceDirect

Journal of Cultural Heritage

journal homepage: www.elsevier.com/locate/culher

Case study

Multi-hazard susceptibility assessment using analytic hierarchy process: the Derwent Valley Mills UNESCO World Heritage Site case study (United Kingdom)

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ARTICLE INFO

Article history:
Received 26 November 2021
Accepted 19 April 2022
Available online 28 April 2022

Keywords:
Cultural heritage
Derwent valley mills
Multi-hazard
Susceptibility
England

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.

Introduction

The UNESCO's List of World Heritage Sites (WHSs) in Danger encompasses several cultural and natural heritage sites threatened by hazards such as wars, natural hazards, pollution and unchecked tourist development [1–2]. Over the long-term, such conditions can potentially induce irremediable damage for the conservation and preservatios of these sites.

Compared to other threats, natural hazards are difficult to predict and usually underestimated. As of 2021, UNESCO considers only 3 of the 435 European WHSs in danger despite authors in [3] identified 16% of WHSs have high seismic hazard, 12% have very high landslide susceptibility, and 7% have high volcanic hazard . As a result, there is a limited knowledge of the impact of single and multiple natural hazards on WHS properties in Great Britain [4]. Multi-hazard susceptibility assessment analyses the spatial relationship between different hazards and is a key tool underpinning planning decisions of WHS managers [5]. In this work, we will use the terms 'hazard' and 'susceptibility' interchangeably.

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 [6–14]. The challenge is now represented by the assessment of the spatio-temporal interaction between different hazards [15–17] and their potential impact [18–20].

The evaluation of multi-hazard susceptibility requires the knowledge of the interaction of the active processes (triggering, increased-probability and catalysis/impedance) that areusually evaluated indipendently within an area [19,21] . According to the type of hazard and available data, stochastic, empirical and mechanistic methods have been developed for multi-hazard susceptibility assessment [22]. Due to the lack of sufficient or reliable data [23], many authors adopt susceptibility-based approaches, where a comprehensive susceptibility scenario to multiple natural hazards is generated from the susceptibility of individual hazards [7].

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https://doi.org/10.1016/j.culher.2022.04.009

Fig. 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.

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 using a multi-hazard susceptibility analysis. This work builds upon the geohazard assessment BGS has carried out for the UK WHSs as part of the PROTection of European cultural HEritage from GeO-hazards (PROTHEGO) project [24].

Research aim

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

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 included in the UNESCO WHS 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 [25].

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 12.3 km^2 zone encompassing historic buildings, features and landscapes that contribute to the universal value of the site. The Buffer Zone (43.6 km^2) includes parts of the landscape that surround the assets but lack the outstanding value of the CA. The UK government, Derwent Valley Mills Partnership [26] and local councils are in charge of the conservation and preservation of the DVMWHS. 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 [27].

Geologically, the site is characterised by the presence of Quaternary alluvium, slope deposits and glacially-derived till deposits overlying a bedrock mostly consisting of thick interbedded mudstone, siltstone and sandstone of the Carboniferous Millstone Grit Group and Bowland High and Craven Groups. Due to the typical alternation of permeable and impermeable layers, such rocks are particularly prone to landslides [24].

Materials and methods

Materials

The multi-hazard susceptibility analysis of the DVMWHS included the following natural hazards: collapsible deposits, compressible ground, debris flow, landslide, running sands, shrink-

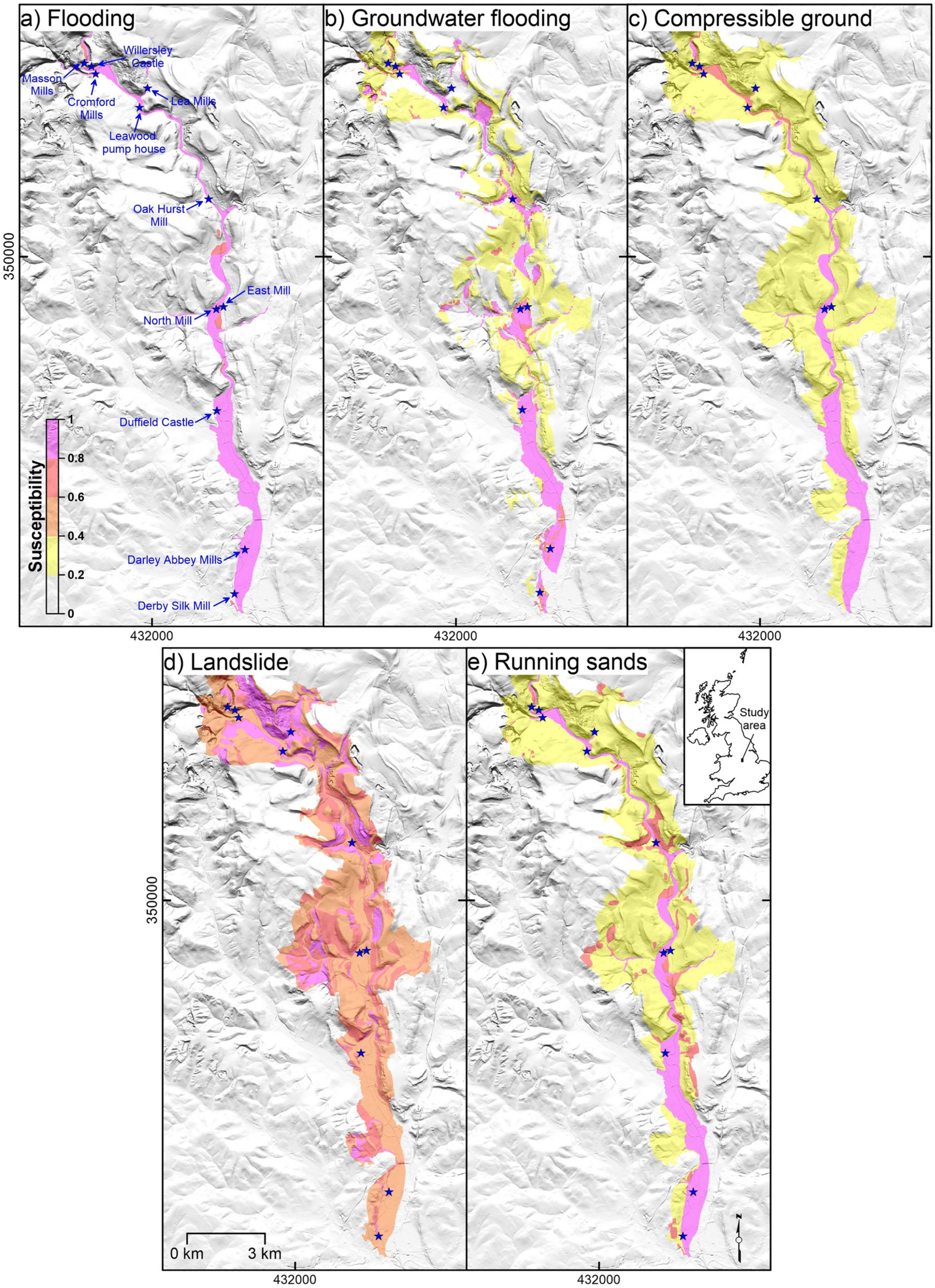

Fig. 2. Susceptibility maps of single natural hazards in the DVMWHS. The largest historic infrastructure is depicted by blue symbols.

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/) and geological indicators of flooding (https://www.bgs.ac.uk/datasets/geological-indicators-of-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 (see Supplementary Material S2): from A (low) to E classification (high) [28]. For the purpose of our analysis, i) only natural hazards with susceptibility levels higher than B were considered thus leaving only flooding (river), groundwater flooding, compressible ground, landslides and running sands, ii) susceptibility classes B to E were converted into equally-spaced numerical values ranging from

Table 1
Results from relative importance analysis 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

0 to 1 (i.e. susceptibility score, H_i) and iii) raster maps on the multi-hazard susceptibility were derived from (ii).

Multi-hazard susceptibility assessment

The multi-hazard was assessed using the Analytical Hierarchy Process (AHP) [29–30]. 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 [31]. AHP is an expert-based methodology characterised by: i) integration of all types of information; ii) expert's knowledge that are fundamental for discussion rules; iii) a reached consensus, weights for each relevant factor are obtained automatically by eigenvector calculation of the comparison matrix and iv) inconsistencies that can be detected using consistency index values developed in [31–32] 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 factor 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 (Table 1). For example, the flooding RSi represents the sum of the susceptibility-to-flooding scores of all the 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:

$$MH = \sum_{i=1}^{n} H_i W_i \tag{1}$$

where n is the number of hazards considered, 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 [30]: 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 supplementary materials – S3). 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 (for more details, see S2). The consistency of the AHP's weights was examined using the Consistency Ratio (CR):

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI} \tag{2}$$

where RI is the Random Index and CI is the Consistency Index (CI) [33] equals to:

$$\mathrm{CI} = \lambda\mathrm{max} - \mathrm{n}/n - 1 \tag{3}$$

where $\lambda_{\max}$ is the largest eigenvalue of the second matrix of order n. 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) [33]. 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 [33], 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 10 m resolution.

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, 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 [34] 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

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	

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/), are primary located on the outer slopes of the valley, some distance from the mills and consist of two dominant types: shallow phenomena in the Quaternary deposits and falls/topples in the bedrock especially in the northern part of the study area [24]. Finally, compressible ground (Fig. 2c) and running sands (Fig. 2e) hazard are moderate and relate to the Quaternary deposits of the CA. According to the RSi (see Table 1), the relative relevance of compressible ground hazard in comparison to landslides and running sands was considered equal and moderate, respectively. Landslides and running sands were considered of equal importance. Differently from previous works [35] which only provide a review of existing hazards individually, the holistic approach we consider here allows the extraction of a ranking for prioritizing hazards and determine their scores compared to each other.

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 Fig. 3. 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 riverine flooding and groundwater flooding susceptibilities, which represent the most significant hazards of the area [24]. Indeed, the area with the highest susceptibility 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 am estimate of local 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.

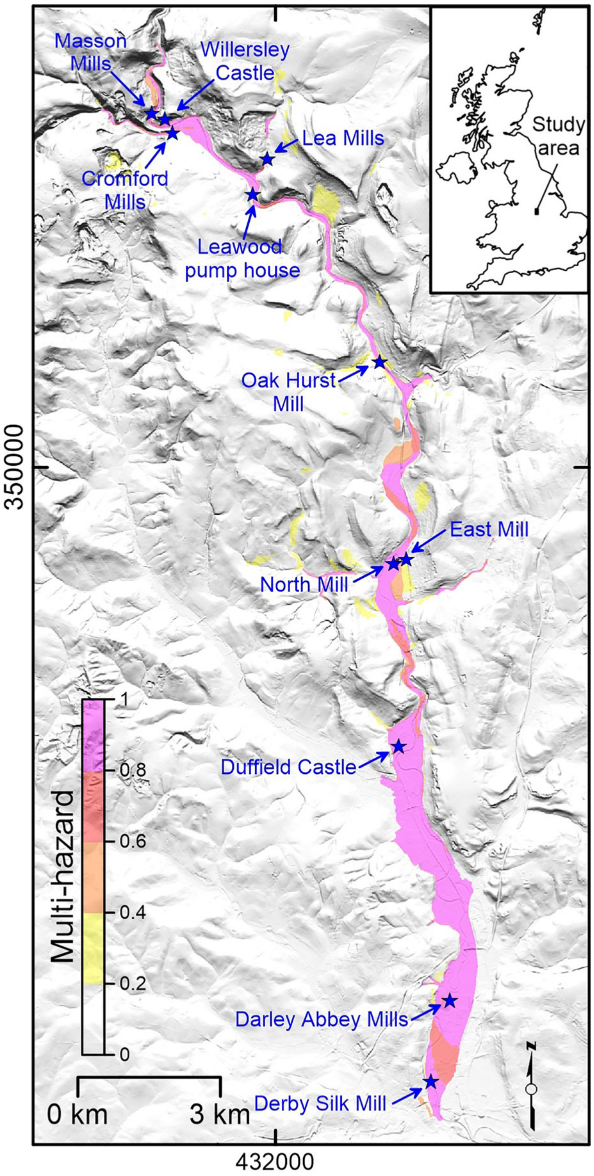

Fig. 3. Multi-hazard susceptibility map derived through the AHP method for the DVMWHS. The largest historic infrastructure is depicted by blue symbols.

There are however limitations of the method used for the analysis that should be noted: firstly, a caveat is the subjectivity in the choice of the comparative scores for individual hazards which is inevitably biased by the experience of the operator [30]. To minimize this we introduced 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 [36]. 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 [37–39]. And thirdly, 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 advantages include: i) AHP provides simple and very flexible modeling process; 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 applications (e.g., planning and benefit and risk analysis) and v) current computer software helps decision-makers to use AHP quickly.

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: river flooding, groundwater flooding, compressible ground, landslide and running sands. The results are not a surprise as the mills had to be located close to a water source as that was their source of power. On the other hand, compressible ground and running sand hazards are only usually of concern where human-intereaction (e.g., building works takes place), however, they could also be activiated under future climate condistions wherby rising/higher groundwater levels are impacting on the normal background environment, causing instability. . 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 for the Lea Mills site and 0.92 for the Oak Hurst Mill. The resulting multi-hazard susceptibility map provides a basis for subsequent estimation of multi-hazard risk of the DVMWHS. 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 are expected to be exacerbated due to the predicted climate change scenarios posing a serious threat to the conservation of WHSs [28] but also can provide evidences on potentially redefining CA and the BZ within the 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 and the Derwent Valley Mills World Heritage Site for supporting PROTHEGO project (PROTection of European Cultural HEritage from GeO-hazards; https://www.prothego.eu/, AH/N504361/1).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.culher.2022.04.009.

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