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THE BAYESIAN NETWORK AS A TOOL SUPPORTING FLOOD RISK MANAGEMENT – AN EXAMPLE OF CULTURAL HERITAGE PROTECTION

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SIEĆ BAYESOWSKA JAKO NARZĘDZIE WSPIERAJĄCE PROCES ZARZĄDZANIA RYZYKIEM POWODZIOWYM NA PRZYKŁADZIE OCHRONY DZIEDZICTWA KULTUROWEGO

STRESZCZENIE: Artykuł poświęcony jest wsparciu procesu zarządzania ryzykiem powodziowym. Głównym jego celem jest przedstawienie Bayesowskiej sieci, jako narzędzia wspierającego proces oceny ryzyka powodziowego. Funkcjonowanie sieci Bayesowskiej jest zaprezentowane na przykładzie oceny ryzyka powodziowego dla dziedzictwa kulturowego. W pierwszej części opracowania przedstawione są podstawowe zagadnienia takiej jak: powódź, ryzyko powodziowe, zarządzanie ryzykiem powodziowym oraz finansowanie katastrof naturalnych. Druga część poświęcona jest w całości prezentacji sieci Bayesowskiej dla oceny ryzyka powodziowego dla dziedzictwa kulturowego ze szczegółowym opisem poszczególnych jej węzłów.

SŁOWA KLUCZOWE: ryzyko powodziowe, zarządzanie ryzykiem powodziowym, sieć Bayesowska, dziedzictwo kulturowe.

Introduction

Between the 1990s and 2016 Poland was hit by three floods on the scale of natural disasters. These events took place in 1997, 2001 and 2010. Lower Silesia, with its capital, the historic city of Wrocław, was one of many Polish regions which suffered most during these floods.

Despite the rapid and prompt measures undertaken by local authorities, emergency response services and all other units, the floods caused very serious damage to the environment, economic activity, public and private infrastructure, cultural heritage, and, most importantly, to human health and life. In the old part of Wrocław in 1997 the flood affected historic architecture (churches, bridges and others), public facilities (schools, offices, hotels and offices) and residential buildings. One of the most tragic examples of the flood in 1997 is the Kozanów district in Wrocław, where residential buildings, because of their unfortunate location and insufficient flood protection, were submerged up to several floors above ground level.

Currently, river floods are considered one of the main dangers in Central Europe[1]. Effective protection against further flooding requires planning and preparedness, which should take into account all the factors that in any way could affect the occurrence of possible flood risks and adverse consequences of flood events. These factors include, for example, climate, land relief, population density, development rate of areas at risk of flooding and its consequences, flood protection structures, both natural and man-made, or the lack of them, and many others[2].

Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks, known as the Floods Directive[3], came into force on 26 November 2007. Its overarching goal was to establish a framework for the assessment and management of flood risks, aiming at the reduction of adverse consequences for human health, the environment, cultural heritage and economic activity associated with floods in the Community (EU).

According to the Floods Directive, to reduce the risk of flood events Member States should establish flood risk management plans for particular areas. This is supposed to be a three-phase process. Member States had to complete the preliminary flood risk assessment by December 2011, the flood hazard maps and flood risk maps by December 2013, and flood risk man-

[1] Z. Kundzewicz, U. Ulbrich, T. Brucher, M. Szwed, *Summer floods in central Europe. Climate change track?*, "Natural Hazards" 2005 No. 36(1), pp. 165–189.

[2] H. Stovel, *Risk preparendness: A management manual for world cultural heritage*, Rome 1998.

[3] (DZ.U. EU L 288/27 of 6/11/2007).

agement plans by December 2015. The aim of this paper is to present the causal Bayesian network modified and adapted for the description of the structure and management of flood risk assessment with respect to architectural heritage.

The modified Bayesian network is intended to complement and support the flood risk management plans mentioned in the Floods Directive.

General considerations

The flood in 1997 had a very negative effect on the architectural heritage in Wrocław and other historic cities in Poland. Floods in 2001 and 2010 also caused a lot of damage to cultural heritage. Therefore, relevant measures have to be undertaken to prevent or reduce the adverse impact of future floods on architectural heritage. Of course, the activities described in this paper also apply to the protection of the rest of urban infrastructure, the environment, human life and health, and other spheres and areas covered by the preventive measures.

The United Nations Disaster Relief Organization published general recommendations for natural disasters and a vulnerability analysis[4]. In 2007, the European Parliament adopted the Floods Directive to establish a framework for the assessment and management of flood risks[5]. It should be emphasized here that of all the documents which address the management and assessment of the risk of natural disasters only the Floods Directive of the European Parliament contains information on the protection of cultural heritage[6]. The UNESCO–UNDRO report published in 1979 recommends that the risks should be expressed in terms of value loss, which may be a very difficult task, especially in the context of the assessment of risk for architectural heritage. Therefore, the assessment of risk for cultural heritage assets is currently based on a combination of quantitative and qualitative criteria where the probability of adverse events and the expected consequences are estimated in the risk assessment matrix.

To create the overall structure of the flood hazard some authors propose to additionally incorporate probabilistic models that are created based on the available hydrological data. The basic hydrometric parameters used in the process of flood risk management include the river flow and the water

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4 UNESCO-UNDRO. *Natural disasters and vulnerability analysis,* Geneva 1979.

5 The Council, *Directive 2007/60/EC on the assessment and management of flood risks,* Brussels 2007.

6 M. Drdacky et al., *Protecting the cultural heritage from natural disasters. Study of the Europen Parliament IP/B/CULT/IC/2006_163, PE 369.029,* Brussels 2007.

level at a specific point of the river. Definitions of these parameters were presented, for example, by Byczkowski[7]. A detailed description and application of probabilistic models to assess flood risks for selected areas of Lower Silesia can be found in other works of the author of this paper[8].

In general, risk analysis tends to consider all possible events in combination with their adverse consequences. Such events are often caused by extreme hazards, including floods. Relevant risk scenarios and risk probabilities need to be estimated, often based on expert reports[9]. The risk for different engineering systems in hazardous situations can also be analyzed using techniques such as event trees, fault trees, cause-and-effect methods, and causal Bayesian network[10]. Previous studies indicated that the causal Bayesian network supplemented with utility and decision nodes is an especially effective tool for the assessment and management of risk[11]. This paper presents an attempt to implement the Bayesian network into the process of assessment and management of flood risk in the context of architectural heritage.

Management of flood risk – selected problems and aspects

This chapter presents basic definitions and concepts related to flood risk.

Flooding is a natural disaster phenomenon which causes material and non-material damage[12]. Flooding also means the temporary covering by water of land not normally covered by water. This definition includes floods from rivers, mountain torrents, Mediterranean ephemeral water courses, and floods from the sea in coastal areas, and may exclude floods from sewerage systems[13]. When the effects of flooding create a hazard to the life or

7 A. Byczkowski, *Hydrologia,* Vol. 1, Warszawa 1996.

8 Ł. Kuźmiński, *Zastosowanie teorii wartości ekstremalnych w prognozowaniu ostrzegawczym dla ciągu niezależnych zmiennych o rozkładzie normalnym*, in: S. Forlicz (ed.), *Zastosowanie metod ilościowych w ekonomii i zarządzaniu,* „Zeszyty Naukowe Wyższej Szkoły Bankowej we Wrocławiu" 2013 No. 2(34); Ł. Kuźmiński, *Funkcje nadmiaru i hazardu jako narzędzia w analizie ryzyka zagrożenia powodziowego na Dolnym Śląsku*, „Zeszysty naukowe Wyższej Szkoły Bankowej we Wrocławiu" 2014 No. 7(45); Ł. Kuźmiński, *Rozkłady graniczne ekstremów w prognozach ostrzegawczych stanów wód*, „Zarządzanie i Finanse" 2013 No. 3 p. 2, pp. 147–161.

9 M. Stewart, R. Melchers, *Probabilistic risk assessment of engineering systems,* Berlin 1997; R. Melchers, *Structural reliability analysis and prediction,* Chichester 2001.

10 M. Stewart, R. Melchers, op. cit.

11 M. Holicky, *Risk assessment in advanced engineering design*, "Acta Polytechnica" 2003 No. 43(3), pp. 10–16; M. Holicky, *Probabilistic risk optimization of road tunnels*, "Structural Safety" 2009 No. 31(3), pp. 260–266.

12 UNDRO, *Mitigating Natural Disasters Phenomena, Effects and Options,* New York 1991.

13 The Council, *Directive 2007/60/EC on the assessment and management of flood risks,* Brussels 2007.

health of a large number of people, property on a large scale or the environment in large areas, and assistance and protection can be effectively undertaken only with the use of extraordinary measures, in co-operation with various bodies and institutions, and specialized services and units working under a single management, then the flood is classified as a natural disaster[14].

Currently, the European continent is struggling with various natural disasters, which are largely river floods. The United Nations launched an effective platform for discussing the problems of disasters named the *International Strategy for Disaster Reduction*, and the publication *Living with Risk* contributed to a better understanding of these phenomena[15]. The United Nations General Assembly designated the 1990s as the ***International Decade for Natural Disaster*** Reduction. Several years after the end of this period we can see that this initiative increased scientific and practical efforts to reduce the consequences of natural disasters, including floods. Increased interest from economists in methods for the assessment and analysis of the impact of natural disasters, including floods, on welfare and recovery plans has been observed.

Risk is often defined for actuarial purposes as the possibility or probability of loss, and as such it can be adopted for the analysis of floods and other natural disasters[16]. In an alternative definition, which is also suitable for the analysis of flood risk, the risk means the probability of the failure of the system or its element p_f, which can be treated as the probability of flooding[17]

$$RY = p_f \tag{1}$$

Today, risk is very often defined as the mathematical ratio of probability and consequences of flooding (system failure), which is denoted with *S.* For this definition the risk can be calculated from the following equation

$$RY = p_f * S. \tag{2}$$

The use of this definition makes it possible to quantify the economic consequences of flood and to express the risk of its occurrence.

Risk is determined by factors such as vulnerability, i.e. the properties of an object exposed to risk which are relatively objective, and the hazard, i.e. a combination of conditions that makes the occurrence of a peril, flood in this case, more likely. Vulnerability is defined as "the extent to which an indi-

14 (Dz. U. of 2002 No. 62, item 558, No. 74, item 676).

15 ISDR, *Living with Risk. A global Review of Disaster Reduction Initiatives,* Geneva 2002.

16 H. Kunreuther, R. Roth, *Paying the Price,* Washington 1998.

17 B. Yen, *Stochastic methods and reliability analysis in water resources*, "Advanced Water Resources" 1988 Vol. 11.

vidual/object is susceptible to harm due to exposure, in conjunction with its ability (or inability) to cope, recover or basically adapt”[18].

Financing related to natural disasters such as floods involves many different instruments relevant to the needs at every stage of the operation. One of the areas of financing is the liquidation of damage after the flood event. The second area is the financing of the system preventing potential risks of flood, which includes expenditures in the period preceding a possible flood, whose purpose is to prepare for the coming flood, or protection against its consequences or the complete avoidance of such consequences. The third area is the financing of flood mitigation measures and protection of people and their property during flood actions. Each of the presented areas requires a huge budget throughout the country. That is why appropriate (optimised) flood risk management is an important issue.

Flood risk management is a process which includes the estimation and analysis of flood risk, and implementation of sustainable methods to reduce the probability or consequences of floods.

There are three main objectives of flood risk management:
1) preventing further increase of flood risks;
2) minimisation of the existing flood risks;
3) improvement of the flood risk management system.

The main objectives of flood risk management are implemented through the following measures taken before, during and after a flood event:
- prevention and protection to reduce or eliminate the likelihood of flooding and/or its consequences by taking both structural and non-structural measures;
- preparedness, including flood forecasts and early warning systems to increase the awareness of people and relevant authorities; preparation and updating of emergency response plans, and increase of resources necessary for effective emergency response;
- emergency response, including the implementation of emergency response plans, provision of aid to flood victims, prevention of the spread of existing hazards, and reduction in losses and damage;
- recovery, i.e. removal of the effects of natural disasters: returning property affected by flooding to normal, restoration of telecommunication, energy and fuel supply, and transport networks, mitigating the social and economic impacts on the affected population, property and natural environment; and review and improvement of risk management strategies based on lessons learned.

[18] P. Jedynak, *Ubezpieczenia gospodarcze,* Kraków 2001.

The Bayesian cause-and-effect network presented in the next subsection has been designed as an effective tool to support actions implementing the main objectives of the flood risk management plan.

The Bayesian cause-and-effect network in the assessment of flood risk

The Bayesian network (a graphical structure for reasoning) modified for the purpose of the assessment and management of flood risk with a focus on cultural heritage is presented in Figure 1. The network consists of the following elements:

- event nodes for flow, effects of flood, structural damage, geotechnical conditions and structural properties;
- decision nodes for permanent and provisional measures;
- utility nodes for the cost of used measures, social and economic consequences, total cost and value loss of cultural heritage.

The direct arrows connecting all nodes indicate the cause-and-effect relationship between a parent and a child. It should be noted that this network is very simplified. In practice, each node can represent a separate subsystem, which may include additional utility nodes.

The event flow node denotes the extreme flows for the respective types of flooding (river floods, torrential floods, floods in cities, floods from the sea in coastal areas) estimated using statistical methods based on available data. Probabilistic models for forecasting extreme flows can be a key element in the assessment and management of flood risk.

The event node for the effect of flood denotes various events that can occur during floods, including hydrostatic effects (lateral pressure and capillary growth), hydrodynamic effects (relating to the flow velocity or surge), erosion and wash-outs, buoyancy, and non-physical events (chemical and biological); more details on this can be found in Kelman and Spence[19]. The effects of flooding depend on two decision nodes – permanent and provisional preventive measures.

The permanent measures include, for example, levees, actions associated with the management of the river (changes of direction, maintenance and/or restoration of floodplains and modification of the depth, width and shape of river channels) that can modify the impact of flooding. Protective barriers, relocation of movable property, immediate removal of floating debris from the supports of bridges, and the evacuation of people and movable elements

19 I. Kelman, R. Spence, *An overview of flood actions on buildings*, "Engineering Geology" 2004 Vol. 73, No. 3–4, pp. 297–309.

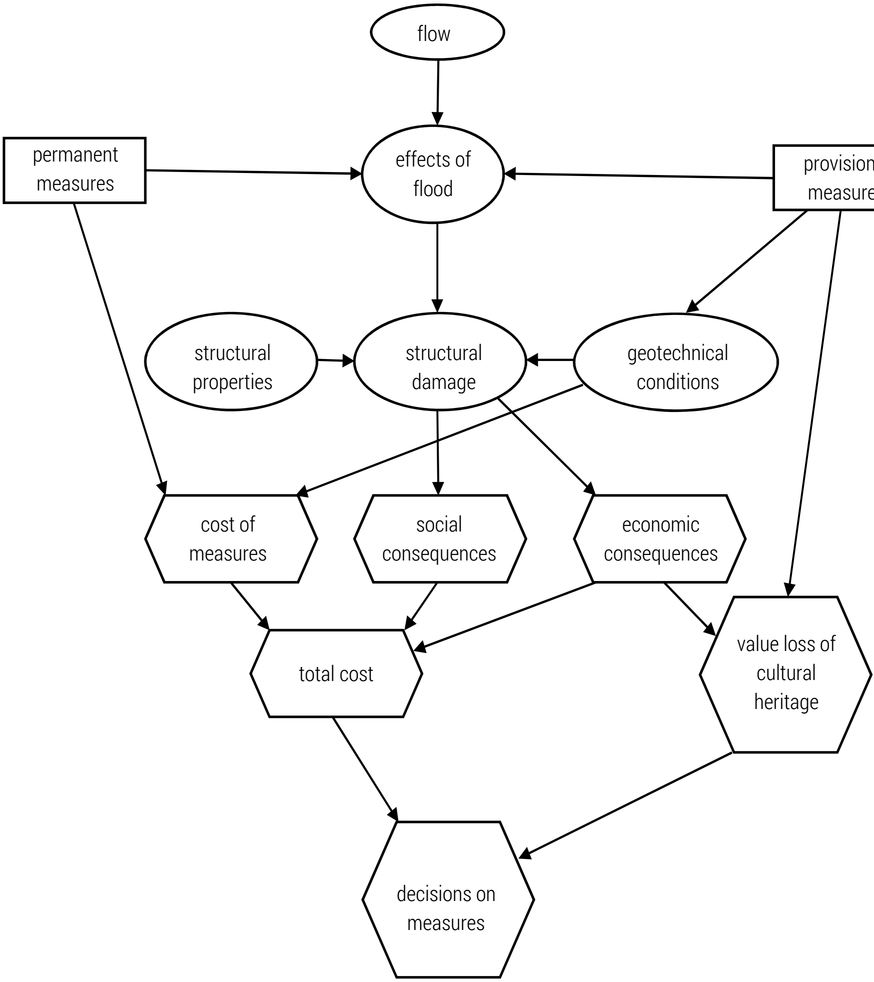

Figure 1. Bayesian cause-and-effect network

of cultural heritage from the affected areas may also be considered as provisional measures. The cost of measures is presented in the utility node, which denotes the expected expenditures on permanent and provisional protective measures.

The effects of flooding, even on a small scale, can directly lead to loss in the value of cultural heritage. For example, increased humidity can damage equipment, fittings, collections, libraries, and archival records[20]. However, appropriate provisional measures may prevent or reduce these losses.

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20 H. Stovel, *Risk preparendness: A management manual for world cultural heritage*, Roma 1998.

Floods can cause structural failure such as damage, local malfunction, or partial or total collapse of structures; these effects of flooding are presented in the Bayesian network as a random node of structural damage. The likelihood of structural damage and its size depends on the geotechnical conditions (soil, level and flow of groundwater) and structural properties (structural integrity, susceptibility of structural materials to increased moisture). The reliability of analyses for architectural heritage can be ensured by the preparation of an annex to the international standard for the assessment of existing structures (ISO 13822 2008). This annex will be mainly based on the fundamental recommendations presented in documents of the International Council on Monuments and Sites[21].

Structural damage can have social and economic consequences and cause losses in architectural heritage. The utility node for social consequences denotes the expected social consequences dependent on the expected number of fatalities per year due to structural failure caused by flooding, and acceptable expenses for averting one fatality, which can be estimated using the social value of life time[22].

The value loss of cultural heritage denotes the ratio of the value of the analysed architectural heritage lost during the flood to the total value of this architectural heritage. This ratio is usually estimated based on expert reports. Nevertheless, the estimation of the value of cultural heritage is a difficult task.

It should also be noted that the value loss of cultural heritage leads to significant social and economic consequences. However, it may be appropriate to consider the value of cultural heritage and the economic and social consequences alone, especially when the value of cultural heritage is assessed only in qualitative terms.

Decisions on permanent and provisional measures should be focused on the optimization of the total cost and minimization of loss in the value of cultural heritage. When the value of cultural heritage is assessed only in qualitative terms, a separate assessment should be done for the value loss of cultural heritage and the total cost.

The cooperation of different professionals from the construction industry and experts on heritage assets, such as engineers, architects, surveyors, archaeologists, historians and the responsible local and international authorities can be highly beneficial in this regard.

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21 ICOMOS. *Recommendations for the analysis, conservation and structural restoration of architectural heritage,* Paris 2003.

22 M. Holicky, *Probabilistic risk optimization of road tunnels*, "Structural Safety" 2009 No. 31(3), pp. 260–266.

Conclusions

Floods are part of the natural world in which we live and will certainly occur in the future. The strategy for flood protection should cover the entire river basins and consist of two parts: national and regional. Some of the main measures should be the same for the whole country, but each region should have an appropriate regional strategy of flood protection, tailored for local characteristics in terms of local flood risk.

The paradigm needs to be changed through the transition from defensive measures to risk management and emergency response actions. The efficient cooperation of all the bodies involved in the process of flood risk management at all levels is also important.

The presented Bayesian cause-and-effect network is a potential tool for improving the system of flood risk management at national and local levels.

The valuable architectural heritage in the city of Wrocław, for which this modified Bayesian network was created, is only one example illustrating its capabilities. This tool can also be used for the development of flood risk management plans related to any aspect of social and economic life.

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