CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE
FACULTY OF ENVIRONMENTAL SCIENCES
Department of Land Use and Improvement

DIPLOMA THESIS

TOURIST TRAILS IN KRKONOŠE MOUNTAINS NATIONAL PARK – IDENTIFICATION OF THE EXISTING AND POTENTIAL AREAS THREATENED BY EROSION

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CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Department of Land Use and Improvement

Faculty of Environmental Sciences

DIPLOMA THESIS ASSIGNMENT

Marta Brichová, BA

Landscape Planning

Thesis title

Tourist Trails in the Krkonoše Mountains National Park Identification of the Existing and Potential Areas Threatened by Erosion

Objectives of thesis

The aim of the thesis is to identify localities in Krkonose Mountains NP that might be threatened by tourist trail erosion. The other objective is to determine the financial cost of the maintenance and repairs of the existing erosion hotspots.

Methodology

First, the erosion hotspots (i.e. places on tourist trails that are often impacted by erosion) will need to be determined. This information will be acquired from Mr. Radko Novotny, the Head of Investments, KRNAP. These hotspots will be then described in terms of the geographical position, slope of the terrain, slope of the trail, soil type surrounding the trail, underlying geology, annual precipitation, surface of the trail and technique used, and tourist numbers; as well as in terms of the frequency and financial cost of maintenance and the value of annual damages caused by erosion. Some of the data will be gathered in a field survey (the geographical position, slope of the terrain, slope of the trail, surface of the trail and technique used), some will be determined from relevant maps and records (soil type surrounding the trail, underlying geology, annual precipitation), and the source of the rest of the data (tourist numbers, frequency and financial cost of maintenance and the value of annual damages caused by erosion) will be KRNAP. Correlations between erosion and other factors will then be investigated, using statistical methods. Correlating factors will then be extrapolated to a map containing digital terrain model, soil types, geology, precipitation and road network layers for the whole area of the Krkonose Mountains NP. This map will be created with the help of GIS software.

The proposed extent of the thesis

ca 70 pages including graphs, tables, pictures and maps

Keywords

tourist trails/paths; erosion; Krkonose NP; erosion risk

Recommended information sources

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Electronic approval: 1. 4. 2015

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Dean

Prague on 16. 04. 2015

Declaration

I hereby declare that I wrote this diploma thesis independently, under the direction of prof. Ing. Miloslav Janeček, DrSc. and Ing. Michaela Hrabalíková. I have listed all literature and publications from which I have acquired information

Prague, 22nd April 2015 ______________________________

Marta Brichová

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Marta Brichová

Abstract

Tourist trails are an important resource for recreation, particularly in mountainous areas, and their erosion causes numerous problems and requires significant financial investment. Tackling this issue calls for information that trail managers could use in their decision-making. This work maps the erosion-associated characteristics of fourteen water-, wind- and snow-eroded trails in Krkonoše Mountains National Park, and uses them to define the areas prone to these types of trail erosion. Concrete erosion-threatened localities within the national park are identified. However, this study found that the level of erosion in these areas is difficult to measure and predict. The study also determines the financial costs of erosion of the surveyed trails. The identified costs range from 190.000,- CZK to 6.3 million CZK, however they are found not to be comparable across the sample and no conclusions can therefore be drawn about which type of surface is financially the best investment. This study contributes to identification of gaps in the research of the erosion of constructed and maintained trails and of trail erosion cost analysis.

Key words: tourist trails, trail erosion, Krkonoše Mountains, erosion risk, financial cost

Abstrakt

Turistické chodníky jsou významným prvkem rekreace, zejména v horských oblastech. Jejich eroze způsobuje mnoho problému, vyžaduje značné finanční investice a řešení bývá komplikované. Správci cest potřebují fakta, která by jim zápolení s cestní erozí usnadnila. Tato práce mapuje čtrnáct turistických chodníků v Krkonošském národním parku (KRNAP), které trpí vodní, větrnou nebo sněhovou cestní erozí. Na základě analýzy jejich vlastností spojovaných s výskytem eroze definuje charakteristiky oblastí a chodníků, které jsou ohrožené cestní erozí, a identifikuje konkrétní, takto charakterizované, oblasti a chodníky v KRNAPu. Studie ale zároveň odhaluje, že míra eroze v identifikovaných oblastech se dá jen velmi těžko změřit či predikovat. Práce také zjišťuje finanční náklady spojené s erozí mapovaných turistických chodníků. Ty se pohybují mezi 190.000,- Kč a 6,3 miliony Kč, nejsou však srovnatelné napříč studovanými chodníky a nelze tedy určit, který typ povrchu je z finančního hlediska nejlepší investicí. Tato studie identifikuje oblasti potenciálního budoucího výzkumu, a to cestní eroze chodníků s nepřírodním povrchem a finančních nákladů cestní eroze.

Klíčová slova: turistické chodníky, cestní eroze, KRNAP, erozní ohrožení, finanční náklady

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1. INTRODUCTION

Tourist trails are an important instrument in a natural environment, as they enable human contact with it and secure one of the objectives of the existence of national parks: access of public and recreation. From the perspective of erosion, tourist trails are essentially channels for water and thus create problems, particularly in a mountainous environment, where conditions for erosion are often ideal. With an increasing number of visitors to national parks (NPs), the problems become more serious.

It has become an essential part of the work of NP managers to stop and prevent erosion from trails and this effort is often both time-consuming and a significant financial strain. They also face a dilemma in trying to combine the protection of nature, public access and the aesthetic effect of trails. It is therefore essential to have reliable data on how and where trail erosion occurs. It is also desirable to know what is the most sensible solution from a financial perspective.

Although research within the area of trail erosion is fairly extensive, the aspects affecting erosion can differ from place to place and thus each region requires tailored and localised research, which will then be applicable to that particular area.

This diploma thesis contributes to the research of the trail erosion issue in the most-visited Czech national park - Krkonoše Mountains National Park (KRNAP) - and provides valuable facts to the managers of this national park.

2. THE OBJECTIVES OF DIPLOMA THESIS

The first aim of this thesis is to identify localities in Krkonoše Mountains NP that are currently or may be threatened by tourist trail erosion. This objective will be achieved by surveying a sample of erosion 'hotspots' (i.e. trail sections where trail erosion occurs). Mapping of the characteristics of these hotspots and their surroundings, and the subsequent comparison of which, should reveal both characteristics that these trails have in common and those in which they vary. It should then be possible to define what characterises other localities and trails prone to erosion. Using map datasets, locations of areas complying with the defined characteristics will be found. The mapped characteristics will be those that are generally known as being significant in the soil erosion process (i.e. type of soil, slope of the terrain, amount of precipitation, prevailing vegetation, underlying geology, aspect of the terrain, number of tourists, trail aspect, slope and surface, and technical solutions for water drainage).

Defining localities that are potentially threatened by trail erosion can help the NP managers with decision-making on which areas they should avoid when proposing new trails, and possibly which characteristics of a trail need to be carefully thought through and which ones are not so significant.

The other, subsidiary, objective of this diploma thesis is to determine the financial cost of the maintenance and repairs of the existing erosion hotspots, in other words the direct financial impact of erosion. Analysis of the financial data could also help to answer the question of which type of trail is the best investment from the financial viewpoint. Such information would be very valuable for KRNAP trail managers.

3. LITERATURE REVIEW

3.1 Trail degradation

Hiking trails or tourist paths are one of the most important resources for tourist recreation in mountainous areas as they provide access to the natural environment. The mere existence of tourist trails is evidence that they have an impact on the natural environment. Cole (2004) states that impact on the natural environment happens wherever hiking occurs. In fact, the degradation process starts by the creation of the inevitable necessity for hiking – trails. Their formation almost always results in a reduction in the vegetation and compaction of earth, which causes the development of channels for runoff, which in turn causes path erosion (Harden, 2001). Trail degradation and its prevention has been an issue for researchers and trail managers for many years (Lucas, 1978; Leung & Marion 1996 and 1999a, 2001; Newsome, Moore & Dowling 2002; Hardiman, 2008; Selkimaki & Mola-Yudego 2011; etc.). There are several types of trail degradation, such as multiple treads, track widening, root exposure (Leung & Marion, 1999a in Newsome, 2002), loss of vegetation and changes to its composition, soil compaction, muddiness (Marion & Wimpey, n.d.) and, of course, erosion.

3.2 Trail erosion - process of initiation, consequences, influencing factors

Erosion is a natural process of the detachment of soil and rock and their removal and deposition in another place. This natural process has been greatly accelerated by humans (Julien, 2010). While erosion of farmed land has been intensely studied and measured, trail erosion research still lacks the depth and breadth of its agricultural equivalent. The following paragraphs summarize the general understandings of trail erosion in the existing relevant literature.

Depending on the erosive agent, there are several types of soil erosion – water, wind (aeolian), snow (nival), glacial and anthropogenic (Zachar, 1982). The majority of literature devoted to trail erosion either does not distinguish between erosive agents or focuses primarily on water erosion.

The mechanics of the initial phase of the erosion process – the detachment of particles – caused by a hiker was described by Duchoňová (2007). She states that detachment of particles is activated by the vertical force of a foot at the first stage of a step, which is then followed by the rotary shear force of the big toe. This force strongly deforms the ground, particularly during wet conditions and in an uphill direction.

Some works mention the consequences of trail erosion that include siltation of water streams with runoff (Lynn & Brown, 2003) or even changes in water regime (Harden, 2001). Erosion often leads to difficulty using the trail, and thus to track widening and the occurrence of multiple threads (Suchý et al, 2006). Soil loss also causes root exposure. Ultimately, the decrease in attraction and accessibility of an area due to trail erosion can have an adverse impact on the recreational experience (Jewell & Hammitt, 2000) and consequently an economic impact on tourist services (Lynn & Brown, 2003). Because of these consequences, trail erosion is now recognized as a major management issue (Newsome, 2002).

Many of the existing studies focus on factors that determine the occurrence and level of erosion. Coleman (1981) studied slope and recreational pressure and their relationship. Slope and type of surface appear to be the important factors in trail erosion in the study of Suchý et al (2006), while the number of tourists is less significant. Wilson & Seney (1994) in Newsome (2002) as well as DeLuca et al. (1998) claim that the critical factor in initiating erosion is the detachment of particles (or the ease with which they are detached). In contrast, Garland (1990) in Newsome (2002) states that the most important factors of erosion risk are rainfall, slope and soil type. Leung & Marion (1996) in Newsome (2002) name climate, geology, user type and intensity of use as the primary factors affecting trail degradation, while topography, soil, vegetation and user behaviour have only intermediate importance. While there is no unified perception of the order of importance of individual factors, it can be concluded from research that the following factors have some level of influence on path erosion: slope, soil type, geology, vegetation, number of users and their behaviour, type of activity and climate/rainfall.

3.3 Trail erosion in mountainous areas

Mountainous areas are naturally prone to soil erosion thanks to steep and long slopes, and reduced ground cover (as a result of altitude or slope). As Harden (2001) describes:

> 'Essentially, soil is vulnerable to erosion where it is exposed to moving water or wind and where conditions of topography or human use, such as steep slopes, compacted surfaces, removal of vegetation, or years of plowing [sic], increase the force of the moving fluid or decrease the cohesion of the soil.'

Most mountain ranges were shaped by the natural erosion processes; however, some anthropogenic factors, such as hiking, massively accelerate the soil erosion process. Monz (2000) in Newsome (2002) states that 'mountain regions throughout the world attract many hikers and are at risk due to the steep slopes and harsh environmental conditions'. Impacts of erosion in mountainous areas are also more severe because of the fragile environment (Anon, 1992) and much longer time is needed by nature to regenerate. As Cole (2004) states, the majority of research in the area of the impact of recreation on soils has been conducted in the mountainous environment, therefore the findings are relevant to the studied area.

3.4 Methods of trail erosion measurement

Because of the complex set of factors mentioned above, measuring trail erosion is not a straightforward task. The Universal Soil Loss Equation (USLE) cannot be applied as one of the pre-requisites of this empirically-based soil erosion model is a wider area (Selkimaki & Mola-Yudego, 2011), while trail erosion occurs in a narrow corridor.

Jewell & Hammitt (2000) summarized the existing techniques for the assessment of erosion on trails, namely Condition Class Method, Census of Erosional Events, Maximum Incision Post-Construction (and its variation - Maximum Incision Current

Tread), Cross-Sectional Area Method, Census of Active Erosion, Stereo Photography, Quadrat Measurement and Aerial Photo Appraisal. All of these techniques were applied to natural (i.e. non-constructed) trails and while some of them, such as Condition Class Method, can only be applied to these, other ones, such as Aerial Photo Appraisal or Maximum Incision Post-Construction, could also be used for assessment of constructed trails. These techniques represent the reactive methods that measure existing soil loss. Some research has been conducted to create proactive (predicting) methods. Selkimaki & Mola-Yudego (2011), for instance, came up with a model predicting the path width and depth. It assessed the following characteristics of a trail: slope, elevation, square root of the number of visitors, types of vegetation and soil types. The limiting factor of using this model, as well as many others, is that it considers the impacts on natural (i.e. non-constructed) paths.

3.5 Hiking trails management, construction and maintenance

As mentioned above, trails are an essential resource for tourist recreation and trail erosion can have serious impacts. Therefore, trail maintenance is a vital part of the management of a natural area. Often the goal of academic research is to be relevant, which in the research area of trail impacts means to aid in the management process of tourist trails (Cole, 2004; Lynn & Brown, 2003). Managers of hiking trails have to provide access to the natural environment while at the same time protecting the ecosystems in which these trails are located (Lynn & Brown, 2003). This often contradictory task means deciding where and how to design a trail (and alternatively if a natural trail should be surfaced), and how to maintain it.

Edington (1986) distinguishes two management strategies used when dealing with tourist path erosion. The first one is a diversion of the path; the second one a construction of an 'artificial' surface of the path. In the USA and also in the Czech Republic, a third strategy is also very often used – the diversion of water away from the path (often by the construction of water bars, check dams, grade dips, etc.). All of the above can be called 'hard' solutions, and these are mainly used when trail erosion is already occurring. There are also strategies for the management of the impacts of hiking, which could be called ‘soft’. These are usually less invasive (e.g. don’t involve construction) and rather have a preventive effect. These approaches work more with factors that can be influenced, such as hikers’ behaviour, and they build on the findings of ongoing research in this field. For example, Cole (2004) came to a conclusion that the impact caused by hiking and camping is dependent on the amount of use in a curvilinear manner (they both increase up to a certain point from which the increase of impact slows down or turns to a decrease). This, according to Cole, has consequences for management and implies that use should be concentrated in popular areas but dispersed in unfrequented places. The ‘hard’ and ‘soft’ strategies are often used in combination with each other.

The principles of decision-making vary from country to country or even between areas. In some mountainous areas, such as the Lake District (UK), managers prefer an as close-to-nature approach to trail reconstruction as possible (Hardiman, 2008). In others, the commanding factor is the trail resistance to the weather and number of tourists (Novotný, 2007). And for some managers in the USA, ‘the ideal recreational trail is one that requires minimal maintenance’ (State of New Hampshire, 2004). Despite these differences, some commonalities can be derived. It is generally understood by trail managers that prevention of erosion is more effective than its mitigation (Cole, 2004; Hardiman, 2008).

Should a trail be (re)constructed, one of the most tangible decisions that a trail manager must make is the choice of trail surface. Many factors play a role in such selection, apart from the type of intended use and money. In USA, for instance, setting, zoning and trail standards determine, whether the trail surface will be natural, modified with hardeners or paved (Lechner, 2003). A very sensitive approach to trail construction was displayed during the extensive project of repairs of eroding trails in the Lake District NP (UK). The key imperatives included using only natural, locally-found materials and maintaining the natural appearance as much as possible (Hardiman, 2008).

4. CHARACTERISTICS OF THE STUDY AREA

The study area is located in the Krkonoše Mountains, which is the highest mountain range in the Czech Republic. Its peaks climb above the alpine line and the highest peak Sněžka, with the top lying in Polish territory, reaches 1603 m (Stonišová, 2014). The mountain range forms the Czech Republic's northern border with Poland and stretches in a northwest-southeast direction for some 35km (see Figure 1).

Figure 1 Location of the Krkonoše Mountains in the Czech Republic

The flat relief of the crest is both typical and unique for this mountain range (Brychtová, 2004). The tops of the Krkonoše Mountains are geologically formed by granite and other hard rocks, such as slate, and the soils are predominantly the frost-influenced types (Brychtová, 2004). The crest of the mountain range lies above the tree line and its characteristics are similar to arctic as well as alpine tundra vegetation zones (Brychtová, 2004). Thanks to its geographic position, the climate in Krkonoše is wetter, colder and rougher than the climate in the Šumava Mountains and even in the High Tatras (KRNAP, n.d.a). Krkonoše belongs among the wettest parts of the Czech Republic and the average precipitation exceeding 1200mm/year increases with the altitude (KRNAP, n.d.).

KRNAP was established in 1963 to protect the unique natural environment of the mountain range. Today, the national park covers 550 km2 and its territory is divided into 3 zones (see Figure 2). 1. zone is located in the highest parts of KRNAP and has the strictest nature protection (KRNAP, n.d.b). Shortly after its foundation, KRNAP became the most visited national park in the country. Today, approximately 5-6 million visitors come to the national park annually (Hřebačka, 2011) and most of them use some of the 700km of marked tourist trails.

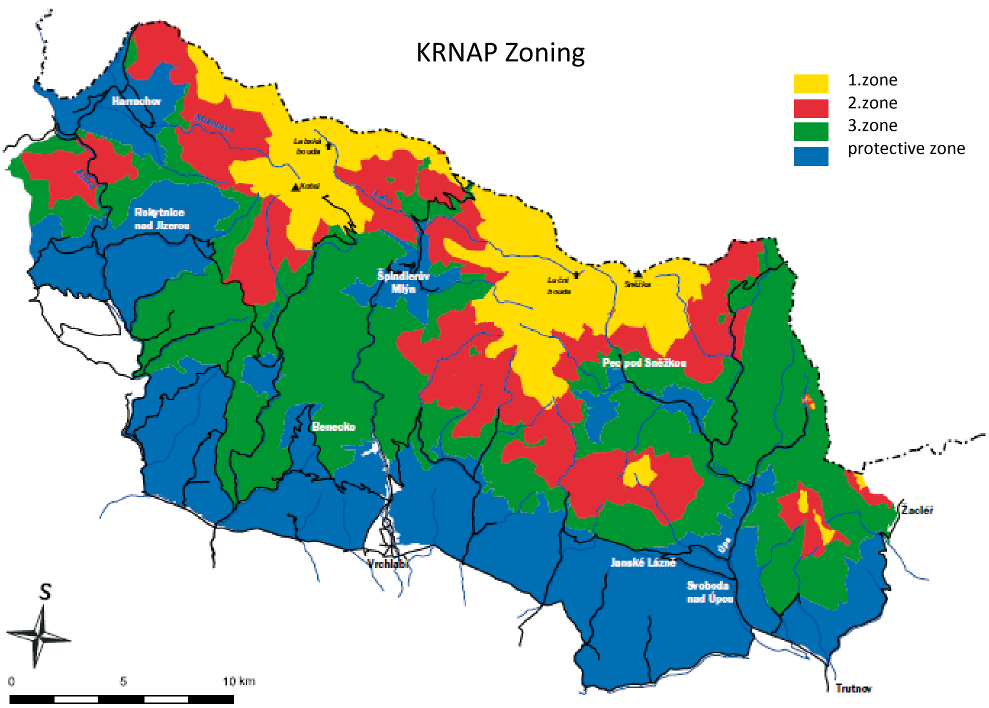

Figure 2 KRNAP zones (Source: Štursa & Bašta, 2013)

5. METHODOLOGY

5.1 Data gathering

As the first step, it was necessary to identify the trail erosion hotspots. After consideration of other options, such as field survey, which would include extensive search for trails with signs of erosion, the erosion hotspots were selected by the method of expert judgement with the assistance of the Head of the Department of Investments, KRNAP. The reasons behind the choice of this method as well as its shortcomings are further discussed in Chapter 8. From the list of identified hotspots, fourteen randomly selected trails were studied as a part of this diploma thesis.

As the above literature review demonstrated, there are many influencing factors that can have effect on erosion. Therefore, information about potentially relevant factors for each of these hotspots was gathered. The mapped characteristics included:

- geographical location and elevation
- slope of the trail and of the surrounding terrain
- soil type
- vegetation surrounding the trail
- underlying geology
- precipitation
- aspect of the trail and of the surrounding slope
- material and technique used on the surface of the trail and drainage solution
- number of pedestrian passes

N.B. Information about trail erosion (type and extent) was also gathered.

Some of the data was primary and was gathered during field survey (i.e. geographical position and elevation, slope of terrain and the trail, surface of the trail and the technical solutions of drainage, vegetation, aspect and state and type of erosion). The field survey was conducted between September and November 2014. A Garmin GPS was used to record geographical location, elevation and aspect. A Silva clinometer was used to collect the slope data (in degrees). Characteristics of the trail were gathered at selected points along the trails. These points were chosen as places showing signs of erosion and at the same time displaying characteristics typical for that particular trail section. More points were surveyed on the trail if the character of the trail changed significantly.

The rest of the data was collected from secondary resources. The soil type under and around the trail and the underlying geology were extracted from digital maps provided by KRNAP in a form of Shapefile layers. The map dataset acquired from KRNAP also contained the digital terrain model. The amounts of average annual precipitation from five meteorological stations located in the surveyed area were received from the Czech Hydrometeorological Institute (CHMU) and the same data for the weather station Sněžka was acquired from the Polish meteorological institute (IMGW-PIB). Data about number of tourists from trail counters were acquired from PhD students at CZU, who received them from KRNAP.

Financial data linked with the surveyed hotspots was extracted from the financial records provided by KRNAP.

5.2 Transformation of data

The following paragraphs describe the character of the collected data and how and why some of the data were transformed in order to be used for further analyses.

Precipitation data

The acquired data, received in the form of a chart, expressed the annual amount of precipitation calculated from data for 2010-2014. Precipitation measurements include snow precipitation (i.e. the amount of water gathered from snow melting in a measuring device). MS Luční bouda did not collect precipitation data for a period of time between 1.1. and 10.1.2011. Total precipitation for January 2011 was therefore calculated by interpolation of precipitation from other surrounding CHMU meteorological stations using GIS.

The data was received for six meteorological stations (Pec pod Sněžkou, Dvoračky, Pomezní Boudy, Luční Bouda, Labská Bouda and Sněžka). These ‘point’ data had to be transformed to provide information about precipitation in the surveyed trail sections. The weather stations were georeferenced in a map in the ArcGIS program and the geoprocessing technique Thiessen Polygons was used for the interpolation of the precipitation averages from points to surface. This technique is often used for interpolation of precipitation data in meteorology (Sluiter, 2008).

Recorded data for erosion, vegetation, trail surface and drainage solution

These data were recorded descriptively. To ease further analysis, they were transformed into a chart, which contained categories for erosion type, vegetation type and trail surface type. A number 1 was recorded in the chart cell that corresponded with the type of erosion, vegetation and trail surface that characterised that particular surveyed point on the trail. Based on the observed signs of erosion and information from the experts in KRNAP, three types of soil erosion were recorded – water, wind and snow erosion.

The type of trail surface was unified for the whole trail section for the purpose of the analysis of financial costs. The unification was done on the basis of man-made and prevailing surface type.

The variety of combinations of drainage features and their state did not allow for categorisation. Thus the recorded data were kept in a descriptive form.

Soil type

Type of underlying soil was extracted from the soil map using ArcGIS. As the soil map uses Czech soil classification, identified soils were then matched with the equivalent soil unit according to the World Soil Classification. As the diploma thesis is written in English it is thus expected that an internationally recognised classification would be preferred by readers.

Number of tourist passes

The received data contained Excel tables and a map shapefile. It expressed the quantity of pedestrian passes, not the number of tourists (i.e. if a tourist walks there and back, he/she is calculated twice). For this thesis, the number of passes is more relevant for assessment of the impact on the trail than the number of tourists. The provided data was transformed to an average number of passes in a 12-month period. This number was calculated as the average of 11 of 12-months averages from the available data of a 22-month-long period from September 2011 to June 2013. The average number of tourist passes was then added to the attribute table of the GIS shapefile and displayed over the trails network.

Because trail counters are not available on every trail, an estimate of the number of passes was made for the surveyed trails where no counter was placed. The estimate was based on the data from the nearby counters and the author's knowledge of the popularity of a given trail. Such estimates were made for 7 out of the 14 surveyed trail sections.

Aspect of trail and terrain

The aspect data gathered during the field survey was categorized. Categorization was adopted from Novotný (2013) and adjusted. Unlike in Novotný (2013), where differentiation of aspect is based on the influence of aspect on the production ability of soils, categorization for the purpose of this study was made on the basis of the prevailing direction of winds and weather. Weather in Krkonoše is most commonly brought by winds coming from the South-West, West and North-West. These aspects were therefore grouped into one (see Figure 3) and given a code 1. All other directions were also grouped together and coded 2. A flat surface with an aspect of 0-360° was marked 0.

Figure 3 Table of aspect categorisation

Code	Aspect
0	Flat surface open to all directions
1	South-southwest to North-northwest (200°-340°)
2	North to South (341° - 199°)

Financial data

Two types of data were received – investment costs (i.e. costs for constructions and major reconstructions) and maintenance costs (including cost of repairs claimed from insurance after torrential rains and flooding events). Investment data was provided in raw form as a so-called ‘property record’, which shows the sums invested into the trail that increase its value, as well as information about the years of investments. Property records did not contain details of individual reconstructions, such as the size of the reconstructed area. Maintenance data was received in the form of an electronic excerpt from the financial system. Provided maintenance data included expenses for the last 6 years, i.e. from 2009 to 2014, broken down to individual years and items. It did not include expenses for staff responsible for the maintenance of trails.

5.3 Analysis

The objective of the trail characteristics analysis was to find common and variable factors that would define the features that other localities and trails prone to erosion would show. A simple comparison of the individual characteristics across the trails was used for that.

Trails were divided into three groups according to the type of erosion. First group, containing trails suffering from snow erosion, second group has trails with prevailing wind erosion and a third group to which all trails with predominantly water erosion problems were assigned. Trails in each group were analysed within that group.

Trails suffering from water erosion were then further categorized according to the slope of the trail, aspect, surface, number of tourist passes, precipitation, geology, soil type, vegetation and elevation. Similarities in characteristics were searched for in these categories using simple comparison. This analysis was conducted not to lead to the characteristics of erosive areas, but to reveal possible interesting links between the individual factors.

Outcomes of the above described analyses (i.e. identified set of common and variable factors for each erosion type), were projected onto a map of the whole national park using the ArcGIS software. Firstly, layers corresponding with the relevant characteristics (e.g. precipitation) were selected. Some layers, such as slope and aspect had to be created as they were not part of the initial dataset. A Spatial Analyst Tool called Surface was used to create both Slope and Aspect raster layers.

All relevant vector layers were converted to raster, using Conversion Tool Polygon to Raster and Polyline to Raster. (N.B. To display the numbers of tourist passes as characteristic of a section of a trail, rather than a point, polylines were drawn along the trail sections from the tourist counter point in all directions to the first crossroad.)

Values in raster layers were then classified to match the values or the ranges of values, which matched the results of the analyses. Each raster layer was then reclassified using Spatial Analyst Tool of Reclassify, so that the searched-for values equalled 1 and the rest of the values equalled 0. After that, the Raster Calculator tool was used to select only those areas where all characteristics intersect (i.e. where values in all layers equalled 1).

Finally, the outcome layers for potentially erosive trails were transformed to polylines in order to enhance their visibility on the map. Some characteristics (e.g. trail surface or surrounding vegetation), which were not possible to analyse with the use of the Spatial Analyst tools in ArcGIS were then determined manually with the help of an ortophoto map (from WMS Server geoportal.cuzk.cz) and the author's knowledge of the trails. Polylines' sections which did not match the required characteristics (e.g. a specific type of trail surface) were deleted.

The goal of the financial analysis was to determine the financial cost of erosion in each of the surveyed hotspots. For that, the cost of investments and maintenance for each trail were added up. This index is called the Total Cost.

To get data which would help to answer the question of the best value-for-money type of trail, the financial cost of individual trails needed to be comparable to each other. Such data needs to reflect the characteristics of the trails, mainly the type of material and length of the constructed/maintained trail. Unfortunately information on the length proved difficult to access; therefore the originally planned method of calculation of cost per km/m was not possible to conduct. Nevertheless, the author attempted to calculate indexes that would demonstrate various perspectives of the cost. Apart from the Total Cost, two other indexes were calculated:

The average annual maintenance cost (AAMC) from the latest reconstruction to 2014. This index shows how much is invested into each trail every year to repair damages after extreme weather events (e.g. torrential rains) and to conduct smaller scale repairs. The financial cost recorded between the last known reconstruction and 2014 was divided by the number of years since the last reconstruction. If reconstruction was conducted in 2014, maintenance costs were calculated as the annual average for the years preceding this reconstruction.

The average annual total cost (AATC). This amount shows how much in total has been invested into each trail per year, if both investment costs as well as maintenance costs are considered. The AATC was calculated as the investment cost of the last reconstruction plus AAMC, which was multiplied by the number of years since the last reconstruction. The result was then divided by the number of years since the last reconstruction. For trails reconstructed in 2014, the year and cost of the penultimate reconstruction and the AAMC between the penultimate and the last reconstruction was used.

Out of interest, the Total Cost was then used for correlation with the number of average annual pedestrian passes and type of trail surface. The statistical function COREL in MS Excel was used to perform the correlation operations and scatter graph was used to illustrate the result of correlation analysis. This graph helps to understand the calculated correlation factors.

6. CURRENT STATE OF TRAIL EROSION IN THE STUDIED AREA

The policies and attitudes towards nature protection and public access have seen some dramatic changes throughout KRNAP's 50 years of existence. These changes are reflected in, among others things, the management of tourist trails. In the 1970s, the high number of tourists led to the rapid degradation of trails and the first planned effort to repair them. Štursa & Bašta (2013) describe this unfortunate era, when strong basic material (e.g. dolomite and melaphyre) was used for maintenance and repairs of tourist trails. This decision affected the flora surrounding the trails for decades, as the alien material leaked Ca and Mg, changed the pH of the soils and consequently the composition of the surrounding vegetation (Vítek & Vítková, 2000). Even though only local materials have been used since the 1990s, the changes to the vegetation composition are still visible in the landscape (Vítek & Vítková, 2000). Nowadays, locally-sourced material is used for the surfaces of trails in Krkonoše Mountains NP and a strict directive on types of materials that can be used above the tree line guides the decisions (Štursa & Bašta, 2013). On the other hand, construction of tourist trails in the Czech Republic is not regulated or guided by an official directive and decisions on construction and technologies used in KRNAP are therefore based on gathered experience (Novotný, 2007).

Although trail erosion has been the main reason behind trail repairs and the management of KRNAP would appear to pay attention to the conclusions of scientific research, trail erosion has not been thoroughly studied. Some research was conducted as a part of a larger research project carried out in 2003-2005 by Suchý et al (2006). As mentioned above, this research concluded that slope (the steeper the worse) and type of surface (paths with large boulders and paths with compacted sandy earth or sandy grit) seem to be the important factors in trail erosion, while the number of tourists is less significant. This conclusion was also made by Vítek & Vítková (2000) who state that a positive correlation between the number of tourists and the state of the trails was not found. In contrast, the current Head of the Department of Investments believes that the number of tourists and the extreme weather conditions are the key elements responsible for trail erosion. Trail erosion is also touched on in a book written for the 50th anniversary of the foundation of the national park. In this publication, Štursa & Bašta (2013) describe in detail the state of the most used trail from Růžová Hora to Sněžka and its repairs in the 1990s. According to Štursa & Bašta (2013), the costly repair of the above mentioned trail was well worth the investment as it enabled a slow, and nowadays visible, recovery of the natural environment surrounding the trail. A diploma thesis written by Duchoňová (2006) also represents a relevant piece of academic research. She compared the erosive influence of mountain-bikers and hikers on trails in the western parts of Krkonoše. The most important conclusion of her work is that the decisive factors in the process of detachment of particles are given by the characteristics of the trail, rather than the type of user (hiker vs. biker). The only difference was noted in the steep parts of the trails, where bikers' impact is greater. Despite her conclusions, the majority of tourist trails in the 1.zone of KRNAP are for pedestrians only and the use of bicycles is prohibited.

Responsibility for repairs and reconstructions of tourist trails lies under the Department of Investments of the NP Authority, and daily maintenance of trails (clearing of water bars, etc.) is a responsibility of the rangers or so-called terrain workers. The amount of money invested every year into reconstructions and repairs of tourist trails is in the tens and sometimes hundreds of millions of crowns. For example, in 2014, KRNAP planned to repair 97km of tourist trails and stream beds for 150 million CZK (Drahný, 2014). Most of this amount came via EU-funded projects and the majority of the funding was invested in repairs of the damaged trail surfaces and the trail water drainage systems (Drahný, 2014).

According to the type of surface, trails in Krkonoše Mountains NP can be categorized in the following way: compacted earth, stone-tiled path, stone-pitched path and wooden path (Novotný, 2007). Locally sourced compacted weathered granite gravel (CWGG) (see Figure 4) called 'perk' in Czech, which is used on Krkonoše's trails to replace the non-native alkaline gravel, belongs amongst the compacted-earth category of surfaces.

In the last two decades, a traditional path-building technique of stone-pitching has been brought back to life. This technique uses stones of a minimum length of 30cm (Novotný, 2007). These stones are pitched on their longest narrow side next to each other. Smaller stones are then wedged in the gaps between the stones so that the whole structure is firmly fixed. Large boulders form the edges of such a trail (see Figure 5). This type of trail is constructed manually and requires specific skills and knowledge of the technique. Well-constructed stone-pitched trail can survive extreme weather conditions and remain functional for decades (Novotný, 2015).

Figure 4 Trail with compacted weathered granite gravel surface (Photo:Author)

Figure 5 Trail with pitched-stone surface (Photo: Author)

Technical features that guide water away from trails are also important components of trail construction. Novotný (2007) states that with the increasing frequency of torrential rain and flooding events, it is necessary to put into place such measurements that will minimize the erosive power of water, which means the installation of frequent water bars and in some cases changing the slope of the trail or the cross-section of the slope. In the recent years, the so-called Bavarian method has been used for removal of water from trails (Drahný, 2014).

6.1 State of the studied trails

All of the studied trails are located in the 1.zone of KRNAP. They have been marked and used as tourist trails for decades. It is important to point out that all of them have a constructed surface (although not all of them for the entire length of the trail) and they have been regularly maintained. All the studied trail sections are nowadays property of KRNAP. The following section focuses on description of each studied trail section, with particular focus on the observed level of erosion.

6.1.1 Růžová Hora – Sněžka (yellow trail)

This is by far the most popular trail in Krkonoše NP. This trail starts at the bottom station of the chair lift going to Sněžka and climbs in the same direction. The studied trail section starts at the southern saddle of Sněžka and finishes on the top of the mountain. This section of the trail is predominantly surfaced with pitched stone and compacted weathered granite gravel. Steps with a metal face have been used at the steepest sections of the trail. Construction of this part of the trail was conducted in 1997-9 and it was one of the first trails where the technique of stone pitching was used in modern times. The extensive use of the trail and flaws in the construction mean that signs of trail erosion clearly visible today (loose stones, originally 15cm high steps eroded to a depth of 30cm (Figure 6), sediment in water bars).

Figure 6 Trail to Snezka - eroded steps (Photo: Author)

6.1.2 Sněžka – Jelenka (red and blue trail)

A ridge trail passing along the Czech – Polish border above the tree line, through geomorphological areas typical for the Krkonoše Mountains called ‘stone seas’. These are strictly protected areas displaying geological processes active for hundreds of thousands of years that form the shapes and positions of stones, and therefore keeping tourists on the path is highly desired. The surface of a large part of this trail is covered by pitched stone, which was mainly constructed in 2012. Erosion is manifested as sediment (gravel, small and larger stones) in water bars and parallel ditches (Figure 7).

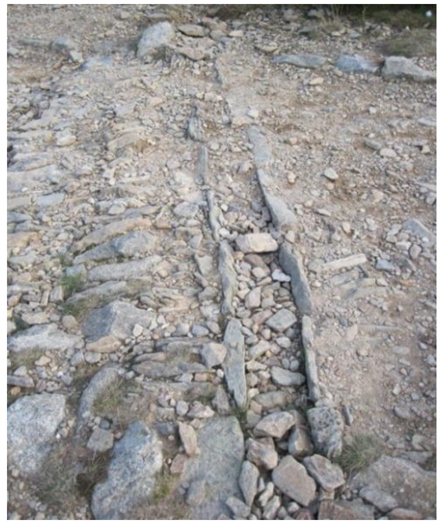

Figure 7 Sediment in water bars – Jelenka trail (Photo: Author)

6.1.3 Obří důl (blue trail)

A trail that runs through the steep valley of Obří důl (‘Giant Mine’) and is a popular access route to Sněžka, though it is not accessible in winter due to avalanche danger. The upper parts of the trail are steep and combine stone sections (tiled and pitched) with compacted weathered granite gravel (Figure 8). The latest reconstruction in 2011 focused on some of the most eroded sections, where erosion had forced people off the trail. Today, the repaired segments show minor signs of erosion, such as sediment traces at the orifice of water bars, and the top layer of compacted weathered granite gravel has been washed away in some places to reveal underlying stones.

Figure 8 Reconstructed (left) and old (right) sections of trail through Obří důl (Photo: Author)

6.1.4 Harrachovy Kameny – Růženčina zahrádka (red trail)

This trail section is a part of a trail starting at Jestřábí boudy. It is a gently sloping trail on the edge of a plateau. The trail was surfaced with compacted weathered granite gravel (CWGG) along its whole extent in 2009. Erosion signs, such as removed fine particles of the top layer and revealed stones from the underlying layer of the trail surface, but a minimal amount of sediment in water bars, indicate that wind is the prevailing erosive agent in this area.

6.1.5 Pramen Labe – Česká budka (yellow trail)

This short stretch is a part of a longer trail starting at the crossing of tourist trails called U Čtyř pánů. As this trail leads to one of the landmarks of Krkonoše and a point of national interest – the spring of the river Labe - it belongs among the popular routes and therefore is very wide. The latest reconstruction in 2007 built a CWGG surface. Only minor visible erosion signs indicate that the erosive agent is wind as well as water - several places with exposed stones from the underlying layer of the path, some granite gravel sediment found in the water bars orifices and in the surrounding vegetation (Figure 9).

Figure 9 Recently cleaned water bar orifice - Pramen Labe trail (Photo Author)

6.1.6 Tvarožník - Vosecká bouda (red and yellow trail)

Figure 10 Trail to Tvarožník - prior to the reconstruction (Photo: KRNAP)

This trail partially follows the border with Poland (red trail) and turns to the South towards Vosecká bouda at a point called Svinské kameny (yellow trail). This trail is one of many where alkaline gravel was used. During the latest reconstruction, which was completed in autumn 2014, the alkaline material was removed and replaced with locally sourced CWGG. The steepest parts of the trail were surfaced using the pitched stone technique. As the reconstruction was completed only several weeks before the data collection, no signs of erosion could be detected on this trail. Based on the pre-reconstruction photos (Figure 10) and a discussion with the Head of the Department of Investments, the trail has been included among those suffering predominantly from water erosion.

6.1.7 Vosecká bouda to Krakonošova snídaně (yellow trail)

The studied trail section is a 1-km-long CWGG part of this trail. It begins by the Vosecká chalet and finishes by an asphalt road at a point called Pod Voseckou boudou. This route is the only one that is not purely pedestrian as it serves as an access route for cars delivering supplies to Vosecká bouda, and since 2010 also for cyclists. Clear signs of erosion are visible on this trail – ruts created by cars, holes, and in some places removed fine top-layer material as well as gravel (see Figure 11). Metal water bars and the parallel ditch show sediment run-off from the trail.

Figure 11 Vosecká trail - ruts with eroded CWGG (Photo: Author)

6.1.8 Hanč & Vrbata Memorial and Lookout to Pančava waterfall (red trail)

Both trail sections are a part of one trail leading from Vrbatova bouda to Labská bouda, which runs along the western edge of Labský důl. The trail passes by several points of interest and can be accessed by bus; it therefore belongs among the most popular tourist paths. The section from Hanč & Vrbata Memorial to the Pančava waterfall lookout was reconstructed in 2012 and now has a CWGG surface. The lookout point and the following stretch of the trail towards Labská bouda are mainly formed of compacted earth. Erosion is visible in both sections, the first part shows washed out gravel, which can be found in water bars and uncovered large boulders on the trail. The erosion signs in the second part of the trail are much more prominent – eroded rills, the top layer washed away, revealed underlying stone layer, and multiple treads (see Figure 12).

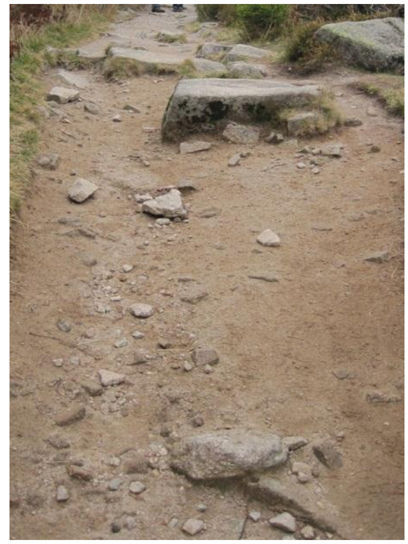
Figure 12 Eroded trail at Pančava waterfall (Photo: Author)

6.1.9 U Čtyř pánů - Krakonošova snídaně (blue trail)

The studied trail section lies at the upper end of the trail. In this section, the trail is almost flat as it copies the terrain of a plateau called Mumlavská louka. It is situated above the tree line, surrounded primarily by dwarf pines and grasses. The surface of this trail section is covered with CWGG and it is equipped with stone water bars and a parallel ditch on both sides of the trail. Erosion is demonstrated as a removed top layer in some parts of the trail (particularly in the middle of the trail, where the constructed surface was highest) and visible under-layer stones. Clean water bars and ditches suggest that wind erosion is the prevailing force carrying the detached material away.

6.1.10 Horní Mísečky – Jestřábí bouda (yellow trail)

Yellow trail running uphill from Horní Mísečky represents an alternative route to the red trail, which follows the asphalt road. It has been acquired by KRNAP only in 2013 from the municipality of Vítkovice. The trail surface was covered partially by alkaline gravel (see Figure 13) and in some sections by stone; the majority of the trail is, however, compacted earth. The trail had not been maintained appropriately and thus the man-made sections are in a very poor state. Rill erosion, loose boulders and eroded fine particles can be observed along the course of the trail. The parallel ditch, where it exists, is


Figure 13 Eroded trail to Jestřábí bouda with alkaline material (Photo: KRNAP)

overgrown and has lost its function. A short stretch of the trail (approx. 200m in the upper, steep part of the trail) was repaired in 2014. The basic material was removed and replaced by a stone-pitched surface with stone water bars and a parallel ditch.

6.1.11 Kotelní Jámy (part of a green trail Benzina-Dvoračky)

The studied section of said trail is located in the lower part of the ravine called Malá Kotelní Jáma. The trail is not accessible in the winter season due to the high risk of avalanches. It is the only section of the trail with a stone surface. A zig-zag direction and stone steps were put in place to mitigate the steep slope. Although it lies in the tree zone, thanks to the steep slope of the terrain and the winter conditions, no trees are surrounding this trail section. Some water erosion signs were identified on site (erosion rills, loose boulders, removed soil); however, according to the Head of the Department of Investment, it is the movement of snow during winter and early spring that is the most severe erosion threat for this trail.

6.1.12 Labská bouda - Špindlerův mlýn (blue trail)

The section of the trail that this study focused on lies directly under the chalet Labská bouda. It is the steepest part that passes by a waterfall (Labský vodopád) and then continues in zig-zag towards the bottom of the valley (Labský důl). The very top part of the trail is constructed as CWGG in wooden frames, which form steps. This part was built approximately 15 years ago and weathering of the materials as well as erosion is clearly visible (Figure 14) – removed top layer of the trail, underlying stones revealed and loose stones. Some eroded spots have led tourist to finding alternative routes and multiple treads and trail widening can therefore be found here too.

Figure 14 Erosion on trail to Labský důl (Photo: Author)

6.1.13 Kotelské sedlo – Dvoračky (red trail)

This trail section is fairly uniform, with compacted earth and local material covering the surface. Its upper part starts above the tree line and the lower part finishes in the forested zone. The erosion signs indicate that water is the major erosive agent – many of the water bars and sediment holes are filled with top layer material, gravel and even larger stones; the stone underlying layer is revealed in some places and shallow erosion rills can be detected.

Overview of the state of the financial cost related to trail erosion in the above-described studied trails is provided in Figure 15.

Figure 15 Financial costs of erosion to the mapped trails

Trail code in KRNAP records	Trail code for this study	Trail name	Constructed surface	Investment costs [CZK]	Maintenance and repairs 2009-14 [CZK]	Date of last known reconstruction
3427	1	Rúžohorky - Sněžka	pitched stone, CWGG	6,361,000	0	1997-8
3426	2	Sněžka – Jelenka	pitched stone	1,053,000	364,000	2012
3431	3	Obří důl	CWGG, tiled stone	3,640,000	190,000	2011
3460	4	Růženčina zahrádka	CWGG	1,993,000	152,000	2009
3454	5	Pramen Labe - Česká budka	CWGG	780,000	283,000	2007
3451	6	Vosecká bouda - Tvarožník	pitched stone, CWGG / prior 2014 - compacted earth, gravel	2,900,000	417,000	2014
3057	7	Vosecká bouda - Krakonošova snídaně	CWGG	0	648,000	not found
3169	8, 9	Hanč and Vrbata Monument and Pančava waterfall	CWGG	707,000	67,000	2012
3452	10	Krakonošova snídaně - U Čtyř pánů	CWGG	582,000	0	2010
3459	11	Horni Mísečky-Jestř.bouda	pitched stone (cca 300m)	650,000	40,000	2009 / short section in 2014
3461	12	Kotelní Jámy	tiled stone (cca 300m)	0	287,000	2010
3177	13	Labská bouda - Špindlerův mlýn	CWGG, pitched stone / prior 2014 - CWGG	114,000	76,000	2014
3455	14	Kotelské sedlo	CWGG	0	225,000	before 2007

7. RESULTS

7.1 Tourist trails threatened by erosion caused by snow

There is only one studied trail section that is subject to snow-driven erosion. It is trail number 12 Kotelní jámy (see Appendix 1). Comparative analysis could not be conducted due to the lack of data from other trails, so spatial analysis of the trail surrounding's natural characteristics (slope of the terrain, aspect of the terrain, geology, soil type, elevation and precipitation) was conducted.

The resulting map (see Appendix 2) shows areas with aspect of 112°-247° (i.e. oriented towards the southwest, west and southeast), slope angle between 35° and 55°, precipitation of 1265mm/year and more, lying on schists and phyllites and on Histosol or Stagno-gleyic Cambisol, and in an elevation above 1200 m.a.s.l. (above the tree-line). The largest such localities can be found in the surveyed area of Kotelní jámy, on the western side of Labský kotel near Pančavský and Hančův waterfalls, and also on the northern face of Labský důl above Labský waterfall. Smaller patches are located in Martinova jáma, near Brádlerovy boudy and along the upper parts of Velká Mumlava and Malá Mumlava streams. Only two of these areas have a tourist trail running directly below them - Kotelní jámy and Martinova jáma. These two green tourist trails are the only identified paths with a potential of snow erosion damage.

7.2 Tourist trails threatened by wind erosion

Three of the studied trail sections were identified as showing signs of wind erosion – trails number 4 (Harrachovy kameny - Růženčina zahrádka), number 5 (Pramen Labe - Česká budka) and number 10 (U Čtyř pánů - Krakonošova snídaně).

Comparison of data gathered for the wind-erosion impacted trails yielded the following results (see Appendix 3):

- trail surface (compacted weathered granite gravel), surrounding vegetation (grass) and underlying soil (Ferro-Humic Podzol) corresponded in all three trails,

- trail and terrain slope (≤ 5°), terrain aspect (North-northwest to South-southwest or open), geology (two types of medium-grained granite) and elevation (≥ 1330 m.a.s.l.) were alike, and
- precipitation as well as the number of pedestrian passes varied; however, in all trail sections, the values exceeded 1265mm/year and 13550 passes respectively.

Based on the above results, characterisation of localities and trails that have the potential to suffer from wind erosion can therefore follow: lying on medium-grained granite and Ferro-Humic Podzol, above 1330 m.a.s.l (above the tree line), in a terrain of a slope of less than 5 degrees, with an open aspect or oriented towards a North-northwest to South-southwest direction. The trails have a slope of less than 5 degrees, they are surfaced with CWGG and the number of pedestrians passing exceeds 13550 in a year. Precipitation was not included in the characterisation of the trails as water is not a factor linked with wind erosion.

Extrapolation of these characteristics to a map of the whole national park shows that there are four areas where such trails can be found (see Appendix 4). The first area is the plateau between the mountain tops of Kotel, Violík and Sokolník. The second is located along the Liščí hřeben ridge. The third locality can be found on the plateau surrounding Luční bouda. The fourth, and smallest, area is located south of Svinské kameny.

Eleven trails (or their sections) were determined by spatial analysis as those that fulfil the criteria for the occurrence of wind trail erosion:

- Pramen Labe – Česká Budka
- U Čtyř pánů – Krakonošova snídaně
- Růženčina zahrádka – Kotelské sedlo
- Vrbatova bouda – Labská bouda
- Vosecká bouda - Labská louka
- Vosecká bouda – rozcestí Svinské kameny

- Na Rozcestí - Liščí louka
- Luční bouda – Rennerova studánka
- Luční bouda – Bouda U Bílého Labe
- Luční bouda – border crossing Rownia pod Sniezka
- Luční bouda – Obří sedlo

The top of Stoh Mountain as well as the southern ridge below the top of Stříbrný hřbet Mountain also came out of the spatial analysis as potentially threatened by wind erosion. No tourist trails run through these areas, which is why none have been identified here.

Areas of surface prone to wind erosion were identified also around Klínové boudy, below Svorová hora, along Lesní hřeben ridge and along the ridge line between Velký Šišák and Dívčí kameny. Although these localities are intersected by tourist trails, for the reasons discussed in the following chapter, these trails are not highlighted as prone to wind erosion.

The wind-erosion prone localities on the Černá hora Mountain and between Růžová hora and Růžohorky, which are also displayed on the map, cannot be considered as relevant. The reasons for this are explained in Chapter 8.

7.3 Tourist trails threatened by water erosion

Ten of the fourteen trails show signs of water erosion. Analysis of their characteristics revealed that there are no factors that would correspond exactly in all trail sections (see Appendix 5). In fact, the variety of features in many characteristics (vegetation, geology, soil type, trail surface and aspect) covered all possibilities in the areas of the NP above 1200 m.a.s.l.. It can thus be stated that the surveyed trails classified as eroded by water have these characteristics:

- slope of the trail between 3 and 20 degrees
- slope of the terrain at least 3 degrees
- elevation above 1200 m.a.s.l.

- precipitation above 1070mm per year
- at least 20000 tourist passes per year
- aspect of any direction apart from open aspect
- any type of vegetation, geology, soil that can be found above 1200 m.a.s.l.
- any type of trail surface

Areas and trails in Krkonoše prone to water erosion are likely to show similar characteristics. Extrapolation of these characteristics onto a map of KRNAP was conducted and the outcome shows areas and trails that might have predispositions for water erosion.

As the final map reveals (see Appendix 6), the area of potential or actual water erosion forms almost a continuous strip stretching along the top of the main mountain ridge from Harrachov in the West to Pomezní boudy in the East. It also juts out to the perpendicular ridges and plateaus, the most prominent being the plateau and ridge top between Sokolník, Lysá hora and Medvědín; the ridge top from Bílá louka to Světlý vrch extending to Stoh and Liščí hora; and the southern ridgeline of Sněžka all the way to Růžohorky. A separate locality is found on Černá hora and nearby Světlá Mountain.
Eighteen trails came out of the spatial analysis of water erosion criteria:

- Sněžka – Jelenka
- Sněžka – Růžohorky
- Obří sedlo – Obří důl
- Obří sedlo – Luční bouda
- Luční bouda – border crossing Równia pod Śnieżka
- Luční bouda – Úbočí Kozích hřbetů
- Luční bouda – Údolí Bílého Labe
- Luční bouda – Na Rozcestí
- Na Rozcestí – Liščí louka
- Růženčina zahrádka – Dvoračky
- Vrbatova bouda - Labská bouda
- Hanč and Vrbata Memorial

- Labská bouda – Labský důl
- Labská bouda – Martinovka
- Martinovka – rozcestí Pod Smielcem
- Pramen Labe – Česká budka
- Vosecká bouda – Svinské kameny
- Vosecká bouda – Pod Voseckou boudou

Similar to the map of wind-erosion prone areas, there are areas on the map where trails are not identified as threatened, even though there are tourist trails running through these localities. The most obvious is the area at Černá hora. The other areas are Lesní hřeben, Světlý vrch and Stoh, and the Labská louka plateau. The reasons for the lack of identified trails are discussed in the following chapter.

No indicative similarities were identified among the characteristics within the category of water-eroded trails during further analysis.

7.4 Financial cost of the trails

7.4.1 Total cost

The below table (Figure 16) shows the direct financial cost of erosion for each of the surveyed trails. The trails were ordered from the most to the least expensive to demonstrate the differences.

Figure 16 Direct cost of erosion on surveyed trails

Trail code	Trail name	Total cost
1	Růžohorky - Sněžka	**6,361,000.00**
3	Obří důl	**3,830,000.00**
6	Vosecká bouda -Tvarožník	**3,317,000.00**
4	Růženčina zahrádka	**2,145,000.00**
2	Sněžka - Jelenka	**1,417,000.00**
5	Pramen Labe - Česká budka	**1,063,000.00**
8, 9	Hanč and Vrbata Monument and Pančava waterfall	**774,000.00**
11	Horní Mísečky – Jestřábí bouda	**690,000.00**
7	Vosecká bouda - Krakonošova snídaně	**648,000.00**
10	Krakonošova snídaně - U Čtyř pánů	**582,000.00**
12	Kotelní Jámy (part of trail Benzina-Dvoračky)	**287,000.00**
14	Kotelské sedlo (part of trail Od staré Hájenky - U čtyř pánů)	**225,000.00**
13	Labská bouda - Špindlerův mlýn (blue trail)	**190,000.00**

7.4.2 Annual average maintenance cost (AAMC)

Analysis of the financial data revealed that the AAMC ranges from 176.000,- CZK to less than 1000,- CZK (see Figure 17).

Figure 17 The most and least expensive trails according to AAMC

Trail code	Trail name	AAMC
2	Sněžka – Jelenka	**176,000.00**
7	Vosecká bouda - Krakonošova snídaně	**108,000.00**
6	Vosecká bouda -Tvarožník	**82,000.00**
12	Kotelní Jámy (part of trail Benzina-Dvoračky)	**55,000.00**
5	Pramen Labe - Česká budka	**47,000.00**
14	Kotelské sedlo (part of trail Od staré Hájenky - U Čtyř pánů)	**38,000.00**
13	Labská bouda - Špindlerův mlýn (blue trail)	**31,000.00**
4	Růženčina zahrádka	**30,000.00**
3	Obří důl	**22,000.00**
8, 9	Hanč and Vrbata Monument and Pančava waterfall	**20,000.00**
11	Horní Mísečky – Jestřábí bouda	**20,000.00**
1	Růžohorky – Sněžka	**0.00**
10	Krakonošova snídaně - U Čtyř pánů	**0.00**

7.4.3 Annual average total cost (AATC)

The last analysis performed with the AATC shows the range from 1.230.000,- CZK to 20.000,- CZK (see Figure 18).

Figure 18 Trails cost according to AATC

Trail code	Trail name	AATC
3	Obří důl	**1,230,000.00**
2	Sněžka – Jelenka	**702,500.00**
4	Růženčina zahrádka	**429,000.00**
1	Růžohorky – Sněžka	**374,176.47**
8, 9	Hanč and Vrbata Monument and Pančava waterfall	**373,500.00**
5	Pramen Labe - Česká budka	**158,428.57**
10	Krakonošova snídaně - U Čtyř pánů	**145,500.00**
7	Vosecká bouda - Krakonošova snídaně	**108,000.00**
6	Vosecká bouda -Tvarožník	**82,000.00**
12	Kotelní Jámy (part of trail Benzina-Dvoračky)	**55,000.00**
14	Kotelské sedlo (part of trail Od staré Hájenky - U čtyř pánů)	**37,500.00**
13	Labská bouda - Špindlerův mlýn (blue trail)	**31,000.00**
11	Horní Mísečky – Jestřábí bouda	**20,000.00**

The additional analysis of the total cost did not indicate any correlation with the trail surface; however, correlation between the total cost and the number of tourist passes was revealed, showing a correlation factor of 0.634. This moderate positive relationship as displayed in a graph (see Figure 19) indicates that more tourists means that higher cost had to be invested into reconstruction and maintenance (or vice versa), regardless of the trail surface.

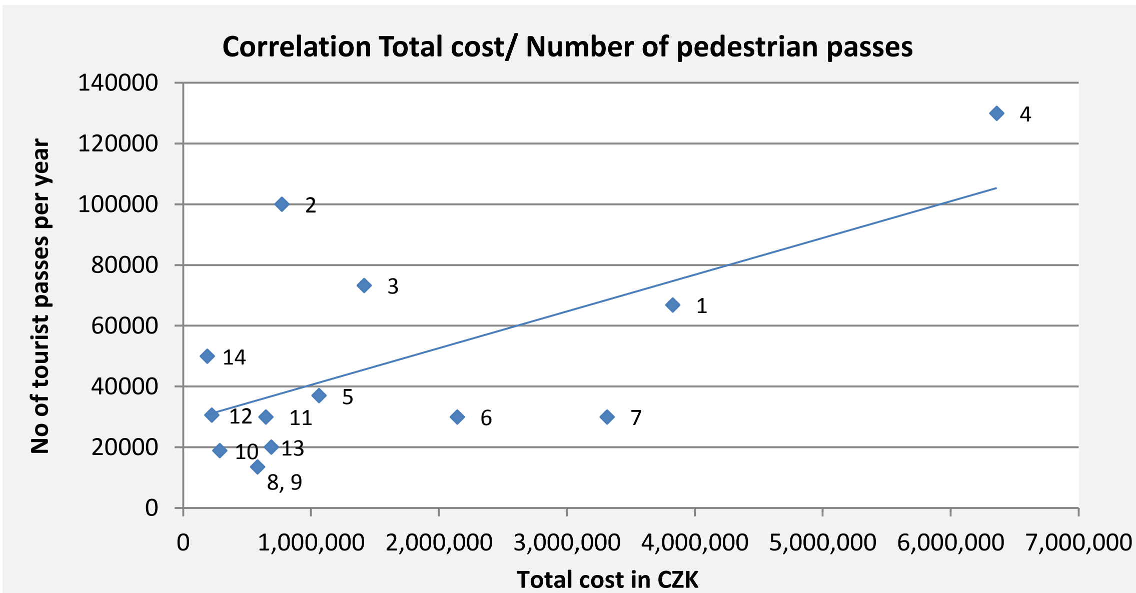

Figure 19 Trails (trail codes) displayed in a positive correlation between the Total cost and the number of pedestrian passes per year

8. RESULTS INTERPRETATION AND DISCUSSION

8.1 Interpretation and discussion of trail erosion results

8.1.1 Interpretation of snow erosion results

As mentioned in the previous chapter, there are two identified trails with a potential for snow erosion. In fact, only one trail can be considered to have potential, as the other was part of the mapping and thus is an existing, not a potentially problematic, area. The identified result shall be interpreted in the following way: the tourist trail running under Martinova jáma displays the same characteristics as the surveyed trail and thus has the potential to suffer from snow erosion. Whether this trail is already suffering from snow erosion would need to be assessed by a confirmatory measurement.

As to the results of the identified areas threatened by snow erosion, these shall be understood as localities, in which trail erosion caused by snow movement might happen or is happening. The author, however, acknowledges that the results can by no means be taken as comprehensive and have many limitations.

The first limitation comes from the fact that some assumptions and generalisations had to be made for the spatial analysis. The natural characteristics of the surveyed trail suffering from snow erosion selected for extrapolation were those that are assumed have influence over the accumulation of snow and its downward movement, i.e. precipitation, aspect, elevation (above the tree-line), geology, soil type and slope of the terrain. Even though the slope of the terrain at Kotelni jamy was 35°, the extrapolation was conducted with a value range of 35 to 55 degrees. That is because above 55 degrees snow is physically not able to hold to the slope (Marynčák, 2010). Also, precipitation in the trail section was taken as the bottom threshold and it was assumed that higher precipitation would only enhance the potential erosion problem, and so the value range of 1265mm/year and more was used as a criterion. Characteristics of the trail (number of tourist passes, slope, aspect, surface and technical features of drainage) were not included into the extrapolation criteria, as it is assumed that they have no influence on the occurrence of areas with potential for snow erosion. Trails are simply ‘in the way’ of it.

The second and more important limitation is that the natural characteristics used for spatial analysis of the whole national park were based on only one identified trail. No comparison to any other trails with a similar issue could therefore be conducted. Such comparison could reveal that any of the natural characteristics used for extrapolation can be different and thus the outcome of the extrapolation would be different. For instance, if annual precipitation was lowered to 1050mm, areas around Sněžka such as Obří důl or Studniční Jámy would be identified as potentially threatening to trails. This does not mean that the identified areas are not threatened by snow erosion, but it is important to emphasize that these are most probably not all of the areas where snow erosion to trails happens or might happen.

A survey specifically focusing on snow erosion on trails needs to be conducted in order to identify key characteristics that play a role in this type of trail erosion.

8.1.2 Interpretation of wind erosion results

The result of the wind-eroded trail characteristics’ analysis indicates that eleven trails in Krkonoše National Park are prone to wind erosion. As expected, these trails contain the surveyed ones, namely Pramen Labe - Česká budka and U čtyř pánů - Krakonošova snídaně. The fact that the last of the surveyed trail sections is not among the presented trails is due to the fact that only trail sections where tourist counters are located (see Methodology on how such sections were determined) were included into the spatial analysis. The surveyed section Harrachovy kameny - Růženčina zahrádka is not one of such sections and the number of annual tourist passes for this trail section was an estimate, as acknowledged earlier.

While it can be stated that the nine newly identified trails have characteristics corresponding to the surveyed trails and therefore are likely to be prone to wind erosion, it cannot be claimed that the map shows all trails with the same features within the perimeter of the national park. This is again caused by the limitation of the locations of tourist counters. It is highly possible that at least some of the tourist trails crossing the wind erosion areas of Klínové boudy, Svorová hora, Lesní hřeben ridge and the ridge line between Velký Šišák and Dívčí kameny have a frequency of tourists exceeding 13550 passes per year and consequently they should be included in the final map. Moreover, keeping in mind that the number of tourist passes criterion for the spatial analysis was based on just three trails, additional research needs to be conducted in order to establish whether the number of tourist passes at all indicates the relevant threshold, or whether it should be lower.

Some of the trail sections identified as potentially threatened by wind erosion overlap with the surveyed trail sections categorized as suffering from water erosion. These are specifically Růženčina zahrádka-Kotelské sedlo (partially overlapping with surveyed trail no. 14), Vrbatova bouda–Labská bouda (partially overlapping with trail section no. 9) and Vosecká bouda–rozcestí Svinské kameny (partially overlapping with trail no. 6). Although these trails cannot be used to prove the correctness of the analysis (one trail has recently been reconstructed and shows no signs of erosion and due to weather conditions it was not possible to assess signs of wind erosion at the other two trail sections), in retrospect, all of them have the potential to be subjected to wind erosion. Nevertheless, further observation of all newly identified wind erosion trails is necessary to confirm the accuracy of the analysed criteria.

Apart from the trails, the final map also shows localities identified as prone to erosion (the areas are listed in the previous chapter). These localities shall be interpreted as areas that exactly match the wind erosion terrain selection criteria (i.e. all criteria without the tourist passes and trail surface and slope). As such, they are potentially (or actually) threatened by wind erosion.

However, here the limitations of the results are also important to take into consideration. The selection criteria for the areas were based on the description of only three trails. Should any of the criteria be broadened, the map of the identified localities would look different and would certainly include many more localities. There are some valid indications (e.g. a wind erosion effect on Sněžka) that the criteria for the angle of slope, aspect or soil type might be much broader than considered in this study. Furthermore, some factors, which were not considered in this study, such as wind speed and direction, as well as morphology of the terrain, might play an important role. It could be argued that if these criteria were taken into account, the resulting map might not include some of the areas identified currently. Needless to say, if the criteria changed for the areas then there would be many more trails identified as potentially threatened by wind erosion.

The final note belongs to the areas of Černá hora Mountain and between Růžová hora and Růžohorky. Both of these localities are situated within forested areas and therefore are not considered as significant. Grass was found to be one of the matching characteristics for all three surveyed wind-eroded trails; however, it was not possible to make the type of vegetation a selection criterion for the spatial analysis (no map data for vegetation cover was available). The elevation criterion was used to partially compensate the missing information about vegetation cover. The Alpine upper treeline in Krkonoše lies between 1200 and 1350 m.a.s.l. (KRNAP, 2010) and therefore only areas without trees should have appeared in the results. In the two above mentioned cases, this was not the case.

To summarize, the identified localities (with the exception of the two previously named areas) and trails are potentially or actually suffering from wind erosion. Further research would establish if these areas and trails can also be found elsewhere in KRNAP.

8.1.3 Interpretation of water erosion results

The identified areas threatened by water erosion are essentially all parts of Krkonoše Mountains that lie above 1200m.a.s.l and have a slope exceeding 3°. (Precipitation selection criterion included the entire extent of KRNAP and thus was not relevant). The interpretation of this result is that in all these areas trail erosion caused by water happens or can happen. It can be argued that the elevation criterion might not be relevant for water erosion on trails. Although it is true that it might not directly influence erosion occurrence, it is understood that with increasing altitude the amount of precipitation also increases (KRNAP, n.d.a). That being said, it is likely that there are areas in Krkonoše likely to suffer from trail water erosion that extend below the altitude of 1200 m.a.s.l.

As mentioned in the Results chapter, there are areas identified as prone to water erosion, where, despite being intersected by tourist trails, such trails are not identified on the final map. The reasons behind this are mainly that they either do not have a counter, or the frequency of tourist passes is below 20000 per year. It is also possible that some trails are not identified because their slope is below 3° or above 25°. There are, however, not many official tourist trails over 25° in Krkonoše.

The eighteen indicated trails include nine of the surveyed ones. The tenth assessed trail which did not come up among the results is the yellow tourist trail Jestřábí bouda – Mísečky. The reason is again that this trail does not have a counter and the pedestrian passes were estimated. The selection also includes one trail (Pramen Labe – Česká budka) which was classified as wind-eroded. However, signs of water erosion were noted on this trail too. Furthermore, assessment of trail no. 4 (Harrachovy kameny - Růženčina zahrádka), also classified as wind-eroded, indicated a water erosion problem too. This trail is not included among the identified trails, but that is only because of the missing people counter. The estimated number of tourists in this section is around 30000. There is one other surveyed trail that is located in the same area - trail no. 10 (U Čtyř pánů - Krakonošova snídaně). This trail is not identified as prone to water erosion based on the number of tourist transits (13550 per year). No signs of water erosion were noticed on this trail. The above evidence suggests that the number of tourists plays an important role in water erosion and the lower threshold lies somewhere between 13550 and 20000 passes per year. Such finding contradicts the conclusions of the research by Suchý et al (2006) and Vítek & Vítková (2000) and supports the theory of the Head of the Investment Department. However, this would have to be proven by research focusing on the link between the number of pedestrians and water erosion on trails with constructed surfaces.

It is important that the results within all three types of erosion are interpreted in light of the fact that all of the surveyed trails were concentrated in just two areas, both of which are located on or near to the ridge tops and are the most visited parts of the mountains. Should further research be conducted, it should include a variety of trails of different altitudes, popularity and parts of the national park. Such a variety could result in either a larger variety of characteristics and thus enlarge the potentially threatened areas, or would result in a confirmation of the limits applied in this study.

8.1.4 Discussion of trail erosion results

It could be argued that although it is possible to state with a fairly high degree of certainty that erosion of some kind or another will appear in the above-described areas and trails, this diploma thesis does not provide an answer to the questions of how much erosion will occur there. This is a relevant argument; however, it is not possible to determine the level of erosion as there are currently no models that can be used to estimate soil loss (or rather material loss) on trails in the same manner as USLE is used for the agricultural land. The existing research, which focuses on predicting trail erosion, such as the model created by Selkimaki & Mola-Yudego (2011), is based on measurements of natural trails. Models or research concentrating on trail erosion on the managed trails or trails with man-made surfaces have not yet been described in literature. In addition, there is one more aspect connected to the level of erosion and that is that it is not known what is the acceptable level of erosion. Such a level is known for agricultural land (4t/ha/year in the Czech Republic), but again, not enough research has been conducted in this area to know what the acceptable level of material/soil loss from trails is. Cole (2004) suggests that it is the park managers who need to decide on the acceptable level of impact.

This diploma thesis did not study the combinations of different characteristics or how strongly they affect trail erosion. Combinations and the power of individual factors certainly affect the erosion rate but they are very difficult to study and there is also a lack of research in modelling trail erosion that would take the two into account (Selkimaki & Mola-Yudego, 2011). The existing models do not always consider all important factors, such as precipitation (Selkimaki & Mola-Yudego, 2011) and their other shortcoming is, again, that they are designed for natural trails.

Finally, an argument could be raised that the extent of erosion on the surveyed trails was not considered. This is because the data gathering process revealed that all of the surveyed trail sections have been maintained and most of them have or had a man-made surface. In order to obtain erosion data that would be comparable to other trails, many factors would have to be taken into account. Factors such as the type of surface, year of its construction, frequency and quality of the maintenance, suitability of the water drainage solution, and the quality of the construction would have to be assessed. Not only did the extent of such an assessment exceed the possibilities of this diploma thesis, but also there is no established methodology on how to conduct such an assessment. Many methods were developed on how to measure eroded trails (Jewell & Hammitt, 2000, Ramos-Scharrón et al, 2014). None of them, however, suggests how to compare the results in light of the above-listed factors. Because the observed erosion signs of individual trails did not provide comparable information, the initially intended correlation analysis of erosion and trail characteristics was not conducted.

8.1.5 Discussion of methodology

The choice of trails to be surveyed was a crucial first step in the mapping. The method of 'expert judgement', which was used to select the erosion hotspots was chosen because of Mr Novotný's (the Head of the Department of Investments) extensive knowledge of the studied subject. He has worked in KRNAP for over 30 years and is responsible for management of tourist trails. Conversations with Mr Novotný revealed that many signs of erosion on trails are the results of a one-off torrential rainfall event and therefore could be misleading when judging how much a particular trail is affected by erosion in the long run. The result of the discussion with Mr Novotny led to a list of trails that are frequently, and over many years, problematic in terms of significant erosion. The acknowledged weakness of this method is that the correctness of the list of trails could not be checked. However, expert judgement and other methods based on the assessment by NP workers are not uncommon in other studies (Torn et al. 2009).

Map data received from KRNAP contain information about the trails' surfaces; however, this information does not distinguish the various surfaces of unpaved trails. For this reason, selection of trails with the compacted weathered granite gravel was conducted manually as a part of the spatial analysis of wind erosion. The author acknowledges that this method would not be appropriate to use for the whole extent of KRNAP trails; however, there were very few identified trails and thus this method was used as the most efficient.

8.2 Discussion of financial cost results

The Total Cost gives an idea of the amount of money invested in each of the surveyed trails. Looking at each individual trail provides important information about the direct cost that erosion prevention and damage has caused in that particular erosion hotspot.

The other way of looking at the Total Cost (i.e. looking at the most to least expensive order) should by no means be interpreted as 'the cheapest is the best'. This order mixes trails with different constructed surfaces (N.B. different types of surfaces have different prices per m^2), different lengths of the constructed surface, and it also does not indicate how long a certain reconstructed section lasted. The last mentioned aspect is an important indicator for trail managers, as it might indicate suitability of a certain surface for a given trail.

The results of AAMC reveal which are the most expensive trails among those surveyed in terms of annual investment into their maintenance. Even though this index is relatively meaningful even without the information about the length, the order does not mean that the most expensive ones are those with the largest erosion problem and those where no money was invested did not need maintenance. For instance, trail no. 1

Růžohorky – Sněžka had nothing invested into its maintenance in the last six years, but it is now so eroded that a new reconstruction of the whole trail is planned for 2016. From this viewpoint, it is necessary to take into account the cost of the reconstructions. Caution when using and interpreting the results of the maintenance cost should be taken for the following reason. From the records provided by KRNAP, it was difficult to distinguish what are the actual items hidden within the maintenance costs. It is therefore possible that some costs should be considered as investment, rather than maintenance.

The AATC results mean that a given trail costs the indicated amount of money every year, including the initial investment. Even this indicator is, however, problematic and it cannot be stated that, for instance trail no 3 Obří důl, will cost 1.2 million crowns every year. The indicator does not measure the cost for the whole life span of a particular surface, but only since the last reconstruction. In the case of trail no 3, the last costly reconstruction was completed in 2011 and thus the whole amount is now spread over only 3 years. To be able to use AATC as an indicator of effectiveness of the invested finance, financial records of the whole time from one reconstruction to the next would have to be taken into account. Most of the trails and records are, however, too new to conduct such analysis.

To summarize the above, the total cost for each trail is meaningful information if taken as such, without comparing it to the costs of other trails. None of the analysis results can be used to determine which is objectively the most and the least expensive trail. Many more factors would have to be taken into account and much longer time is needed to determine whether CWGG, pitched-stone, tiled-stone or another surface is the best choice of investment from a financial viewpoint. As mentioned above, the financial records that the author had access to unfortunately, in most cases, do not provide detailed-enough information about the size of the area of the reconstructions; this was the single most important factor prohibiting the possibility of calculation of a comparable indicator, i.e. price per km/m of a trail. It has also become clear during the study that immeasurable factors, such as quality of the reconstruction and quality and (ir)regularity of maintenance of drainage systems, play an important role in the prevention of erosion and thus have an impact on financial cost.

The attempt to construct an index that could help trail managers discover which type of surface is the best value for money highlights the fact that methodology for analysing the financial cost of trails has not yet been developed. There are plenty of studies on the economic impact of trails (e.g. Bowker et al, 2007; Gardner Pinfold Consulting Economists Limited**,** 1999) but no evidence of analysis of financial cost of trails has been discovered in literature. As the financial aspect of trail management is certainly an important one, such research could bring invaluable information.

The identified correlation between Total Cost and the number of tourist passes indicates that with a growing number of tourists the amount of money invested into the trails also increases. Interpretation of such a result should, however, be done carefully. Causality of the relationship can certainly not be determined form the available data. Furthermore, the results which suggest that a positive correlation between the number of pedestrian passes and the cost of trail surfaces exists are drawn from 13 inputs. Financial data and tourist numbers for more trails would have to be analysed in order to confirm this finding.

9. Conclusion

There are areas and tourist trails in KRNAP that are threatened by wind, water and snow erosion. This diploma thesis identified some of them.

Trails prone to wind erosion can be found at elevations above 1330 m.a.s.l., in open terrain of a slope below 5° and oriented towards the prevailing direction of weather, lying on Ferro-Humic Podzol and medium-grained granite. These trails are surfaced with compacted weathered granite gravel, surrounded by low vegetation and walked at least 13550 times per year.

Trails likely to suffer from water erosion are located in areas above 1200 m.a.s.l. with annual precipitation above 1070mm, on a terrain with a slope of at least 3° of any aspect and on any kind of geology, soil type and vegetation that can be found in this altitude in KRNAP. Water-erosion prone trails are characterised by at least 20000 pedestrian passes per year, a slope of 3°-20° and no difference among the type of the constructed surface used for tourist trails in these altitudes in the Krkonoše NP.

Trails threatened by snow erosion are characterised by an area above 1200 m.a.s.l. with a slope of 35°-55°, oriented towards Southwest – Southeast, with precipitation exceeding 1265mm a year, lying on schists and phyllites and Histosol or Stagno-Gleyic Cambisol that lies directly above the threatened trail.

Although the identified areas and trails are threatened by erosion, the level of erosion was not possible to determine. It was also not possible to determine whether the level of trail erosion in the identified localities will be tolerable or if it exceeds an acceptable level. This is because such a level has not yet been established.

The surveyed erosion hotspots incurred a financial cost between 190 thousand CZK and 6.3 million CZK. These are the costs of damages caused by trail erosion and its prevention. The identified cost of each trail can only be considered within a context of that particular trail. Trail costs cannot be compared to each other because they do not consider the differences between trails, such as the type and the length of the constructed surface. No conclusion can therefore be drawn as to which type of surface is the best investment from a financial viewpoint.

In general, this diploma thesis fulfilled the set objectives as it defined the trail-erosion threatened areas and determined the financial cost of the erosion hotspots. However, the outcomes need to be further processed in order to have a practical use for the management of the national park. The results could therefore be utilized as a solid basis for further research of trail erosion in the Krkonoše Mountains, particularly research in the areas revealed by this work, such as the interaction among various factors influencing erosion, the revealed relationship between the number of tourists and the financial cost of trails, or the recognized link between trail erosion and the number of tourists.

This diploma thesis confirmed the generally acknowledged lack of research in the areas of trail erosion and highlighted the need for further research, particularly in the areas of measuring and modelling trail erosion on managed and maintained trails, and in the intact area of the analysis of the financial cost of managed trails.

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