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The 1916 catastrophic flood following the Bílá Desná dam failure: The role of historical data sources in the reconstruction of its geomorphologic and landscape effects

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ABSTRACT

This paper describes the reconstruction of the geomorphologic and landscape effects of the most catastrophic flood owing to dam failure within the territory of today's Czech Republic, namely, the Bílá Desná dam failure of 1916. Because of the realisation of the significant later transformation of the Bílá Desná river catchment almost 100 years after the flood event, the field research performed during the summer and fall of 2013 had to be supported by extensive research in regional archives for documentary data. Various data types and sources (such as court investigation notes, investigation reports for insurance companies, old maps, and old photos, as well as video and recorded testimonies of survivors) were used to reconstruct the magnitude (discharge, flood wave extent) of the flood and its effects on the channel morphology and landscape. According to the reconstruction of the dam failure, which was caused by the internal erosion of the dam, the calculated peak discharge ranged between 418.2 and 1491.7 m^3s^{-1} and therefore exceeded the mean flow rate of the Bílá Desná River by more than 850 times. The river channel immediately upstream and downstream of the dam reclaimed its former meandering pattern with higher sinuosity, and new gravel point bars and irregular bars have been formed. Moreover, the river channel immediately below the dam shifted by up to 30 m following the flood wave. The most significant flood impacts were apparent in the village of Desná, where the flood wave, together with transported boulders (up to 2 m in diametre) and logs from sawmills situated upstream, killed 62 inhabitants and damaged or destroyed 101 buildings. The reconstructed flood wave in the towns of Desná and Tanvald exceeded the bankfull water level twice, with a width ranging between ~50 and 250 m in contrast to the average channel width of a few metres.

1. Introduction

Hundreds of catastrophic floods resulting from man-made dam failures have been recorded across the globe (e.g., Costa, 1985; Peng and Zhang, 2012), including those in the Czech Republic (see Table 1). This specific type of flood is characterised by extreme discharges that frequently exceed the maximal flow rates of 'classical' hydrometeorological floods by several times. Thus, this type of flood is also well characterised by its great potential to cause significant material damage and to claim lives. In addition, geomorphologic and landscape effects are often considerable and identifiable after years (e.g., Jarrett and Costa, 1986; Costa and O'Connor, 1995; Bathurst and Ashiq, 1998).

This article aims to reconstruct the geomorphologic and landscape effects of the most catastrophic flood from a man-made dam failure within the territory of today's Czech Republic, namely, the Bílá Desná dam failure, which occurred on 18 September 1916, only one year after the completion of its construction. At the same time, the specific aim of this paper is to evaluate and to discuss methodological frameworks for the use of documentary data that are currently accepted by geomorphologists (Glade et al., 2001), mainly in respect of data types and their analysis.

Despite the facts indicating that the volume of impounded water was relatively low (~290,000 m^3) in comparison with recorded failures of earthen dams worldwide and that people living downstream were warned approximately 30 min before the dam failure, this event directly claimed 62 lives and also caused significant material damage (Žák et al., 2006). Most victims were registered in the village of Desná, which is situated ~5 km downstream from the position of the former reservoir.

Most studies of this event have predominantly focused on geotechnical causes, mechanisms and socioeconomic effects of the catastrophe. These studies include early works presented, e.g., by Smrček (1917), Gebauer (1920), Gnendiger (1920), or Karpe (1935) and later works presented by Mikolášek (1966), Žák (1996), or Žák et al. (2006). Information concerning hydrological significance of the flood, geomorphologic and landscape effects are found in these works and are generally noncomprehensively presented in the form of a by-product of other

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Table 1
Reported man-made dam failures in the Czech Republic.

Dam	Construction	Failure	Cause (trigger)	Escaped volume [×1000 m^3]	Loss and damages	References
Strážný	14th Century	1587	Not known	Not known	Not known	http://www.turistika.cz/mista/strazny-prehrada
Mladotický pond	14th Century	25.5.1872	Intense rainfall	About 3000.00	Several fatalities, significant material damages	http://www.nebreziny.cz/
Bílá Desná	1915	18.9.1916	Insufficient geotechnical survey	290.00	62 victims, significant material damages	Gnendiger (1920); Žák et al. (2006)
Zlatá Ktič	1796	2002	Intense rainfall	98.50	None	http://www.sobenov.cz/mis/
Soběnov	1925	2002	Flood wave from Zlatá Ktiš dam failure	73.20	None	http://www.sobenov.cz/mis/
Blažnov pond	–	28./29.3.2006	Intense rainfall/snowmelt	10.37	None	Šobr et al. (2008)

investigations (e.g., court notes). Therefore, the compilation of this fragmented information from various data types and sources and the production of a new aggregate context supported by newly presented analysis and reconstructions will fill the gap in the current knowledge of this event.

2. Study area and characteristics of the former Bílá Desná dam

The Bílá Desná River springs in Jizerské hory Mts. (northern Bohemia, Czech Republic) in a peat-bog called 'Na Kneipě' at an elevation of approximately 1000 m asl on the southern slopes of the Jizera

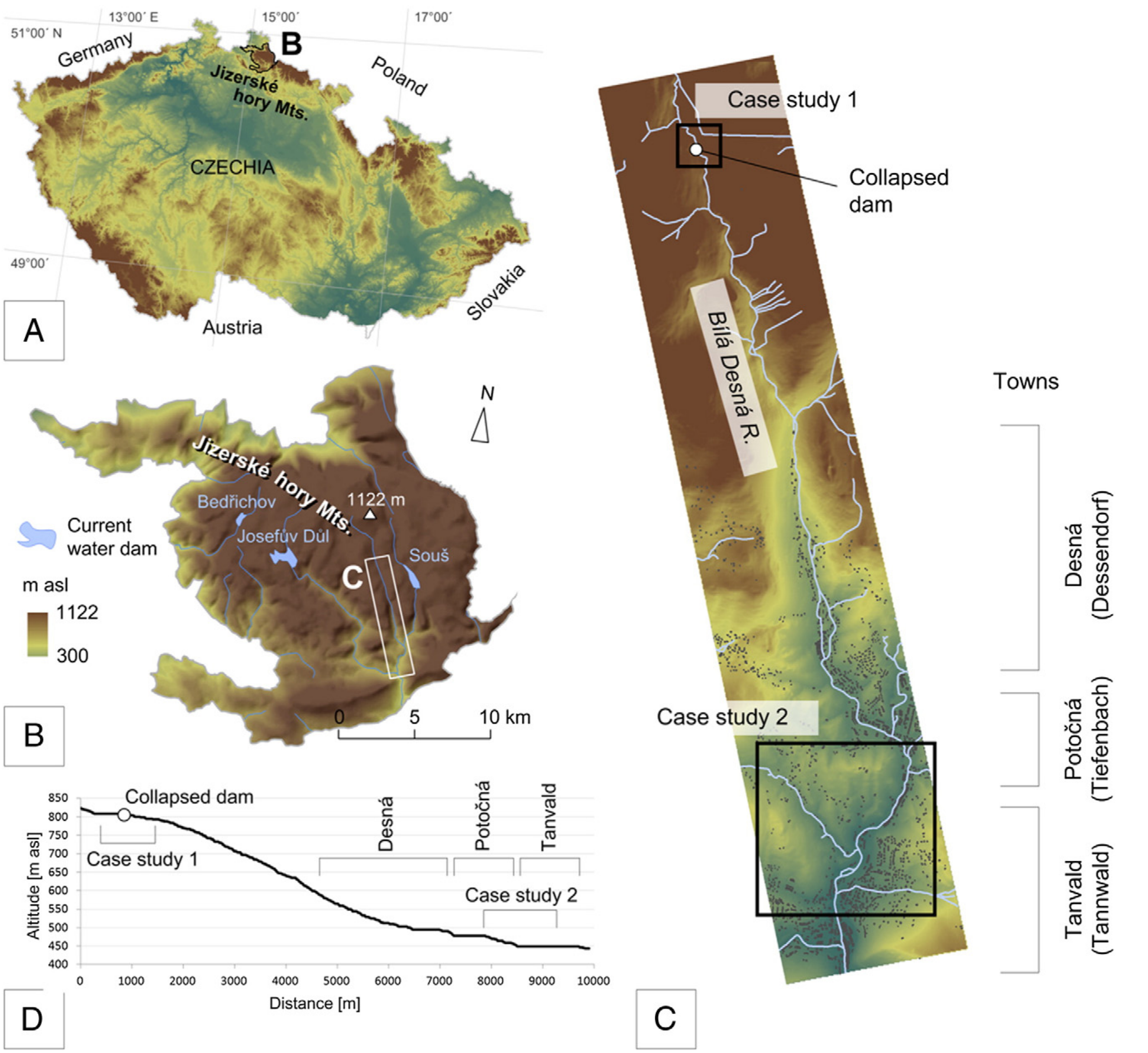

Fig. 1. Study area of the Bílá Desná River and the position of the former dam.

hill (1122 m asl). The river, with a length of ~12 km and a catchment of 16.0 km^2, joins the Černá Desná in the village of Desná to form the Desná River (Fig. 1), which is a left-sided tributary of the Kamenice River belonging to the Labe River catchment. The Jizerské hory Mts. are considered one of the rainiest parts of the Czech Republic. The average annual precipitation in the highest parts exceeds 1200 mm/y (ČHMÚ, 2013), and the maximal 24 h precipitation in the Czech Republic was measured at Nová Louka, which is situated in the western part of the Jizerské hory Mts. (345 mm; 28–29 July 1897), causing the most catastrophic flash floods in mountain ranges at the northern borderland of the country (Štekl et al., 2001).

The flood that followed the above-mentioned heavy rainfalls at the end of July 1897 caused significant material damage in densely settled valleys and initialised a discussion concerning the construction of a system of dams to prevent (mitigate) potentially catastrophic effects of future floods (Žák, 1996). This effort resulted in the construction of several dams during the first two decades of the twentieth century in the Jizerské hory Mts. and in its foothills, including the masonry arch dam Bedřichov at Černá Nisa, which was built between 1902 and 1909; the masonry arch dam Mšeno at Jablonec nad Nisou, which was built between 1906 and 1908; the masonry arch dam Fojtka, which was built at Mníšek between 1904 and 1906; the masonry arch dam Harcov, which was built at Liberec between 1902 and 1906; the embankment earthen dam Souš at Černá Desná, which was built between 1911 and 1915; and the embankment earthen dam Desná at Bílá Desná, which was built between 1911 and 1915 (Fig. 2).

2.1. Characteristics of the former Bílá Desná dam

The Desná dam was built in the upper part of the Bílá Desná River, ~5 km far from its spring, at an altitude of 806 m asl. The dam was designed to be a 14.16-m-high embankment earthen dam with one outlet controlled from the spool tower. The reservoir was designed to retain 400,000 m^3 of water. Excess water was distributed through the tunnel to the Souš reservoir, which was situated in the adjacent valley, and spillways were available. The basic characteristics of the former Desná dam and reservoir are listed in Table 2.

3. Data sources and methods

3.1. Historical data sources

Documentary data represent an important source of information for various types of historical natural hazards where the natural proxy indicators are missing or were erased by subsequent human activity. Although the spectrum of documentary data is quite broad (Ingram et al., 1981; Hooke and Kain, 1982), only a few types are used in geomorphology, which can be ascribed to the prevailing focus on the creation of historical time series of natural hazards (cf. Glade et al., 2001). Considering the specific aim of this paper, which is to reconstruct a single historical natural disaster, we employ different types of data with respect to their time dimension and purpose of origin, with special attention devoted to stationary and quasi-stationary sources (Raška et al., 2014). Furthermore, these data were subject to critical analyses before the information concerning the studied flood was cited. Table 3 shows the summary of the data that were analysed in this study, together with their types and sources. Most of these data were acquired by detailed study in the regional archive of the Jablonec nad Nisou in northern Czechia; however, national and regional archives, libraries, personal collections, and web repositories were also searched.

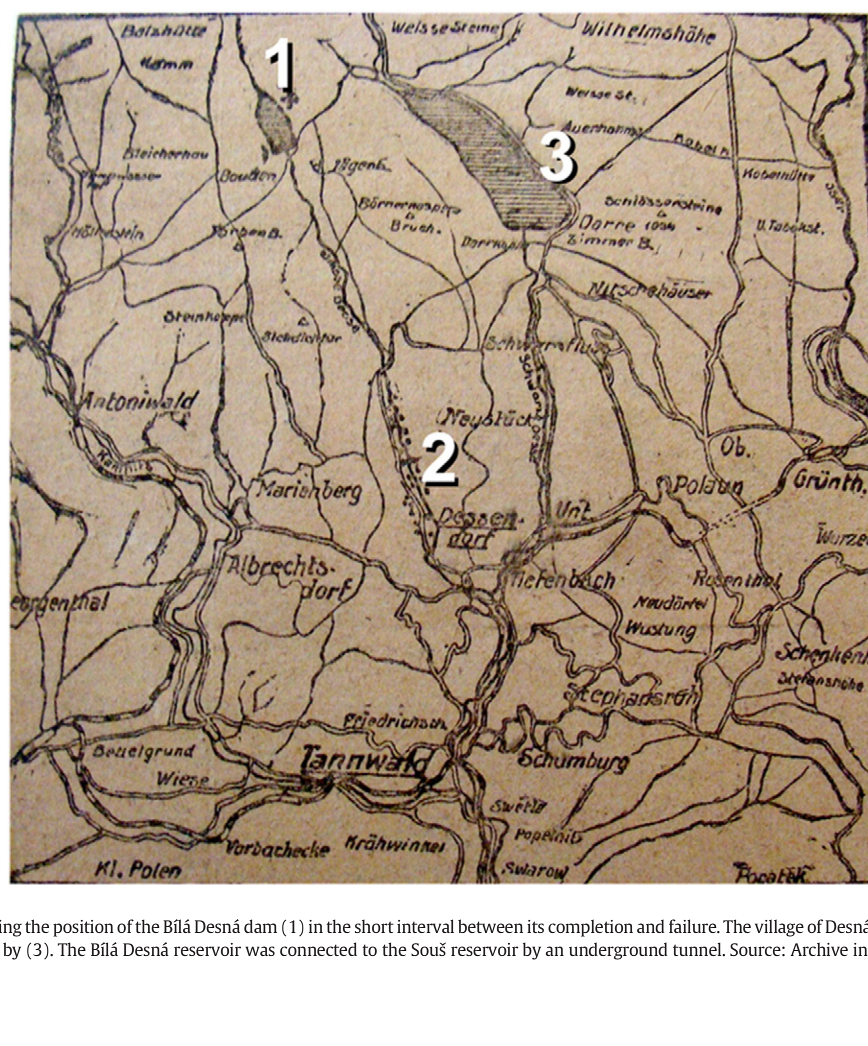

Fig. 2. Unique archival map showing the position of the Bílá Desná dam (1) in the short interval between its completion and failure. The village of Desná (Dessendorf) is represented by (2), and the Souš dam is represented by (3). The Bílá Desná reservoir was connected to the Souš reservoir by an underground tunnel. Source: Archive in the Jablonec nad Nisou.

Table 2
Basic characteristics of former Desná dam (according to Smrček, 1917; Žák et al., 2006).

Characteristic	
Dam type	Embankment (earthen) dam
Built	1911–1915
Dam height (vertical distance between dam abutment and dam crest)	14.16 m
Dam crest width	172.8 m
Width of dam crest	5.2 m
Width of dam abutment	54 m
Distal face inclination	1:1.5
Proximal face inclination	1:1.5–1:2
Dam crest elevation	820.50 m asl
Elevation of maximal water level	818.90 m asl
Elevation of the bottom	806.34 m asl
Volume of dam body	31,920 m^3
Maximal volume of accumulated water	400,000 m^3
Catchment area	8.2 km^2
Maximal discharge through the outlet	5.20 $m^3 s^{-1}$
Maximal discharge through the tunnel	36 $m^3 s^{-1}$
Maximal discharge through the spillway	37.6 $m^3 s^{-1}$

3.2. Methods

3.2.1. Peak discharge estimation

Costa (1985) presented an overview of simple empirical methods for estimating the peak discharge from man-made dam failures. We have chosen only those methods to estimate the approximate peak discharge at the Desná dam failure, for which all the data required for the calculation are available. Methods that provided more conservative (lower) peak discharges were chosen, namely, the methods presented by Brater and King (1976), Kirkpatrick (1977), Price et al. (1977), the Soil Conservation Service (1981), Wetmore and Fread (1981), and their variations. For the dam height-based calculation (Kirkpatrick, 1977; Soil Conservation Service, 1981; Costa, 1985), the real dam height (14.16 m) was also reduced by the dam freeboard (2.90 m) to 11.26 m for the purpose of more conservative and representative results because the reservoir was not full when the dam failed; thus, calculated results of dam height-based calculations would be overvalued.

In addition to the empirical equation-based calculations, the Hjulström curve, which describes the relation between the flow velocity and the dimensions of transported boulders (Hjulström, 1935), and graphical hydrograph-based estimations were used. The obtained results were compared with recorded transversal profiles documenting the maximal achieved water level during the flood. Hydrological significance of the flood was investigated by confronting with the mean flow rate and with the measured 1913 hydrometeorological flood peak discharge of the Bílá Desná River. Classification of the geomorphic impacts of the flood based on defined qualitative geomorphic alterations according to Costa and O'Connor (1995) was used for selected parts of the affected river channel.

3.2.2. Detection of erosion and of accumulation processes and modelling the flood wave magnitude

Dominant geomorphic processes (erosion or accumulation) were primarily recognised from photographs taken during the first few months after the event and from technical maps created during the investigation of the dam failure causes. Although the basic geomorphic impacts related to erosion and accumulation processes have been identified for the entire river reach, the detailed analysis of channel changes and flood wave effects on the mid-segment of the river have been

Table 3
Documentary data analysed within this study.

Origin[a]	Title	Year(s)	Type[b]	T-D[c]	Source
Offic.	Court reports (prosecution, defense)	1916–1932	man	(Q)St	Archive of the Jablonec nad Nisou (N Czechia)
Offic.	Court reports by invited experts	1916–1932	man	(Q)St	Archive of the Jablonec nad Nisou (N Czechia)
Offic.	Insurance investigation reports	1916–1917	man	(Q)St	Archive of the Jablonec nad Nisou (N Czechia)
Offic.	Cadastral maps (1:2880)	1843	cart	(Q)St	Czech Office of Land Survey and Cadastre
Offic.	3rd Military maps (1:25,000)	1877–1880	cart	(Q)St	Österreichisches Staatsarchiv—Kriegsarchiv Vienna
Offic.	Official photos of impacts		icon	(Q)St	Archive of the Jablonec nad Nisou (N Czechia)
Offic.	Aearial photos	1952, 2010	icon	(Q)St	Military Geographical and hydro-meteorological Office of the Czech Republic
CSc.	Prager Tagblatt (*Katastrophalen Talsperren-Bruch*)	1916	news	(Q)C	Web repository
CSc.	Deutsche Bauzeitung (*Der Talsperren-Dammbruch an der Weißen Desse im Isergebirge am 18. September 1916*)	1916	news	(Q)C	Librarian web repository (http://www.kobv.de)
CSc.	Reichenberger Tageblatt (*Zum Dammbruch der Weisen Desse-Talsperre*)	1916	news	(Q)C	Web repository
CSc.	Věstník organizačního komitétu Strany katolického lidu pro diecézi královéhradeckou (Bulletin of the organizing committee of Catholics in Hradec Králové diocese)	1916	news	(Q)C	Librarian web repository (http://kramerius.lib.cas.cz/search)
CSc.	Immergrün Illustrierte Kriegs-Chronik (Die Dammbruch-Katastrophe in Dessendorf)	1916	pop	(Q)C	Archive of the Jablonec nad Nisou (N Czechia)
CSc.	Der Talsperrenbruch an der Weissen Desse	1916	pop	(Q)St	Scientific library in Liberec (N Czechia)
CSc.	Smrček A: O bezpečnosti zemních hrází (On safety of earthen dams)	1917	sci	(Q)St	Scientific library in Liberec (N Czechia)
CSc.	Neustück Darre a.d. Talsperre	1920	pop	(Q)St	Scientific library in Liberec (N Czechia)
CSc.	Gebauer E: Zum Dammdurchbruch der Talsperre an der Weissen Desse	1920	sci	(Q)St	Scientific library in Liberec (N Czechia)
CSc.	Gnendiger E: Der Dammbruch der Talsperre an der Weissen Desse	1920(?)	sci	(Q)St	Scientific library in Liberec (N Czechia)
CSc.	Karpe L: Der Dammbruch an der Weissen Desse am 18. September 1916	1935	sci	(Q)St	Scientific library in Liberec (N Czechia)
CSc.	Mikolášek V: Protržení přehrady na Bílé Desné 18. září 1916 (Dam-failure at the Bílá Desná River on 18th September 1916)	1966	pop	(Q)St	Scientific library in Liberec (N Czechia)
CSc.	Žák L: Katastrofa na Bílé Desné—80. let (Catastrophe on the Bílá Desná River—80 years)	1996	pop	(Q)St	Scientific library in Liberec (N Czechia)
CSc.	Žák L et al.: Jizerskohorské přehrady a katastrofa na Bílé Desné—Protržená přehrada (Dams in the Jizerské hory Mts. and the catastrophe on the Bílá Desná River—dam failure)	2006	pop	(Q)St	Scientific library in Liberec (N Czechia)
CSc.	Catastrophe at the Bílá Desná River—movie	1916	av	(Q)St	Web repository
P	Photographic collection	1916	icon	(Q)St	Archive of the Jablonec nad Nisou (N Czechia)
P	Postcards	1916	icon	(Q)St	Antiquarian web repositories

[a] Origin = purpose of origin: Offic.—official, CSc—commercial and scientific, P—personal.
[b] Type = data type: man—manuscript, cart—cartographic document, icon—iconographic document, av—audiovisual recording, sci—proto-scientific or scientific report in periodical or monograph, news—newspaper report, pop—popular periodicals and books (regional literature).
[c] T–D = time dimension of the source document: (Q)St—quasi-stationary and stationary data, (Q)C—quasi-continual and continual data (typology according to Raška et al., 2014).

performed in two detailed case studies. First, the channel changes after the dam failure directly above and below the former dam have been identified by a comparison of technical maps from 1916 and of aerial photos from 1954 and 2010 in a GIS environment and corrected using historical photos from archives. Second, the flood wave extent and its effect on the mid-segment of the Bílá Desná River have been modelled in GIS from a DEM (digital elevation model). Clearly, the DEM precision is crucial for the flood wave modelling. To produce the most precise results, we used a combination of a TIN (triangular irregular network) model and a raster model (source data: the Czech Office of Land Survey and Cadastre 1:10,000), which was derived using the spline method with tension interpolation from original elevation data with a calculated root mean square error (RMSE) of 1.10, i.e., adequate to the limit value of 1.0 m sensu Svobodová (2008). We used the current digital elevation data as no data are available for the years around the 1916 dam-failure event. The scale of the data set was chosen to exclude possible influence of channel modifications after the 1916 event (such as steps). The old maps and aerial photos from the 1950s and the present day were compared in order to identify the locations of anthropogenic transformations of the surface (new buildings, roads, etc.), which may influence the results of flood wave modelling. Finally, the water level during the flood was derived from six preserved investigation reports prepared for the insurance companies and included the detailed plans and sketches of the buildings with water level marks. The water level data were transformed to cross section profiles across the river valley, and the water surface during the flood was created. The final flood wave extent was modelled as a surface difference between the original earth surface and the water surface and compared with current flood plans of Q_5 and Q_{100} floods (VÚV, 2014) to verify the correctness of the results from the peak discharge estimation.

4. Results

The results of our investigation are divided into two subsections. The first part is devoted to the reconstruction of the flood and its effects, exclusively based on available documentary data sources (see Section 4.1). The second part is focused on a supplementary description of the channel evolution after the flood event, as documented by field survey and documentary data (see Section 4.2).

4.1. Reconstruction of the flood and its geomorphologic and landscape effects

4.1.1. Chain of events

The Bílá Desná dam construction began in 1911 because of discussion concerning the construction of dams in the Jizerské Mts., which started after catastrophic hydrometeorological floods at the end of June 1897 and finished four years later with dam approval on 18 November 1915 (Fig. 3). The longevity of the dam was only 10 months, before the dam failed on 18 September 1916.

The chain of events describing the process of dam failure on 18 September 1916 in detail was outlined from existing data in the literature (Smrček, 1917; Žák, 1996; Žák et al., 2006) and from archival documentary data. The first evidence of piping through the dam was observed by loggers returning from work along the dam at 15:30 h. At that moment, 290,000 m^3 of water was retained in the reservoir. The dam keeper ordered the immediate draining of the reservoir by the full opening of the dam outlet; nevertheless, the piping continued, and the flow rate was exponentially increasing. At 16:00 h, the inhabitants living downstream in the Desné village were warned for the first time by telegraph against the increasing discharge from the dam. Fifteen minutes later, at 16:15 h, the dam failed with an accumulated water volume of 250,000 m^3. The village of Desná inhabitants were warned again against a flood following the dam failure at that time. An additional thirty minutes later, at 16:45 h, the dam was completely empty (Fig. 4). The escaped water swept through the valley, leaving behind 62 fatalities and tremendous material damage.

Another point of view concerning the Desná dam failure is represented by a hydrograph describing the change in the flow rate and the decreasing volume of accumulated water between 15:30 h and 16:45 h on 18 September 1916 (Fig. 5). Costa (1985), and later by Tsakiris and Spiliotis (2013), showed that hydrographs describing earthen dam failures are particularly characterised by a steep rising limb and by a steep falling limb, with a peak discharge within minutes to hours, depending on the accumulated water volume, dam characteristics, and failure mechanism.

4.1.2. Peak discharge

It is quite desirable to at least estimate the peak discharge, which is not known exactly, and to put the peak discharge into the context of the recorded geomorphologic and landscape effects of the event. The total volume of 250,000 m^3 was accumulated in the reservoir at the moment of dam rupture and that the reservoir was empty in 30 min (Žák et al., 2006). These numbers provide the mean flow rate of 138.9 m^3s^{-1}; however, the peak discharge, which is responsible for most of the damage, had to be several times greater. The rough graphical hydrograph-based estimation of the peak discharge (Fig. 5) showed that the peak discharge apparently exceeded 1000 m^3s^{-1}, with a discharge of 57,000 m^3 in 60 s (mean flow rate of 950 m^3s^{-1}). In addition, several empirically based calculations (see Table 4) were used to approximate the peak discharge. The obtained results ranged from 524.3 m^3s^{-1} to 1491.7 m^3s^{-1} at the dam. More conservative results, which were calculated with a reduced dam height, ranged from 418.2 to 971.8 m^3s^{-1}.

Historical photographs of the flood effects, which were provided by Gnendiger (1920), showed that the dimensions of the largest boulders transported during the flood were greater than 2 m, with weights of several tons. According to the Hjulström diagram (Hjulström, 1935), to erode and to transport boulders of these given dimensions, the mean flow velocity had to be greater than 4 m s^{-1}. Based on the historical scheme of the failed dam, the breach area (the cross-sectional area of gap in the dam measured from its abutment to the water level at the time of the dam failure) was estimated to be 163.9 m^2. Clearly, the flow rate may be calculated as a product of the breach cross-sectional area and the flow velocity. These input data provide a peak discharge

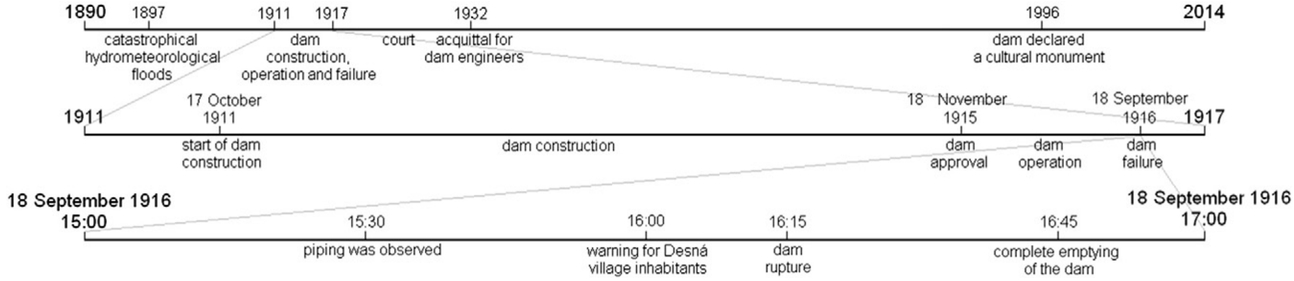

Fig. 3. Chain of events connected to the Desná dam failure (according to Smrček, 1917; Žák et al., 2006).

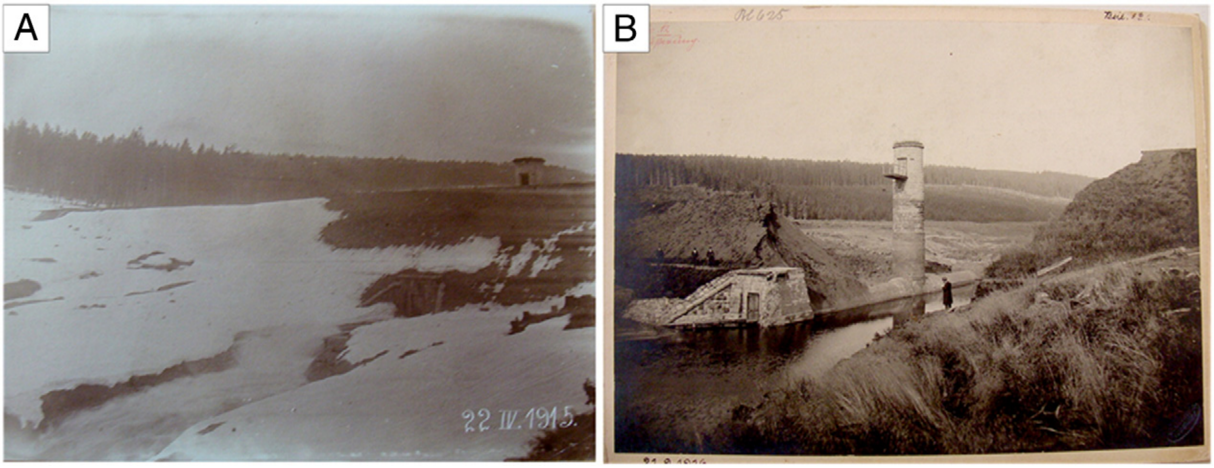

Fig. 4. Upstream view of the Desná dam before (A) and after (B) the dam failure.
Source: Archive of the Jablonec nad Nisou, Court reports.

>655.6 m^3s^{-1}, according to the mean flow velocity. This result corresponds with the results of the more conservative numerical calculation of the peak discharge (Table 4).

The flood wave following the dam rupture uprooted fully grown trees growing downstream in the affected valley and transported suspended material, including large boulders, with volumes up to 10 m^3. Smrček (1917) noted that transported wood, tree trunks and large boulders dragged away by the flood wave caused repeated formations and subsequent failures of temporary blockages in the upper part of the mostly deep and narrow Bílá Desná valley. According to Gnendiger (1920) in Žák (1996), eyewitnesses described these barriers as at least 20 m high, and the sudden one-off escape of the temporarily accumulated water most likely significantly increased the peak discharge and might have caused several local peak discharges.

The volume of transported material considerably increased when the flood wave struck the wood-processing factory (sawmill) situated upstream of the village of Desná. Between 4000 and 5000 m^3 of stored wood was carried away (Mikolášek, 1966). We suppose that the amount of dragged material and the effect of temporal barriers are two of the most important reasons why the peak discharge was higher than generally expected, particularly farther downvalley from the position of the dam, and together are the reason why the flood had such catastrophic effects on the village of Desná. A sudden increase in the flow rate (rapid increase in the Jizera River water level for ~0.2 m) was also registered in Mladá Boleslav, which is situated more than 60 km away (Mikolášek, 1966).

To realise the hydrological significance and the magnitude of the peak discharge achieved during the event, the obtained results should be interpreted in the context of the mean flow rate of the Bílá Desná River, which is 0.49 m^3s^{-1}, according to Vlček (1984). Therefore, the most conservative calculated peak discharge (418.2 m^3s^{-1}; see Table 4) exceeded the mean flow rate by more than 850 times. The peak discharge of a 'classical' hydrometeorological flood that occurred on 17 September 1913 was measured at 43 m^3s^{-1} (Smrček, 1917). The most conservative calculated result overcame this hydrometeorological flood peak discharge by almost 10 times.

4.1.3. Erosion and accumulation processes

The identification of erosion and accumulation processes, as well as the effects of the flood on the infrastructure and buildings, was based on a detailed analysis of the documentary data, which were primarily old photos. Although the amount of available data is high (see Table 3, Section 3.1), most of the photos depict the flood effects in detail (e.g., an individual building from a close distance) and can be exactly located with difficulty. This difficulty is also because of the absence of a detailed map from the year of the flood event, which would provide information regarding the spatial context of the depicted object. The older cadastral maps (1840s) and, in turn, the later aerial photos (1950s) that

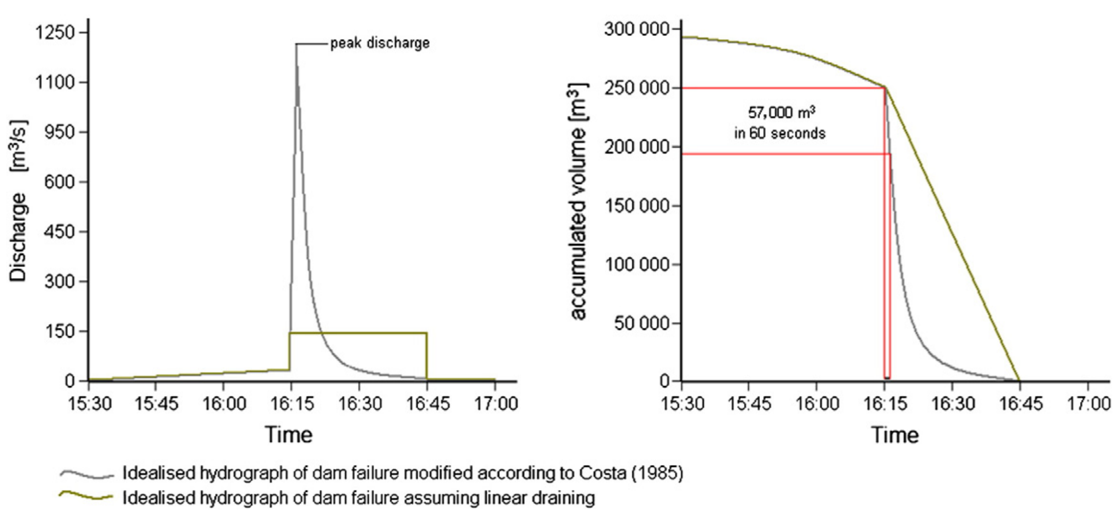

Fig. 5. Approximate hydrograph of the event (based on the recorded time sequence of the dam failure).

Table 4
Peak discharge estimation based on empirical calculations.

Author(s) of the method	Equation	Variable(s) [units]	Value	Calculated peak discharge [$m^3 \cdot s^{-1}$]
Soil Conservation Service (1981) (conservative variation according to Costa (1985))	$Q_{max} = 10.5 \cdot H^{1.87}$	Q_{max}—peak discharge [$m^3 \cdot s^{-1}$]	H = 11.26 m [a]	971.8
		H—dam height [m]	H = 14.16 m	1491.7
Kirkpatrick (1977)	$Q_{max} = 2.297 \cdot (H + 1)^{2.5}$	Q_{max}—peak discharge [$ft^3 \cdot s^{-1}$]	H = 36.94 ft [a]	576.8
		H—dam height [ft]	H = 46.46 ft	1009.3
Costa (1985)	$Q_{max} = 961 \cdot V^{0.48}$	V—reservoir volume [10^6 m^3]	$V = 0.29 \cdot 10^6$ m^3	530.5
Costa (1985)	$Q_{max} = 325 \cdot (H \cdot V)^{0.42}$	Q_{max}—peak discharge [$m^3 \cdot s^{-1}$] H—dam height [m] V—reservoir volume [in 10^6 m^3]	H = 11.26 m [a] $V = 0.29 \cdot 10^6$ m^3	534.2
			H = 14.16 m $V = 0.29 \cdot 10^6$ m^3	588.2
Price et al. (1977)	$Q_{max} = 8/27\ g^{1/2} \cdot y^{3/2} \cdot (0.4\ b + 0.6\ T)$	Q_{max}—peak discharge [$m^3 \cdot s^{-1}$] g—gravitational acceleration [$m \cdot s^{-2}$] y—reservoir depth upstream [m] b—width of breach base [m] T—top width of breach [m]	$g = 9.81\ m \cdot s^{-2}$ y = 10.26 m b = 8 m T = 30 m	646.6
Brater and King (1976); Wetmore and Fread (1981)	$Q_{max} = 3.5 \cdot W \cdot [c/(t + c/H^{0.5})]^3$, where c = 23.4 SA/W	Q_{max}—peak discharge [$ft^3 \cdot s^{-1}$] W—average breach width [ft] t—time of breach formation [hours] H—dam height [ft]	W = 62.3 ft t = 0.75 h H = 36.94 ft [a] SA = 24.71 ac	418.2
		SA—reservoir surface area [ac]	W = 62.3 ft t = 0.75 h H = 46.46 ft SA = 24.71 ac	524.3

[a] Reduced value (see Methods section).

are available did not correspond to the exact situation in 1916. Thus, the combination of photos, different maps and audio–visual recordings, together with written reports, were employed, and only the objects that could be exactly localised were included in the evaluation of geomorphologic and landscape effects.

First, the results of the overall assessment of flood effects along the Bílá Desná River are presented, and then we focus on two detailed case studies.

Fig. 6 shows the identified effects of the flood along the river between the failed dam and the town of Tanvald. The detected effects include (i) damage to buildings and to infrastructure and (ii) modifications of the river channel (erosion and accumulation processes), and their intensity can be divided into three segments relative to the longitudinal profile of the Bílá Desná River (Fig. 1D). More than one-third of the studied river length (0–3.2 km) is situated in a narrow intra-mountain valley, with an average slope inclination of ca. 2.80° (806–650 m asl).

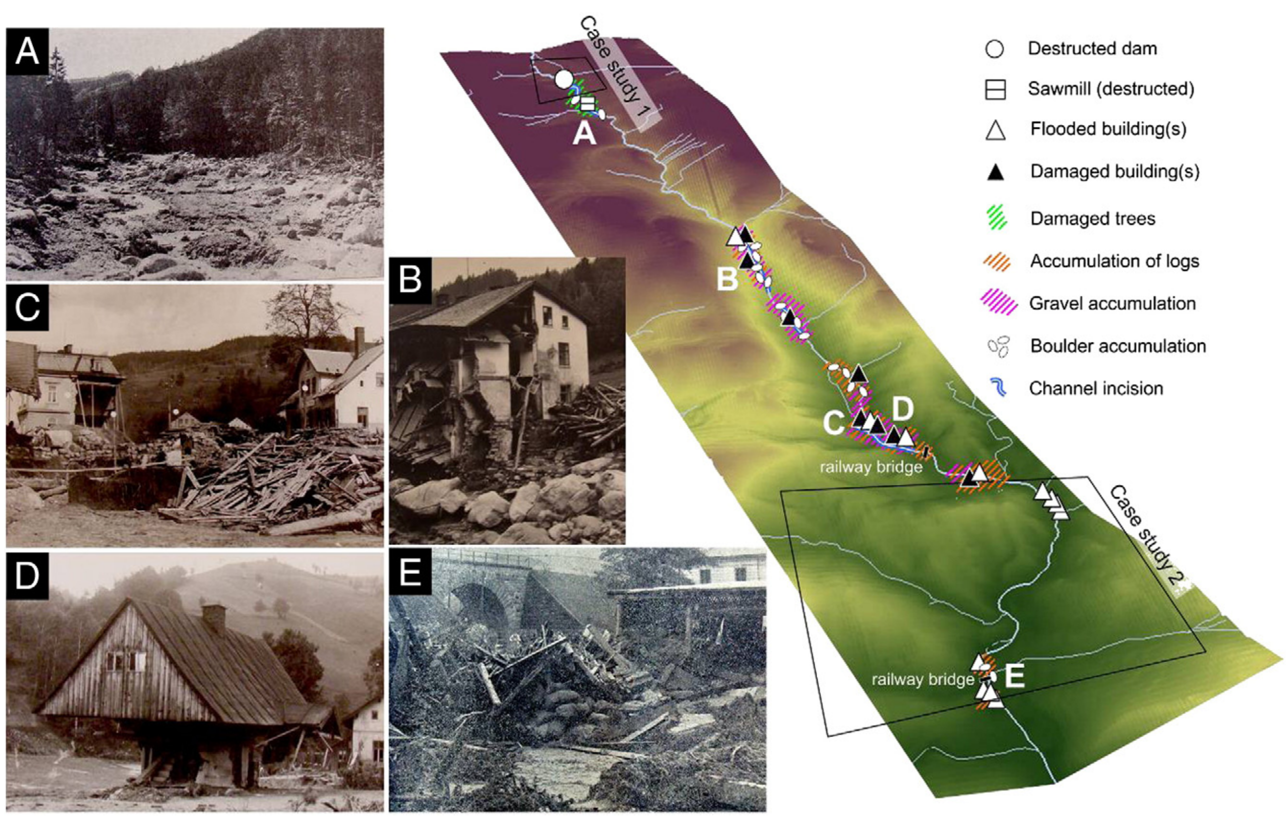

Fig. 6. Effects of the flood along the Bílá Desná River based on documentary data. Note: Of the large amount of documentary data, only those data that could be exactly localised were used.

The high gradient of this river segment enabled the stream to transport a large amount of material, which consisted of fractions varying from sand to boulders of up to 2 m in diametre. The flood wave damaged the forest ecosystem in the narrow valley, and the channel underwent a lateral shift (see below in case study 1) and a slight incision in some segments. After reaching the end of the narrow valley, the Bílá Desná River reaches the open space with the settlement of the village of Desná. Between 3.2 and 5 km, the gradient slightly increases to ca. 3.8° as the river channel enters the foothills; however, this gradient gradually decreases from 5 km downstream. The decrease in the gradient, which causes a loss of flow velocity, resulted in the gradual, but massive, deposition of boulders and of timber (approximately between B and D in Fig. 6) that damaged or destroyed tens of buildings, including a few industrial facilities (Gnendiger, 1920) in this river segment. The woody buildings localised near the channel and in the open floodplain (D in Fig. 6) were primarily affected. Owing to the transformation of the flood wave, the last analysed segment of the river (approximately within case study 2) was primarily affected by flooding; however, the destruction of buildings was not frequently documented. This lack of documentation can be ascribed to not only the increasing share of buildings constructed from stones and bricks in this segment but also the decreasing volume of boulders and timber that reached the lower parts of the river. In contrast, the documentary evidence has shown that part of this transported material (both timber and boulders) reached as far as the railway bridge in Tanvald (E in Fig. 6), ca. 8 km below the failed dam.

4.1.3.1. Case study 1. The disturbance and modification of the valley and riverbed of the Bílá Desná River following the dam failure has been reconstructed in case study 1, which covers the area of the former reservoir (see Fig. 1). The detailed reconstruction of other river reaches could not be performed because of the limited availability of old maps and photos. Following the dam failure and the rapid discharge of 250,000 m^3 of accumulated water during only 30 min, the channel below the dam was significantly modified. The comparison of historical maps from investigation reports of the event and of aerial photos from the early 1950s and from 2010 has shown that the meandering channel below the dam was subject to channel migration and lateral accretion (Fig. 7). The channel width in the reach below the former reservoir varied around 5 m before the dam failure and is currently 8 m in average. The magnitude of channel migration reached up to 30 m in the second meander below the former dam, whereas the lateral accretion only slightly increased the sinuosity of the channel. Instead of channel straightening (cf. Pizzuto, 2002), which could be expected as a result of flood wave flow, the return to the original meandering channel seems to be caused by geometry of a dam-breach and by extreme discharge that disrupted the channel geometry artificially established during the dam construction. This seems to be caused by the disrupting impact of the flood wave caused to channel segments. As documented by cadastral maps from the mid-nineteenth century, the Bílá Desná River channel approximately returned to its original position before the dam construction, with a meandering pattern. The reestablishment of the meandering

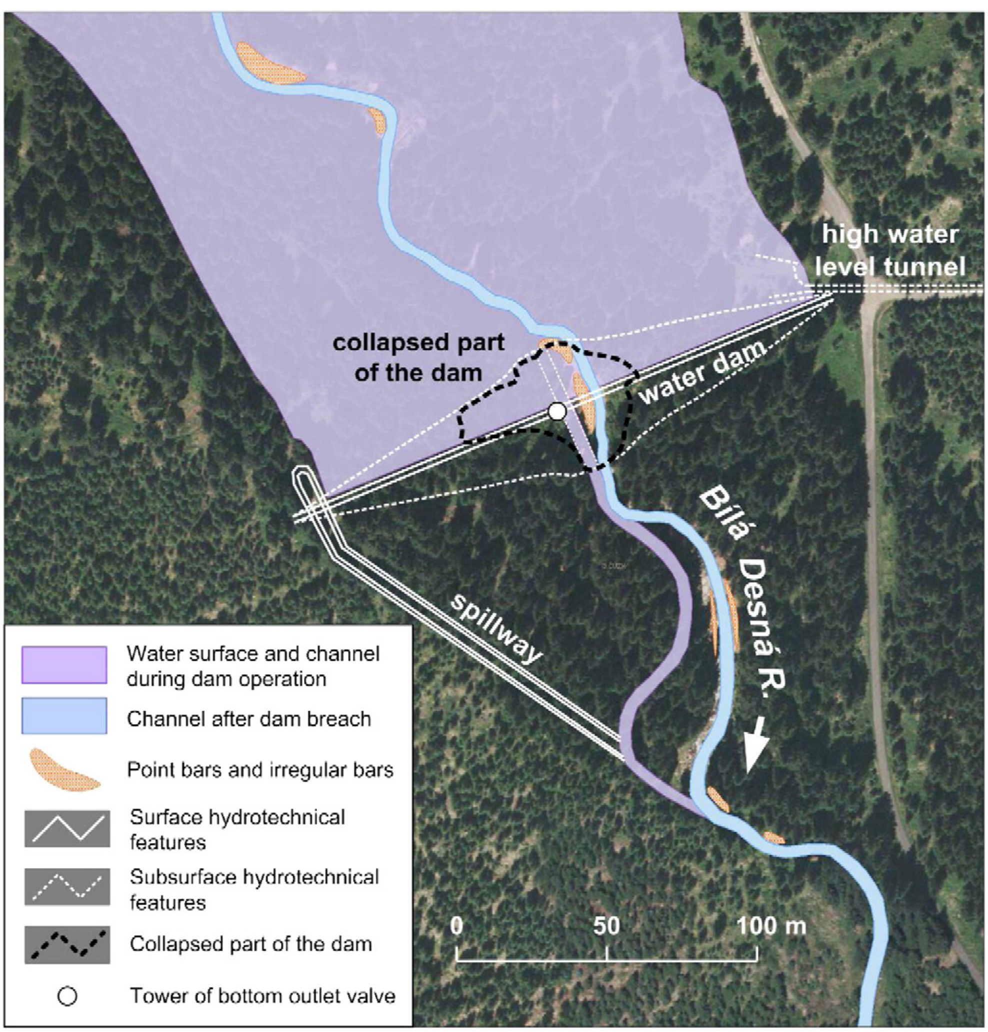

Fig. 7. Changes in the channel morphology after the dam failure.

channel pattern and increased sinuosity by lateral accretion enabled the evolution of several gravelly points and irregular bars, which are characteristic of other high-gradient streams in the area. According to Costa and O'Connor (1995), the above-described geomorphic changes are characterised as 'extreme disruptions' of the river channel.

4.1.3.2. Case study 2. The flood wave extent was reconstructed to estimate the effects of the dam failure on towns downstream of the Bílá Desná River and to verify the reliability of the peak discharge calculated from empirically based equations and from other methods used (4.1.2). Because of the incompleteness of documentary data that would document flood effects along the entire Bílá Desná River, the reconstruction was only performed for a selected river reach between the towns of Potočná (southern margin of the village of Desná) and Tanvald (case study 2; Fig. 1). Six preserved investigation reports for insurance companies, which included detailed sketches and cross profiles of the flooded buildings, enabled the reconstruction of eight cross profiles indicating the water level. Using these profiles, the flood wave extent was estimated for the river reach of ~2 km in length (Fig. 8). All of the flooded buildings used for the flood wave estimation are still standing and the surface around them has not been modified significantly. By comparison of old and present maps and aerial photos, we identified only three localities within the estimated 1916 flood wave extent that were subject to further anthropogenic transformation of the surface (white dots in Fig. 8). The modelled flood wave estimation can therefore be considered relevant, despite the absence of historical elevation data.

The width of the flooded area ranged between ca. 50 and 250 m, with the highest width reached in built-up areas of the towns and in the meandering channel in the central part of the studied channel reach. In contrast, the minimal width was typical of narrow valley segments, where an increase in the flow velocity can be expected. However, the documentary data did not provide the cross profiles for the central part of the studied river reach. Therefore, the results for this part of the area must be considered only rough estimations. According to the classification presented by Costa and O'Connor (1995), this part of the Bílá Desná River channel was affected by 'small disruptions' from the point of view of geomorphic impacts.

The comparison of the reconstructed flood wave extent with available current flood maps (VÚV, 2014) has shown that the flood wave following the 1916 dam failure exceeded the width of Q_5 and Q_{100} floods 10 times and 5 times, respectively, at some locations. This result can be ascribed to both the extremeness of the peak discharge reached after the dam failure and the subsequent modifications of the Bílá Desná River channel during the last 100 years.

4.2. Contemporary field evidence and later modifications of the river channel

4.2.1. Artificial river channel modifications

After the catastrophic flood in 1916, the primarily affected section of the Bílá Desná River channel (from the upper part of the village of Desná to the confluence with the Černá Desná River; see Fig. 6) was artificially

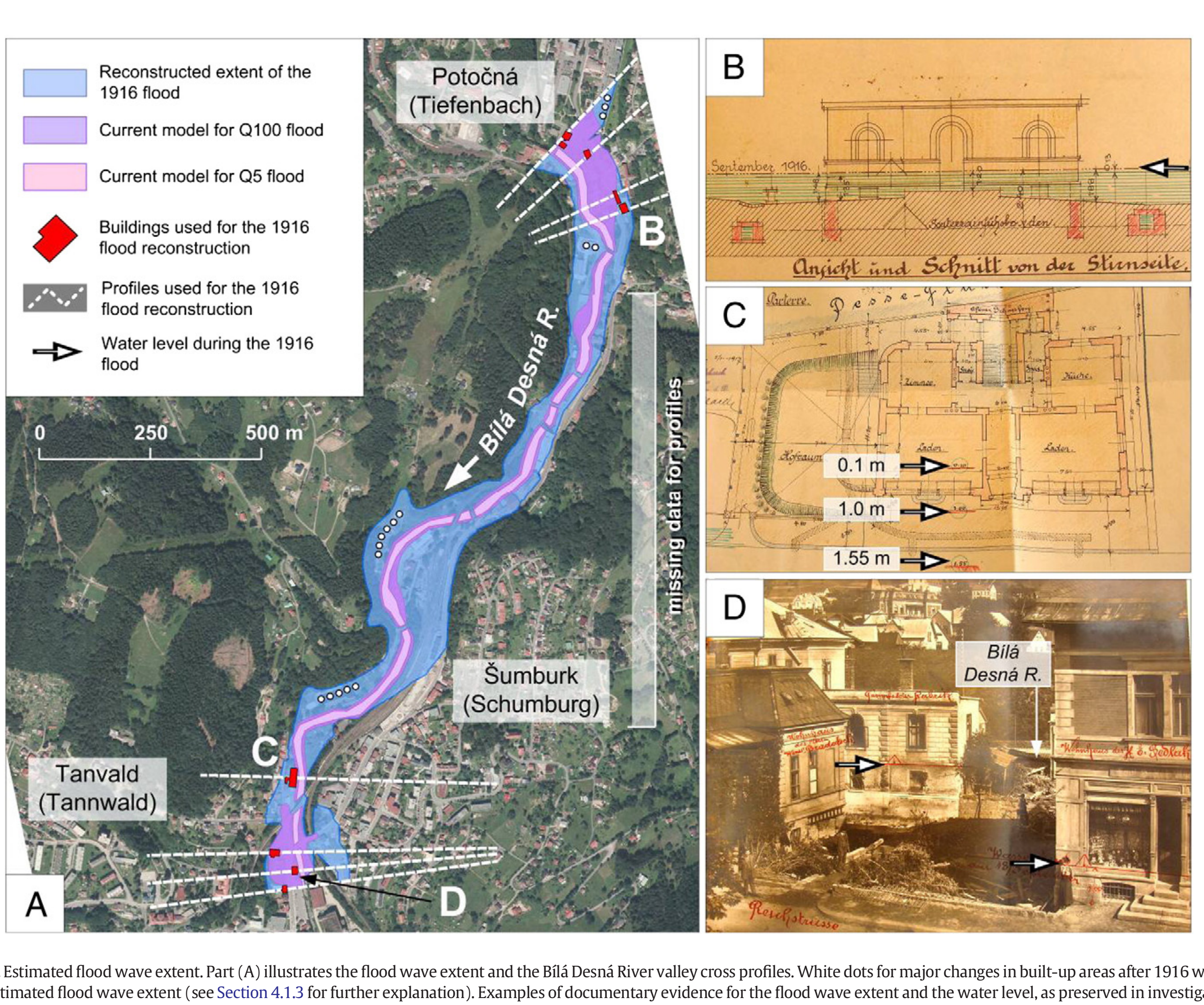

Fig. 8. Estimated flood wave extent. Part (A) illustrates the flood wave extent and the Bílá Desná River valley cross profiles. White dots for major changes in built-up areas after 1916 within the estimated flood wave extent (see Section 4.1.3 for further explanation). Examples of documentary evidence for the flood wave extent and the water level, as preserved in investigation reports for insurance companies. Cross-profile (B), plan (C), and photo (D) with an indicated water level mark.

modified between 1923 and 1936. These technically demanding and expensive remedial works included the complete pavement of the river bottom along the 1.5-km-long lower part and the construction of 34 stony steps in the steeper 2-km-long upper part (Fig. 9A); bedrock-based parts of the river bottom were left without modifications (Fig. 9B). The stony steps are between 1.0 and 4.2 m high and 11.0 to 18.0 m long and serve as a sediment trap (prevention against the initialisation of debris-flow movement). All of these artificial elements are designed for a maximal flow rate of 60 $m^3 s^{-1}$ (Žák, 1996). The section from the upper part of the village of Desná to the former Desná dam position has a natural character, with no artificial channel modifications (Fig. 9C).

Table 5
Extreme rainfalls (more than 150 mm/d) in the Jizerské hory Mts. between 1916 and 2014 followed by flood and flash flood events; compiled from Štekl et al. (2001), Bubeníčková et al. (2003), Kulasová et al. (2006), and Kašpar et al. (2013).

Year	Maximal daily rainfall totals [mm]
1920	214.5
1934	151.0
1937	169.0
1958	153.2
1992	154.9
1997	162.8
2002	278.0
2010	179.0

4.2.2. Effects of later hydrometeorological floods on the river channel

During the decades after the 1916 event, the Bílá Desná River has been affected by several flash flood events summarised in Table 5. Only during the last three decades (since the early 1980s) has the maximum daily rainfall exceeded 100 mm in seven years (Kulasová et al., 2006). Among the most serious events that have had significant effects on the river channel and its surroundings, the floods in 2002 and 2010 must be mentioned. The summer 2002 flood struck almost the entire territory of Czechia, with significant socioeconomic impacts on small mountain watersheds and on the largest rivers, such as Vltava and Labe. The daily maximal rainfall in the Jizerské hory Mts. was 278 mm (Kulasová et al., 2006), and some of the artificial steps at the Bílá Desná River channel were damaged during the subsequent flood and needed to be repaired (Žák et al., 2006). In 2010, two major flash flood events occurred in the territory of Czechia (Daňhelka and Šercl, 2011). Although the first flash flood following the heavy rainfall in May 2010 primarily affected the eastern part of the country (Moravia), the flash flood in August 2010 was territorially concentrated in the northern part of the country, with a daily rainfall maximum of 179 mm (Kašpar et al., 2013). The severity of this unanticipated event was also characterised by its 100-year rainfall recurrence interval, in contrast to the Moravian floods in May with a recurrence interval of 20 years. The flash flood event again damaged or destroyed artificial modifications of the Bílá Desná River channel and the channel surroundings (Collective, 2010).

Considering these flash flood and flood events during the last century, therefore, clearly field evidence for the 1916 flood cannot be easily identified in the current terrain. This difficulty in identification holds true not only in the inhabited segments of the Bílá Desná River valley (the towns of Desná and Tanvald), with significant anthropogenic

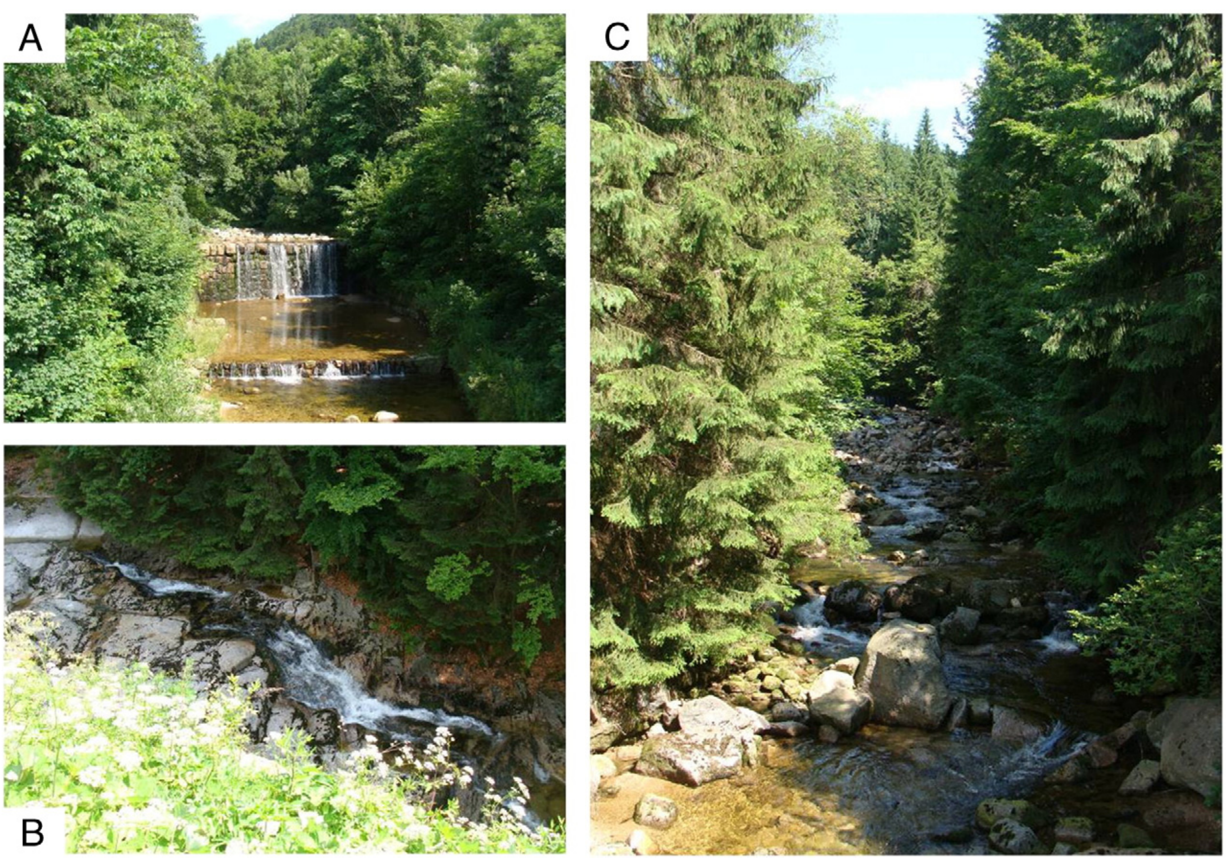

Fig. 9. Part (A) shows an example of stony steps built into the steeper part of the Bílá Desná River channel to protect against floods (debris flows). Part (B) shows a natural bedrock-based part of the river channel bottom. Part (C) shows a natural (unremediated) part of the Bílá Desná River channel.

transformation and with the increase in built-up areas during the twentieth century, but also in noninhabited segments of the river valley. In the noninhabited river valley segments, the anthropogenic modification of the channel is accompanied by a succession in permanent grasslands and in mixed-forest areas surrounding the channel and affected by the flood events.

5. Discussion

5.1. Reliability and completeness of documentary data

Documentary data, including both iconographic and written sources, have been widely employed in the research of different types of natural hazards (Hooke and Kain, 1982; Glade et al., 2001), such as meteorological extremes and their relation to climate change (e.g., Pfister et al., 2008; Brázdil, 2009), historical floods (e.g., Guzzetti et al., 1994; Brázdil and Kundzewicz, 2006), earthquakes (e.g., Cammasi, 2004) or landslides (e.g., Ibsen and Brunsden, 1996; Raška et al., 2014). Major attention has been devoted to continual (periodical) data that enable parametric time-series to be built as a basis for magnitude–frequency analysis. The reconstructions of individual natural hazard events necessitate the integration and critical analysis of various data types (continual and stationary) and raise new questions regarding data availability and reliability. With respect to data availability, this study shows that a broad spectrum of sources exists. This data availability can be ascribed to the fact that the causes of the catastrophic flood at the Bílá Desná River were originally assigned to human fault and resulted in the systematic collection of documentary evidence and reports by the court. This situation is in contrast with historical hazards with natural causes in Czechia, which are often documented by photos and by descriptions; however, these historical hazards were scarcely subject to systematic study and interpretation.

A significant share of the available sources used in this study was only accessible via personal detailed searches in regional archives. The digital on-line catalogues (if any) contain only brief descriptions of so-called funds, i.e., parts of archival sources devoted to a certain topic (e.g., local administration in 1848–1918) that include hundreds of unsorted documents. Moreover, the study illustrates, that although the amount of documentary data may be sufficient to provide the basic information concerning the individual catastrophic event into the time-series, the data do not provide all information necessary to reconstruct the causes, impacts, and recovery after the individual event. Analogous to the higher frequency of available data in regions or periods more prone to these events (e.g., Tropeano and Turconi, 2004), we have documented differences in data availability within the areas affected by an individual event.

When documenting flood impacts along the studied part of the Bílá Desná River, distinct differences were found in the amount and quality of preserved data for individual river segments. Those segments that suffered from the most serious impacts were documented by many photos and comments, which, in contrast, could not be frequently localised accurately, and their paraphrasing in further texts resulted in informational ambiguities. The downstream segments in the towns of Desná and Tanvald, characteristic of factories, manufacturers, and houses of the rich social class (built from bricks and stones), suffered from minor effects in terms of the number of victims and the number of destroyed buildings. Therefore, these segments were documented by less sources but, simultaneously, with high precision, enabling the reconstruction of the flood wave extent, for instance. These findings confirm the fundamental sensitivity of documentary data to differences in social vulnerability and in the perception of risks. Therefore, these data must be understood as a social construct created by historical communities and influenced by their perception of the event rather than as parametric information suitable for interpretation on a statistical basis (Stanford, 1986; Raška et al., 2014).

5.2. Accuracy of the hydrometrical estimations

Peak discharge is generally calculated as a passed volume of water divided by a given time interval. Because the dam discharge following the dam failure is a nonlinear process, the peak discharge is subordinated to the exact definition of the time interval. The typical hydrograph curve shape of the dam failure posed by Costa (1985) clearly shows that the estimated peak discharge will increase together with a shortening of the time interval used for the calculation (see also Fig. 4). Therefore, only the hydrograph-based estimation of the peak discharge is quite susceptible to error.

The empirical equation-based calculation of the peak discharge based on different input data [volume-based equation (Costa, 1985), the dam height-based equation (Kirkpatrick, 1977; Soil Conservation Service, 1981), the breach shape-based equation (Price et al., 1977), and a time-dependent equation (Brater and King, 1976; Wetmore and Fread, 1981)] were also used to approximate the peak discharge. Nevertheless, all these methods are subordinated to the uniformity and representativeness of the original data sets used for their construction. The last method used (Hjulström curve-based estimation; Hjulström, 1935) is particularly limited for extreme flow velocities and/or for extreme grain sizes.

As shown above, each type of method used for peak discharge estimation has its own potential sources of errors. However, we suppose that the combination of all of the above-mentioned methods limits the error rate of each method and provides useful results (proven reliability of mutually obtained results).

5.3. Comparative perspective on the event magnitude and impacts

In comparison with recorded floods following dam failures in Europe, the Bílá Desná dam failure claimed a high number of fatalities relative to the volume of escaped water (Fig. 10). The discharged volume of 290,000 m^3 and 62 fatalities provide an extremely catastrophic ratio of 4677 m^3/victim. From this point of view, the Bílá Desná dam failure is considered one of the worst dam failures ever recorded worldwide. In the regional context of the Czech Republic, no recorded hydrometeorological flood (e.g., the great floods in 1997 and in 2002) claimed such fatalities. According to the number of fatalities, this event is currently ranked among the most catastrophic earthen dam failures in Europe. When we consider the time of the dam failure, this event was ranked as one of the most catastrophic dam failures until 1916 and, therefore, significantly affected the engineering of earthen dams in the entire Central Europe region (Žák, 1996).

From the perspective of the achieved peak discharge (or the ratio of the peak discharge to the mean flow rate), the flood following the Bílá Desná dam failure is characterised by extreme values, which are out of the order of magnitude of 'classical' hydrometeorological floods in the context of the hydrological regime of rivers in the Central Europe region.

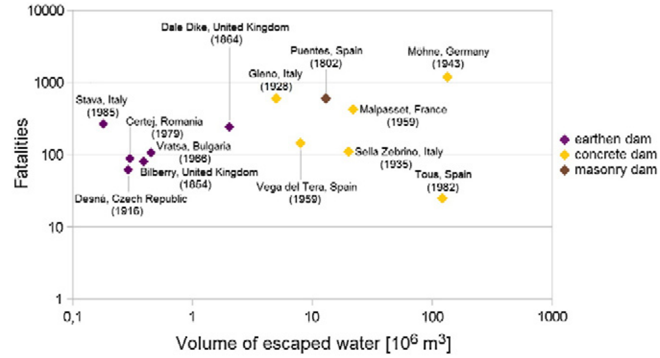

Fig. 10. Comparison of the most catastrophic European dam failures. (Data: Harrison, 1974; Costa, 1985; Alcrudo and Mulet, 2004; Peng and Zhang, 2012).

These findings correspond with those findings presented, e.g., by Costa (1985), who noted that this characteristic is a typical feature of floods following man-made dam failures. Our investigation also showed that from the point of view of geomorphic impacts, the Bílá Desná dam failure is characterised by rather expectable changes in the river channel (valley) in comparison with comparable recorded dam failures worldwide and with regard to the event magnitude (e.g., Costa and O'Connor, 1995; Bathurst and Ashiq, 1998; The Dolgarrog Disaster, 1925).

6. Conclusions

In addition to the often catastrophic social and economic effects, floods following man-made dam failures are also characterised by significant geomorphic and landscape effects, which are frequently disregarded. Our investigation of the catastrophic flood effects following the Bílá Desná dam failure on 18 September 1916 showed the great potential of documentary data sources for the reconstruction of an individual catastrophic event, where the direct geomorphic and landscape evidence has been covered by human activities. First, the analysis of these data enabled the estimation of the peak discharge during the flood, the documentation of the geomorphic effects of the flood on the channel morphology downstream of the dam and the reconstruction of the flood wave extent in downstream segments of the Bílá Desná River. Considering the acquired results, the flood following the Bílá Desná dam failure may rank among the most serious disasters in terms of the number of victims per discharged water volume that have occurred worldwide during the twentieth century. These results also provide insight into the vulnerability of historical communities to natural hazards and into their recovery measures. Second, the performed research confirmed previous studies emphasising the critical analysis of documentary data as a necessary step for their employment in geoscientific studies.

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