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Modeling human induced soil erosion hot spots in a medium-sized agricultural catchment in the Thayatal region, Lower Austria

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Authors declaration

Herewith I confirm that this diploma thesis was written by me. I did not use any sources besides those cited as reference. Furthermore, this diploma thesis was not submitted prior to this as an examination paper in any form. This thesis is identical with the version evaluated by the advisor.

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(Stefan Haselberger)

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"Reality is frequently inaccurate."
Douglas Adams (1952-2001)

Abstract (english)

Water-mediated soil erosion affects arable land all over the world. Agricultural production facilitates on-site effects of soil erosion, such as soil degradation, as well as off-site effects as, for instance, sediment-mediated fertilizer and pollutant transport into freshwater ecosystems. The conservation area of the Thayatal National Park in Lower Austria is negatively impacted by these aspects of sediment connectivity due to hillslope to channel sediment transfers within the Fugnitz watershed, the main tributary system of the Thaya River. The objective of this Master's thesis is to enhance the understanding of soil erosion processes in this medium-sized agricultural watershed. Embedded in the FugnitzSED project, the present thesis aims at investigating potential source areas for high amounts of sediment yield and at testing a process-based erosion model (WEPP/GEOWEPP) for challenges in the context of environmental management.

Methods applied include erosion modeling on catchment- and on subcatchment-scale. On catchment level, areas with potentially high amounts of sediment yield are simulated while modeling of small scale (2 – 8 ha) target areas is conducted to simulate on-site processes and to test flow path delineation. Subsequent field investigations seek to provide information on the validation of catchment wide modeling, the comparison of observed erosion rills with modeled flow paths and local erosion processes. In order to provide management options, different land use scenarios are simulated and mitigation strategies are discussed.

Hotspot modeling of high amounts of sediment yield show increased rates across the whole catchment area. Comparison of model results and information obtained via field surveys indicate broad agreement. Nevertheless, model validation lacks comparison with actual sediment yield rates, therefore, future research ought to quantify soil erosion in the Fugnitz catchment. The analysis of flow-path-delineation smaller scale target areas (B and C) indicates that micro-topographic features (e.g. plough lines, field boundaries) are not captured by the model, revealing its weaknesses (location/direction of flow paths, location of deposition areas). Simulation of different management scenarios indicates a considerable influence of crop rotation on predicted erosion rates and highlights the importance of reasoned management strategies. Based on literature research and WEPP/GEOWEPP results,

different mitigation strategies for the Fugnitz catchment are developed. As a result possible actions and localization of potential target zones constitute a starting point for future management discussions.
The present thesis leads to an improved comprehension of soil erosion processes within the Fugnitz catchment and facilitates the development of different mitigation strategies based on the obtained results.

Abstract (german)

Bodenerosion durch Wasser beeinflusst fruchtbares Land weltweit da landwirtschaftliche Nutzung die lokalen Auswirkungen von Erosion, wie beispielsweise Bodendegradation, verstärkt. Hinzu kommt, dass transportiertes Sediment das Gerinne erreichen und damit Einfluss auf fluviale Ökosysteme nehmen kann.
Der Nationalpark Thayatal in Niederösterreich wird stark vom angrenzenden Einzugsgebiet der Fugnitz beeinflusst. Die landwirtschaftliche Nutzung im Bereich des Zubringers und der dadurch erhöhte Eintrag von Feinsedimenten in das Gerinnesystem hat negative Auswirkungen auf die ökologische Situation der Thaya.
Die vorliegende Arbeit ist Teil des Projektes "FugnitzSED" und verfolgt das Ziel, ein vertieftes Verständnis für Erosionsprozesse in einem mittelgroßen, landwirtschaftlich genutzten Flusseinzugsgebiet zu erlangen sowie potentielle Gebiete mit erhöhten Erosionsraten auszuweisen. Dabei wird ein prozessbasiertes Erosionsmodell (WEPP/GEOWEPP) verwendet und dessen Eignung für angewandtes Umweltmanagement getestet.
Modellierungen wurden dabei auf Einzugsgebietsebene (Sedimentaustrag) sowie für ausgewählte Fokusbereiche (Bodenabtrag) erstellt. Für die Fokusbereiche wurden darüber hinaus modellierte Fließwege getestet. Anschließende Feldbegehungen hatten zum Ziel, die tatsächliche Situation vor Ort aufzunehmen. Der abschließende methodische Schritt bestand darin, die Auswirkungen verschiedener Fruchtfolgen auf den Sedimentaustrag auf Einzugsgebietsebene zu simulieren.
Erhöhte Austragsraten wurden vom Modell im Bereich des gesamten Einzugsgebietes ausgewiesen. Felderhebungen und Modellergebnisse deckten sich dabei weitgehend. Hier muss jedoch angemerkt werden, dass in Ermangelung an Daten kein Vergleich mit tatsächlich gemessenen Austragsraten möglich war.
Die Schwächen des Models wurden besonders durch den Vergleich zwischen modellierten Fließwegen und kartierten Erosionsrillen bei den beiden kleineren Fokusbereichen (B und C) aufgezeigt. Der Einfluss von mikrotopographischen Strukturen (Pfluglinien und Feldränder) auf die Bildung von Erosionsrillen wurde dabei vom Model nicht erfasst. Simulationen der Verwendung unterschiedlicher Fruchtfolgen zeigte den deutlichen Einfluss

landwirtschaftlicher Bearbeitungsweisen auf Bodenabtragsraten. Die vorliegende Arbeit trägt aufgrund dessen zu einem tieferen Verständnis über Erosionsprozesse im Einzugsgebiet der Fugnitz bei. Basierend auf Modellergebnissen (WEPP/GEOWEPP) und in Anlehnung an Fachliteratur wurden abschließend Handlungsoptionen zur Minderung des Sedimenteintrags aufgezeigt.

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Chapter 1

Introduction

1.1 Background and problem statement

Soil erosion governed by water is a natural process which takes place continually and universally.(Hillel 2008) As soon as cultivation of arable land emerged, humans had to face the problem of loss in fertile soil due to the erosive forces of water. Agricultural production modifies the relief and is closely related to increased soil loss rates and subsequent deposition.(Price et al. 2011) Extensive land use leads to, for instance, a reduction in vegetation cover, which, in turn, increases the erodibility of the soil.(Dotterweich 2013)

Besides on-site effects such as soil degradation and loss, off-site processes, too, pose a severe threat to different types of ecosystems.(Mekonnen et al. 2015) Especially freshwater ecosystems are very sensitive to environmental changes occurring in their catchments.(Hynes 1975) Water governs the transport of sediment and nutrients from arable land to stream channels.(Bracken and Croke 2007) Furthermore, chemical pollution of freshwater, too, is a severe problem due to the ability of certain sediment grain sizes to transport pollutants and fertilizer.(McIsaac et al. 1989). Rates and temporal variation of these fluxes influence the state of the ecosystem including the composition of biological communities in the river system.(Resh et al. 1988; Jackson et al. 2001; Ouyang et al. 2002) Moreover, direct sediment shifting by human activity modulates the morphology of stream channels.(Foley et al. 2005) Hence, reduced water storage capacity and increased water turbidity enhance the negative effects on sensitive ecological processes.(Mekonnen et al. 2015)

The main concerns that lie at the center of erosion research are to keep agricultural areas fertile, to control sediment fluxes and to prevent pollutants from entering the channel systems of rivers.(Renschler and Harbor 2002) Soil erosion research further improves our knowledge with regard to soil conservation and prevention of water pollution.(Issaka and Ashraf 2017)

In order to gain site-specific process understanding it is inevitable to investigate controls and dynamics of sediment transport in different landscape compartments.(Bracken et al. 2015) To deal with the problems posed by soil erosion, it is necessary to gain a deeper understanding of the fundamental processes causing it.(Gares et al. 1994) The dynamic components that form the link between hydrological systems and soil systems are described through aspects of connectivity.(Bracken and Croke 2007)
Seiberth (2001), who investigated the relation between soil loss and sediment yield in different catchments in Switzerland, highlighted the need for instruments and methods to efficiently locate areas which contribute to sediment mediated water pollution (i.e. above average soil loss and sediment yield) in the context of landscape planning. For the investigation of soil erosion patterns and trends, scientists conduct different types of models.(Renschler 2003) Computer-based modeling is a tool for investigating soil erosion patterns and trends on different accuracy levels.(Kuznetsov et al. 1998) A severe challenge in this context is to conveniently capture processes on different temporal (from minutes over days to several years) and spatial scales (from microtopography to whole watersheds).(Li et al. 2017) Nevertheless, a vast number of soil erosion models were developed to gain scientific knowledge and to support landscape management.(Pandey et al. 2016)
This thesis was written in cooperation with the National Park management in order to investigate sources of soil loss for fine-grained lateral sediment input into the Fugnitz river by means of computer-based-modeling. The understanding of erosion processes ought to help future management decisions in order to improve the ecological situation within the National Park area. Figure 1 more or less visualizes the whole problem for the nature conservation efforts of the National Park administration. The picture shows the Fugnitz entering the Thaya river in the city of Hardegg. After an intense rainfall event, heavy loads of fine sediments enter the Thaya river. However, the connection of the National Park area with adjacent watersheds outside the protected area, hence outside the direct administrative control, constitutes a serious challenge to the nature protection and management efforts. Therefore, it is necessary to investigate the current situation in the watershed and to pin point problem areas in order to be able to provide convenient suggestions for future management.

Figure 1: *Outlet point of the Fugnitz watershed at Hardegg (Source: Thayatal National Park, P. Lazarek, 2009)*

The main objective of the Thayatal National Park in Lower Austria is to actively manage protected areas. The organization recognized the importance of sediment transfer within the tributary system of the Thaya river based on different studies. Pichler-Scheder C. (2016), for example, investigated different reaches of the Fugnitz from source to sink and showed the negative influence of intensive land use on both water chemistry and aquatic ecology. The study highlighted that the most severe ecological stress comes from fine sediments and bacteria that are washed into the Fugnitz during heavy precipitation events. The Fugnitz River directly drains into the Thaya and influences subsequent ecotopes. Therefore, the watershed area of this tributary system is important for nature conservation planning and management.

1.2 Objectives and research questions

This thesis is embedded in the INTERREG project "FugnitzSED" managed by the Thayatal National Park GmbH. The main objective of this overarching project is to identify and to establish management strategies to diminish the lateral input of fine-grained agricultural sediments into the Fugnitz River and thereby to improve its ecological situation.
In the present study, the focus lies on the identification and further investigation of agriculturally used hillslope areas with high amounts of sediment yield. The derivation of "Hot Spots", for both sources and lateral input, will

provide a basis for possible future implementation of mitigation strategies such as sediment retention basins and further management of the catchment area. For this purpose, the modeling approach of the Water Erosion Prediction Project (WEPP) is used to gain deeper understanding of the processes involved and to evaluate the site-specific situation in the Fugnitz watershed. Model performance and possible model deficiencies are examined based on knowledge obtained in from ground truthing sessions.
As guidance for the whole research activity and to account for all the previously mentioned issues the following objectives were formulated: In the course of this thesis the use of a process based soil erosion model (WEPP) for environmental management in a medium-sized agricultural watershed in Lower Austria is examined. The goal is to identify potential hot spots for high amounts of sediment yield within the Fugnitz catchment (i.e. catchment scale approach). On hillslope scale the ability of WEPP to delineate flow paths during small scale soil loss assessment is tested. In order to provide local management authorities with suggestions for action, different scenarios on the effects of different land use practices on soil loss and sediment yield are tested. Finally, possible mitigation strategies to reduce soil loss and sediment yield to riverine ecosystems is discussed. After highlighting the intentions and aims for this thesis, the following main research questions can be postulated to guide further steps:

RQ1 *To which extent can process-based soil erosion modeling (WEPP) be used to determine potential "hot spots" for high amounts of sediment yield in a medium-sized agricultural watershed?*

RQ2 *Where are "hot spots" for high sediment yield in the Fugnitz watershed located?*

RQ3 *To which extend does GEOWEPP/WEPP account for micro topographic structures during flow path delineation?*

RQ4 *How does a change in agricultural land use affect the sediment yield distribution within the Fugnitz watershed according to GEOWEPP/WEPP?*

RQ5 *Which mitigation strategies to reduce potential amounts of sediment yield and to limit sediment influx to the Fugnitz channel system can be derived from the obtained findings?*

1.3 Thesis structure

This diploma thesis focuses on soil erosion modeling and its implications for integrated environmental management in a small watershed dominated by agricultural land. To put the specific research approach into perspective, the opening chapter (see: Chapter 2) will give a detailed theoretical background on the treated topics and important underlying concepts, principles and classifications of the main field of research. As soil erosion research depends on soil physics, hydrological interrelations, a multitude of governing parameters will be discussed.
After this general introduction, the study area will be presented with a focus on the discussion of its environmental characteristics and controlling parameters in the context of soil erosion and potential lateral connectivity. The main part of this thesis comprises the methodological setup, consequential results and a subsequent discussion. In the methods section the WEPP model, available data, preparatory work, model configuration as well as different model modifications in the course of research will be presented. Moreover, the ground truthing and associated fieldwork procedure will be discussed in detail. The results of the research process will be stated in a separate chapter followed by a comprehensive discussion. Based on the obtained findings the postulated research questions will be discussed again. The final conclusion chapter will put the results of this study into a broader context and give future perspectives.

Chapter 2

Theoretical background

2.1 Soil erosion: a global phenomenon

In order to gain better understanding of soil erosion and sediment transport, the main objective of this section is to unravel the physical properties of involved mechanisms. If one assesses the so called “bigger picture” of erosion, the process can be described as the constant leveling of the relief in all landscapes due to the forces of wind and water.(Edwards et al. 1998) In this context, this thesis focuses on water driven surface erosion. Water-mediated soil erosion is defined as the hydrologically forced detachment of soil particles, the subsequent transport of the sediment and the intermediate or final deposition.(Morgan 2006) It is possible to look at the this subject with different spatial and temporal scales. Responsible for this process are the combined forces of tectonic uplift, weathering of rocks, chemical decomposition of rocks and the eroding power of water, wind, ice and mass movements, due to gravitation.(MacArthur et al. 2008) Almost 25 years ago, Hooke (1994) emphasized the role of humans as most important geomorphic agent due to their global shaping of the earth. Human-induced and accelerated soil erosion is a main driving force in this transformation. On regional scale, erosion by water is either caused by natural phenomena, like rainfall or snowmelt, or by anthropogenic influence.(Foster 1982)

2.2 Physical fundamentals

In this context, it is necessary to focus on the interaction between soil particles and their reaction to water, as this relationships are important for soil erosion research.(Brooks et al. 2012) Soil erosion processes are governed by their inherent physical properties and mechanisms.(Hillel 2003) Soil particles are grouped in aggregates which form a certain soil matrix.(Al-Kaisi et al. 2017) Cohesion, the sticking together of similar molecules(Huggett 2017), leads to the aggregation of soil particles which in turn contributes to an increased pore volume and, therefore, facilitates the entry of air and water.(Kemper and Rosenau 1984) The aggregates determine the structure and the geometric characteristics of pores; hence, they are crucial for the movement of liquid and gaseous media.(Tisdall and Oades 1982) A quantitative measure for this compaction is bulk density, which is described as the mass of the soil per unit volume of area of land (expressed in g/cm^3).(Hossain et al. 2015) The present soil particles vary in size, shape and chemical properties, which determine the soil structure and soil health or quality.(Al-Kaisi et al. 2017)

If we look at the hydrologic effects of the soil compaction, hydraulic conductivity describes the possibility for liquid substances to move through the soil.(van den Akker and Soane 2005) It depends on the compaction of the soil and, specifically, on the size of the conducting pores and not necessarily on the total porosity.(Hillel 2008)

For soil erosion, it is important how different soil particles react to detaching forces and how much water is available for erosion. For structural detachment of particles, it is necessary to look at the shear strength which can be defined by two main parameters: the previously described cohesion and the internal angle of friction ("angle measured between the normal force and resultant force" (Fattet et al. 2011: 61).(Singh and Goel 2011) Before a soil particle starts moving, the critical shear stress must be exceeded. This can be seen as a measure of soil resistance to the forces of erosion.(Léonard and Richard 2004)

Apart from soil inherent cohesiveness, the availability of water and, to be precise, the presence of water on the surface is paramount. If precipitation reaches the soil surface, there are two possible directions for further movement. Either the water stays above ground and moves downslope as surface runoff, or it infiltrates into the soil.(Toy et al. 2002) The rate of infiltration, i.e. the amount of water entering the spaces between soil particles, is a major control for the availability of water for surface runoff.(Morgan 2006) Figure 2 gives information about typical infiltration rates for various grain sizes. As we can see, infiltration rates decrease over time as soil pores fill up. Due to coarser structure of sand, soil permeability, hence infiltration rates, tends to be high. In contrast, clay particles show high bulk density and lower infiltration rates.(Morgan 2006)

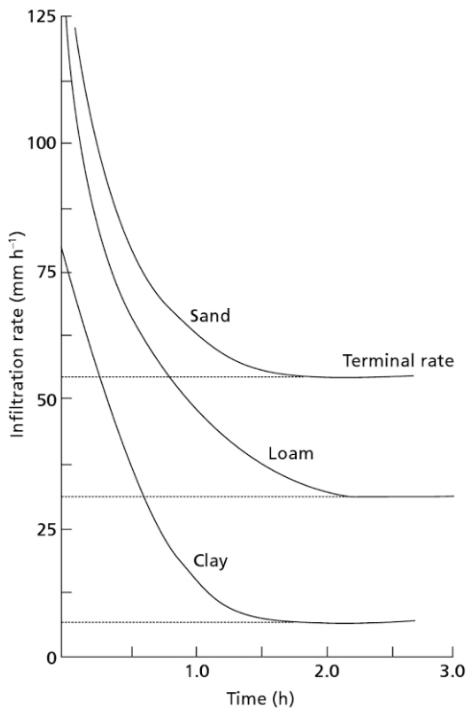

Figure 2: *Infiltration rate for different grain sizes per unit time.(Morgan 2006: 5)*

2.3 Soil erodibility

Hudson (1995: 75) defines soil erodibility as ability of the soil to resist detachment as "a function of soil texture, structure, permeability, organic matter content and also the management of the soil". With these variables it is possible to calculate an index for soil susceptibility to water erosion.(Borselli et al. 2012) In theory, soil erodibility is described as the ratio of soil loss (t/ha/h) per unit of rainfall erosivity (MJ/mm/ha^{-1}/h^{-1}) (Meshesha et al. 2016), which is calculated as the total soil loss per total rainfall intensity within the duration of an erosion event.(Wischmeier and Smith 1978) Sanchis et al. (2008) stressed that soil erodibility highly depends on seasonal dynamics and local climate characteristics as it is not a measurable single parameter but rather a combination of different variables that effect soil-water interactions (e.g. particle size, organic matter content, infiltration rate, permeability). Borselli et al. (2012) tried to meet the requirement of the climatic complexity and provided an algorithm which distinguishes statistical erodibility values for cool and for warm conditions.
Apart from site-specific climate factors, cultivation has a significant influence on soil erodibility rates. Agricultural practices may decrease the erodibility

of clay soil whereas sandy soils show increased erosion rates.(Morgan 2006) Furthermore, vegetation plays a key role as it protects the soil from rain drop impact and, thus, decreases the vulnerability of the soil for erosion.(Roose et al. 1996) Besides thes conditions it is important to investigate present land use and management practices in order to assess local soil erodibility. Many research approaches focus on estimating realistic soil erodibility values for different environments as it is seen as one of the key parameters in appropriate soil erosion susceptibility analyses.(Meshesha et al. 2016; Iaaich et al. 2016; Wang et al. 2015; Bonilla and Johnson 2012; Borselli et al. 2012) Besides modeling soil erosion using different variables a preferred method to estimate soil erodibility are long-term direct measurements of erosion. For this purpose, either experimental set ups (runoff plots) with predefined and controlled conditions or simulated laboratory analyses are used.(Kulikov et al. 2017) In order to keep arable land fertile, it is necessary to reduce soil erodibility as much as possible.(Svoray and Ben-Said 2010)

2.4 Rainfall erosivity

A short and precise definition of Nearing et al. (2017) describes rainfall erosivity as the power of rainfall to cause soil erosion. It can be calculated as the product of measured maximum 30-minute rainfall intensity, and total storm kinetic energy for a series of single storm events. Rainfall intensity is described as "the ratio of the total amount of rain falling during a given period to the duration of the period" (depth units per unit time, usually mm/h).(Critchley and Siegert 1991: 32) (Wischmeier and Smith 1978) Kinetic energy of rainfall is basically the "force of each individual raindrop that strikes the soil" and depends on the drop size and fall velocity.(Salles et al. 2002: 256) The site-specific infiltration rates of the soil, the storage capacity of the surface and the vegetation and topographical circumstances complement this calculation.(Cook 1937) Potential erosivity, as defined by Cook (1937), is the capacity of a storm event to produce erosion for a standard area ("unit strip of land running up and down the slope"(Nearing et al. 2017).

The prediction of potential soil erosion for the future is based on erosion models which use rainfall erosivity as a major input factor.(Panagos et al. 2017) To derive sound information from rainfall erosivity analyses, it is important to consider its interannual dynamics.(Wang et al. 2002) Rainfall intensity shows different patterns, i.e. a succession of dry and wet periods, throughout the year and, therefore, its impact on soil erosion changes.(Borselli et al. 2012) As rainfall erosivity is widely used for assessing and predicting rates of soil erosion(Nearing et al. 2017), a multitude of recent research approaches which try to measure and model rainfall erosivity can be named.(Ballabio et al. 2017; Panagos et al. 2017; Xie et al.

2016; Lobo and Bonilla 2015; Duan et al. 2016) Application of the rainfall erosivity parameter within a modeling environment will be discussed later on (see: section 2.11).

2.5 Sediment transport capacity

On the one hand, soil particles are eroded under different circumstances as the previous sections showed and, on the other hand, sediment is transported during an erosion process. To move material from one location to another during water erosion processes, the presence of a transport medium is necessary.(Foster et al. 1985; Weggel and Rustom 1992; Hillel 2003; Lin et al. 2017) The required water can come from local precipitation or from an upslope zone.(Borselli et al. 2008) The maximum sediment load a certain amount of surface runoff can transport is described with the sediment transport capacity.(Zhang et al. 2009) Generally, this parameter is influenced by the topography (e.g. slope angel and length), surface roughness and the amount of water available.(Julien and Simons 1985; Moore et al. 1988; Chanson 2004; Guy et al. 2009) Increasing slope angles as well as increasing flow accumulation (depending on the spatial distribution of rainfall events) are linked with a higher transport capacity.(Poeppl et al. 2012) The overland flow is size selective, in other words, a particular flow energy can transport sediment with a certain grain size.(Issa et al. 2006; Mahmoodabadi et al. 2014) A decrease in sediment transport capacity can be expected on vegetated areas (in agricultural areas dependent on crop type and management)(Wang et al. 2015), as a matter of altered infiltration rates (Gabet and Sternberg 2008) and/or surface roughness (Ahn et al. 2009) and as a result from buffering landscape features(Fryirs et al. 2007), which results in deposition of the sediment.

2.6 Frequency magnitude relationship

Rates of soil erosion are not steady, in fact, they are influenced by seasonal dynamics and especially affected by the quantity of rainfall events.(Toy et al. 2002) The frequency-magnitude relationship of rainfall events and corresponding erosion events describes the relative probability for events of various sizes, which supports the evaluating of stochastic natural hazards.(Riley 2012) Many effort has been put in the research of frequency-magnitude relationships of rainfall events together with soil erosion rates (Cammeraat 2004; Boardman and Favis-Mortlock 1999; DePloey et al. 1991; Tucker 2004), as this knowledge can help land management approaches and increase our understanding of landscape evolution.(Boardman and Favis-Mortlock 1999) Data about frequency and magnitude of natural events are used for parameterization and accuracy assessment of hazard risk estimation.(Riley 2012).

Coppus and Imeson (2002) highlight the importance of low-frequency but high-magnitude rainfall-runoff events for the generation of big erosion rates. When looking at the frequency and magnitudes of different natural events, like rainfall, wind speeds, floods and erosion, we see an approximate log-normal distribution.(Wolman and Miller 1960) In the context of soil erosion, a few big events are responsible for the majority of the eroded material. 3 shows this frequency-magnitude distribution based on measurements at 270 field sites on arable land in England and Wales.(Morgan 2006) We clearly see the high amount of low-magnitude events as just described.

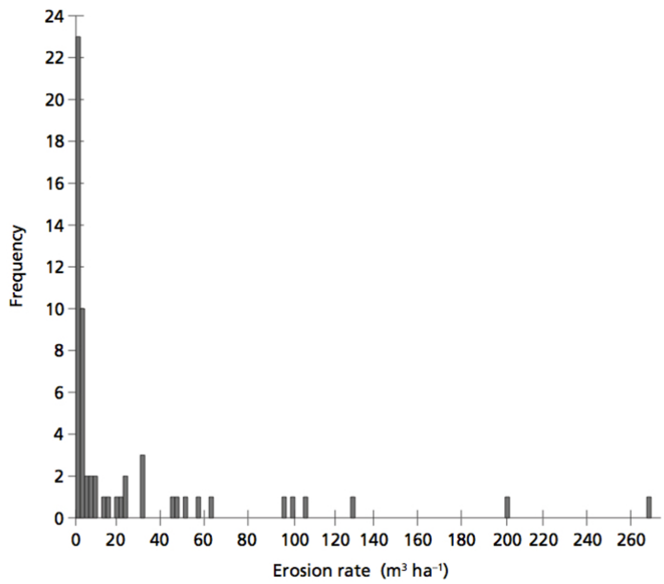

Figure 3: *Typical frequency-magnitude relationship for annual soil erosion rates for England and Wales.(Morgan 2006: 6)*

2.7 Soil degradation

After defining some of the physical driving forces of soil erosion, we need to look at the long-term consequences as well. Soil degradation is defined as the long-term loss of the inherent ecosystem functions of fertile soil.(Bai et al. 2008) As soon as the fertile top soil has been lost, there is no natural restoration within reasonable time periods (Schmidt 2000) and sustainable agricultural production, environmental health and subsequent socioeconomic conditions are threatened.(Telles et al. 2011) The severity of soil degradation also depends on the decomposition rate, which is mainly a factor of local climate and the respective vegetative cover.(Hillel 2005) Den Biggelaar et al. (2003) reported that around 2–12 million ha of arable land are affected by degradation processes around the world every year. Soil erosion by water is proven to be one of the main drivers in in this global soil degradation.(Pimentel et al. 1995; Bridges and Oldeman 1999) The main driver is water erosion, other relevant ones are climate aridization, industrial mining, extensive and unsustainable agricultural production, inadequate irrigation systems and overgrazing as the main drivers in global soil degradation.(Hooke et al. 2012; Vanwalleghem et al. 2017; Guillaume et al. 2016; Mackey et al. 2017) Nevertheless, ther is no convenient quantification of soil degradation at global scale as the evaluation varies between different landscapes.(Hatfield et al. 2017) Bai et al. (2008) recommend the measurement of changes in net primary productivity by using the normalized difference vegetation index derived from remote sensing data. To prevent soil degradation in the first place, appropriate and sustainable management techniques and site-specific mitigation strategies are essential.(Fournier 2011)

2.8 Definitions and classifications of processes

Underpinned by the different physical circumstances we just discussed, soil erosion is manifest in different processes. It makes sense to investigate the different classifications from small to large spatial scale to understand the different consequences of these processes. In light of the present research problem, the thesis will focus on the influence of the erosive agent water, which can be responsible for the detachment of individual soil particles and their subsequent transport.(Morgan 2006) In order to design and apply effective soil management techniques, it is crucial to understand the different erosion processes and forces involved.(Keesstra et al. 2016) In the following section we will discuss splash erosion, sheet erosion, rill erosion and gully erosion. Although there are different other soil erosion processes, like subsurface flow, erosion due to mass movements or different aeolian processes, the following classifications are convenient for this research.

2.8.1 Splash erosion

The first stage of soil erosion governed by rain is the detachment of soil particles as a result of impacting raindrops.(Fernández-Raga et al. 2017) citetMorgan2006 describes the process of splash erosion with the momentum of a single rain drop hitting a downslope area. During this process, the energy of the impact normal to the surface is partly transferred, partly reflected. On the one hand, soil particles are compacted by the raindrops impact, which results in an increased bulk density of the soil and, on the other hand, the current compaction is disrupted. Due to the physical stress caused by the impact, soil particles are rapidly displaced by splash transport, which can be described as laterally flowing jets.(Angulo-Martinez et al. 2012) This movement of soil particles can be as high a 1.5 meters vertically

(Ryzak et al. 2015), and – when supported by wind - as wide as 5 meters horizontal (Erpul et al. 2009). Especially bare soil is vulnerable to splash erosion as raindrop impact is not inhibited by the covering effects of vegetation.(Seutloali and Beckedahl 2015) As splash erosion is widely considered a key mechanism in soil erosion processes there is a multitude of different research approaches focusing on splash effects of raindrops. Fernández-Raga et al. (2017) stressed that a total of 557 articles specified on splash erosion were published after 2016.

Figure 4: *Close-up of soil particles getting detached by water. (Flanagan and Livingston 1995: 14)*

2.8.2 Sheet or interrill erosion

The next step in the chain of soil erosion processes is sheet erosion, defined as soil detachment and transport due to an overland flow of water on hillslopes during a rainstorm. Sheet erosion is often used synonymously with the term interrill erosion as the flow is rarely a single sheet of water and more commonly occurs as a mass of anastomosing or braided water courses.(Morgan 2006) Zhang and Wang (2017) state that the detachment component in interrill erosion processes is negligible because the main detaching force is still rain drop induced splash erosion. Therefore, the main result of sheet erosion is the transport of previously detached soil particles. The driving force for this sediment transport by interrill erosion is shallow, hydrological overland flow.(Morgan 2006) Fine topsoil particles are collected by this flow, the moving water is mixed with sediments and transports the material downslope.(Descroix et al. 2008; Koiter et al. 2017) If the different hydrological storage capacities of a slope, like surface depression storage, soil moisture storage and infiltration capacity are exceeded by an intense and/or prolonged rainfall event, surface runoff and, accordingly, sheet erosion processes occur.(Morgan 2006) For sheet erosion processes, it is possible to define a certain sediment transport capacity which is expressed as „the maximum, equilibrium sediment load that a raindrop-impacted sheet flow can carry in a given width per unit time for a given soil under a given hydraulic and rainfall condition“.(Zhang and Wang 2017: 652) Koiter et al. (2017) highlight the selective nature of sheet erosion processes. The preferential mobilization of fine-grained soil particles (63 μm) and organic carbon affects the physical and bio-geochemical properties of the transported and deposited material.

Figure 5: *Sheet erosion on a fallow field in the United States.(U.S.D.A. 2017b)*

2.8.3 Rill erosion

In contrast to the previously discussed sheet erosion, where still splash impact of rain drops due to intensive rainfall events can be seen as the main factor for soil detachment, rill erosion is caused by the concentrated flow of water.(Knapen et al. 2007) Overland flow converts into rills after the water passed a critical distance downslope. At this point, overland flow becomes channeled.(Morgan 2006) Moss et al. (1982) examined this break up of surface flow at a certain point into erosion rills, which can be defined as the effect of surface flow exceeding a certain threshold of soil resistance.(Knapen et al. 2007) This process was divided into four significant stages by Merritt (1984): First, unconcentrated overland flow is present followed by the deployment of concentrated flow paths, which progress into micro channels without headcuts and, finally, micro channels with a clear definable headcut occur. As soon as erosion rills have been fully developed, the retreat of this headcut extends the structure upslope. The rate of this retreat is governed by the cohesiveness of the soil, the velocity and discharge of the flow as well as the micro-topographic structure (height and angle) of the headwall.(Morgan 2006) Furthermore, the rill extends downslope as well, which is mainly controlled by the shear stress of soil particles and flow energy.(Savat and Th 1979) Stefano et al. (2017) argue that rill erosion processes can be considered the most important source of sediment mobilization. Nevertheless, splash erosion, sheet erosion and rill erosion cannot be seen independently. In fact, the different processes affect one another. Splash erosion detaches soil particles, interrill processes transport loose sediments by the means of overland flow and, apparently, this material enters into the erosion rills where the velocity and depth of concentrated flow increases compared to the more dispersed overland flow.(Bruno et al. 2008)

Figure 6: *Rill erosion developed on clayey hillslopes in Spain.(Jordán 2014)*

2.8.4 Gully erosion

One of the main sources for sediment yield on catchment scale is gully erosion.(Valentin et al. 2005) Up to 95% of the total amount of eroded sediment in a watershed can originate from gullies.(Poesen et al. 2003) Considered one of the most destructive types of erosion processes, gully erosion has been recognized as a major factor in land degradation throughout history.(Dotterweich 2013) Gullies are defined as deeply incised erosion channels with an actively eroding head cut, steep sidewalls, and a stepped longitudinal profile.(Salleh and Mousazadeh 2011) The channels are usually created from a depression in land by increased runoff, which removes topsoil to a considerable depth(L. and B 2012). Structural failure of the headcut extends the gullies upslope.(Goodwin et al. 2017) To separate gullies from previously mentioned erosion rills Poesen (1993) determined the cross-sectional area as greater than 1 m2. In contrast to stable river channels with a smooth, concave-upwards long profile, gullies show greater depth and smaller width as well as clear headcuts and knickpoints along their course.(Morgan 2006) V-shaped gullies can be traced to surface runoff whereas U-shaped gullies are formed by a combination of surface and subsurface flow. The results of gully erosion are severe and can cause ecological problems, such as eutrophication of water bodies or irreversible land degradation on a broad scale.(Valentin et al. 2005) In this case, as with all previously mentioned processes, numerous factors contribute to the occurrence of erosion, ranging from the present topography, geology, climate patterns, soil properties over to land use and management practices.(Le Roux and Sumner 2012)

Figure 7: *Gully erosion near a dairy farm in the United States.(U.S.D.A. 2017a)*

2.9 Controlling factors

Apart from the physical basics and the different soil erosion processes we already distinguished, certain factors which determine the reaction of a location to erosional stress are of special interest. As these factors are crucial for site-specific analyses and modeling in soil erosion research, the structure for this section is closely inspired by the parameters used as model input in (see: section 4.2).

2.9.1 Climate

Climate, "the variability of weather conditions through time" (Toy et al. 2002: 26), has direct and indirect impacts on soil erosion. The influence of precipitation is closely related to the previously described rate of rainfall erosivity (see: section 2.4). Among the different climate variables, precipitation is essential for soil erosion processes and can be seen as the main driver for soil erosion in the context of climate influence.(Pruski and Nearing 2002) There is a distinct correlation between water erosion and rainfall intensity (precipitation rate per hour).(Critchley and Siegert 1991: 32) This is due to the increased effect of splash erosion during high-intensity storms and the high amounts of rain leads to higher rates of infiltration excess runoff, which has an increased ability to transport suspended sediment.(Mohamadi and Kavian 2015). This relationship, however, is not linear and it is likely that the same average rainfall intensity may not have the same kinetic energy and, therefore, not the same spatiotemporal influence on the soil due to intra-storm variations.(Parsons and Stone 2006) Annual precipitation and subsequent erosion rates vary greatly over time.Wischmeier and Smith (1978) investigated erosion data in the United States for a 20 year period and showed that the highest amounts of erosion are about seven times as high as the lowest recorded amounts due to changing precipitation patterns. Furthermore, there are significant variations throughout a year depending on the local climate pattern.(Toy et al. 2002) On the one hand, high erosion rates are related to months with high amounts of precipitation and, on the other hand, management practices and respective periods of vegetation cover are related as well. These crop related parameters depend on the local climate as well.
There are two different types of rain events which can be related to erosion: The short-lived intense events rapidly exceed the infiltration rate of the soil and lead to high amounts of surface runoff and prolonged events of low intensity, which constantly saturates the soil and slowly initiates erosion.(Morgan 2006) Previous meteorological conditions may influence the response of soil to rainfall events as well. In a series of precipitation events the amount of detached soil particles and the rates of soil moisture change and, therefore, the rate of eroded material is not constant.(Morgan 2006) The form of pre-

cipitation is determined by another climate variable: the air temperature, which also effects the rate of erosivity.(Toy et al. 2002) High amounts of precipitation in the form of snow is not erosive whereas high amounts of rain is very erosive. Air temperature and respective temperature of rain drops also influence the hydraulic conductivity of the soil. The higher the temperature, the lower are the rates of water viscosity and surface tension, which effects soil moisture and subsequent storage potential.(Morgan 2006) Apart from precipitation patterns, wind and solar radiation influences the vulnerability of soils for erosion as well. The angle in which droplets hit the surface is governed by air circulations; therefore, the erosive impact of raindrops is affected by different wind velocities and directions.(Iserloh et al. 2013)
In the context of climate patterns influencing soil erosion rates, we need to put some focus on the current change of environmental conditions. There are direct and indirect impacts of climate change on soil erosion.(Li and Fang 2016) On the one hand, changing rainfall amounts and the likelihood of an increasing number of extreme weather events (Planton et al. 2008) may lead to increasing erosion rates.(Li and Fang 2016) On the other hand, rising temperatures effect the vegetation cover and soil moisture, which indirectly influences soil erosion rates.(Nearing et al. 2004) On top of that, socioeconomic change and subsequent alterations of management practices, too, change the vulnerability of the soil.(Li and Fang 2016) The actual effect of different climate patterns on erosion rates vary with different soil properties.(Defersha et al. 2012) Therefore, the next section will focus on different soil properties and their effect on erosion.

2.9.2 Soil structure

It goes without saying that the physical structure of the present soil is a considerable factor in erosion processes. As different soil types show different rates of erodibility (Agassi et al. 1996), it is always necessary to look at site-specific conditions. Toy et al. (2002) stress that soil texture is the single most important variable for erosion processes. Soils with different particle sizes show different responses to erosive stress and to the impact of water water.(Morgan 2006) In general, large sediment particles require greater forces to be entrained and moved whereas fine sediments are not easy to detach since their cohesiveness holds them together. Soils with a silt content above 40% are highly prone to erosion as the least resistant sediment particles are silts and fine sands.(Richter and Negendank 1977) Another possibility is to define the erodibility in relation to the clay content. Evans (1980) indicate that soils with a clay content between 9 and 30% as most susceptible to erosion.(Morgan 2006)
Apart from grain size distribution, soil roughness can be considered a main factor for erosion processes.(Auzet et al. 2002) Different small-scale surface

depressions affect the capability to store and infiltrate water, hence, limit surface flow amount and energy during rainfall events.(Darboux and Huang 2005) Furthermore, individual stones and soil aggregates, which exceed the flow depth in size, increase surface roughness.(Burt and Allison 2010) In some circumstances, soil roughness is able to channel runoff due to linear plough lines.(Kirkby 2002) The direction of this agricultural management practice is either increasing (downslope ploughing) or decreasing (perpendicular ploughing) surface flow.(Vieira et al. 2016)
When investigating catchment wide soil properties, it is necessary to consider temporal modifications. Annual weather conditions, agricultural management of the fields and the growth period of vegetation influence and alter soil properties.(Toy et al. 2002) Hence, soil parameters, such as infiltration rates, surface roughness or bulk density, must be considered dynamic. Information about catchment wide soil properties are usually stored in soil maps which use a classification system for different soil types.(Brevik et al. 2016) These maps are the result of soil resource inventories and store information in connected polygons on different scales.(Rossiter 2004) The information stored in soil maps support decision making processes in land use planning and environmental management.(Pásztor et al. 2017)

2.9.3 Topography

Topographic conditions are crucial for geomorphic development and affect many different processes, such as pedogenesis, formation of microclimatic patterns or the distribution of vegetation cover.(Schaetzl and Anderson 2005; Emeis and Knoche 2009; Sebastiá 2004) In terms of topographical influence on soil erosion, slope length and slope angle are the two most important factors.(Fournier 2011) On the one hand, increasing slope steepness and slope length tend to increase erosion due to an increased volume and velocity of surface runoff.(Morgan 2006) On the other hand, slope length reflects the source to sink relationship, i.e. “distance between runoff source and distance to the outlet”.(Bracken and Croke 2007: 1756-1757) As previously stated, this distance influences the amount of sediment yield (see: section 2.10). Nevertheless, for soil erosion modeling, the determination of slope-steepness factors is a focal task.(McCool et al. 1993) Additionally, the geometrical shape in the profile view and the shape in the plane view can be considered influential as well.(Toy et al. 2002) It is possible to distinguish between different slope shapes whose influence on erosion processes my differ.(Gray 2013) One can distinguish between four main slope forms.(Toy et al. 2002) The most simple shape are uniform slopes which have no clear change in slope angle. A non-uniform slope can either be convex (steepness increases downslope), concave (steepness decreases downslope) or complex (a sequence of convex and concave elements).
Sensoy and Kara (2014) used field experiments to investigate the role of slope

shape on the amount of surface runoff and sediment yield. They reported that uniform hillslope plots showed higher values of surface runoff and sediment yield compared to concave and convex plots. Rieke-Zapp and Nearing (2005) used a similar approach and tried to simulate the influence of slope shape on rill patterns under laboratory conditions. Their results showed that slope topography leads to convergence and divergence of rills, resulting in different distributions and efficiencies of rills. It is also important to take the influence of different slope positions into account. The gradation along a catena (upper – middle – foot slope) gives information about soil formation and energy of hydrologic processes.(Bui et al. 2017) For water erosion, delivery pathways whose distribution and density is governed by the present topography are essential (either incisional or dispersive).(Bracken and Croke 2007) Therefore, the topographic effect on the direction of hydrological processes guides soil erosion.

2.9.4 Land use and management

As previously stated, land cover respectively vegetation cover plays a decisive role in different erosion processes. As stated in previous sections, this thesis focuses on the effects of soil erosion on agricultural areas. Therefore, this thesis focuses on land use on arable fields. As Dotterweich (2013) examined, the history of soil erosion and the history of human land use is closely interwoven and cannot be considered separately. All around the globe, socioeconomic development and corresponding agricultural management practices played a decisive role in the dynamics and rates of soil erosion in the course the history of humankind. The effect of vegetative land cover can be divided into two categories: bioprotection and bioconstruction.(Naylor et al. 2002)
In terms of bioprotection, vegetation acts as a buffer during rainstorm events and can intercept and store precipitation due to the absorbing effect of above-ground biomass, such as leaves and stems.(Morgan 2006) The efficiency of this interception depends on the density of covering biomass which is described in the leaf area index (leaf area per unit of ground area).(Toy et al. 2002) Poeppl et al. (2012) showed that vegetation, especially dams built by plant roots, have buffering effects within a sediment cascade and can prevent sediment from entering a channel network. This effect can be classified as bioconstruction. Apart from these above-ground effects of roots, their presence below the surface also influences the soil and, therefore, the condition for soil erosion.(Morgan 2006) Plant roots stabilize the soil by modifying mechanical and hydrological properties.(Vannoppen et al. 2017) Root-microbe interactions play an aggregating role for soil particles and, therefore, help stabilize the soil and provide protection from detachment.(Jin et al. 2017; Angers and Caron 1998) Furthermore, roots increase the soils ability to infiltrate water and, thus, reduce the amount and velocity

of runoff.(Reubens et al. 2007) Amézketa (1999) highlighted the providing role of vegetation for decomposable organic residues which is supports soil development and provides additional cover from force of direct rain drop input.
In terms of management practices and their influence on soil erosion processes, the thesis needs to consider the role of tillage and crop rotation. The type of tillage can have negative and positive effects on the rates of soil erosion.(Bogunovic et al. 2018) Conventional tillage (mouldboard ploughing) decreases organic matter content and increases soil erosion.(Hösl and Strauss 2016) In this context, the direction of tillage is crucial.(Heckrath et al. 2006) Whereas perpendicular ploughing can help decrease flow velocity and sediment transportation, tillage in downslope direction increases runoff and the tendency for erosion rills.(Blanco and Lal 2008) Tillage also effects the spatial distribution and selection of soil particles with a specific grain size.(Wang et al. 2016) Usually erosion by tillage occurs on the top of a hillslope where small-grained sediments are detached, washed down and deposited at the foot of the slope. The sequence of planted crops and the subsequent time of different cultivation steps influence the buffering capacity of vegetation against the influence of rainfall erosivity.(Farina 2008) Adaptive and sustainable planning of crop rotation can split and lower the risk for erosion and can help farmers protect their soil.(Howden et al. 2007) Sindelar et al. (2015) investigated alternative management practices at the Great Plains in the United States and reported that a reduction in tillage and fallow in combination with a change in crop rotation improved agricultural production and reduced soil erosion. This result indicates that it is important to look at the soil erosion and land use relationship as reciprocal. There is, apart from the already mentioned influence of vegetation and management on erosion processes, also an influence of soil erosion on the anthropogenic land use. Due to degrading soils, fertility of arable land and subsequent harvest yield decreases as well.(Morgan 2006)

2.10 Connectivity in geomorphology - A catchment perspective

As the present thesis focuses on watershed problems, it is necessary to identify mechanisms of sediment transfer on a bigger scale than previously described. For effective environmental management in a watershed, it is necessary to gain process-based understanding of the mechanisms that drive landscape development.(Bracken et al. 2013) In this context, connectivity research may provide some useful insight.(Chorley et al. 1969)
What is connectivity in a geomorphological context? One of the first researches concerning connectivity defines this concept as the transfer of energy and matter between two landscape compartments or within a sys-

tem as a whole.(Chorley and Kennedy 1971) Connectivity can either be seen in a structural or functional context: The physical link between landscape compartments stands for the structural aspect and the interactions between those structural elements and their influence on geomorphological, hydrological and ecological processes are described as functional connectivity.(Turnbull et al. 2008) Furthermore, connectivity can be seen in different spatial dimensions: Longitudinal connectivity is the upstream-downstream link along a channel, lateral connectivity describes the slope-channel relationship and vertical connectivity refers to surface-subsurface interactions of water, nutrients and sediment.(Brierley et al. 2006) In relation to the research context of this thesis, the lateral connection between agricultural areas on hillslopes and the channel system is most important. Based on the definition of Croke et al. (2005), we focus on diffuse connectivity because sediments are transported to the channel on overland flow pathways and no new channels are created. In the context of geomorphology and hydrology, we talk about water-mediated transfer of sediment between two different compartments of a catchment cascade(Thompson et al. 2016). This catchment cascade can be seen as the different transport steps from source to sink, which can either store or offer sediment with temporal variations.(Fryirs et al. 2007) These relationships within a catchment are not homogeneous as various contrasting soils and different runoff-generating processes as well as various obstructing elements are present.(Buda et al. 2009)

Furthermore, as we talk about the water mediated transport of sediments, the connection of different landscape compartments is dependent on the presence of this possible transport medium. Therefore, rainfall event magnitude and accompanying amount of overland flow in combination with catchment area give information about the possibility for connection.(Morgan 2006) On catchment level, there are distinct problems related to connected sediment pathways. The connectivity concept allows researchers to analyze a river system from source to sink and address problems in a more global fashion.(Bentley et al. 2016) Apart from the on-site effect of soil degradation, eroded material may cause further off-site impact by depositing transported material and entrained substances (i.e. fertilizer and pesticides). Especially water bodies are vulnerable to long-term eutrophication and toxification, once sediment-bound chemicals enter the hydrological system.(Schmidt 2000)

Over the last decades, humans have significantly changed the landscape and acted as drivers in connectivity processes on a large scale.(Pöppl et al. 2016) Therefore, it is always necessary to keep the role of human agents in mind. Especially when dealing with connectivity, anthropogenically driven alterations of the landscape and the implementation of different non-natural features influence sediment and water fluxes. Different research approaches focus on the measurement and quantification of these connectivity processes. Borselli et al. (2008: 268) provides two different indices for the quantification

of connectivity: His index of connectivity (IC) is derived from a GIS environment and "represents a connectivity assessment based on land-scape's information". The field index of connectivity, on the other hand, tries to directly gain knowledge about connectivity relationships in the field. Further development was made by Cavalli et al. (2013). They refined the previous approach by Borselli et al. (2008) and developed another index for connectivity processes in alpine catchments.
We already discussed that the transfer of sediment is mediated by water and governed by sediment, which is detached on the hillslope, transported by the means of surface flow and may enter the channel at some point.(Bracken and Croke 2007) The present thesis investigates the first two parts of this sediment cascade. We focus on the detachment (i.e. on-site soil loss) and the transportation of sediment at a certain outlet of a predefined subcatchment (i.e. sediment yield). Toy et al. (2002) define sediment yield as the amount of sediment to a certain point of measurement. This target point is usually located on the foot of a hillslope, the boarder of an agricultural field or the outlet area of a watershed. The outlet point cannot be equated with the entry point into the channel system because neither the subcatchments necessarily enter the stream network (see: section 4.1) nor do we consider structural elements that buffer sediments and prevent them from entering the channel. Because of the disconnecting effects of buffers, barriers and blankets, described by Fryirs et al. (2007), the sediment yield of a catchment may be significantly lower than the rates of soil loss.(Dutta 2016) Large catchments potentially increase the travel distances for sediments from hillslopes to the stream network, yet, at the same time, sediment delivery ratios (ratio of sediment yield to soil loss (Lin et al. 2002)) decrease.(Walling 1999) Therefore, Poeppl et al. (2012) highlighted that the emphasis within lateral hillslope-channel connectivity needs to be put on agricultural source areas on valley floors or directly adjacent hillslopes as they tend to be the main source of sediment.

2.11 Soil erosion modeling

Why do we model our environment? What benefits are there to be gained from numerically describing and analyzing natural processes? Wainwright and Mulligan (2004) identify two main reasons for environmental modeling: On the one hand, models can provide applied management useful knowledge for their decision-making and, on the other hand, we can use models to increase our understanding of the shaping process of our environment. With respect to soil erosion, modeling approaches can help to understand erosion patterns and trends which allows scenario analysis of potential landscape change.(Millington 1986) Although models are always simplifications of reality, these methods can help to simulate soil erosion under different

circumstances (e.g. a change in land use or management), to identify main source areas for soil loss and to subsequently evaluate possible conservation measures.(Haiyan and Liying 2017) In the early 20th century, research reacted to severe problems caused by water-induced soil erosion in the United States.(Chapline 1929) Zingg et al. (1940) recognized the relationship between topographic circumstances and soil erosion processes and tried to describe these mechanisms through the application of equations and models for soil erosion.
The first catchment scale erosion model able to depict the whole hydrological cycle was the Stanford Watershed Model (SWM) (Crawford and Linsley 1966). Soil erosion models try to represent the interaction of landscapes with mathematical equations which provide numerical descriptions of form an process relationships.(Hutton 2012) Figure 8 illustrates an example of an early and simple description of relationships for interrill processes used by (Meyer and Wischmeier 1969) for their conceptual model approach. It focuses on detachment and transport mechanisms of soil erosion on hillslopes and predicts the amount of soil carried downslope.

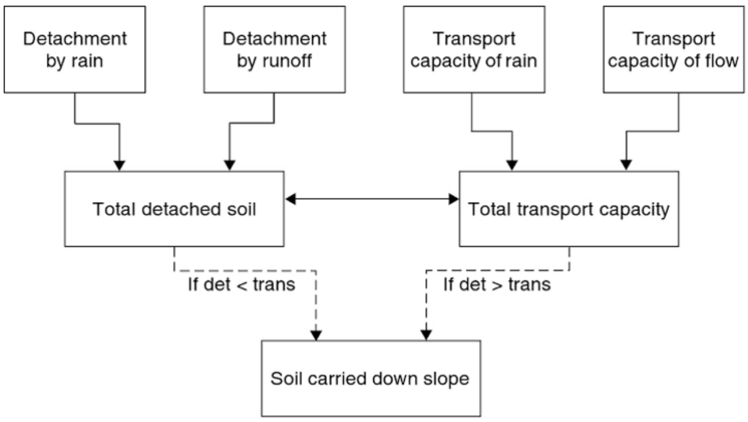

Figure 8: *Conceptual Model of interrill processes, Meyer and Wischmeier (1969) and modified by Wainwright and Mulligan (2004)*

Progress in computational power and the development of complex algorithms in combination with comprehensive data availability in terms of temporal and spatial resolution accelerated model development rapidly in the last decades.(Pandey et al. 2016)
Figure 9 illustrates the flow chart of a more complex modeling approach: The European Soil Erosion Model (EUROSEM) is a dynamic model which describes processes of soil erosion for fields or small catchments on a minute-by-minute basis.(Morgan et al. 1998) The model was tested in several countries under different environmental conditions.(Khaleghpanah et al. 2016) Smets et al. (2011) report that EUROSEM can simulate total runoff and

peak discharge for different environments reasonably well, although rates of erosion contain uncertainty(Smets et al. 2011) As the flow chart indicates, the model considers the physical processes (e.g. splash detachment, infiltration, transport capacity, rainfall interception, sediment load) we previously examined and combines them to dynamically predict the distributed amounts of erosion and deposition as well as runoff. For this prediction, EUROSEM considers information about soil properties, climate conditions (i.e. information about rainfall events), present vegetation and topographic information on different scales (catchment wide topography and microtopography)

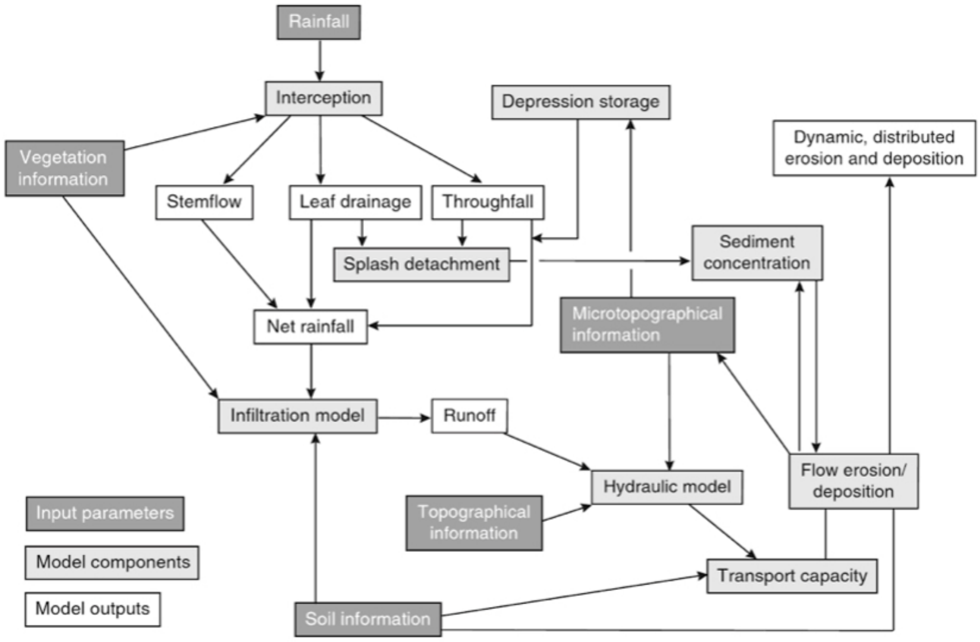

Figure 9: *Flow chart of the European Soil Erosion Model (EUROSEM), Meyer and Wischmeier (1969) and modified by Wainwright and Mulligan (2004)*

As there are a variety of different modeling approaches which vary significantly in terms of complexity, spatial and temporal extent, input requirements, practical usability and final output (Pandey et al. 2016), the next section gives a conceptual overview about different model types and their functions.

2.11.1 Types of models

The above mentioned concepts are all mathematical models which provide states and rates of change via previously expressed mathematical rules. (Mulligan and Wainwright 2004) These numerical models translate landscape forms and processes into mathematical equations.(Hutton 2012) These

types of models can be distinguished into three main categories, empirically based models, conceptual models and physically based models, although most approaches tend to present a mixture of these concepts.(Mulligan and Wainwright 2004)
Empirical models are based on observed behavior and try to make statistical predictions (e.g. erosion prediction).(Eslamian 2014) They do not take physical laws or their relationship into account and have low explanatory depth.(Mulligan and Wainwright 2004) Cannon et al. (2003), for example, used information about debris flow in a certain, burned catchment to empirically derive probabilities rule for future occurrences. This knowledge is then transferred to other locations in order to make predictions. The derived laws are empirical-causal idealizations and cannot explain underlying mechanisms.(Beven 1996)
Conceptual Models use a set of empirical models for different sub processes of a system to make assumptions and can be seen as intermediate between empirical and physically based models.(Eslamian 2014) Although conceptual models have an inherent empirical character, understanding the process is needed to identify relationships within a system.(Mulligan and Wainwright 2004) The virtues of these conceptual approaches are their relative simplicity, low requirements for computational power and the fact that it is easy to implement them into decision making processes.(Soulis et al. 2017)
Physically based models try to numerically simulate the physical characteristics of a process or a system.(Barzel 1992) Researchers use physically based models to simulate complex processes and feedbacks of landscape relationships.(Gregory and Goudie 2011) Established physical principles ought to act as starting point for the generation of these models.(Beven 2002) Nevertheless, some empirical assumptions are needed in order to fill data gaps or a lack of knowledge.(Mulligan and Wainwright 2004) Barzel (1992) identify classical dynamics with rigid or flexible bodies, interbody interaction, and constraint-based control as common elements in physically based models.(Barzel 1992) The big strength of physically based models is their explanatory depth (Mulligan and Wainwright 2004) and their ability to be transferred into different environments.(Soulis et al. 2017) A problem for the application of these models is their requirement of a large number of complex input data. These parameters are often not available or may be complicated to measure.(Nachtergaele et al. 2001) Furthermore, these models show a low predictive power and their results often differ from those of field observations.(Mulligan and Wainwright 2004)
Another way to distinguish models is the possibility to examine and alter the internal logic structure of the model.(Chinmay 2015) A “black box” model require little or no information about the different algorithms or computations and solely focus on the relationship between input and output variables(Chorley and Haggett 2013) whereas “white box” models require the understanding of the system physics and enable the user to work with the

underlying algorithms. Hence “white box” models can be considered as process based models.(Afram and Janabi-Sharifi 2015) Two further possibilities to classify models are according to their mathematical type, thus, whether the model use deterministic or stochastic variables and the distinction static or dynamic models in a temporal context.(Mulligan and Wainwright 2004)

2.11.2 Universal soil loss equation (USLE)

One of the first attempts to model the effects of soil erosion processes was the UNIVERSAL SOIL LOSS EQUATION (USLE) by Wischmeier and Smith (1965, 1978). The mathematical model correlates soil loss information gained from experimental plots with site specific information about topography, soil, climate and land use parameters.(Schmidt 2000) USLE is an empirical modeling approach which simplifies processes of soil erosion.(Blanco and Lal 2010) This model is the most widely used prediction tool worldwide due to its simple handling and the easy-to-obtain input data.(Bagarello et al. 2017) Central to this approach is the Wischmeier equation (Wischmeier and Smith 1978), which can be described as follows:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \qquad (2.1)$$

The result of this mathematical model is the long term erosion rate for a given area (A). Key for USLE modeling are the factors R and K, which describe the rainfall erosivity (R) and the soil erodibility (K). Topographical influencing parameters are field length (L) and slope (S). Furthermore, the influence of land use (C), especially the effect of crops, is considered as well. The last factor describes different management practices (P). As there are not all complex factors and process of soil erosion considered within USLE computations (e.g. rill and gully physics), the model cannot be used for all environmental conditions and can neither simulate runoff and soil loss on watershed-scale nor event or daily based soil loss.(Blanco and Lal 2010) Nevertheless, many different soil erosion modeling approaches use components of the basic USLE equation.(Nicks 1998)

2.11.3 Choosing the model

Pandey et al. (2016) name four steps for successful model application. The next two sections will deal with this process. First, we need to select the appropriate model for a given problem. In the process of choosing an appropriate model for scientific and management purposes, one needs to keep in mind the commonly used expression by Box (1976: 792) “All models are wrong but some are useful”. That said, there are no perfect representations of natural processes and it is necessary to find the most suitable approach to fit the present research or management objectives. Therefore,

a clear statement of the objectives is the starting point for model selection.(Morgan 2006) It is important to identify the specific problem of the present research or management task and to elucidate the desired output or the required information the model ought to provide.(Pandey et al. 2016) Spatial and temporal scale and resolution determine the model choice as we can look at a time span for a year, a day, a storm or short periods within a storm on the basis of a single field, a hillslope or a whole watershed.(Morgan 2006) Apart from this scale related question, we need to clarify which processes (e.g. rill, interrill or gully erosion, runoff distribution) ought to be considered within the chosen model.(Pandey et al. 2016) A big influence on the selection of the model is the data available, which is needed for input parameters as well as for model calibration and validation.(Wainwright and Mulligan 2004) For application, it is important to consider the complexity of the model and compare it with the present skill of operators in order to utilize the full power of the model.(Pandey et al. 2016)
In terms of erosion models, there is a multitude of different approaches, such as the already named USLE, EUROSEM or the Griffith University Erosion System Template (GUEST) (Rose et al. 1998), the Limburg Soil Erosion Model (LISEM)(De Roo et al. 1996), that focus on the mass balance (erosion and deposition) of sediment. In addition, there are different models that allow prediction of detailed hydrological parameters, for example the Soil Water Assessment Tool (SWAT)(Arnold et al. 1998), or models which focus on a certain area, for example the Mediterranean Desertification and Land Use Model (MEDALUS)(Kirkby et al. 1993). Furthermore, apart from physical mechanisms, some models focus on chemical properties of erosion as well. In this context we can name the Chemicals, Runoff and Erosion from Agricultural Management Systems Model (CREAMS)(Knisel 1980) or the Agricultural Chemical Transport Model (ACT-MO)(Frere et al. 1975).
For this thesis, the Water Erosion and Prediction Project Model (WEPP) and its advanced version - GEOWEPP (Renschler 2003), which automates the WEPP functions in a GIS environment were chosen. If the model ought to consider runoff in determining the decisive, erosive stress and account for spatial variations in runoff patterns, process based approaches, such as WEPP, are superior to other approaches.(Kinnell 2010) Furthermore, physically based models can be used in different environments and locations (Mulligan and Wainwright 2004), and the GEOWEPP model can predict soil loss and sediment yield – both important for our underlying problem situation – on catchment level.(Renschler 2003) Hence, application for the Fugnitz watershed was possible from a scientific perspective. Chapter 2 will discuss the structure and application of WEPP and GEOWEPP in detail.

2.11.4 Model calibration and validation

In order to produce sufficient predictions, it is necessary to conduct model calibration and validation steps.(White and Chaubey 2005) Model calibration is defined as the process of changing input values in order to compare if observations are matched by equivalent simulated values and to determine whether the model accurately represents the investigated system.(Hill 2000) In other words, it is necessary to collect field measurements which are then compared to the prediction of single parameters and with the entire model results. It is possible to simulate rainfall events in a specific area in order to compare the effect with the model predictions.(Mahmoodabadi and Cerdà 2013) It is rather difficult to monitor and survey actual amounts of soil loss and sediment yield. Usually, measurement of eroded material is limited to small experimental plots but these synthetic approaches cannot do justice to the complexity of involved processes.(Schmidt 2000) After comparison with the model prediction, it is possible to adjust the model computation in order to get better estimates.
(Mulligan and Wainwright 2004) Furthermore, it is important to look at the influence of different input parameters. This sensitivity analyses is part of the calibrations process and describes the impact of input parameters on the model results, which is essential for efficient model parameterization.(Pandey et al. 2016) As this analysis "indicates by how much the output of a model alters in relation to a unit change in the value of one or more of the inputs", it is possible to detect parameters that need to be measured or estimated most accurately.(Morgan 2006: 146) In terms of soil erosion, usually sediment yield is sensitive to rainfall quantity, crop management and rill and interrill erodibility.(Pandey et al. 2016) After calibration and sensitivity analyses, it is necessary to validate the model results.(Pandey et al. 2016) The validation process is similar to calibration – prediction and observation are compared in order to determine if the objective function is met.(White and Chaubey 2005) It is important to separate the calibration dataset and the validation dataset by using a split ample approach. Otherwise the model would inevitably show perfect predictions.(Mulligan and Wainwright 2004) In contrast to calibration, the model parameters are not adjusted after validation.(White and Chaubey 2005) In order to numerically describe the quality of model results, it is possible to use goodness-of-fit measures, like the mean error (ME), the root mean square error (RMSE) and the coefficient of determination (R2).(Morgan 2006) After calibrating and validating, the model can be used for simulations in other areas with similar environmental conditions, although the transfer of models always requires a critical, site-specific look.(Pandey et al. 2016)

Chapter 3

Study area

The Fugnitz River is located in the northern part of Lower Austria. It drains into the Thaya River near the city of Hardegg directly at the Czech Border. The whole watershed area is part of the Waldviertel region and is to some extend part of the Thayatal National Park. The catchment has a total area of 138.4 km^2 and the main stem of the Fugnitz has a length of 29.7 km.(Poeppl et al. 2012)
The following sections will focus on site specific information about the physiogeographical setting of the region. The structure for this part of the thesis will be closely related to the previously mentioned controlling factors of soil erosion (see section 2.9) as well as the upcoming input factors for soil erosion (see section 4.2). Additionally, information about the Thayatal National Park will be provided in order to illustrate the specific problem situation.

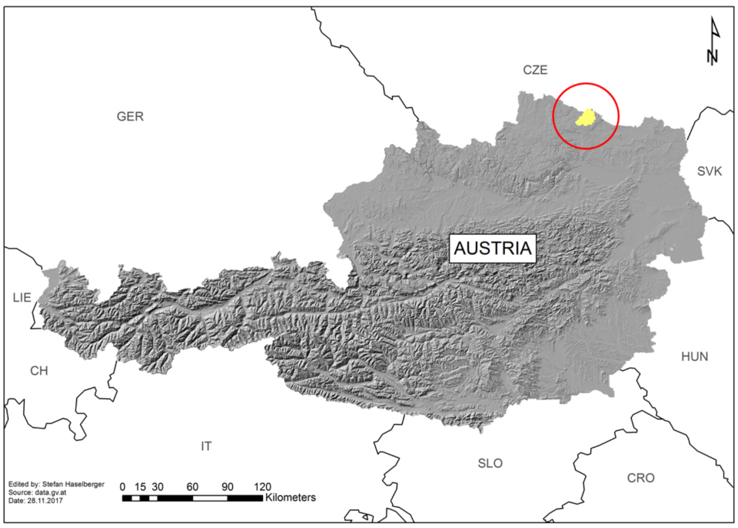

Figure 10: *Location of the Fugnitz watershed next to the Czech border.*

3.1 Climate

The Waldviertel region is located on the border of two different climatic influences. The warm and dry Pannonian climate from the south-east meets the rather cool and moist Atlantic climate from the north-east.(Grulich 1997) The Fugnitz catchment is characterized by a humid, temperate climate with a mean annual temperature of 8.3 °C and annual precipitation of around 600 mm.(Poeppl et al. 2012) Figure 11 shows a Walter-Lieth-Diagram for the Fugnitz watershed with information on average monthly temperature maxima (red line and precipitation maxima (blue line). Months with temperatures below 0 degree are indicated by blue squares (December to March). Highest precipitation values can be observed during summer month from June to August. Due to its position, the Waldviertel is exposed to wind circulations. This leads to cooler temperatures than in neighboring regions (e.g. Weinviertel) with the same altitude.(Fischer 1994) Maximum precipitation levels are measured between April and September. The river runoff regime reflects the input in these particular months. Additionally, snow melting processes in spring lead to an increased runoff.(Poeppl et al. 2012) The tributary area of the Fugnitz is frequently affected by flash floods. The last major flood event occurred in June 2006, which inundated areas next to the river channel. The event had the magnitude of a 100-year flood.(Poeppl et al. 2015)

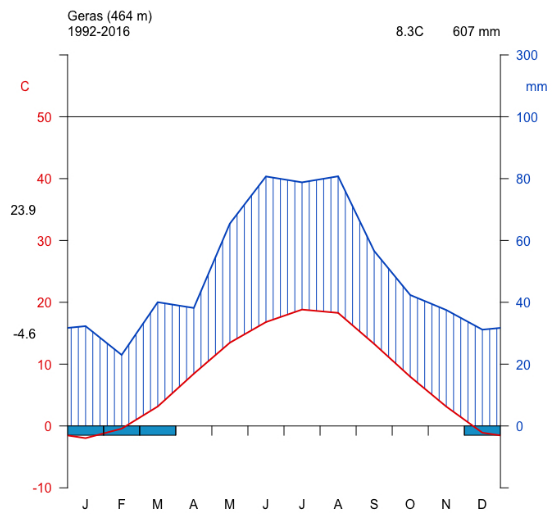

Figure 11: *Walter-Lieth-Diagram for the Fugnitz watershed.(Own illustration, data source: NÖL, climate station Geras)*

3.2 Geology

The Waldviertel area is part of the Bohemian Massif, the oldest mountain range in Austria.(Roetzel and Fuchs 2001) It is divided into the eastern, tectonically deeper-lying Moravikum and the higher Moldanubikum. The watershed is located in the first geological unit. The underlying bedrock – the so called Thaya-Batholit, a plutonic complex originating in the Cadomian orogeny during the Proterozoic - consists of crystalline mica granite and mica shale. The oldest geological structures in the region can be dated back to around 600 million years.(Roetzel et al. 2005) The Bohemian Massif, whose eroded remains are present today, emerged during the Variscan orogeny (around 350-310 million years ago).(Roetzel and Fuchs 2001) In vast areas, loess layers overlie this foundation. These sediments were formed by aeolian processes in the Pleistocene. Wind-blown silt from alpine debris and local erosion material from the Miocene as well as periglacial material from the crystalline rocks accumulated to this characteristic sediment layer.(Roetzel et al. 2005) In a few areas, Tertiary silts, clays and sands can be found.(Roetzel and Fuchs 2001; Poeppl et al. 2012). The Waldviertel has a soft profile highland with rounding summits. The highest elevation – the Tischberg - is at 1.063 m.a.s.l. Due to a remarkable altitude decrease towards the Danube (210 m.a.s.l.) in the south, dissected valleys with high discharge streams occur.(Delvaux et al. 2004) The main characteristic of the Fugnitz watershed are easily erodible material (Loess and fluvial deposits) in the upper parts and solid rock in the steeper parts at the outlet area. The topographical arrangement with rather gentle slopes in the source area and steeper slopes in the eastern part of the watershed are responsible for this dichotomy distribution.(Chytry et al. 1999)

3.3 Topography

The topography of a catchment is important for the understanding of sediment cascading processes.(Fryirs and Gore 2013) In figure 12, a topographic overview (hillshade) of the catchment area is given. The Fugnitz originates in the southwest of the watershed and drains into the Thaya River in the north-eastern part. The elevation of the catchment ranges between 540.5 m 286.4 m a.s.l. and is characterized by an average slope angle of 2.6°and maximum slope angles up to 32°.(Poeppl et al. 2012) Poeppl et al. (2015: 44) describe the Fugnitz as "mixed-loaded single-threaded perennial wadable stream". The upper parts of the Fugnitz are situated in a relative flat landscape with low river gradients, low slope angles and no bedrock steps, while the lower reaches are characterized by comparatively steep slopes, V-shaped valleys and bedrock steps. This distinct topography in the lower river reaches is a result of vertical incision processes of the Fugnitz River towards the Thaya River. In this area of the river system, mass movement processes (e.g. rockfalls) tend to bring sediments into the channel system.(Poeppl et al. 2015) This is contrasted by wider valleys and gentle slopes in the upper parts of the catchment, which are more affected by the transport of fine-grained sediments due to water-induced soil erosion.(Poeppl et al. 2012) Special features of the catchment area are various old fish dams. This anthropogenic structures can been seen as the main contemporary driver of river evolution.(Poeppl et al. 2015)

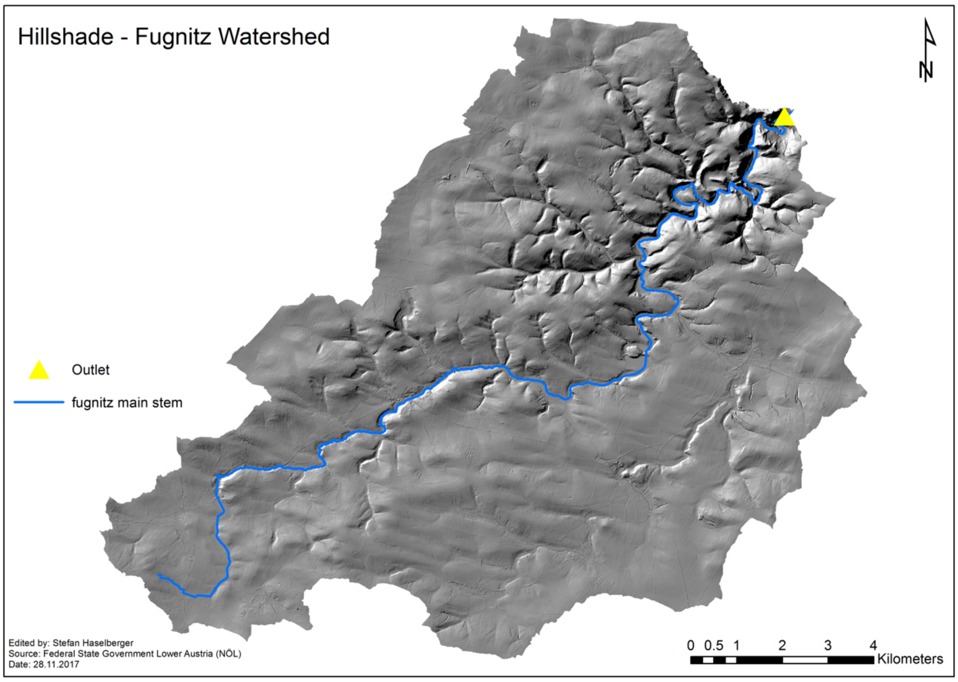

Figure 12: *Topography of the Fugnitz watershed.*

3.4 Soils

Due to the underlying bedrock formations and the distinct topography of the Bohemian Massif, lower slopes and valleys are characterized by gleyic podzolic soils with a higher amount of humus due to accumulating water because of downslope flow.(Delvaux et al. 2004) The upper slopes are dominated by well drained acid cambisols. Brown podzolic soils are found around the plateaus whereas thin acid cambisols are located on steep slopes.(Strebl and Gerzabek 1996). Usually, soils are thin, gravelly and stony on steep slopes whereas soil depth on the plateau depends on the thickness of underlying coarse grained crystalline rock layers. Podzolation is favored by the acid source material, cool humid climate and high water infiltration rates.

Furthermore, surface horizons are marked by the accumulation of organic matter – mostly moder.(Strebl and Gerzabek 1996) Acidic cambisols on the plateaus often show podzolized features with bleached quartz grains and a pronounced reddish brown AB horizon.(Delvaux et al. 2004) Soil texture distribution in the Fugnitz catchment is shown in figure 13. Different soil types are aggregated according to the United States soil texture triangle based on the topmost soil layer investigated.(Marshall 1947)

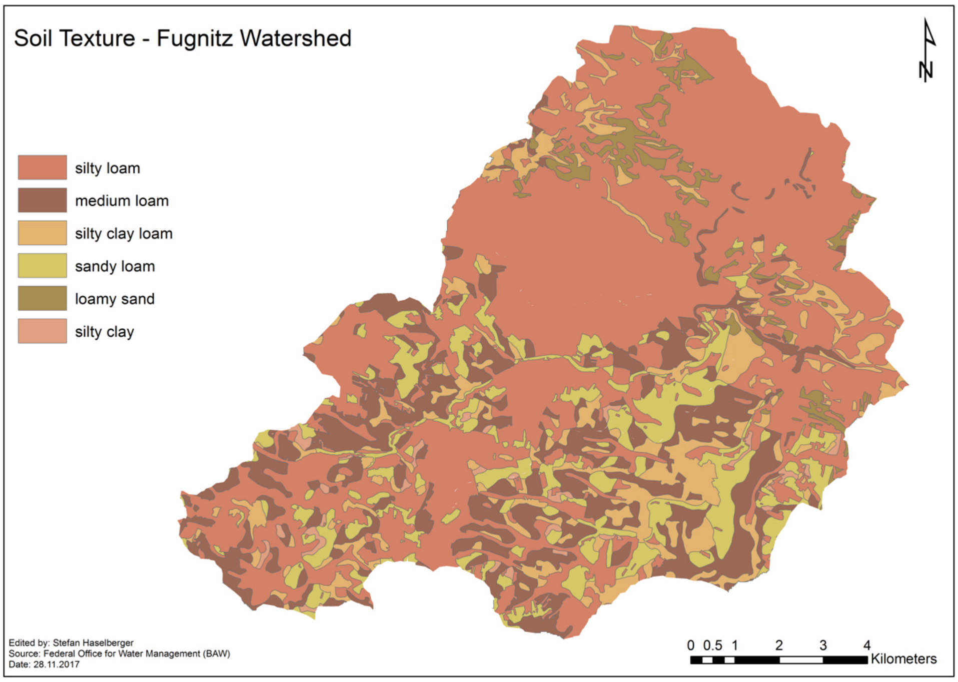

Figure 13: *Soil texture distribution for the Fugnitz watershed.*

3.5 Land use and vegetation

The Fugnitz catchment area is dominated by agricultural areas mainly used for the cultivation of crops (cereals, lucerne, oil squash and rape). According to land use data from the Federal Office for Water Management (BAW) agricultural land occupies 56% of the total area., forests and woodland 34%, grassland 7% and 3% anthropogenic settlement structures (see figure 14). The upper parts of the catchment are mainly covered by grassland and arable land whereas the previously mentioned steeper parts along the lower channel reaches are dominated by woodland (mainly mixed an deciduous forest).(Poeppl et al. 2012) Dominant tree species are spruce (Picea abies) and beech (Fagus sylvatica) which are locally mixed with fir (Abies sp.).(Wrbka et al. 2006) Understory vegetation typically consists of: Vaccinium myrtillis, Oxalis acetosella, Calamogrostis sp., Dryopteris sp., Dicranum sp. and other mosses.(Wrbka et al. 2006). As agricultural areas are prone to soil erosion processes (Vanwalleghem et al. 2017; Dotterweich 2013), this part of the Fugnitz watershed will be of particular interest for this research. Tillage practices are dominated by autumn ploughing which lead to bare ground during late autumn and early winter. Detailed information about crop rotation will be presented in the input section for the methodological part. The whole area has a long tradition of anthropogenic valorization. Poeppl et al. (2015) highlighted that, during the 13^{th} century extensive deforestation, efforts and following changes in agricultural activities led to significant alterations of the geomorphic system.

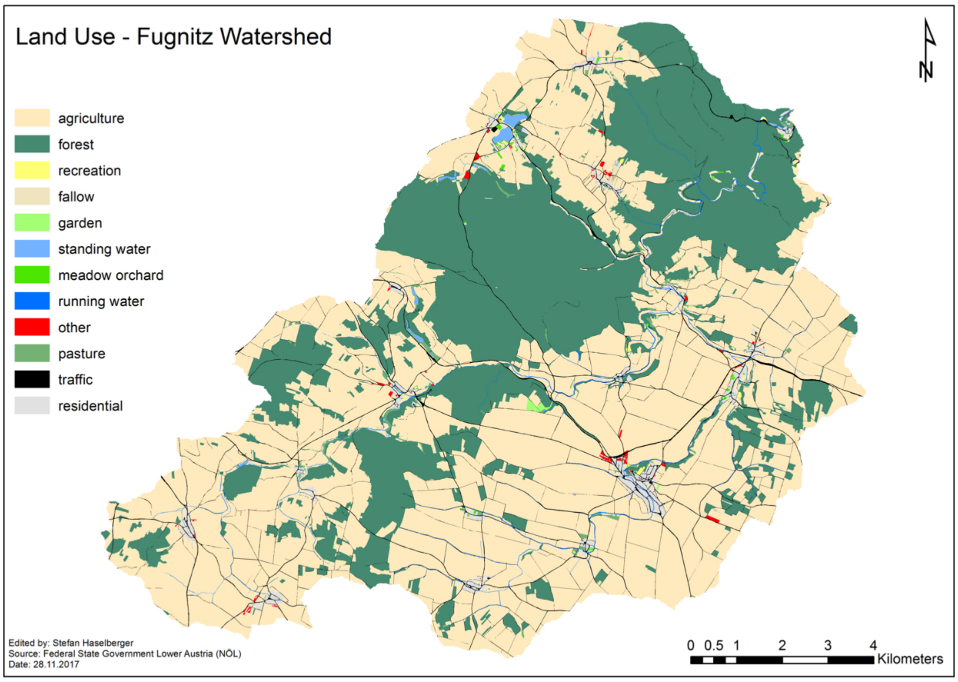

Figure 14: *Land use – legend ranked according to their total area.*

3.6 Thayatal National Park

The Thayatal National Park was founded in 2000 as the fifth National park in Austria. With a total area of 1.330 ha, the park is the smallest of its kind in Austria, but with the partner project in the Czech Republic – the Podyji National Park - a total area of 7.590 ha are protected. Together the two parks form the international conservation area Thayatal-Podyji.(Essl and Hauser 2003) Figure 15 shows the extent of the combined park area. The blue point indicates the outlet point of the Fugnitz catchment. The transnational territory is divided by the Thaya River, which acted as part of the Iron Curtain after the Second World War and until the end of the Cold War. During this 46 year period (1945-1991), the area was not exposed to anthropogenic pressure and, therefore, local flora and fauna were able to thrive undisturbedly.(Brunner 2010). The main characteristic of the region is the pronounced meandering shape of the Thaya River. Over a distance of 8 km of linear distance, the river is 18 km long. The epigenetic formation of the river valley is strongly influenced by differences in rock hardness. Because the harder bedrock (quartz-rich gneiss and granite of the Thaya-Batholit) resisted erosion processes, so extensive meanders were formed. The mean difference between valley top and valley floor is 100 m.(Berger and Priemetzhofer 2010) The largely forested valley slopes (mainly Fagus sylvatica) are predominantly exposed to the north-east. The rocky and steep landscape frames a narrow river course.(Berger and Priemetzhofer 2010) According to the classification of river branching complexity by Strahler (1957), the Thaya at the town Hardegg can be identified as a sixth-order stream. Within the national park borders, two rivers from the Austrian side drain into the Thaya. These are the Fugnitz and the Kaja (both are third-order stream).(Wimmer and Moog 1994) The Fugnitz is the biggest tributary of the Thaya within the Thayatal National Park and shows similar meander formations in the parts close to the outlet.(Berger and Priemetzhofer 2010) The mean annual discharge of the Thaya, measured at the outlet point of the Fugnitz in the town Hardegg is 7.1-10.1 m3$\cdot s^1$.(Holzer and Hinterhofer 2007) The marked geology and geomorphology in combination with the areas location on a climatic gradient is responsible for a high number of different biotope types and, accordingly, a high biodiversity.(Wrbka et al. 2001) Of special interest for botanists and zoologists are habitats in meadows and dry grassland as well as the diversity of fish and macrozoobenthos.(Rabitsch 2005) Apart from these almost natural habitats, the flatter areas of the region host extensive used arable land.(Essl and Hauser 2003)

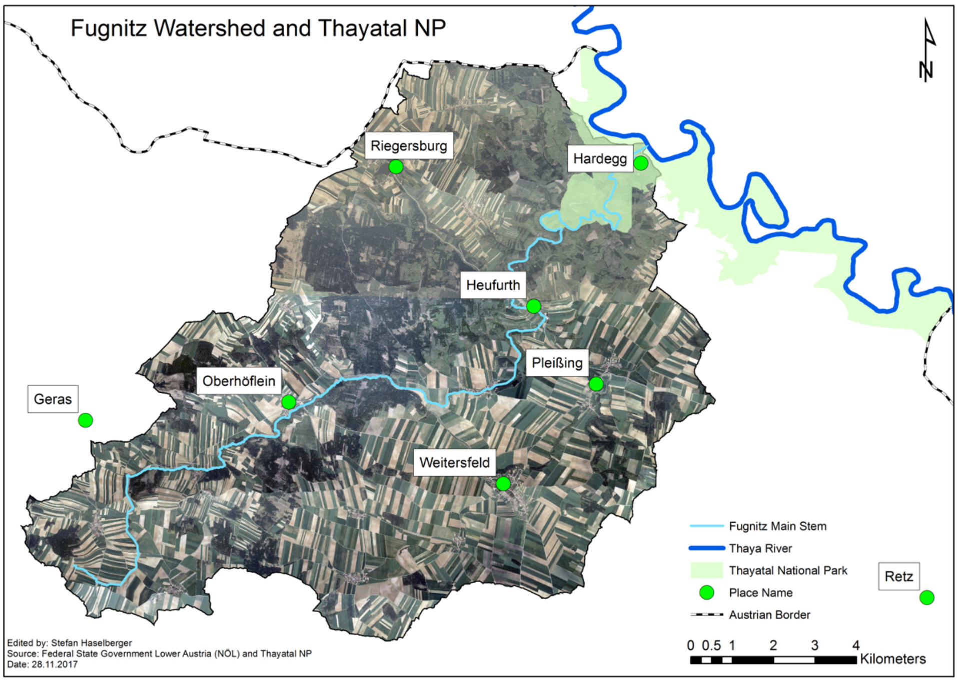

Figure 15: *Geographical setting of the Fugnitz watershed and the adjacent Thayatal National Park.*

Chapter 4

Methods

In order to meet these objectives and to answer the research questions proposed in the introduction of this thesis, a combination of spatial modeling and field investigations was chosen. At the catchment level it is necessary to determine the drainage area of the Fugnitz, delineate subcatchments and model the specific sediment yield for each of these areas (assessment of off-site effects). To validate the results, the focus is shifted to off-desk work in the field. Field survey checklists are used to map and visualize indications of soil erosion processes. Based on this field knowledge, the above-mentioned first model run will be validated. In the second stage, the focus will shift to certain target areas modeled in detail in order to gain information about location and distribution of flow paths and erosion rills (assessment of on-site effects). Again, subsequent field investigations, this time with support of measuring equipment (geodesy), will provide information for further model evaluation. In order to investigate the effects of different parameters on the rates of soil loss and sediment yield hillslope profile modeling in WEPP is conducted. A predefined set of topographic circumstances and land use options with present soil and climate information from the Fugnitz watershed ought to provide information on soil erosion rates for different scenarios. This approach is supplemented with a simulation of different land use scenarios on catchment level. As there is currently a lack of any quantifications of soil erosion processes within the Fugnitz watershed, the field investigations are necessary in order to assess and validate the results obtained in the course of erosion modeling. The on-site examinations and mappings of the situation aim at testing the modeling approach of the research.
Figure 16 visualizes the above-described methodological approach of the thesis. Two sets of modeling steps for two different scale levels (catchment, subcatchment) with corresponding field validation sessions form a four-step-procedure. The next few sections will introduce WEPP/GEOWEPP modeling in detail and discuss the necessary preparation and implementation of each of the four steps. Information will be provided about necessary data

inputs and related data preprocessing challenges. Furthermore, it is important to describe the model setup and how the field investigations aim to validate model results.

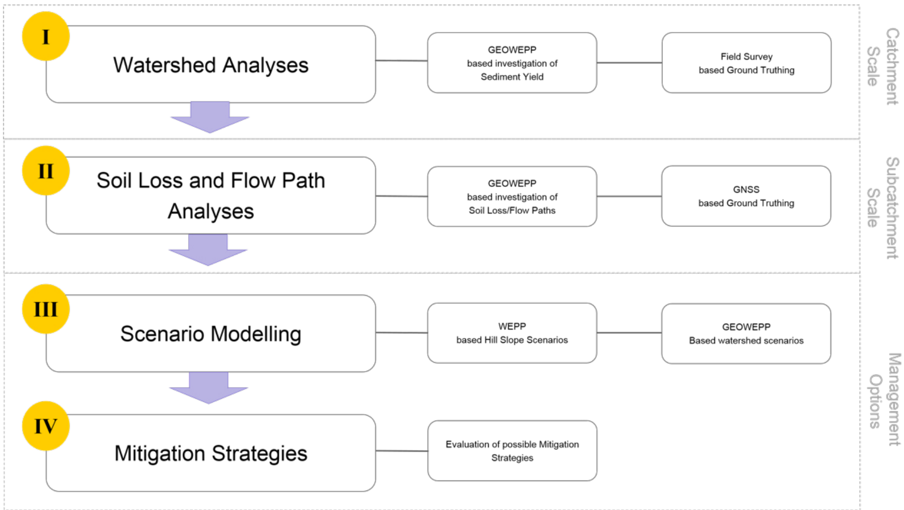

Figure 16: *Methodological steps of the present thesis.(Own illustration)*

4.1 The Water Erosion Prediction Project (WEPP)

The WEPP modeling approach is based on fundamental physical principles and predicts water driven soil erosion either for a single hillslope or a full watershed.(Flanagan and Livingston 1995) With knowledge on hydrological and erosion processes, the model is able to simulate spatial and temporal distribution of soil loss, sediment yield and runoff.(Laflen et al. 1991) The WEPP computer model is applicable for different environmental settings (Mirzaee et al. 2017; Brooks et al. 2016; Gould et al. 2016; Mahmoodabadi and Cerdà 2013; Grønsten and Lundekvam 2006; Singh and Goel 2011) and is able to provide scenario-based information for appropriate and sustainable measures for soil conservation and soil control.(González-Arqueros et al. 2017) Established 1995, the model is based on ten years of research by the United States Departments of Agriculture.(Flanagan and Livingston 1995) The main objective of this research was to replace commonly used empirical soil erosion models like USLE with a process-based approach which is able to estimate sediment delivery from fields to off-site channels, locate soil erosion within a watershed, take impoundments into account, simulate runoff and give information on watershed sediment yield.(Flanagan et al. 2007) Various input parameters are needed to derive the necessary information for involved hydrologic and erosion processes. WEPP uses this input variables to compute information on climate variability, surface and subsurface processes of hydrological flow, different plant growth habits, effects land management practices, and information about the previously described soil erosion processes (splash erosion, interrill erosion, rill erosion and runoff).(Flanagan et al. 2000) The output of the model is information on average annual rainfall, runoff, soil loss, and sediment yield, either in graphical or textual format.(Flanagan et al. 2007) Furthermore, it is possible to investigate the likelihood of high magnitude erosion events for runoff or sediment yield with return period analyses.(Elliot et al. 2006) As it is very difficult to obtain exact predictions for future erosion rates from field measurements, numerical modeling is the most reliable method to generate reproducible predictions of soil loss and sediment yield in order to support management and conservation activities in a certain area. The simulations provide efficient and a cost-effective tool to investigate short- and long-term strategies for the management of a variety of different locations.(Klik 2004) The power of geographic information systems for spatial data analyses, like processing and generating of spatial data on catchment level and especially the ability for better data visualization, led to the development of GEOWEPP.(Renschler 2003) The software was developed at the USDA-ARS National Soil Erosion Research Laboratory (NSERL) and allows the user to import relevant parameters for soil erosion analysis as GIS-layers. (Flanagan et al. 2013) The concept of GEOWEPP is visualized in figure 17. The model uses spatial information about topography, climate, soil, land cover and management practices to compute spatially distributed, annual amounts of sediment yield, soil loss, total runoff and peak discharge based on the equation of the WEPP model within a GIS-environment.(Renschler 2003) Results within GEOWEPP are reported based on a target value (T-value) which is pre-set to one ton per hectare per year for erosion loss and sediment yield.(Minkowski and Renschler 2008) The resulting grid layers of GEOWEPP are represented as a percentage of this T-value.(Yüksel et al. 2008)

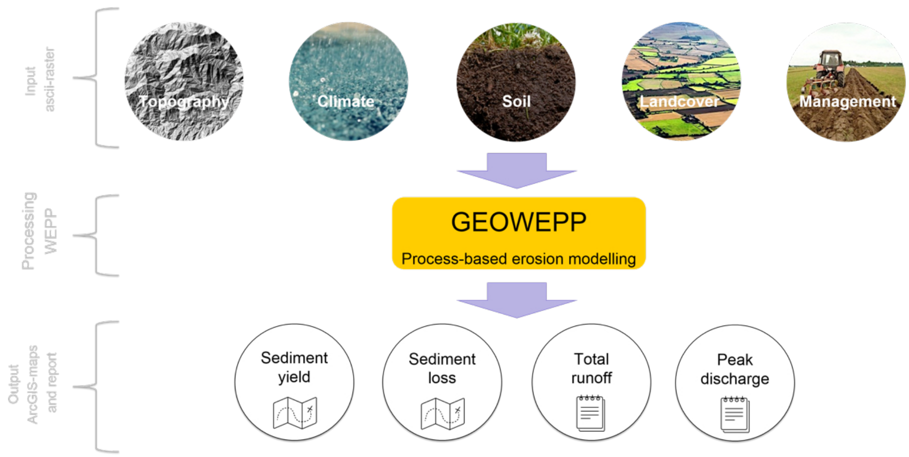

Figure 17: *Basic concept of GEOWEPP modeling with necessary input variables and available output information (Source: own illustration)*

For the present study, three different software products were used. The WEPP Model Version 2012.800 was linked to ArcGIS 10.4.1 (ESRI, Redlands, CA) via GEOWEPP for ArcGIS 10.4 (`http://www.geog.buffalo.edu/~rensch/geowepp/arc_index.html`) Integrated in GEOWEPP are two further tools, the Topographic Parameterization tool (TOPAZ) and tool for translation WEPP information into GEOWEPP called TOPWEPP provided by the United States Department of Agriculture - Agricultural Research Service (USDA-ARS).(Maalim et al. 2013)

4.1.1 WEPP computation

As WEPP is a physically-based model which strives to simulate erosion processes with mathematical equations, it is possible to look at the structure of this “white-box-approach”.(Rickson 2006) The model considers interrill and rill processes separately (Flanagan and Livingston 1995), which is described in the following equation:

$$\frac{dG}{dx} = D_i + D_f \tag{4.1}$$

where G is the sediment load (kg $\cdot$ s$^{-1}\cdot$ m^{-1}) and x is the distance down the slope (m). D_i is the detachment and transport of sediment to the rill-gully-channel system by raindrop impact and surface flow (kg$\cdot$s$^{-1}\cdot$m^{-2}), which describes splash and interrill erosion. Df stands for the detachment or deposition rate of sediment by concentrated flow (kg $\cdot$ s$^{-1}\cdot$m^{-2}), which describes rill erosion processes.(Laflen et al. 1991; Mirzaee et al. 2017) These interrill (D_i) and rill (D_f) processes are described by the following equations (Foster et al. 1995):

$$D_i = K_{ib} I q S_f \tag{4.2}$$

where D_i – the interrill component – is calculated by the baseline interrill erodibility ($kg \cdot s \cdot m^{-4}$) (K_{ib}), the rainfall intensity ($m \cdot s^{-1}$) (I), the runoff rate (m· s^{-1}) (q) and a slope adjustment factor (S_f). D_i is either positive in the case of erosion or negative in the case of deposition.(Kinnell 2017)

$$D_f = D_c(1 - \frac{G}{T_c}) \tag{4.3}$$

where D_f – the rill component – is calculated with the detachment capacity of rill flow ($kg \cdot s^{-1} \cdot m^{-2}$) ($D_c$) and the sediment capacity in the rill ($kg \cdot s^{-1} \cdot m^{-1}$) ($T_c$).

$$D_c = K_r(\tau_f - \tau_c) \tag{4.4}$$

where the detachment capacity of rill flow (D_c) is calculated with a rill erodibility parameter (K_r)($m{\cdot}s^{-1}$), the flow shear stress influencing sediment particles (τ_f) and the critical shear stress for rill detachment (τ_c). τ_f and τ_c (kg ·m^{-3} are described as follows (Foster et al. 1995):

$$\tau_f = \gamma R sin(\alpha)(\frac{fs}{ft}) \tag{4.5}$$

where γ describes the specific weight of water ($kg \cdot m^{-2} \cdot s^{-2}$), R the hydraulic radius of a rectangular rill, α the average slope angle of a uniform slope and $\frac{f_s}{ft}$, the ratio between shear stress acting on the soil and total hydraulic shear stress.(Foster et al. 1982)

$$\tau_c = k_t \tau_f^{3/2} \tag{4.6}$$

where τ_c is the product of a transport coefficient (k_t) ($m^{0.5} \cdot s^2 \cdot kg^{-0.5}$) and the hydraulic shear acting on the soil (τ_f). The shear stress is influenced by the development of surface runoff which is implemented with the Green and Ampt infiltration equation (Green and Ampt 1911):

$$f = K_e(1 + \frac{N_s}{F}) \tag{4.7}$$

where f stands for infiltration depth per time unit, K_e stands for effective hydraulic conductivity depth per time unit, F is the cumulative infiltration depth, and N_s is the depth of effective matric potential.(Kinnell 2017) The effective hydraulic conductivity depends on the soil texture and is calculated as follows (Kidwell et al. 1997):

$$K_e = (56.82K_{ef}0.286/1 + 0.051e0.062CN) - 2 \tag{4.8}$$

where K_{ef} is the hydraulic conductivity for fallow conditions and CN is the curve number which is based on the area's soil group, land use, management and hydrologic condition.(Cronshey 1986) Flanagan et al. (2012) stressed that soil loss on a hillslope is most sensitive to the influence of rill soil erodibility (krb), the critical shear stress (τ_c) and the hydraulic conductivity of the soil (Ke).

4.1.2 Hillslope - flow path - watershed

The WEPP model can simulate the effects of erosion either for a representative hillslope or a watershed.(Flanagan and Livingston 1995) Within hillslope analyses, it is possible to investigate single profiles with complex structures - various changes in slope angle, soil properties, and land use and/or management practices.(Nearing et al. 1990) To account for these changes, the model divides a slope profile in up to 19 so-called overland flow elements (OFEs) with a unique combination of the factors just mentioned.(Brooks et al. 2016) Within watershed applications, WEPP considers the linkage of single hillslope profile channels and impoundments and continuously routes water and sediment through this area.(Flanagan and Livingston 1995) Figure 18 shows the hillslope profile (a) and the watershed view (b) within the WEPP desktop application. Each model of a hillslope has a layer for slope parameters, soil properties, a combination of land use and management practices and global information on climatic conditions. The watershed view provides information on individual hillslopes and channels that compose the present subcatchment. Each of the hillslopes within a watershed has a corresponding hillslope profile.

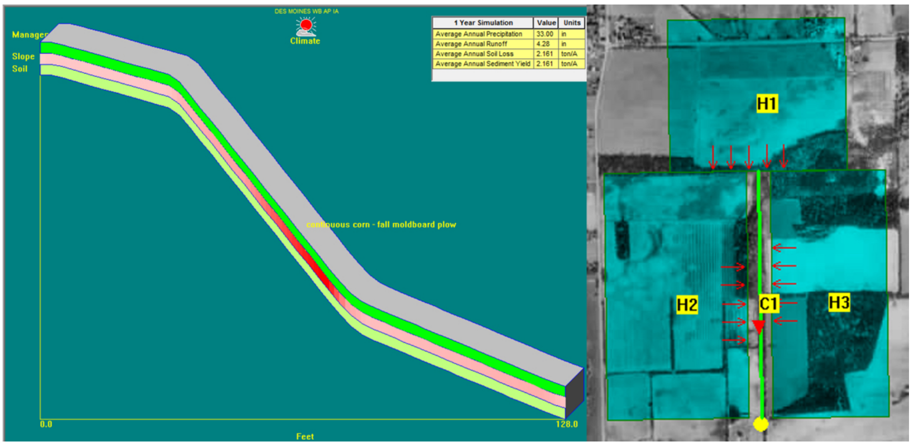

Figure 18: Hillslope profile and watershed view within WEPP desktop application (Source: WEPP Model Version 2012.800)

GEOWEPP uses this concept of erosion modeling for representative hillslopes profiles and their allocation on different subcatchments.(Minkowski and Renschler 2008) Apart from the basic WEPP modeling background there are two different modeling approaches in GEOWEPP: On the one hand, it is possible to model the off-site effect of erosion with the watershed method and, on the other hand, on-site effects are determined by the flow path method.(Renschler 2003) The watershed method focuses on sediment yield per subcatchment and for the whole watershed.(Foltz et al. 2011) For this purpose, GEOWEPP disintegrates the present study area into different landscape elements.(Licciardello et al. 2006) This process is visualized in figure 19. First, a channel network for the given topography is delineated (a), then, subcatchments are generated (b) and, lastly, these catchments are split into elements for which uniform properties are assumed and which comprise a network of channels and planes.(González et al. 2016) A hillslope generated by the watershed method of GEOWEPP is described only by a single OFE with one characteristic value for soil, land use and management resulting in a decrease of spatial variability.(Brooks et al. 2016) This representative profile is a combination of all flow paths within the respective subcatchment and shows the dominant soil, land use and management.(Minkowski and Renschler 2008) Once the different landscape elements are generated, WEPP simulation is performed on each unit and subsequent results are compiled.(Renschler 2003) The result of this watershed approach represents the amount of sediment that leaves a subcatchment and is reported at specific outlet point.(Renschler and Flanagan 2002)

The flow path method of GEOWEPP models erosion and deposition for every flow path within a subcatchment rather than a single slope profile as described before.(Yadav and Malanson 2009) In contrast to the watershed method which only uses one soil, land use and management parameter for an OFE, the flow path method retains the spatial diversity of the input parameters for the investigated study area.(Minkowski and Renschler 2008) It is possible to simulate and merge soil loss along every flow path within a given area.(Renschler and Flanagan 2002) The model is able to determine soil erosion and deposition for every cell of the flow path and, therefore, gives information about the on-site effects of the investigated processes.(Foltz et al. 2011) The slope for this analysis is derived from the elevation of every flow path pixel.(Minkowski and Renschler 2008) Flow paths often converge at lower slope positions next to the channel system resulting in compiled amounts of soil loss from these various contributing sediment transport routes.(Flanagan et al. 2012) The number of flow paths depends on the size of the watershed. It is possible that there are only a few OFEs, but several hundred flow paths modeled.(Renschler 2003)

4.1.3 Topographic parameterization

The Topographic Parameterization digital landscape analysis tool (TOPAZ) is used in WEPP as well as in GEOWEPP for delineating subcatchments,

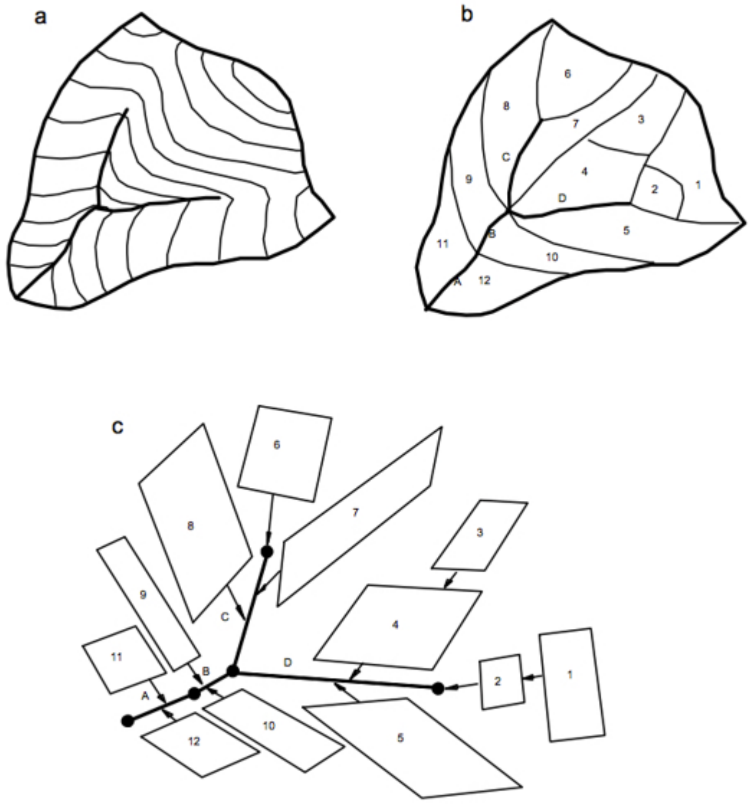

Figure 19: *Discretization of landscape elements into channels and subcatchments within a modeling system (Morgan et al. 1998)*

channel networks and to derive input values for each hillslope profiles.(Flanagan et al. 2013) The hillslope profiles are parameterized using information from a digital elevation model (DEM) in combination with the remaining input parameters.(Maalim et al. 2013) The Channel network is delineated based on the topographic information and under consideration of the D8 which follows the "slope-of-steepest-descent routing concept" (Garbrecht and Campbell 1997: 205). The d8 algorithm compares the elevation value of cells always routing the flow to one of the eight neighboring cells that has the lowest elevation value.(O'Callaghan and Mark 1984) It is commonly used in hydrological analyses.(Wilson et al. 2007) The user is able to modify the size of the resulting subcatchments with the values for critical source area (CSA) and the minimum source channel length (MSCL).(Flanagan et al. 2000) The CSA value is important for determining channel location and length and is defined by the area whose concentrated water flow defines the beginning of a channel.(Garbrecht and Campbell 1997) MSCL is the shortest length for source channels (first order streams) to be generated by TOPAZ.(Garbrecht and Martz 1994) Changes of these values affect the density of the delineated

drainage network and the number of resulting subcatchments.(Minkowski and Renschler 2008)
Figure 20 visualizes the delineation process performed by TOPAZ within WEPP/GEOWEPP.(Flanagan et al. 2013) The first step is to (a) delineate the watershed and channel system for a given outlet point and to consider the CSA and MSCL just mentioned. The distribution of this channel network determines size and arrangement of the subcatchments (step b). For each of the subcatchment, a representative slope profile is assigned in order to perform WEPP modeling and flow paths are routed depending on the above-mentioned algorithms (step c).

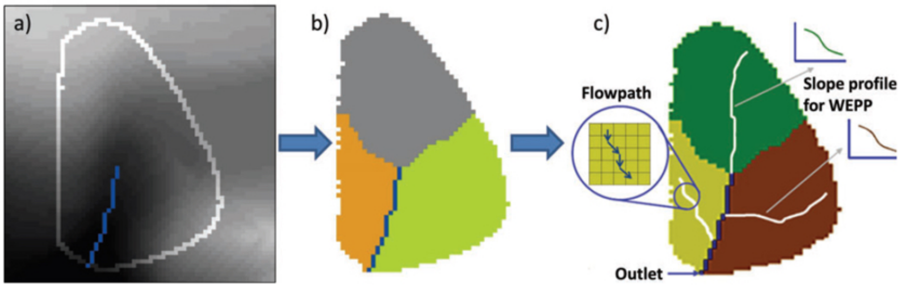

Figure 20: *Delineation steps for channel network, subcatchments, slope profiles and flow paths in WEPP/GEOWEPP (From Flanagan et al. (2013) and based on Cochrane and Flanagan (2003))*

4.2 Data basis

In order to run WEPP/GEOWEPP for soil erosion modeling in the Fugnitz watershed, several datasets were necessary. A key role in soil erosion modeling is the topography of the study area. For the present thesis, a high-resolution (1 m x 1 m) digital elevation model was obtained. The terrain information is based on aerial laser scanning (ALS) data and was provided by the Federal State Government of Lower Austria (NÖL). Climate data for two stations, Geras and Riegersburg, was made available by the Federal State Government of Lower Austria (NÖL). Both stations lie within the Fugnitz watershed area on an elevation of 450 and 460 m, respectively. The stations are maintained by the Hydrographic Service of Lower Austria. The data consists of daily minimum and maximum temperatures as well as daily precipitation values for the period between January 1^st, 1972 and March 1^{st}, 2017. As the Riegersburg-climate-file showed a significant number of missing values, it was necessary to adhere to the Geras data for further model implementation. Apart from daily temperature and precipitation values, information was available about the maximum 30-minute and maximum 6-hour rate of precipitation, which indicate the expected storm intensity in

the region.
Information on soil properties in the Fugnitz area was provided by the Federal Office for Water Management (BAW). The shapefile and the corresponding table hold information about soil properties for different layers stored in polygon format. For each layer, information was available on soil type, soil moisture, coarser material, humus type and properties, lime content, soil texture and structure, color, root penetration, grain size distribution, pH value, bulk density and field capacity. These data were collected by field measurements and subsequent geostatistical interpolation and inference algorithms in a GIS-system.(Walker et al. 2017) Information on land use in the Fugnitz area was provided by the Federal Office for Water Management (BAW) as well. Stored in shapefile-format, the data holds information on 35 different land use categories. The main categories of agricultural land, forest, built up area, water bodies and other areas are distinguished in various subcategories. Data generation by the BAW was done using CORINE-data (Bossard et al. 2000), INVEKOS-data (Nölle and Streit 2002), a digital cadastral map and an Austrian forest map (ÖWK)(Bauerhansl et al. 2007).
Information about common management practices was provided by the Farmers District Division of Hollabrunn. A frequently used crop rotation concept for a four year interval used in agricultural production in the Fugnitz area for the set-up of management parameters was used. Additionally, information on tillage practices (machinery, row width, tillage depth) and commonly used field crops were provided. Furthermore, orthophotos from the Federal State Government of Lower Austria (NÖL) were available and the data was used for general orientation and for a complementary check of land use data.
Table 1 summarises the input data just described for further model implementation. As this raw data cannot be just integrated into WEPP and GEOWEPP modeling, the next few sections will discuss the necessary editing of the data.

4.3 Setup and data preprocessing

To integrate the data previously mentioned, it was necessary to conduct a series of data preprocessing steps. GEOWEPP needs all geographical data in the American Code for Information Interchange (ASCII) format. In order to link the WEPP information about soil and land use, two text files are needed in each case. A final text file provides the climate data. To ensure full transparency, every step in the process for the four main input parameters as well as for the linking text files will be discussed in detail. The following workflow is related to the GEOWEPP Manual for ArcGIS 9.x.(Minkowski and Renschler 2008)

Table 1 *Input Data for GEOWEPP modeling*

Data file	Description	Resolution	Recording date	Source
DEM	Digital elevation model for topographic analyses	1 x 1m	2008	Federal State Government Lower Austria (NÖL)
Ortho	For validation of land use	0.2 x 0.2m	2016	Federal State Government Lower Austria (NÖL)
Land use	Different land use classes (agricultural land, forest, water body, residential area)	1:1 000	2010	Federal Office for Water Management (BAW)
Climate	Maximum and minimum daily temperature and precipitation (climate station Geras and Riegersburg)	daily	1992-2017	Federal State Government Lower Austria (NÖL)
Soil	Soil properties (texture, organic matter, rocks)	1:25 000	2004	Federal Office for Water Management (BAW)
Mgmt	Management practices in the area (tillage, crops, date of tillage/harvest	1x1m	2008	Federal State Government Lower Austria (NÖL)

4.3.1 DEM preprocessing

For the present research, a DEM with a resolution of one meter was available. The “fill” function of the Spatial Analyst toolbox of ArcGIS was used to make sure that there are no elevation values missing, otherwise the model would not able to handle the terrain information. Due to a lack of processing power of GEOWEPP – which will be discussed later on – it was necessary to resample the data in order to reduce the file size. Therefore, 4 different DEMs with a cell size of five, ten, twenty and thirty meters were generated using the ArcGIS tool “resample”. As has been mentioned before, the information about terrain, soil and land use must be stored for each cell respectively. Hence, data preprocessing of soil information and land use information also needed to be done in these four different resolutions. Another step in the process was to change the projection of the data: As GEOWEPP can only handle Universal Transverse Mercator (UTM) coordinates, it was essential to locate the correct UTM zone. The Fugnitz catchment lies within UTM zone 33 N. To change the coordinate system of the raster file, the “project raster” tool of ArcGIS was used. The last step in the work flow was to convert the raster file into an ASCII (American Standard Code for Information Interchange) text file using the tool “raster to ASCII”. Figure 21 shows the final raster layer with a resolution of five meters (resolution 1 m x 1 m).

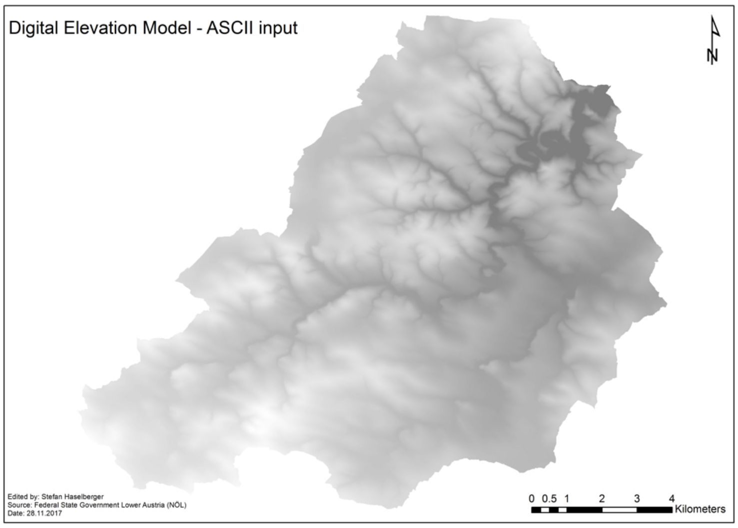

Figure 21: *Digital Elevation Model in ASCII format for model input.*

4.3.2 Soil preprocessing

The original soil data of the Federal Office for Water Management was stored as a shapefile. The first data-preprocessing step was to identify a number which identifies each soil class and can be stored in a raster cell. With the "feature to raster" tool in ArcGIS, this information was stored in every corresponding cell. The generation of the identification number and the different soil classes will be discussed later on. As in the workflow of DEM preprocessing mentioned, GEOWEPP needs a UTM coordinate system. During the projection process, it is possible to simultaneously change the cell size of the raster. Again, the process was completed for the four different resolutions (5, 10, 20 and 30 m). The final step of the process was the conversion into an ASCII file as described above. The resulting raster layer is shown in figure 22 (resolution 1 m x 1 m).

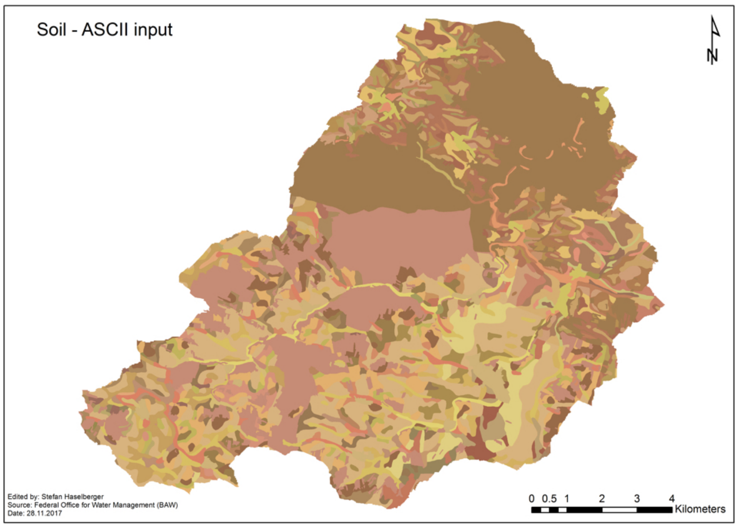

Figure 22: *Soil input file in ASCII format.*

To link the spatial information stored in the newly generated raster data and the soil parameter files in WEPP, it was necessary to create two text-files: soilsmap.txt and soilsdb.txt. As the information stored in each raster cell only represents a certain value, the model needs further information which specific parameters correspond with the information in the raster data. In other words, this preprocessing step basically links the initial soil information with the spatial information edited in the GIS-environment. WEPP uses the following soil parameters for each soil type:

- soil name
- soil texture
- albedo of the bare dry surface soil (%)
- initial saturation level of the soil profile (%)
- interrill erodibility parameter (kg*s/m4)
- rill erodibility parameter (s/m)
- critical flow hydraulic shear (N/m2)
- effective hydraulic conductivity of surface soil (mm/h)

For each of the assigned soil layers, the following data is stored as well.

- soil texture (percentage of sand and clay)

- depth from soil surface to bottom of soil layer (mm)
- organic matter (volume) in the layer (%)
- cation exchange capacity in the layer (meq/100 g of soil)
- rock fragments by volume in the layer (%)

To generate the WEPP soil files, it was necessary to use present soil data as mentioned in the previous section. Furthermore, some values were assigned to soil types based on information from soil specific literature while other parameters were calculated by the model itself. The assigned soil name of the generated WEPP soils correspond to the information in the text-files and to the values in the raster cells. Therefore, this identification enables the model to investigate soil information with spatial location. Soil texture was chosen based on the sand, clay and silt content from the input data.(Kellogg 1937) The default values for albedo (reflectance of the soil), i.e. 0.23 (Muneer 2007), and initial saturation of the different soil types (the value for water content in January), i.e. 75%, were used.(McCullough et al. 2008) The interrill and rill erodibility parameter, critical shear stress and effective hydraulic conductivity of surface soil were modeled by WEPP based on the equations previously presented section 4.1.1. Values for depth, texture, content of organic matter and content of rock fragment for each soil layer were taken from the input soil data. The cation exchange capacity was set to 0.20 based on the classification by Donahue et al. (1977) Furthermore, no restricting bedrock layer were chosen.

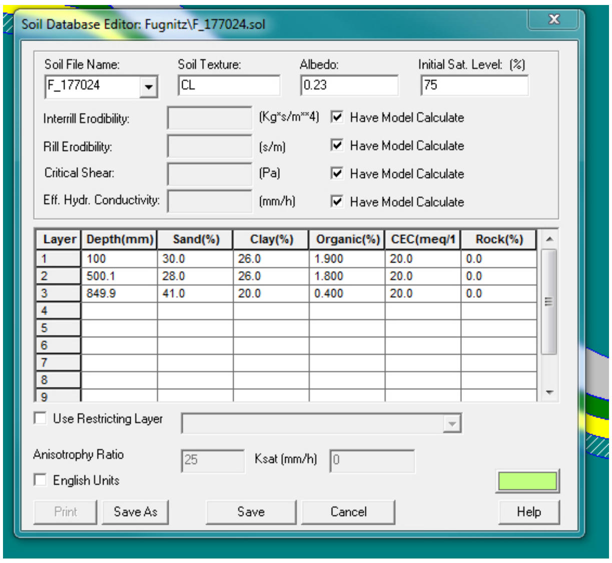

Figure 23: *User interface of WEPP for soil database editing.*

4.3.3 Land use preprocessing

Similar to the soil data, the land use data of the Federal Government of Lower Austria was stored as shapefile. To assign a convenient identification number, it was necessary to convert the land use information into the United States Geological Survey (USGS) coding system. Altogether, 21 classes of the input file (Source: BAW) were translated into 7 different USGS classes:

- Open water
- Low intensity residential
- Bare rock/sand/clay
- Mixed forest
- Pasture
- Small grains

GEOWEPP uses this system in the provided test data. Hence, it was easier to use this classification. The computed classes were used to convert every single feature into one raster file. Again, this was done using the "feature to raster" tool in ArcGIS. To enable the final model implementation, the newly generated raster layer was projected into UTM coordinate system and converted into a raster file using the same tools as described in the previous sections. Figure 24 shows the final land use layer ready to integrate into the GEOWEPP model. To link our raster data with the land use information, a similar process as described in the previous section was necessary. Via the text-files landcov.txt and landusedb.txt, a bridge between raster cell values and WEPP land use information was provided.

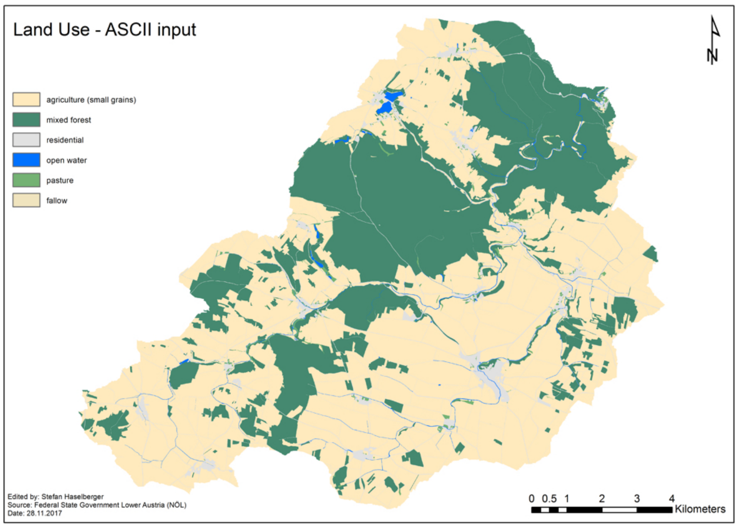

Figure 24: *Land use input file in ASCII format.*

4.3.4 Climate preprocessing

For the preparation of climate input parameters the WEPP implemented application CLIGEN – a stochastic weather generator was used.(Nicks et al. 1994) For the development of the necessary CLIGEN parameter file the above mentioned climate date from the station in Geras were available (daily minimum and maximum temperatures and precipitation values). Additionally information on maximum 30 minute rate of precipitation – 42.418 mm and maximum 6 hour rate of precipitation – 85.589 mm needed to be specified. The location of the Geras climate station is indicated with geographical coordinates (latitude and longitude value) and the elevation value. CLIGEN is able to generate storm patterns (storm duration, peak intensity and time to peak), which is crucial for the characteristics of rainfall erosivity.(Kou et al. 2007) The computation is based on historic measurements in combination with mathematical equations for the distribution of weather patterns.(Zhang and Wang 2017)
Figure 25 shows the generated CLIGEN parameter file with statistically developed monthly averages for precipitation, number of wet days, minimum temperature (C), precipitation on wet days (C), solar radiation, the maximum 30 minute rainfall intensity, the time to peak intensity of a storm and the dew point of the respective month. Furthermore probabilities of a wet day following a wet day and a wet day following a dry day are calculated as well. WEPP is using this climatic circumstances to generate a series of single storm events for erosion modeling throughout a year.(Zhang and Garbrecht 2003) Having said that, only one erosive storm, with one peak and a maximum duration of 24 hours occurs on a rainy day within the WEPP

model predictions.(Kinnell 2017) The generated CLIGEN parameter file can be used for model import within WEPP.

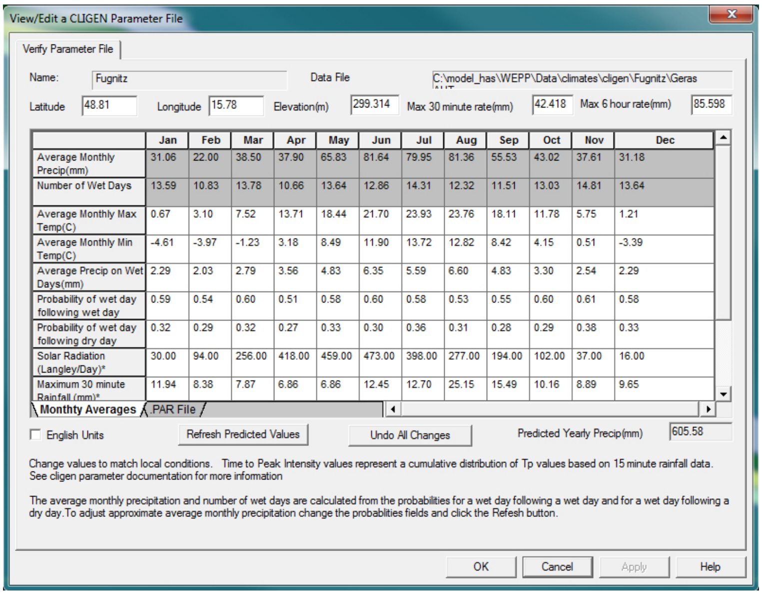

Figure 25: *CLIGEN parameter file with input values of the Geras climate station and calculated weather conditions for one representative year.*

4.3.5 Management preprocessing

Within WEPP, statistically developed values for cropland initial conditions, agricultural operations, and plant growth are stored and used for erosion modeling.(Bavor and Genson-Torrefranca 2016) The management editor allows the user to specify the date and type of agricultural operation.(Newman 2010) As this determines, for example, the time of the year were an agricultural area lies idle, the amount of leaf area covering the soil or the effect of machinery on the composition of the soil, the management practice has significant influence on soil erosion processes.(Brevik et al. 2017) A common crop rotation sequence and information on crops and tillage practices was provided by the Farmers District Division of Hollabrunn and was used for generating the crop management file for WEPP. Parameters for initial conditions and plant variables such as organic residue, roots biomass or plant growth were left unchanged and modeling was performed with the default values. Table 2 indicates the operation dates and different plant, tillage, and harvest practices for four consecutive years.

***Table** 2 Crop rotation for the Fugnitz watershed*

Year	Date	Operation type	Operation information	Additional information
1	01.01.	Initial Conditions	Corn after corn	Jefferson corn
1	05.08.	Tillage	Chisel plow with sweeps	Tillage depth: 15 cm
1	18.08.	Tillage	Chisel Plow	Tillage depth: 15 cm
1	20.08.	Plant - Annual	Canola - Medium Fertilzation Level	Row width: 12 cm
2	01.08.	Harvest - Annual	Canola - Medium Fertilzation Level	Max. leaf area index: 4.5
2	10.08.	Tillage	Chisel plow with sweeps	Tillage depth: 15 cm
2	10.09.	Tillage	Chisel Plow	Tillage depth: 15 cm
2	05.10.	Tillage	Chisel Plow	Tillage depth: 15 cm
2	10.10.	Plant - Annual	Wheat; Winter - Medium Fertilization Level	Row width: 1 2cm
3	05.08.	Harvest - Annual	Wheat; Winter - Medium Fertilization Level	Max. leaf area index: 5
3	10.08.	Tillage	Chisel plow with sweeps	Tillage depth: 15 cm
3	26.08.	Tillage	Chisel Plow	Tillage depth: 15 cm
3	26.08.	Plant - Annual	Alfalfa	Row Width: 19 cm
4	05.03.	Tillage	Chisel plow with sweeps	Tillage depth: 15 cm
4	10.03.	Plant - Annual	Wheat; Spring - Medium Fertilization Level	Row width: 12 cm
4	04.08.	Harvest - Annual	Wheat; Spring - Medium Fertilization Level	Max. leaf area index: 5

4.4 Watershed model Fugnitz catchment

The GEOWEPP model was used to predict soil loss and sediment yield for subcatchments within the Fugnitz catchment. Since no convenient parameterization of the channel processes was available, the present study focusses only on the processes concerning hillslopes. As described in a previous section (see: section 4.3.1) four different DEMs with different resolutions (5, 10, 20 and 30 meter pixel size) and corresponding land use and soil data with the same resolution were generated. For the watershed analysis different sets of these resolutions were tested. As the Fugnitz watershed has an area of roughly 130 km^2 that comprises a large number of subcatchments and flow paths the computational power caused some limitations. Hence, the highest possible resolution to use for watershed analyses of the whole Fugnitz catchment was 20 m. Model simulations were executed using the watershed option within the GEOWEPP toolbox in ArcGIS. During the watershed method GEOWEPP identifies a channel network for the watershed and defines hillslopes draining into each channel segment; for each hillslope a representative profile with topographic, soil, and land use information, based on the main influencing parameters for the specific location is created.(Pandey et al. 2008) These representative hillslopes define the various subcatchments within the model.(Renschler 2003) The critical source area and the minimum source channel length thresholds were set to 20 ha respectively 100 m. These parameters were chosen based on the highest possible density that allows the computational power of the model to perform a model run for the whole catchment area. A total period of 100 years was simulated based on the predefined weather conditions originating from the Geras climate data. The long simulation period ought to account variations in climate effects and the influence of a changing crop rotation. The results of GEOWEPP watershed method provide information on annual total runoff and sediment yield for every subcatchment and information on the effect of single representative precipitation events.(Maalim et al. 2013)

4.5 Field mapping – Sediment yield subcatchments

The intention for this mapping procedure was to discover subcatchments with visible soil erosion features and to document present circumstances in these areas. Furthermore, the data obtained was to support the validation of the above presented watershed model. As it is always necessary to combine modeling approaches with site specific knowledge (Lexartza-Artza and Wainwright 2009; Stieglitz et al. 2003), this thesis combines the previously described WEPP/GEOWEPP modeling with field investigations. Geomorphological mapping is able to provide a landscape inventory for a certain set of processes and helps to quantify and interpret them.(Leser and Stäblein 1975) Field investigations of the whole Fugnitz catchment represented a substantial part of the present research approach. In the course of two lectures (“River Patterns at the Catchment Scale: Analysis of Landscape Connectivity” and “Practical Training in Geomorphology: Field Mapping of Soil Erosion”) and individual field surveys, the study area was visited seven times in the period from October 2016 to October 2017.
In the course of the lecture “Practical Training in Geomorphology: Field Mapping of Soil Erosion”, catchment wide geomorphological mapping was carried out between June 21^st and 23^rd, 2017 and with support from 18 students of the Department for Geography of the University of Vienna. To obtain useful and comparable data for the objectives of this study and to facilitate further data processing and analysis, a standardized and predefined procedure was conducted. The Fugnitz watershed was divided into five similar-sized catchments and each area was investigated by a group of four to six students. Standardized field survey checklists, mapping keys and photo logs were provided to support students in the field and to ensure a uniform mapping approach. These field survey checklists were inspired by those of Borselli et al. (2008) and Poeppl et al. (2012). Furthermore, previously compiled and printed maps aided the mapping procedure. The ArcGIS-based, DIN A3 maps showed an overview of the whole catchment area as well as a detailed map for each group in higher resolution. Two kinds of maps were distributed: aerial images for general orientation on the on hand, and hillshades (generated in ArcGIS with the tools “slope” and

"hillshade"), on the other hand.
Investigation of a catchment for visible soil erosion structures is best performed after a heavy rainfall event.(Gispert et al. 2017) To achieve satisfying results from in situ interpretation of soil erosion features, it is necessary to keep the basics of process response system theory and the process-form-material-relationship in mind.(Chorley and Kennedy 1971) Figure 26 shows the different subsections of the mentioned field survey checklist.

group		**date**		**nr.**	
subcatchment		time			
erosional features	rill erosion	sheet erosion	deposition	entry point	
sediment yield	high	medium	low		
connection hillslope - channel	possible	not possible			
landuse and management					
landuse %	agriculture	rangeland	forest	barren land	built up area
crops	corn	wheat	potatoes	squash	other
plough direction	downslope	perpendicular			
plant cover	25%	50%	75%	100%	
plant height	cm				
slope shape	uniform	convex	concave	complex	other
anthropogenic features	farm track	street	fence	hedgerow	

Figure 26: *Predefined filed-survey checklist for soil erosion feature mapping.*

Okoba and Sterk (2006) classified visible soil erosion features for field investigations into current and past structures. More recent features account for splash pedestals (craters developed due to raindrop impact), sheetwash (smoothened surface or flattened vegetation that shows direction of flow), rills (continuous or discontinuous channel structures), root exposure (visible roots due to top soil retreat), sedimentation (identified by buried crops, nutrient-rich material and/or coarse sandy/stony deposits). Structures which date further back include visible stoniness (small loose stones on the surface, due to retreating topsoil; rock outcrops), partly exposed rocks and gullies (big rill-like features). For the present study sheet erosion, rill erosion and sediment deposition features were mapped. Furthermore, a possible connection of hillslopes with the channel system was investigated and present entry points were mapped. Information on land use, present crops (including plant height and plant cover) and plough direction were included since these parameters are assumed to influence sediment transport and erosion.(Poeppl et al. 2012) Anthropogenic features like farm tracks or streets were recorded as well as these structures tend to act as sediment buffer and obstruct and guide sediment transport.(Hösl et al. 2012; Poeppl et al. 2012) Quantitative information on investigated subcatchments obtained with predefined field survey checklists was subsidized with extensive photo documentation of visible erosion forms.

4.6 Flow path modeling - Target areas

To test the ability of GEOWEPP to delineate flow paths, modeled flow paths are compared to surveyed erosion rills in the field. For this purpose, the study used a second modeling step for preselected target areas. The subcatchments picked for this methodological step are based on field investigations; only areas that were assigned a high sediment yield level were considered. Furthermore, subcatchments of different sizes were chosen in order to investigate scale issues for flow path delineation. For each of these three target areas, a GEOWEPP simulation using the flow path method was generated. As modeling areas are significantly lower than during watershed analyses, it was possible to use a DEM with a resolution of 1m. The input parameters - land use, soil and climate -stayed the same as in the watershed method. The management component was set to an initial condition of corn after corn, since higher amounts of soil loss for this scenario were expected. As the spatial distribution of different crops is not as important for this small scale analysis and as computational demands during the use of the flow path method are high, a simulation period of one year was predefined. This second modeling option of GEOWEPP simulates every flow path within a watershed and assigns in each case the present soil and land use information for each cell of the delineated flow paths.(Flanagan et al. 2000) After simulating sediment detachment, deposition, and delivery for this flow path network, GEOWEPP provides model reports and visualization of results via soil loss maps.(Brooks et al. 2016) The present study focuses on the flow path delineation in this method.

4.7 Field mapping – Soil loss target areas

In order to allow assessment of modeled flow paths a second field session was conducted. To obtain high-accuracy data on erosion rills in the field, a global navigation satellite system (GNSS) receiver was used. Precise geodetic point positioning approaches are extensively used in geomorphological field campaigns.(Kouba and Héroux 2001) This mapping of target areas was carried out on the 22nd of September 2017. Erosion structures were surveyed with a GNSS Leica GS15 System provided by the Department for Geography of the University of Vienna. High precision of field measurements is ensured by receiving live correction data (via the cellular network) from the Austrian Positioning Service (APOS), which enables a 3D-uncertainty lower than 1.5 cm.(Lichtenegger and Wasle 2008). Sheet erosion and rill erosion structures as well as deposition areas were measured for the three abovementioned target areas. Subsequently, measured point data was transferred to GIS and visualized. Data-post-processing in ArcGIS ought to visualize actual soil erosion features and anthropogenic structures that may influence

soil erosion. A particular focus was put on the comparison of modeled flow paths and investigated flowlines and/or erosion rills in the field. For target area A, the post-processing of GNSS-data and he mapping of erosion and deposition features was supported by an aerial image from Google Earth (Google Earth Pro.Ink 7.3.0) from August 15^th, 2017. This complementary work step was only possible for the mentioned target area due to a lack of data for the other areas.
Based on the polylines for the rill features, information on slope angle, curvature, flow accumulation, soil type and land use was extracted using the ArcGIS tool “Add Surface Information” from the Spatial Analyst Toolbox and obtained information was stored for further data interpretation. The obtained information should provide a tool for comparison of modeled flow paths and mapped erosion rills. For further data analysis by means of visual comparison of model flow paths and mapped erosion rills, modeled flow paths were manually sorted into two groups, i.e. low amount of potential soil loss (0) and high amount of potential soil loss (1). The sorting of this “soil loss class” was based on the length of the flow path, the underlying land use (flow paths on agricultural area were preferred) and the modeling results (focusing on areas with high soil loss) in relation to the other flow paths of each target area. This classification ought to help the comparison procedure and highlight whether significant sources of soil loss within the model can be seen in the field or not. During another data preparation step, modeled flow paths which were only present in the computational prediction (0) and those that were present in the model and the field (1) were separated.

4.8 WEPP scenario modeling

Scenario modeling ought to provide information on the influence of topographic factors and a change in land use. This methodological step is divided into two different parts. On the one hand, land use scenarios for representative hillslopes with certain topographic parameters investigates general relationships for soil erosion in the Fugnitz catchment. On the other hand, GEOWEPP based modeling of the whole watershed using different crop rotations ought to provide information about their effect on the spatial distribution of sediment yield.
The objective of hillslope scenario modeling is to test the influence of slope curvature, slope angle and different land use scenarios on WEPP-modeling results. The following input variables were used: a widespread soil type of the Fugnitz catchment in combination with the previously mentioned crop rotation file and the generated climate data from the Geras station with an annual precipitation of 567.8 mm is used. Furthermore, a slope with a length of 200 meters and three different slope angles (2°, 4° and 6°) functioned as predefined profile. For each of the slope angles, three different slope curva-

tures were used, i.e. uniform, convex and concave. For each slope curvature, in turn, five different land use situations were assigned (fallow, corn, wheat, grass and forest). WEPP modeling provided annual values for total runoff in mm per year, amount of soil loss in tons per hectare per year and amounts of sediment yield in tons per hectare per year. The modeling procedure was performed for a period of 100 years in the WEPP standalone application v2012.8.

The watershed method used the same input information on soil and land cover as used in section 4.4. Four different land use scenarios were analyzed, i.e. corn, wheat, grass and forest. Fallow conditions were not considered as it was not a serious alternative for future land use. Default crop rotation files from GEOWEPP were used for each of these four scenarios. Modeling was performed in GEOWEPP for a period of 100 years.

Chapter 5

Results

The following chapter will summarize the results of the present study. The structure of the sections will follow the structure of the previously described methodology (see: chapter 4). The results of the two GEOWEPP modeling steps for the Fugnitz watershed and the corresponding field investigations, i.e. catchment scale and subcatchment scale, will be presented in detail. Model outputs for both scale levels will be visualized with GIS-based maps. The obtained data of the two field investigation sessions will be presented and evaluated as well. The last part of the results will illustrate WEPP scenario modeling for representative hillslopes and provide information on the influence of slope angle, slope curvature and land use/management on the amount of runoff, soil loss and sediment yield. Additionally, GEOWEPP based maps for different scenarios ought to show the influence of different land use approaches on the spatial patterns of sediment yield.

5.1 Watershed analyzes

During watershed analyses, predictions on the annual amount of sediment yield per subcatchment and predictions on runoff for a set of precipitation events for the whole Fugnitz watershed were made. The predictions of the spatial and temporal distribution of runoff depth and sediment yield vary depending on the topography, soil type and land use as partially shown in the previous section.(Maalim et al. 2013)
Figure 27 visualizes the catchment wide predictions of sediment yield for the 100-year simulation run. As the present thesis focuses on hotspots of sediment yield, the visualization of the model results will focus on those areas with high values for these parameters. The coloring is based on a Tolerable Soil Loss scheme for the mean sediment yield outputs. Tolerable Soil Los, the so-called T-value, is the acceptable amount of erosion without affecting crop productivity.(Wischmeier and Smith 1978) Theoretically, it is only accaptable to lose sediment at the rate of soil building processes

to keep present conditions.(Jha et al. 2009) As there tend to be big differences between the rate of soil formation for different soil types, in theory a single T-value will not account for different soil patterns.(Jha et al. 2009) Nevertheless, agronomists agreed on a maximum value of 11.2 t/ha/y for protection of soil and the environment.(Hall et al. 1985) The results shown in figure 27 are based on these assumptions. To visualize hotspot areas of sediment yield, the default T-value (1 t) was applied uniformly across the watershed. The map provides information on the off-site effects of soil erosion for each subcatchment and no information according on-site effects are included. There may be a big difference between rates of soil loss within a subcatchment and the amount of sediment reaching an outlet point.(Fryirs et al. 2007) Since eroded material can be stored on its way through the subcatchment, there is no balance necessary between on-site soil loss and off-site sediment yield. In fact, amounts of sediment yield for a given area are always lower than the mass of soil loss.(Maalim et al. 2013)

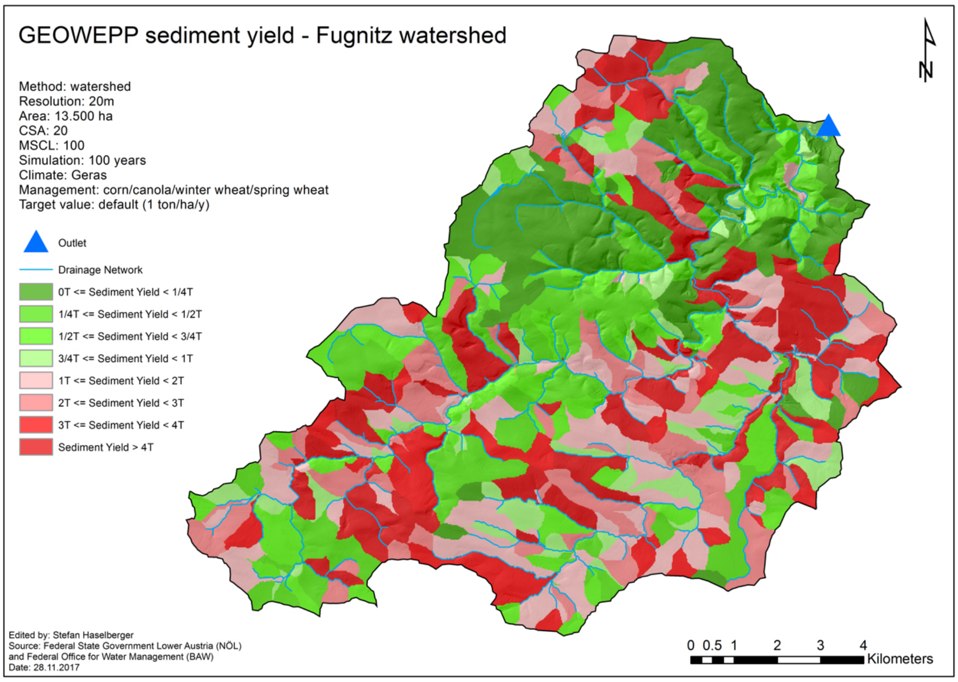

Figure 27: *Distribution of sediment yield for the whole Fugnitz watershed.*

GEOWEPP modeled a total of 731 hillslopes and 295 Channels for the Fugnitz watershed. The erosion processes are based on 154 storms that produced 567 mm of rainfall on an average annual basis. The model considered a total of 23 high intensity rainfall events with a runoff of 18 mm passing through the watershed outlet on an average annual basis. For the 13 000 hectare of the Fugnitz catchment, the model computed an average annual

precipitation volume of 73 571 003 m^3/yr and a water discharge of 2 444 195 m^3/yr at the outlet point. The total annual soil loss from the 731 hillslopes is estimated at 33 988 t/yr, which corresponds to an average soil loss of 2.62 t/ha. The average annual sediment discharge from the outlet is predicted as 93 502 183 tons/yr with a delivery per unit area of 7 192 t/ha/yr. According to GEOWEPP this eroded material consists of 74% silt, 24 clay and 2% sand. Model results and percentage for T-values per model unit (hillslope) are summarized in table 3.
As previously mentioned, WEPP/GEOWEPP estimates low amounts of soil loss and sediment yield for forested areas due to the protective effect of dense vegetation. Therefore, the north-eastern part of the Fugnitz catchment which comprises big areas of woodland show less subcatchments with high values of sediment yield. 51% of the modeled subcatchments show increased values of sediment yield (>1 t/ha/yr). Indicated in dark red are areas with the highest amounts of sediment yield (>4 t/ha/yr). 17% of the subcatchments are in this bracket. On the other side of the scale, 13% of the subcatchments are assigned with a sediment yield amount of lower than 0.25 t/ha/yr. When looking at the influence of land use, there is a significant tendency for agriculturally dominated subcatchments to have high amounts of sediment yield. From 300 subcatchments with more than 80% agricultural area (45% of the total area), 65% show increased values of sediment yield (>1 t/ha/yr). On the other hand, only 23% of subcatchments with more than 80% forest show this increased sediment yield values.

Table 3 *Results of the watershed analyses for the Fugnitz catchment*

Simulation period (years)	100
Modeled hillslopes	731
Modeled channels	295
Modeled area (ha)	12 974.11
Average annual precipitation volume (m3/yr)	73 571 002
Average annual water discharge from outlet (m3/yr)	2 444 195
Average annual hillslope soil loss (m3/yr)	33 988
Average annual sediment delivery per unit area (tons/ha/yr)	2.62
Clay content of eroded material (%)	24
Silt content of eroded material (%)	74
Sand content of eroded material (%)	2
SY > 4 T	117 hillslopes 17%
SY 3-4 T	40 hillslopes 6%
SY 2-3 T	75 hillslopes 11%
SY 1-2 T	117 hillslopes 17%
SY 0.75-1 T	64 hillslopes 9%
SY 0.5-1 T	67 hillslopes 10%
SY 0.25-0.5 T	111 hillslopes 16%
SY 0-0.25 T	90 hillslopes 13%

5.2 Field mapping - subcatchments

This section will provide results of the geomorphological mapping and the various field investigations for the Fugnitz catchment. During the mapping procedure on June 21^{st} and 22^{nd}, 2017, a total of 63 subcatchments were investigated. Out of this, 31 subcatchments showed indications of soil erosion which account for almost 50% of the investigated units. Rill erosion, sheet erosion, deposition areas and present entry points into adjacent channel systems were recorded. The key process for the Fugnitz watershed is rill erosion. 65% of the catchments with visible erosion features showed soil loss due to concentrated flow. 33% of the investigated subcatchments were rated as having a medium to high sediment yield. When looking at the present land use in these areas, 38% of the fields comprise corn, 33% squash and for each potatoes, wheat and sugar beet 9.5%. Fields with corn and/or squash showed an average plant cover of 50% compared to 83% for wheat. There were no subcatchments with erosion features or increased amounts of rated sediment yields for grass or forest areas reported. 29% of the subcatchments from the total area investigated were rated as possibly connected and potentially delivering sediments into the drainage system. 20% of the subcatchments showed erosion features and a possible connection to the channel system. 72% of all subcatchments are influenced by anthropogenic features, mainly linear structures like farm tracks and streets, which potentially obstruct flow paths in the field and could lead to wrong model predictions.
Figure 28 compares investigated subcatchments with high sediment yield and modeled sediment yield computed with GEOWEPP and shows the distribution of subcatchments for each group during field mapping. From 22 subcatchments with high sediment yield observed in the field, GEOWEPP assigned 18 subcatchments with an increased sediment yield (82%). The four subcatchments that were underestimated by GEOWEPP show rather low values for slope angles with an average of 2.6°, compared to a overall mean subcatchment slope angle of 5.6°, while values for area, mean curvature and mean flow accumulation,soil and land use proportion have shown no significant deviations from the subcatchment mean values.

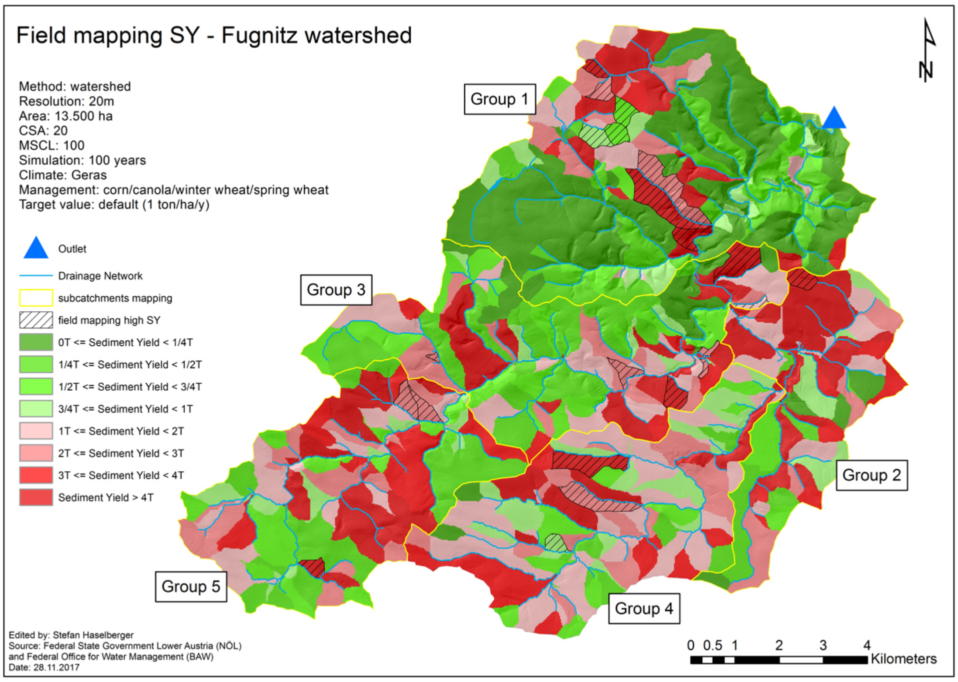

Figure 28: *Field mapping of subcatchments with indication of high sediment yield.*

According to local farmers, most of the erosion features close to Riegersburg (see figure 15) that were investigated during this field campaign were caused by a high-magnitude rainfall event on May 14^{th}, 2017. The precipitation data for the Riegersburg weather station in spring 2017 is shown in figure 29. Increased rainfall events between April 26^{th} and May 7^{th} can be observed in this representation and ought to be responsible for most of the observed erosion features during field investigations in the Fugnitz watershed.

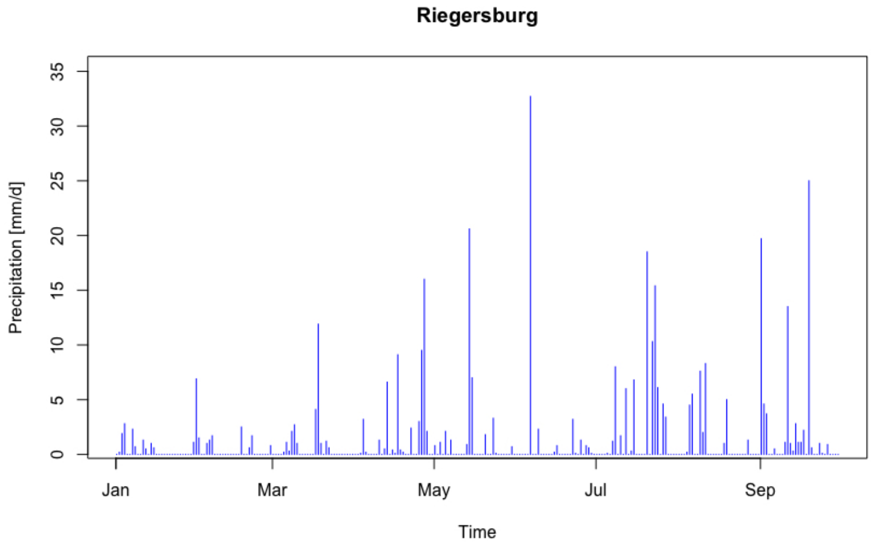

Figure 29: *Daily precipitation sums for the climate station Riegersburg during spring 2017 (Own illustration, data source: NÖL)*

Figure 30 shows erosion rills at various locations in the Fugnitz catchment. Erosion rills with width of 5-30 cm, depth of 5-20 cm and length from one to several meters were found in the study area. As field investigations took place on several days around the year, record erosion rills could be recorded during early stages of crop development (figure 30-a to c) as well as as post-harvest structures (figure 30-d). Apart from the visible surface depressions, a sorting of different grain sizes in and around the rills takes place. This indicates the preferential transport of fine grained sediments (Alberts et al. 1980) that were previously described as one of the main concerns for local environmental management.

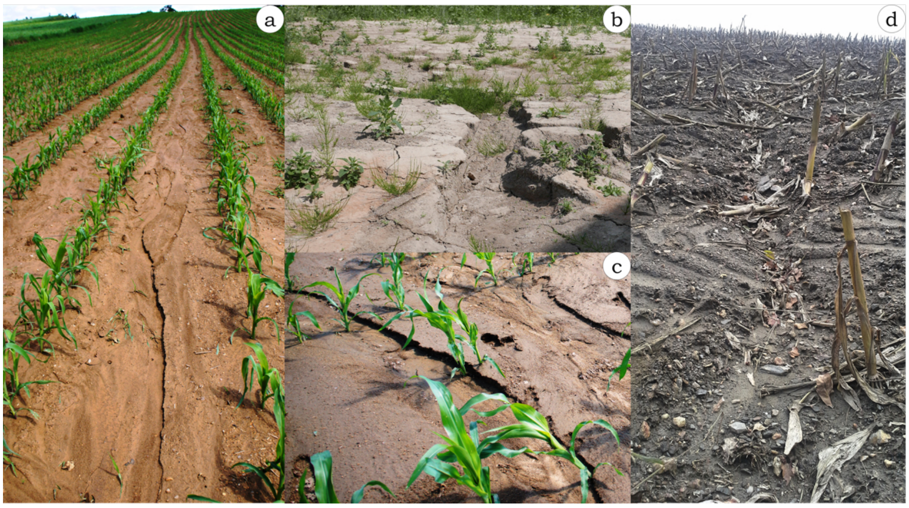

Figure 30: *Rill-erosion-features in the Fugnitz watershed (Source: Elena Kondrlova)*

The second main process responsible for overland transport of sediment in the Fugnitz catchment is sheet erosion (figure 31). It was possible to identify sheet erosion structures at various scales ranging from 2-10 m in width and from 10 up to 200 m in length. The illustration shows missing or buried vegetation due to major erosion events during early stages of crop development, for two different corn fields and planar flattened vegetation, for a grass buffer strip adjacent to a corn field (figure 31-c). Furthermore, a sorting process of smaller grain sizes due to the transport efficiency of overland flow is visible as well.

Figure 31: *Sheet-erosion-features in the Fugnitz watershed (Source: Elena Kondrlova and Ronald Felder)*

As soon as the transport capacity decreases to a critical level, eroded material is deposited again (see: section 2.5.).(Zepp 2017) Hydrologic flow energy rapidly decreases when slope angles drop and in case of an abrupt change of vegetation density.(Jobson and Froehlich 1988) Figure 32 shows different deposition areas in the Fugnitz watershed. As indicated in the literature eroded material in the Fugnitz catchment is deposited at the foot of hillslopes where gentler slopes, slightly elevated field boundaries and/or adjacent vegetated buffer strips are present.(Bracken et al. 2015) Since significant amounts of sediments can be transported on a hillslope, the deposition area may burry local crops as can be seen in figure 32-a to c. The previously mentioned sorting of grain sizes during rill and sheet erosion processes results in a specific composition of sediments in these accumulation zones. Often, this can be clearly separated from underlying material, as shown in a subcatchment of the Fugnitz (figure 32-d).

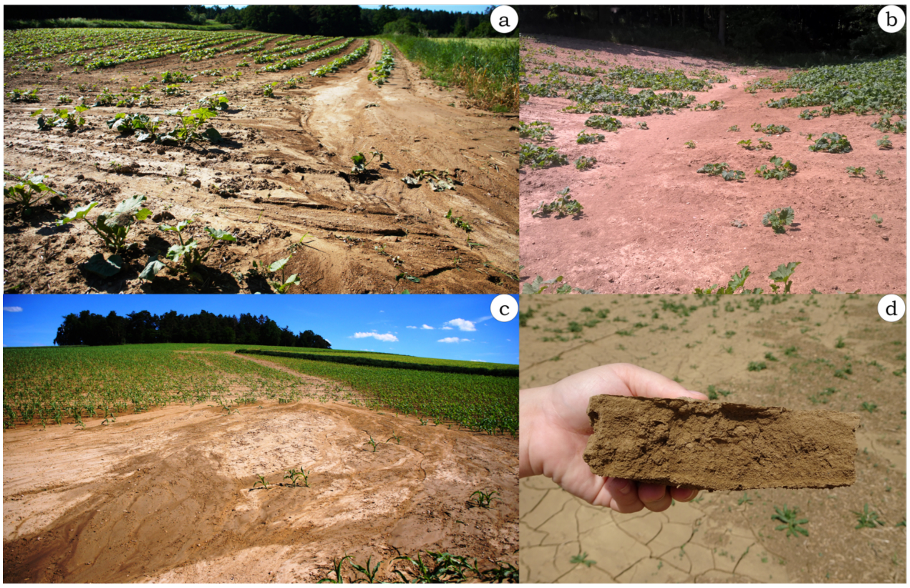

Figure 32: *Deposition areas in the Fugnitz watershed (Source: Elena Kondrlova and Lisa Humer)*

Moreover, the applied approach made it possible to pinpoint locations for potential lateral sediment input from the hillslopes to the adjacent river channels (i.e. hillslopes-channel connectivity). Figure 33 shows two different kinds of entry points observed in the Fugnitz catchment. On the one hand, man-made culverts guide surface flow into the river and may receive eroded material as indicated by the deposited material in front of the structure (figure 33-a to b). On the other hand, sediments can cross riparian buffer strips and enter adjacent channels (33-c). These linkage points are crucial when looking at the transport pathways of sediments through different landscape compartments.(Fryirs and Gore 2013) Nevertheless, there is no constant link between hillslopes and the channel system; instead, certain precipitation events are needed to activate these links.

Figure 33: *Entry points in the Fugnitz watershed (Source: Elena Kondrlova)*

Erosion features shown above, were taken at various locations in the Fugnitz watershed visualized in figure 34

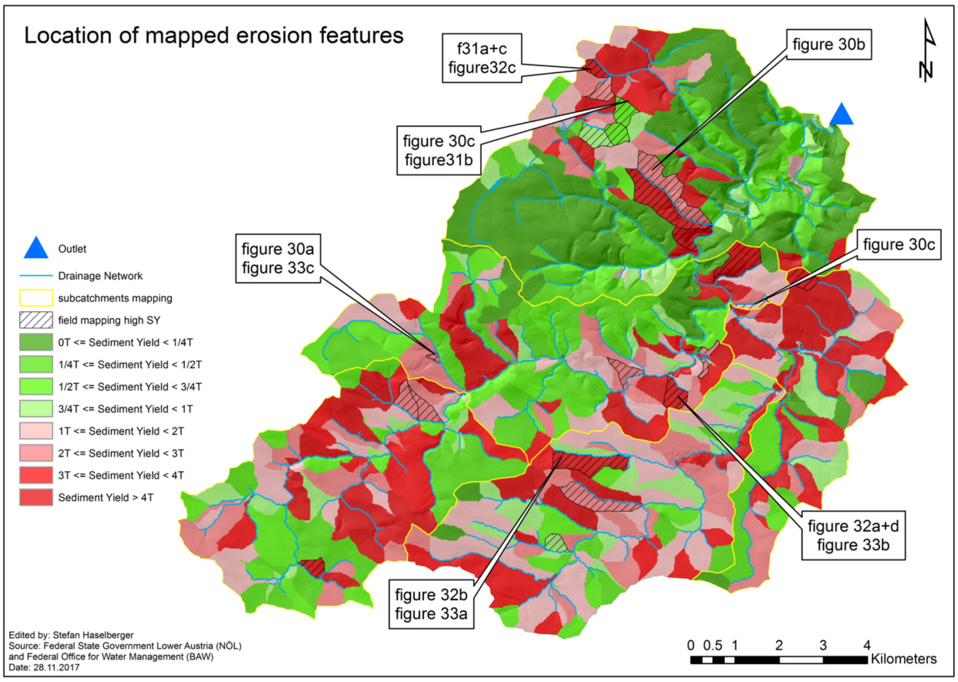

Figure 34: *Location of photographed erosion features.*

5.3 Target area analyzes

To investigate soil loss and the development of flow path and subsequent erosion rills, previously chosen target areas were analyzed using the flow path method of GEOWEPP. As soil loss is defined as the detachment of soil particles from a location (e.g. hillslope), this parameter describes the on-site effects of soil erosion.(Maalim et al. 2013) The subcatchments picked for this methodological step are based on field investigations. Only areas that were assigned a high sediment yield level were considered. Furthermore, subcatchments with different sizes were chosen in order to investigate scale issues for flow path delineation.Figure 35 shows location, shape and size of the chosen target areas. During watershed wide modeling all three target areas showed increased amounts of sediment yield.

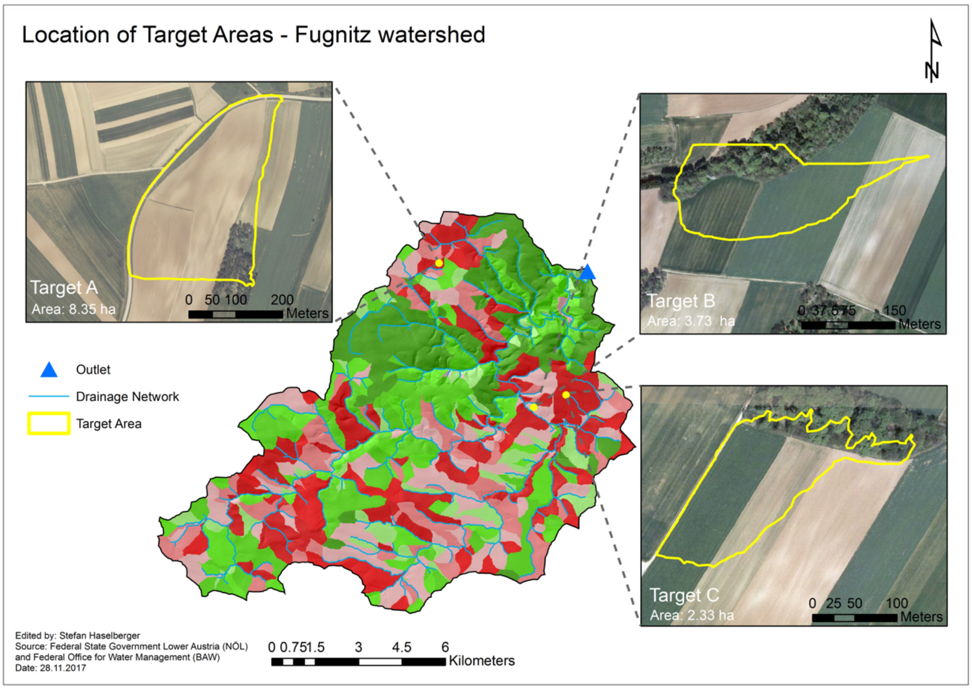

Figure 35: *Location of the three target areas for detailed modeling.*

Figure 36 shows the results of flow path modeling for target area A. Coloring indicates increased soil loss (red) or deposition (yellow). The area comprises a hillslope with a small forested area on the top and a multitude of modeled flow paths that drain into a small man-made ditch adjacent to a street. The linear structure of the street is assigned high values of soil loss with GEOWEPP computation. The man-made ditch channels the arriving flow paths and drain into the top right of the illustration. The whole modeled area shows a significant sequence of low amounts of soil loss at the top of the area (0-0.25 T), increased soil loss in the middle (1-2 T) and again low amounts of soil loss at the bottom of the slope (0.25 T). The middle part of the slope is intersected with linear segments of deposition and erosion. Before draining into the ditch, the modeled flow paths evenly descend along the slope.

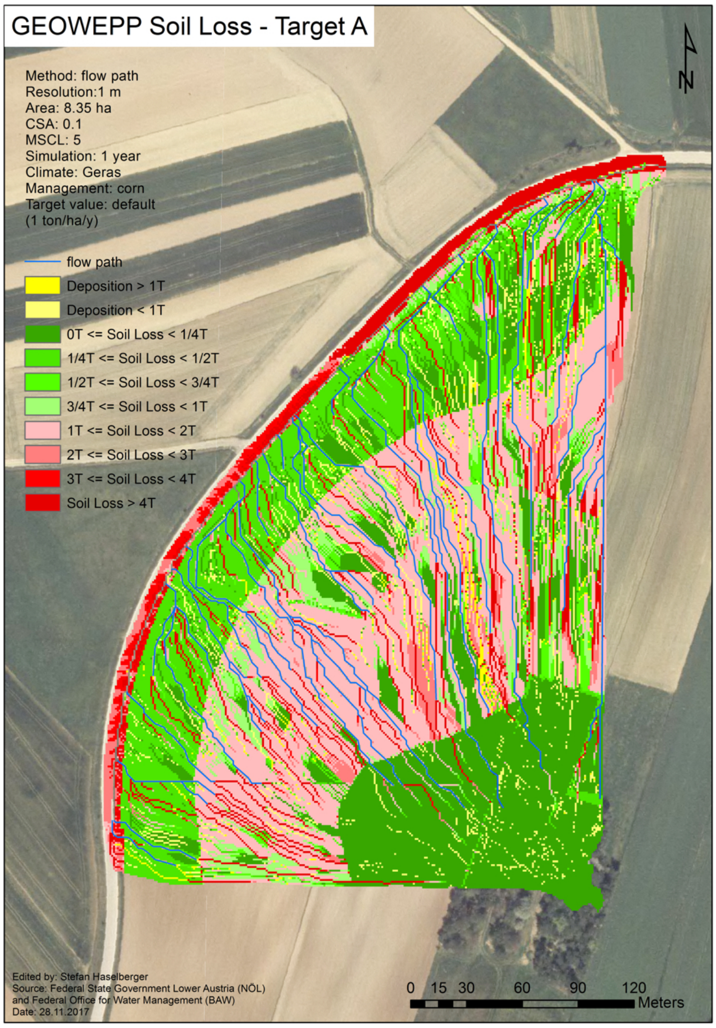

Figure 36: *GEOWEPP modeling of soil loss for target area A.*

As the previous figure 37 shows the distribution of soil loss and sediment deposition for target area B. Flow paths cross three different fields and subsequently enter a forested gully structure with an abrupt change in slope angle. Wide, linear, red lines at the center of the modeled area indicate a farm track which is responsible for the high values of soil loss. Adjacent to this anthropogenic structure, sediment is deposited at the border of the forested area according to the model. The modeled flow paths follow the descending slope and unite at the bottom of the forested area. In the model, runoff is neither obstructed by the field boundaries, the farm tracks nor the plough line, which cut across the flow paths in a right angle.

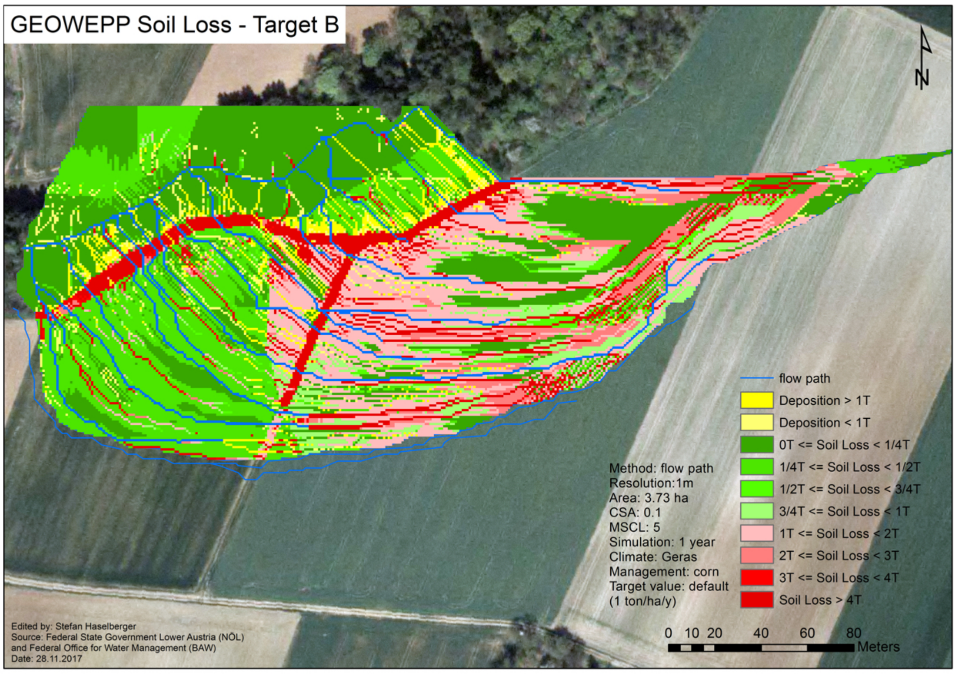

Figure 37: *GEOWEPP modeling of soil loss for target area B.*

The third target area C is depicted in figure 38. Modeled flow paths run along the plough lines and drain into a forested area with underlying gully structure. As with target area B, the linear structure of an adjacent farm track shows increased amounts of soil loss. As soon as the flow paths cross this area and enter the forested gully structure, sediment is deposited again according to GEOWEP. Due to rather low slope angles, the upper part of the hillslope (bottom left in the according figure) shows little to no indication of soil loss.

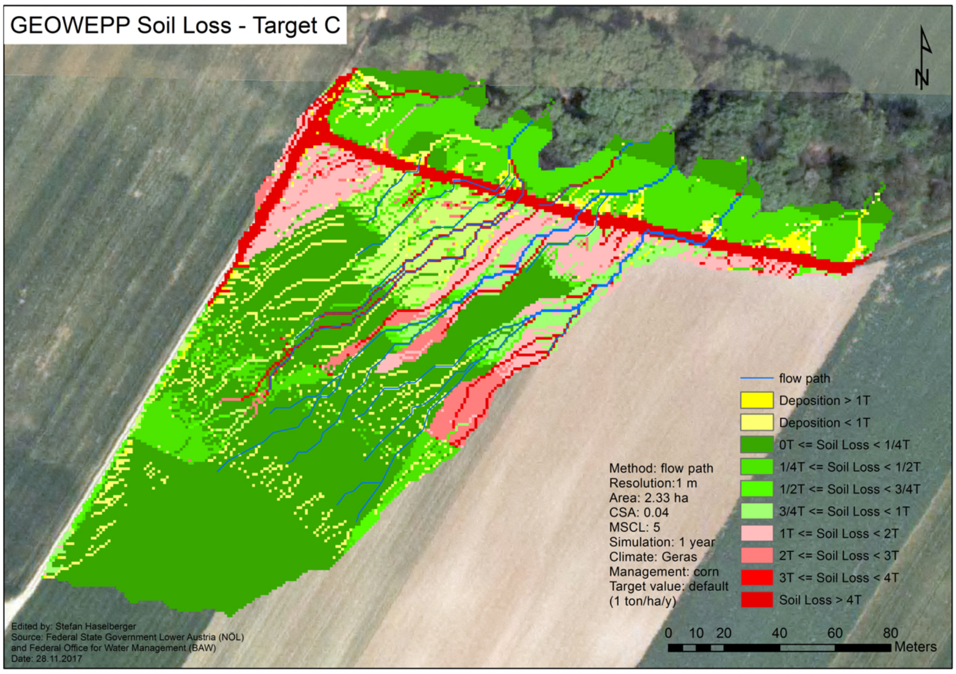

Figure 38: *GEOWEPP modeling of soil loss for target area C.*

Table 4 summarizes the characteristics of the three target areas and provides information on GEOWEPP model results for sediment yield and soil loss.

Table 4 *Characteristics and model results for target areas*

Target area	Area	Nr. of hillslopes	Mean slope	Total Runoff (m3/yr)	Total SL (t/yr)	Average SL (t/ha/yr)	Total SY (t/yr)	Average SY (t/ha/yr)
A	8.35	129	6.3	2 148.3	35.0	4.2	12.5	1.5
B	3.73	102	8.1	608.4	21.3	5.7	2.2	0.6
C	2.32	53	2.8	395.3	4.2	1.8	1.4	0.6

5.4 Fiel mapping - target areas

At target area A, visualized in figure 39, three main sheet erosion structures feeding large areas of sediment deposition at the foot of the slope were present. Accumulation of transported sediment occurs at the field boundary were a vegetated buffer strip and the slightly elevated topography prevents further transportation. Nevertheless, at some points, sediment still enters the previously mentioned man-made ditch next to the street. Several of the modeled flow paths cross field boundaries and a farm track. Sheet erosion structures reach 100-110 m in length and between 1 and 10 m in width. Observed erosion rills are between 40 and 180 m long. A total number of 25 of these linear features were mapped in the field. The sediment deposition comprises an area of roughly 0.39 ha and showed depths of 3-15 cm.

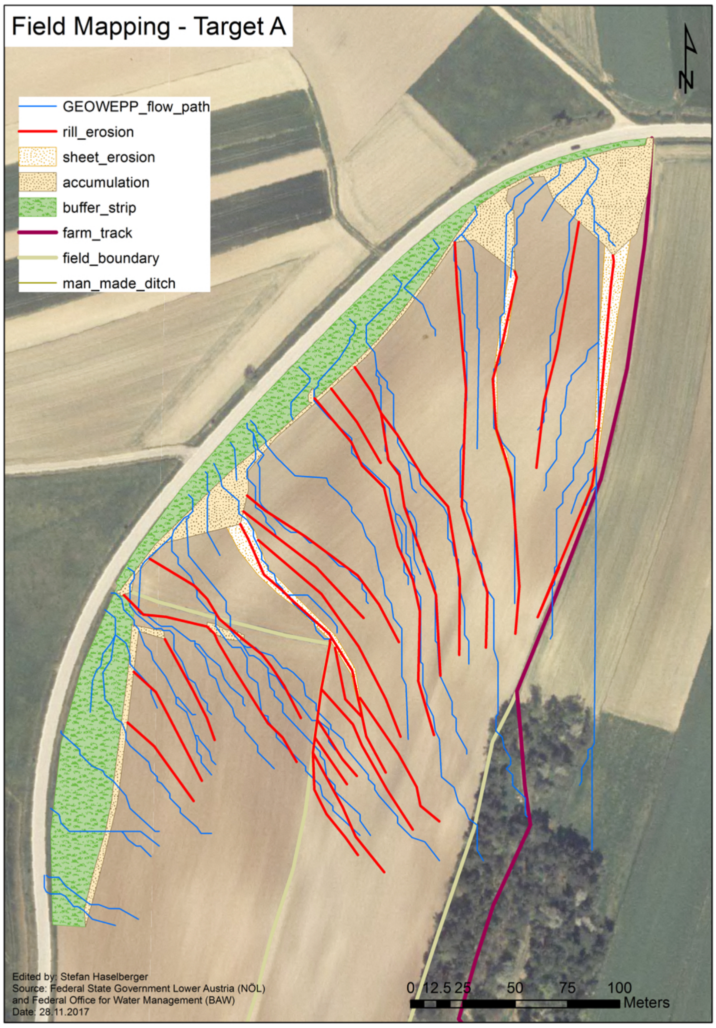

Figure 39: *Comparison of field mapping and delineated flow paths for target area A.*

At target area B (figure 40) sediment is deposited at the field border and the adjacent buffer strip next to the forested area. The accumulation area is fed by a total of 11 erosion rills. These linear structures are between 4 and 35 m long. The deposition area has an extent of around 300 m^2. Erosion rills develop in the small plough lines that are transverse to the slope and follow the descending slope only for the last 10-20 m. The modeled flow paths cross a field, two three field boundaries and a farm track downslope.

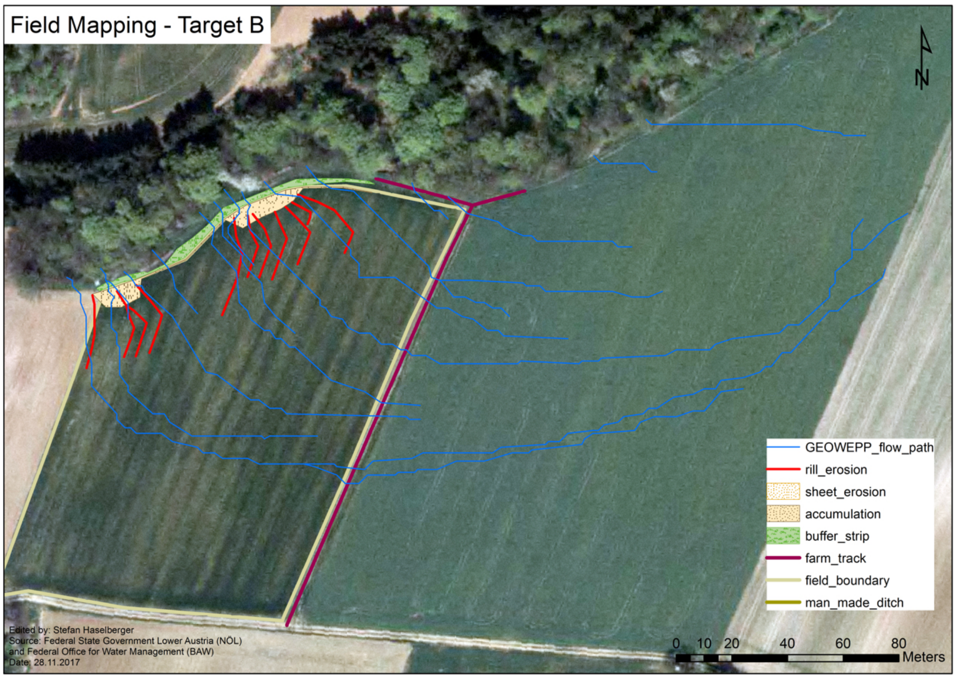

Figure 40: *Comparison of field mapping and delineated flow paths for target area B.*

The modeled flow paths in target area C (figure 41) run along the plough direction, cross the field boundary and a farm track and enter an adjacent forested area. The four mapped erosion rills are between 21-32 m long. Across the farm track in the already forested part, a small deposition area with an extent of 9 m^2 can be found.

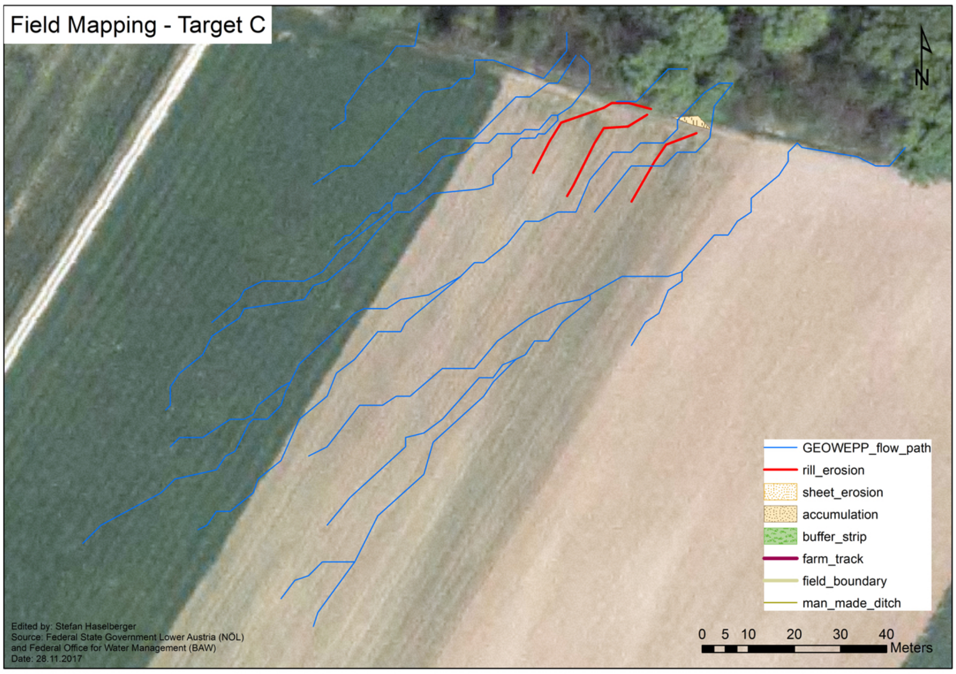

Figure 41: *Comparison of field mapping and delineated flow paths for target area C.*

Table 5 summarizes the parameters for the investigated rills. Observed rills in the field show a higher mean slope with 8.46°and a higher mean length with 72.77 m compared to a mean slope for modlled flow paths of 8.46°and a mean length of 31.87 m. Only 9.4% of the modeled flow paths in soil class 0 were found in the field as well, whereas 61.1% of the modeled flow paths in soil loss class 1 were found in the field.

Table 5 *Comparison of modeled flow paths and observed erosion rills*

	Modeled flow paths	Observed erosion rills
Number	82	39
Mean slope (°)	8.46	10.43
Mean length (m)	31.87	72.77
Number in soil loss class 0	64	-
Present in the field - soil loss class 0	6	-
Number in soil class 1	18	-
Present in the field - soil loss class 1	11	-

5.5 WEPP/GEOWEPP scenario modeling

WEPP hillslope modeling was used to model the effect of different topographic and land use conditions on the annual amount of runoff, soil loss and sediment yield. Modeling was performed for a representative hillslope of 200 meters length with different curvatures, slope angles and management scenarios. All predictions are based on an annual precipitation of 567.18 mm a widely spread soil type for the Fugnitz catchment (clay %, silt %, organic matter %) and a slope length of 200 m. For three different slope angles (6°, 4°, 2°), three different curvatures (straight, convex, concave) and five different land use scenarios (fallow, corn, wheat, grass, forest) were used to predict runoff, soil loss and sediment yield. Figure 6 visualizes the results of this first modeling approach and tries to rank the different scenarios according to the amount of potential erosion. Highest amounts for runoff (112.78 mm), soil loss (18.8 tons/hectare/year) and sediment yield (18.8 t/ha/yr) occur during fallow conditions for a straight slope with an angle of 6°. Lower slope angles result in decreasing runoff and subsequent lower amounts of soil loss and sediment yield. The different land use scenarios show the effect of vegetation on runoff and erosion patterns. A significant influence of these conditions on runoff, soil loss and sediment yield is shown. During fallow conditions, there is no protective capacity and raindrops are not intercepted but directly impact the bare soil. Therefore, fallow conditions show the highest rates of soil loss and sediment yield. The denser vegetation canopies tend to be and the tighter crops are planted, the more rain drops are intercepted, hence soil is less prone to soil erosion. The lowest amounts of soil loss and sediment yield are predicted for areas with either grass or forest cover. As the WEPP-hillslope modeling can be seen as the heart of GEOWEPP watershed analysis, the appropriateness of these values and the drawn conclusions are instructive for the assessment of other modeling steps.

Table 6 *WEPP scenario modeling for representative hillslopes*

P	L	C	M	S	R	SL	SY	DR	S	R	SL	SY	DR	S	R	SL	SY	DR
		straight	fallow		122.936	35.340	35.336	1.000		116.586	18.449	18.456	1.000		107.696	5.409	5.409	1.000
			corn		31.496	9.731	9.733	1.000		28.956	4.629	4.634	1.001		25.908	1.289	1.293	1.003
			wheat		24.892	1.910	1.910	1.000		23.114	0.809	0.809	1.000		19.812	0.330	0.332	1.007
			grass		19.558	0.110	0.110	1.000		19.304	0.101	0.101	1.000		27.178	0.150	0.150	1.000
			forest		28.194	0.211	0.213	1.011		27.686	0.200	0.204	1.022		18.796	0.090	0.085	0.950
		convex	fallow		112.776	18.801	18.797	1.000		107.696	9.651	9.648	1.000		99.942	8.956	8.954	1.000
			corn		27.686	4.811	4.804	0.999		25.908	2.340	2.345	1.002		24.043	2.172	2.176	1.002
567	200		wheat	6°	21.336	0.861	0.863	1.003	4°	19.812	0.439	0.442	1.005	2°	18.386	0.408	0.410	1.005
			grass		19.050	0.101	0.094	0.933		18.796	0.090	0.087	0.975		17.443	0.083	0.01	0.975
			forest		27.432	0.191	0.191	1.000		27.178	0.170	0.168	0.987		25.221	0.158	0.156	0.987
		concave	fallow		112.776	6.169	4.838	0.784		107.950	3.210	2.394	0.746		99.822	2.020	1.116	0.987
			corn		27.686	1.520	0.942	0.619		25.908	0.769	0.399	0.519		49.022	3.011	3.011	0.553
			wheat		21.590	0.361	0.173	0.478		19.812	0.300	0.103	0.343		18.034	0.211	0.038	1.000
			grass		19.050	0.081	0.027	0.333		18.796	0.069	0.016	0.226		18.542	0.040	0.007	0.167
			forest		27.432	0.130	0.031	0.241		27.178	0.101	0.018	0.178		26.670	0.029	0.007	0.231

P= Precipitation (mm/yr), L= Slope length (m), C= Slope Curvature, M= Management, S= Slope angle (°), R= Runoff (mm/yr), SL= Soil loss (t/ha/yr), SY= Sediment yield (t/ha/yr), DR= Sediment delivery ratio (SY/SL), To visualize the spatial patterns of increased sediment yield after changing land use, four different maps of watershed models are shown in figure 42. The simulations for the Fugnitz catchment are each based on a single dominant land cover for agricultural areas. Rather contrasting cropping systems were chosen to visualize the differences in sediment yield. Each of corn, wheat, grass and forest are separately assigned to the agricultural areas.

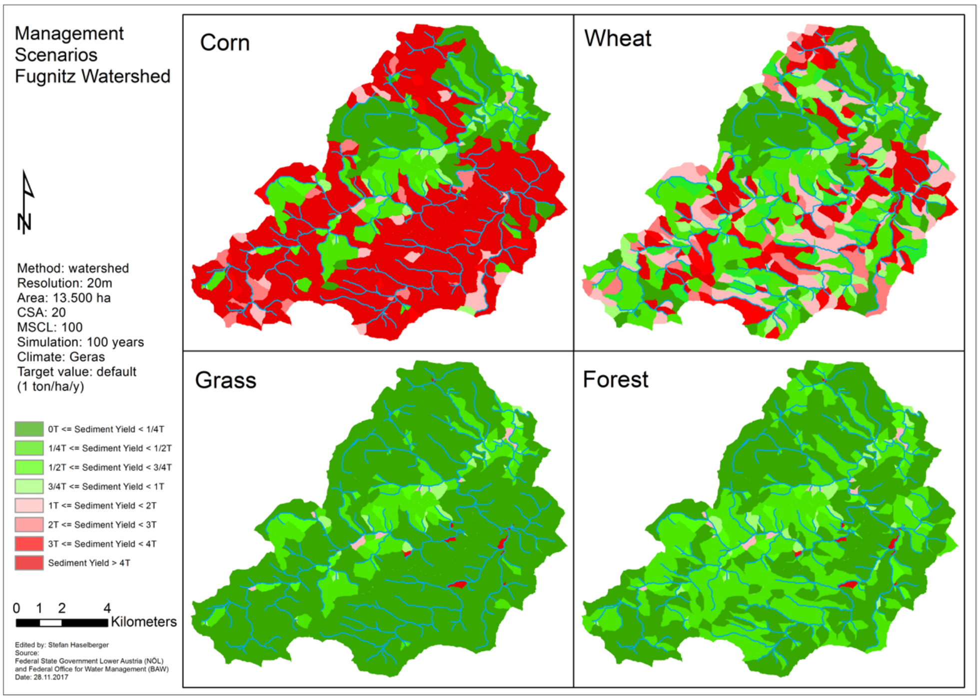

Figure 42: *Four different management scenarios for the Fugnitz watershed.*

Table 7 summarizes the model reports for each of the four scenarios as well as the results of the previously conducted model run with the generated crop rotation for the Fugnitz catchment (see: section 5.1.) Information on on-site effects (hillslope and channel soil loss) and on off-site effects (sediment discharge from outlet) are provided. The different parameters show the effect of an all-embracing change of used crops for agricultural areas in the Fugnitz catchment. The consequences of these drastic changes for the watershed show similar patterns as representative hillslope scenarios. Crop rotation solely based on corn shows the highest on-site and offsite-effects. Values are comparable to the crop rotation used in section 4.4. As only agricultural areas of the watershed were assigned new parameters, results for other land use classes show no difference in this approach. Forested areas, especially in the northeastern part of the catchment, still show mainly low amounts of sediment yield and residential areas small catchments indicated in dark red sill show high amounts of sediment yield.

Table 7 *Comparison of watershed model results for different land use scenarios*

Parameter	Fugnitz	Corn	Wheat	Grass	Forest
Simulation period (yr)			100		
Modeled hillslopes			731		
Modeled channels			295		
Modeled area (ha)			13 000		
Average annual precipitation volume (m^3/yr)			73 571 003		
Average annual water discharge from outlet (m^3/yr)	2 444 195	2 295 045	2 402 891	1 639 320	1 784 308
Average annual total hillslope soil loss (m^3/yr)	33 988	151 197	28 004	3 626	4 992
Average annual sediment delivery per unit area (t/ha/yr)	2.62	11.7	2.16	0.28	0.38
Clay content of eroded material (%)	24	29	13	34	44
Silt content of eroded material (%)	74	69	87	43	56
Sand content of eroded material (%)	2	2	0	23	0

Chapter 6

Discussion

At the starting point of this thesis, five main research questions were formulated referring to the use of process based erosion modeling (i.e. WEPP/GEOWEPP) to investigate soil erosion hotspots in a medium sized agricultural watershed and to assist environmental management for decision making. Results of the different methodological working steps are presented in chapter 5. In the following sections, the previously raised research questions will be discussed. First, the application of GEOWEPP in the Fugnitz watershed will be evaluated and distribution of computed sediment-yield-hotspots will be debated. Furthermore, flow path delineation using GEOWEPP will be addressed. The next step is to discuss the model results of the scenario approach and their implication for different management options. Furthermore, model advantages and limitations will be deduced. This chapter will be concluded by a condensed demonstration of possible mitigation strategies for the present study area in Lower Austria. Each of the following sections will be initiated with the corresponding research question.

6.1 Modeled sediment yield - catchment scale

6.1.1 Utilization of GEOWEPP in the fugnitz catchment

At the center of the present thesis lies the application of a process-based model for catchment scale investigation of hotspot areas for soil erosion. Therefore, the first research question was postulated as follows:

RQ1 *To which extent can process-based soil erosion modeling (WEPP) be used to determine potential "hot spots" for high amounts of sediment yield in a medium-sized agricultural watershed?*

Due to the specific situation in the Fugnitz catchment, with its proximity to the Thayatal Nationalpark, the methodological approach of this thesis was developed to identify potential soil erosion hotspots. The present thesis focused on erosion processes on hillslopes as there were no parameterizations of channel process to obtain. Therefore, it was not possible to state any viable results for the outlet point of the Fugnitz catchment. Channel processes, like bank erosion and stream bed erosion or sediment deposition have a significant influence on the transport routes and amounts of sediment in a watershed.(Knighton 2014) This longitudinal connectivity is an essential part of the sediment cascade and cannot be negated when talking about actual sediment loads at the outlet point. Additionally, Brooks et al. (2016) highlighted that the channel algorithms in WEPP were initially designed for small catchments with less than $3km^2$. Therefore, longitudinal channel routing for an area the size of the Fugnitz catchment would not make sense. Hence, model application was directed towards an investigation of agricultural hillslopes.

Another challenge for the application of GEOWEPP for the Fugnitz region was the extent of the watershed. Klik (2004) stressed that the scale of the investigated area has a significant influence on the quality of model results. The accuracy of the predictions decreases with larger catchment areas which tend to vary. Nevertheless, detailed investigations of larger catchments facilitate the identification of hot spot areas. This information is normally used to identify focus areas for a more detailed analysis.

The accuracy of a model is usually assessed using model simulations and measured values from the field.(Morgan 2006) Its performance is subsequently quantified with a measure of goodness-of-fit. As the present study lacks a convenient dataset for this model validation procedure, the previously mentioned field investigation, based on visual assumptions, is the only possibility for validation. Nevertheless, Morgan (2006: 148) stress that “the success of any model must be judged by how well it meets its objectives/requirements.” Therefore, to assess model performance, it is necessary to answer the postulated research questions in light of the underlying management objective of the Thayatal National Park.

In principle, it was possible to run the GEOWEPP watershed application for the whole Fugnitz catchment and to simulate the spatial distribution of sediment yield for a period of 100 years. Due to a lack of computational power, the highest available input data could not be used. In general terms, a major challenge for assessing soil erosion hotspots in a medium sized catchment like the Fugnitz watershed is the quality of the input data. As it is difficult to obtain data with a high spatial and temporal resolution for larger catchments, there tend to be some generalizations and misinterpretations. Additionally various parameters that influence soil erosion processes may not be covered.(de Vente et al. 2013) The diverse topography in a intricately structured agricultural watershed provides a serious computational task for a process based erosion model like GEOWEPP. Figure 43 visualizes these resolution challenges regarding topographic input parameters by showing a meander mountain in the Fugnitz catchment. On the left side, the flow path was delineated using a DEM with a resolution of 1 m. On the right side, a DEM with a resolution of 20 meters was used. As can be seen, the DEM with higher resolution reflects the actual course of the Fugnitz more accurately while the DEM with coarser resolution is not able to capture the narrow man-made breakthrough on the right side of the meander mountain. This difference in modeled drainage network may not have a significant influence on the results for the whole watershed analysis, but as soon as smaller scale areas are investigated, these small-scale topographic features are not considered by coarser resulted input data. For the present research approach, it was necessary to use a 20 m DEM for the catchment wide model of sediment yield as WEPP/GEOWEPP computation was not able to deal with higher resolution input data. Investigation of target areas, however, used a DEM with the highest available quality (1 m).

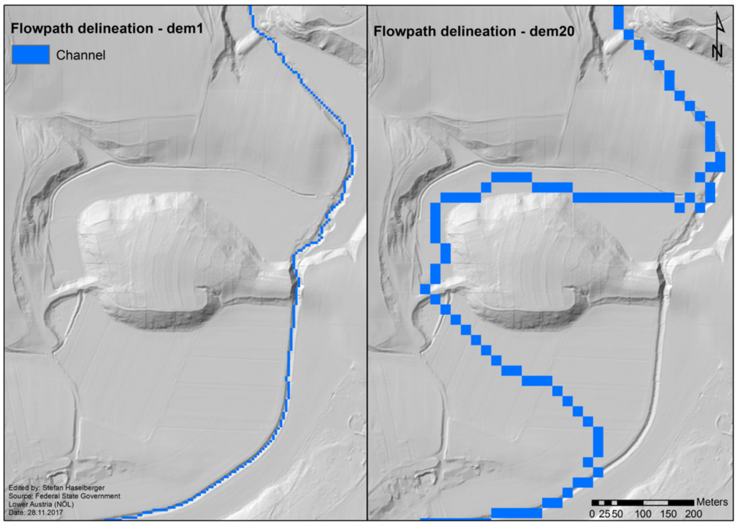

Figure 43: *Delineation of drainage network with two different DEM resolutions.*

Apart from topography, the quality of soil and land use data, too, is crucial for the spatial distribution of erosion rates. Figure 44 compares land use data used for watershed analyses (20 m) and target area analyses (1 m). After data preprocessing, the different pixel sizes lead to generalizations, as indicated by the delineation of the street feature in the upper left corner of the figure. For the interpretation of model results, it is important to keep in mind the effect of the coarser resolution used for watershed modeling of sediment yield.

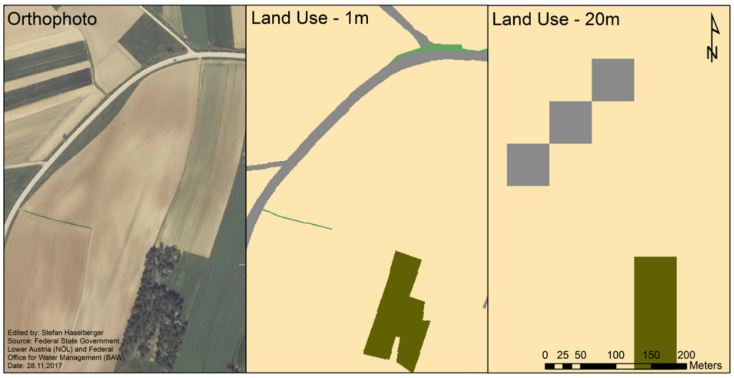

Figure 44: *Influence of pixel size for land use representation.*

Apart from the spatial resolution of the above-mentioned topography, soil and land use data as well as precipitation values are important for erosion modeling. As the present approach uses climate input data from a single climate station, local weather patterns may affect this parameter. Figure 45 compares the climate station of Geras used for the present thesis and the climate station of Riegersburg, which are located in close proximity to each other. As previously mentioned, local farmers reported that a precipitation event on May 14^{th}, 2017 was responsible for the large sheet erosion features in target area A. When looking at the two time series concerning precipitation for Geras and Riegersburg, it becomes clear that the mentioned event was not recorded by the first climate station. Nevertheless, the climate generator of GEOWEPP (CLIGEN) tries to derive sound climate scenarios for model simulation based on empirical data in order to provide realistic climate patterns. Furthermore, generation of weather is based on several years of input data and not just a few months as is depicted in the illustration below. Therefore, it is a matter of scale whether this lack of input data affects the model results or not. If the objective for a model run is to simulate the effects of short time periods on plot or hillslope scale, these data inconsistencies have a big influence on the model results. However, if the model simulation ought to investigate large temporal and spatial scale relations, these monthly discrepancies are negligible. As the present thesis focuses on the latter, the input data from the Geras climate station can be used.

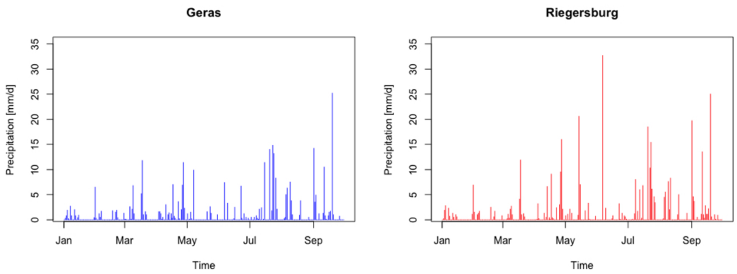

Figure 45: *Comparison of precipitation data for the climate station Geras and Riegersburg.*

In terms of data interpretation, it is wise to keep in mind the publication by Blue and Brierley (2016) where it is stated that results are inevitably influenced by whom they were obtained by as well as the circumstances for the underlying research. It is necessary to always take into consideration the highly contextual nature of produced information. Apart from this inherent bias, misinterpretations by environmental models need to be analyzed. Model failures may be the result of misuse or related to inadequate input data or sometimes the present model may not be the right fit for the objectives envisaged.(Morgan 2006)
To conclude this section and to answer the previously stated research question, it can be stated that GEOWEPP can investigate sediment yield patterns for a medium sized agricultural catchment. Although mapping of subcatchments with visible erosion features provides only a rudimentary foundation for model validation at one point in time, investigated locations are largely in line with subcatchments which show high rates of sediment yield obtained by GEOWEPP. Nevertheless, due to the above-mentioned data and computation limitations of the model, the obtained results need to be treated with distinct caution. Problems discussed for the application of GEOWEPP in the Fugnitz catchment can be seen as a general challenge for the modeling of environmental processes. One of the main strengths of GEOWEPP, i.e. the simulation of different land use strategies, has not been mentioned yet but will be discussed later on (see: section 6.3.).

6.1.2 Soil erosion hotspots in the Fugnitz watershed

The second main objective of this thesis was to investigate hotspots of sediment yield in order to support the Thayatal National Park management in mitigating the negative off-site effects of soil erosion in the Fugnitz watershed. Against this backdrop, research question number two was formulated as follows:

RQ2 *Where are "hot spots" for high sediment yield in the Fugnitz watershed located?*

As presented by the maps in chapter 5, mostly agricultural areas are affected by high rates of soil erosion. As recommended in the literature, annual values of sediment yield are focused on as this is the main timestep for many environmental management decisions.(Maalim et al. 2013) Forested areas in the Fugnitz catchment showed little to no significant amounts of sediment yield. Rangeland, too, was not affected by increased values of soil loss and subsequent sediment yield. As one might expect, agricultural areas are most prone to the negative effects of soil erosion. As the Fugnitz catchment comprises wide areas of agricultural fields, a large number of subcatchments showed concerning amounts of sediment yield during the 100-year simulation. Apart from agricultural fields, the residential areas consistently showed extremely high rates of sediment yield. As these areas are very small and intricately structured, only systematic field investigations can evaluate their specific situation. During the field campaign, it was possible to see that a gentle angle of a slope does not necessarily mean that it is free from erosion. Although Fryirs et al. (2007) indicate that a threshold of 2° for slope angle is convenient for most investigations of sediment transfer processes, some plots in the Fugnitz watershed with lower slope angles showed significant signs of soil erosion processes. Nevertheless, there is, of course, a trend for steeper slopes to provide higher soil erosion rates.(Maalim et al. 2013) This basic regularity can be seen in the Fugnitz catchment as well. A possibility for further limitation of hotspot areas would be a focus on valley floors, as these areas tend to deliver the most soil particles to the channel system.(Poeppl et al. 2013)
As there was no viable parameterization of channel processes, GEOWEPP provided no information as to which subcatchment is responsible for the highest amount of transported sediment yield at the outlet point (i.e. entering point into the Thaya). Nevertheless, the predicted amounts of soil loss in tons per hectare per year are in line with values from similar measurements in Lower Austria.(Klik 2004) investigated a small agriculturally used catchment in Mistelbach, Lower Austria, with a total size of 16 hectares. The measurement of 17 different plots with different crops/vegetation resulted in soil loss rates between 0 and 11.59 t/ha/yr. The values modeled for the Fugnitz catchment ranged between 0.28 and 11.7 t/ha/yr.
Since there was no data on runoff, soil loss or sediment yield for the Fugnitz catchment available at the time of this study, it was impossible to apply the usual procedure for environmental modeling. Due to the lack of data, the implementation of WEPP/GEOWEPP for the Fugnitz catchment lacks two crucial modeling steps:
On the one hand, model calibration was not possible as no observations for the effects of rainfall events were available and it was necessary to use the default computation procedure of WEPP GEOWEPP in terms of interrill and

rill erodibility parameters, critical flow hydraulic shear stress and effective hydraulic conductivity. On the other hand, it was not possible to compare simulated amounts of runoff, soil loss and sediment yield with recorded rates from the field. Hence, this indispensible step in model validation is missing, which means that the results of the model have to be treated with caution. The intention for the field investigations conducted was to provide at least some sort of validation in order to analyze the results of the model. Nevertheless, the qualitative ground truthing approach depict one point in time and highly depends on the bias of the observer as well as the present circumstances in the field. A similar investigation approach in the same location may provide completely different results in the future.
Although convenient model calibration and validation is yet missing, the mapped hot spot areas matched the modeled areas with relative high amounts of sediment yield quite well. According to Morgan (2006), criteria for model validation "are by no means clear-cut and need to be set for individual models in relation to their objective." Additionally, they noted that a qualitative assessment may be all requirements necessary for a given modeling attempt. The shown methodological approach facilitated the designation of areas of interest for possible mitigation strategies. According the research question stated above, it is possible to say that the process-based erosion modeling (GEOWEPP) was able to highlight areas of interest (i.e. high amount of soil erosion) for further management steps. However, it must be noted that present modeling results show only a first approximation of the situation in the Fugnitz catchment. Further model parameterization and validation is necessary to obtain viable information on the distribution of soil erosion in this area. Additional model simulations and comprehensive field investigations will allow for a more detailed selection of soil erosion hotspots for the Fugnitz watershed.

6.2 Modeled flow channels

In order to better understand the mechanisms and computations of WEPP/GEOWEPP on different scales, target areas were chosen and erosion features in the field were mapped. The objective was to investigate the role of micro topographic features for delineation of flow paths and subsequent patterns of soil loss. Research question three summarizes this curiosity:

RQ3 *To which extend does GEOWEPP/WEPP account micro topographic structures during flow path delineation?*

The question is, of course, closely related to RQ2 discussed above, as the performance of WEPP/GEOWEPP for investigations in the Fugnitz watershed is assessed again. GEOWEPP watershed modeling depends on the structure of subcatchments and subsequently derived, representative hillslopes based on topographically generated drainage networks whereas the actual situation in the field highly depends on the structure and distribution of agricultural field boundaries. Furthermore, the obstructing nature of plough lines has a big influence on generation and direction of erosion rills. During field mapping of target areas, it was possible to investigate this influence. As shown in section 5.3, most of the erosion rills for target area A intersect rather well with the modeled flow paths. At smaller scale plots, like target area B and C, micro topographic features led to some distortion. Erosion rill development is highly influenced by plough line direction as shown in figure 40 for target area B. The flow path delineation of GEOWEPP is not able to capture these small-scale features. Furthermore, sediment deposition along slightly elevated field boundaries are not captured by the model as can be seen in target area A (figure 36 compared with figure 39) and B (figure 37 compared with figure 40). Upscaling and downscaling (plot-hillslope-catchment) is known to be a big challenge for soil erosion and sediment connectivity prediction.(Cammeraat 2004) These discrepancies between subcatchment-scale modeling and field-scale process accompany this thesis and constitute a big challenge for catchment-wide erosion modeling. Hooke (2006) highlighted the effect of anthropogenic management practices on fluvial systems. Especially the effect of plot boundaries was named as a big driver for sediment dynamics within agriculturally used catchments.(Vieira and Dabney 2011) A possible solution to integrate the influence of field boundary topography could be to modify the elevation model used as model input based on knowledge gained from land cadastral maps. The legal description of property boundaries is a vital information source for agricultural field boundaries which influence erosion processes due to micro-topographic composition (difference in height). Cadastral map based information could help to shift erosion modeling from subcatchment scale to a bigger focus on field scale circumstances. Literature research on this technique yielded no results. Another possibility to tackle this scale challenges are very-high-spatial-resolution (VHSR) digital elevation models. If the model captured topographic structures in a centimeter range, it would be able take the effect of field boundaries and plough lines into account. Quiquerez et al. (2014) used such techniques to investigate soil surface characteristics in vineyards. VHSR topographic data at a resolution of five centimeters obtained from aerial images enabled the researchers to investigate the influence of micro-topographic soil surface structure, like stoniness and tillage practices, on the distribution of soil erosion processes.

With regard to the postulated research question in this section, it is possible to state that for target area A, which comprises an area of 8.35 ha, GEOWEPP simulation field investigations intersected rather well. As rill incision directly depends on slope steepness and length, the size of the contribution area influences rill development and may superimpose micro topographic circumstances.(Rieke-Zapp and Nearing 2005) As soon as smaller scale plots are investigated (target area B – 3.7 ha and target area C 2.3 ha), modeled flow paths do not capture the micro topographic influence on rill development. At different spatial scales, different soil erosion processes are dominant and a single model cannot capture the whole spatial and temporal spectrum of scales.(Boardman and Favis-Mortlock 1998) Deposition of transported sediment at the field boundary of all three target areas was not captured by the model. Therefore, it is necessary to be cautious when interpreting small-scale, on-site effects of soil erosion modeled by GEOWEPP. In order to do the site specific complexity of circumstances justice, it is necessary to precisely manipulate the input data in order to obtain convenient model results. Concerning both RQ1 and RQ3, it needs to be said that GEOWEPP performance in the Fugnitz catchment depends on the scale of the focus area. Catchment-wide modeling showed good results as far as the present validation method is able to examine that. At this spatial extension, the main influencing factors are topography, soil and vegetation patterns.(Jetten et al. 1999) As soon as the focus shifts to plot or hillslope scale areas, the main influencing factors are timing and volume of overland flow in combination with micro topographic circumstances.(Boardman and Favis-Mortlock 1998) If no detailed parameterization took place, delineation of flow paths in GEOWEPP is not able to capture the topographic details at the plot scale.

6.3 WEPP scenario modeling

In order to provide useful information for future management planning, the present thesis tested different land use strategies and their effect on soil loss and sediment yield patterns in the Fugnitz watershed. This intention is verbalized in research question number four:

RQ4 *How does a change in agricultural land use effect the sediment yield distribution of the Fugnitz watershed?*

First of all, it is vital to state that the conducted scenario modeling assigned the same crop/vegetation (corn, wheat, grass, forest) to the agricultural area of the Fugnitz catchment for a simulation period of 100 years. This scenario is not realistic as no farmer will use wheat or corn year after year as the main crop for his fields. Nevertheless, this approach provides valuable information on the influence of different crops on soil erosion rates in the Fugnitz catchment. As soil erosion models usually tend to overestimate soil loss, it is necessary to interpret the obtained results as relative estimations.(González-Arqueros et al. 2017)

When comparing soil loss rates of the modeled scenarios with reported values in the literature, the results are in line with published results. Soil loss rates for grass covered plots tend to be around 0.(Maalim et al. 2013) Therefore, the re-dedication of agricultural fields as rangeland has the potential for comprehensive reduction of soil erosion rates. Usually, forest soils are considered as having higher rates of infiltration and, therefore, less runoff and soil loss compared to, for example, range land.(Sharma et al. 2013) Nevertheless, the results of scenario modeling in this thesis (with higher soil loss rates for forest compared to grass) stand in contrast to these investigations. The detailed model parameters for each land management scenario (forest and grass) in light of the present input parameter at the Fugnitz watershed would need further investigation in order to determine the reason for this discrepancies. As for the effects of wheat and corn, literature reports soil loss rates of 3.05 t/ha (Nearing et al. 2017) and 12.23 t/ha (Nelson 2002), respectively. Values for the Fugnitz watershed obtained during scenario modeling are in this bracket. With a focus on sustainable land use, these values are not acceptable.(Klik 2004) Nevertheless, the values show the broad range of erosion rates for different crops and highlight the importance of a carefully considered crop rotation.
Apart from a change in crop rotation, cultivation techniques affect soil erosion as well.(Klik 2004) investigated the different effects of conventional tillage, conservational till and sowing with no tillage for wheat and reported significant changes for soil loss rates. Conventional tillage practices lead to soil loss rates of 63.87 t/ha. When changing to conservational tillage, soil loss rates decrease to 2.22 t/ha, while sowing without tillage can limit soil erosion rates even further (1.23 t/ha).
Returning to the research question previously stated, the obtained results of GEOWEPP-scenario modeling provide valuable information for environmental management of the present catchment. Since wide areas of the Fugnitz watershed are agriculturally used, a change in crop rotation has significant influence on the rates of sediment yield for the investigated subcatchments. As seen during field investigations, fields with either corn, squash or potatoes are most prone to the negative effects of soil erosion due to lower plant cover especially during periods with intensive precipitation in spring. The results of scenario modeling support these observations, even though the shown scenarios are, of course, extreme examples of alterations in crop rotation practices. Nevertheless, the effects of different crops and/or vegetation cover are highlighted. A reduction in the cultivation of corn can potentially limit fine grained sediment input into the Fugnitz channel system. Apart from a change in management practice like investigated above, various other options to mitigate negative effects of soil erosion are available. Based on the knowledge obtained via watershed modeling of different land use scenarios, the next section will discuss possible mitigation strategies for the Fugnitz watershed.

6.4 Mitigation strategies

In order to support environmental management the upcoming section provides information on possible mitigation strategies. Literature based research investigates different management options to reduce the on-site and off-site effects of soil erosion. Obtained approaches will be evaluated in the context of the environmental situation in the Fugnitz watershed and in light of the conservational objectives of the Thayatal National Park. During field campaigns, attempts were made to obtain information from land lords on existing measures to cope with the effects of soil erosion. The combination of this information ought to answer the fifth research question raised at the start of this thesis.

RQ5 *Which mitigation strategies can be conducted to reduce potential amounts of sediment yield and to limit sediment influx to the Fugnitz channel system?*

Since anthropogenic valorization of fertile soil for agricultural production occurred, humans are aware of the effects of soil erosion.(Dotterweich 2013) Therefore, a multitude of approaches to investigate the negative effects of soil loss and sediment yield emerged.(Warkentin 2006) In environmental management, five different options to face negative impacts are common: first, it would be possible to avoid the negative impact beforehand; second, minimizing frequency or magnitude of the negative impact; third, reparation, rehabilitation and restoration after a negative impact; fourth, reduction of the impact by preservation and maintenance operations; fifth, compensation of the affected areas by providing substitute resources.(Bredehoeft et al. 2006) In terms of soil erosion, it is possible to intervene during different steps of this methodological approach. Klik (2004) emphasize that only a bundle of different approaches is able to deal with the complexity of soil erosion in a diverse environmental and socioeconomic context and it is important to tackle soil erosion-related challenges from different angles. Beside the endeavor to minimize the impact of soil erosion on agricultural production, mitigation measures seek to protect environmental and fragile ecosystems. Especially fresh water systems are affected by sediment mediated input of pollutants and fertilizer.(Rickson 2014) Although there are various different approaches to face the negative effects of soil erosion, there is still a strong need to asses effectiveness of sediment control measures in protecting freshwater bodies.(Collins et al. 2009) Nevertheless, as the postulated research questions focuses on actual mitigation strategies for the Fugnitz watershed, research related considerations are put aside.

A widely used method to protect soil from the effects of soil erosion is the application of straw as protective layer.(Prats et al. 2016) The straw reduces the impact of raindrops and, therefore, the mobilization of soil particles, runoff and subsequent sediment transport is reduced as well.(Foltz and

Dooley 2003) As the material is easily obtainable, inexpensive for agricultural producers as well as easy to apply, many farmers use straw for planar protection of their fields. Nonetheless, there are a few drawbacks to this method such as the fact that the material is easily displaced by wind due to the low weight of the straw. Furthermore, the material is not available for other agricultural usage (e.g. as bedding in stables) and the straw is easily decomposed and, therefore, the effect is rather short-termed.(Foltz and Copeland 2009) A more stable alternative for protective layering are wood shreds, although the handling of the material is more arduous.(Robichaud et al. 2013) During field investigations in the Fugnitz catchment, the land lords of target area A mentioned use of straw bales as well. The material is used as protective barrier to reduce runoff and interrupt downslope sediment transport at certain points of a field. Nevertheless, they complained about the fast decomposition of the straw bales as stated above. This method can somehow be seen as a form of an on-site buffer strip. The cultivation and application of riparian buffer strips are another recommended strategy to reduce lateral sediment input into channel systems. Hénault-Ethier et al. (2017) describe the use of vegetated buffer strips as a best practice example for mitigating negative effects caused by soil erosion used in many different environments around the world. Narrow linear buffer strips along waterways provide a barrier against sediment transfer and associated nutrient input (N, P) towards the channel.(Stutter et al. 2012) Despite the virtues of riparian buffer strips, it is necessary to assess the influence of buffer strip composition in terms of plants used and the effect of buffer width on the ability to prevent sediments from entering a channel system.(Mayer et al. 2007)
Technical solutions to face soil erosion are structural measures like check dams, retention basins and ponds.(Mekonnen et al. 2015) These retention structures hold water and filter transported sediments, tough the location of the structure is crucial as retention measures can only cope with runoff from certain areas.(Lim et al. 2005) Another structural approach that focuses on on-site mitigation of soil erosion is the establishment of terraces.(Mekonnen et al. 2015) This technique was developed over centuries and is used in many parts of the world.(Dotterweich 2013) A major drawback of this approach is the effort which goes into the installation of the terrace features and the subsequent obstacles for mechanical field work.(Dumbrovskỳ et al. 2014) Artificial discharge of runoff with man-made ditches in order to limit surface runoff and subsequent sediment transport is another structural option.(Klik et al. 1996)
The landlords of target area A collect lost soil at the accumulation areas downslope and transport it back to the source areas of the hillslope. This operation seeks to keep fertile soil on site and save the land from progressive degeneration. This salvaging for top soils is widely used to retain fertile topsoil and to promote soil health via collecting and returning organic matter, soil microbes, and certain grain sizes that are responsible for increased water-

holding capacities.(Abella et al. 2015) A more regional-based approach to mitigate negative effects of soil erosion would be to restructure agricultural fields in order to reduce the effects of unfavorably shaped plots.(Klik et al. 1996) As surface homogenization by ever growing plot areas in modern agricultural production increases the length of furrows, thus increasing runoff and subsequently leading to an increase in shear stress for the detachment of soil, shape and distribution of agricultural plots and their redistribution can potentially mitigate negative effects of soil erosion.(Souchère et al. 2003)
Apart from the selection of the canon of mitigation strategies just described, the implementation of a certain approach is always conditioned by a legal and organizational framework.(Kibblewhite et al. 2012) For environmental management, the choice of a certain method depends on two parameters: the effectiveness of the planned measures in relation to the spatial and temporal circumstances and the costs of their implementation.(Klik 2004)
As the modeling results (see: section 5.1) showed, areas with increased amounts of sediment yield are distributed over the whole catchment area. Therefore, single point-based measures like retention basins alone are not recommended as amounts of sediment yield change in relation to the used crops and the structure can affect only very small subcatchments. The previously shown scenarios for different land use strategies showed the effect of changes in management. As vast areas of the Fugnitz watershed are agriculturally used, an extensive management response may be needed to meet the challenges posed by the complexity of the catchment. In order to tackle the challenge of high amounts of fine grained sediment input into the river system, a convenient and sustainable approach would be to combine interventions in agricultural management and structural measures to decouple the channel system from adjacent hillslopes. This strategy would take into account the effects of soil loss on-site (soil loss) and the off-site effects (sediment yield) as well as the connection between hillslope and channel. On the one hand, a change in the selection of crop rotation could reduce periods with low protective vegetation cover and, therefore, make the soil less vulnerable for rainfall erosivity. This managerial alteration would entail less additional effort for land lords than having to apply a protective layer. On the other hand, buffer strips could be used to decouple agricultural hillslopes from adjacent channels, however, it would certainly need some effort to convince land lords to follow this mitigation strategy and spare areas of their agricultural fields. Nevertheless, this structural change of land use could provide a long-term solution as this spatial integration of soil erosion mitigation means no extra work for farmers and the restructuring of land could be more easily accepted in the long run.
In order to broaden scientific knowledge on soil erosion in the Fugnitz catchment and to support the Thayatal National Park management directive, a series of research approaches are in line. “FugnitzSED”, a project of the Thayatal National Park, accompanied this thesis and tries to reduce the

negative effects of sediment mediated pollutant and fertilizer input into the Fugnitz channel system. The starting point was the analysis of the biodiversity of the Thaya by means of macrozoobenthos measurements. Then, the main approach of this thesis entered the project stage. In the course of the "FugnitzSED", a combination of soil erosion modeling with investigations on connectivity links between hillslopes and the channel system was initiated. The entanglement of these two approaches aims at providing information on entry points with a potential for high sediment input into the Fugnitz channel system. After determining entry points, local mitigation measurements like retention basins will be installed in these areas. Another objective of "FugnitzSED" is to provide a management plan of administrative division based on the mentioned research. The different components of the project are visualized in figure 46.

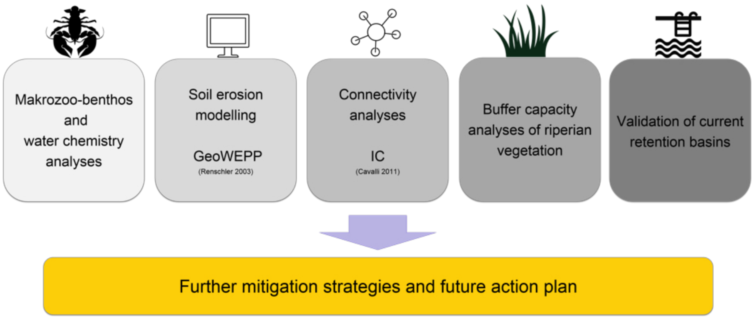

Figure 46: *Concept of the FugnitzSED project (Source: own illustration)*

The instalment of an automated sediment sampler at the outlet point of the Fugnitz watershed near the town Hardegg is planned. This will provide information on sediment load and river discharge of the Fugnitz which, in combination with local climate stations allow the quantification of the influence of different precipitation events on the fine sediment input of the Fugnitz to the Thaya. Furthermore, plot scale investigations of the buffering effect of riparian vegetation on the sediment yield of agricultural areas will be pursued as well. Knowledge about the buffering capacity of different vegetation types will help to assess the effect of possible mitigation options. Artificial buffer strips along the channel system may be a solution for high inputs of fine grained sediments into the Fugnitz.
Although automated samplings can provide useful information on the amounts of sediments transported to the outlet point of the Fugnitz catchment, no assertion about the processes along the sediment cascade (i.e. buffers, barriers, blankets, fluvial erosion processes) can be made. Sediment fingerprinting techniques are one possibility to track the actual course of sediments through different landscape compartments in the Fugnitz watershed.(Collins et al. 2017) As traditional monitoring techniques are not able to exactly estimate the source and course of fine sediments, sediment fingerprinting approaches

use chemical tracers (e.g. radio nuclides) to obtain detailed information on sediment transport. Even when facing the challenges of soil erosion on a local scale, it is nevertheless necessary to consider global developments as well. Climate change may provide a serious challenge for future soil erosion management.(Li and Fang 2016; Routschek et al. 2014) Short term management decisions may not be effected, but mid- to long-term strategies have to keep in mind changing climate patterns, especially according to the occurrence of high intense precipitation events, and alterations in crop rotations. Although soil is a fundamental resource for life on our planet, there is little political and institutional awareness of soil protection compared to other resources like water and air.(Morgan 2006) Derived knowledge on possible management plans and the advancement of tools for environmental managers, such as the process based erosion model conducted during the present thesis, can help future decision making processes to ensure sustainable use and protection of this key resource. Based on previously presented model runs and in light of the above described mitigation possibilities the following management strategies and future research steps are recommended (visualized in figure 47):

- 40 m vegetated buffer strip along perennial channel system (Mullan et al. 2016)
- Controlled management* for catchments with high modeled sediment yield in target zone** (Frankl et al. 2018)
- Automated sediment sampler at outlet point and at confluence of Fugnitz and Pleißingbach respectively (Perks et al. 2017)
- Plot-scale measurement (boxes, fences) of certain target areas for model calibration (Pieri et al. 2007)
- Mapping and consideration of anthropogenic drainage strucutres as they tend to bypass buffer strips (Hösl et al. 2012)

* Controlled management: less corn in crop rotation, use of cover crops and no down slope ploughing
**Target zone: subcatchments with high amounts of modeled sediment yield that are at least partially within an area of 200 m of the channel system

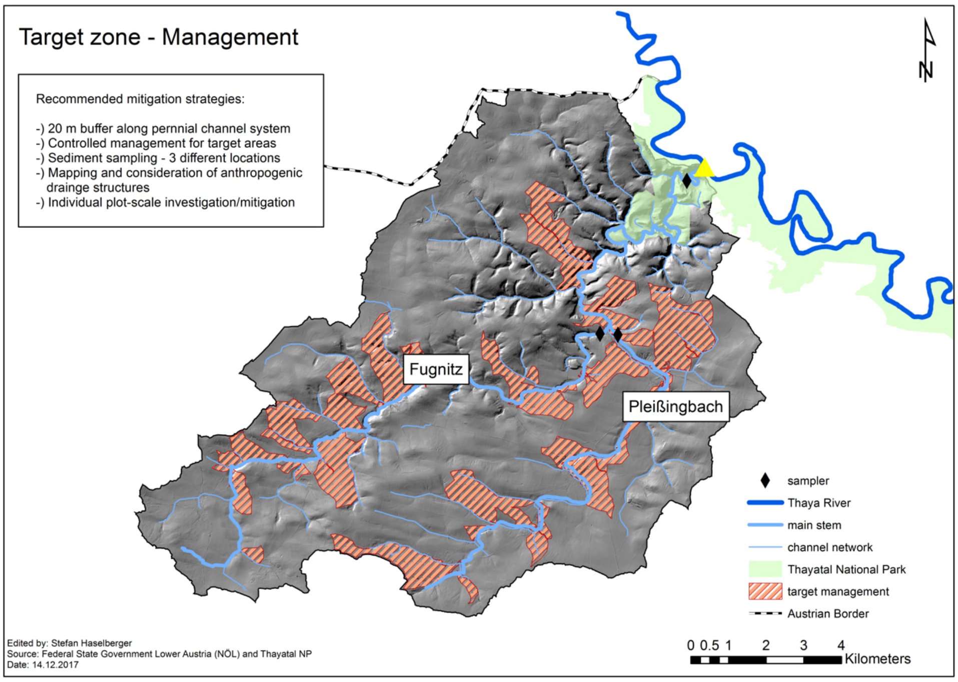

Figure 47: *Target areas for management and recommended mitigation strategies*

Chapter 7

Conclusion and outlook

The aim of this thesis has been to investigate human induced soil erosion in a medium-sized agricultural watershed in Lower Austria. An approach for assessing sediment yield hotspots using process-based erosion modeling in a medium-sized agricultural catchment in Lower Austria was made. The background for the study is an environmental management challenge for the Thayatal National Park. The tributary system of the Fugnitz transports significant amounts of fine sediments to the nature conservation area. Thus, sediment mediated pollutants and fertilizer enter the fragile fluvial ecosystem of the Thaya River. The overarching project of the Thayatal National Park seeks to limit fine sediment input into the Fugnitz and, subsequently, into the Thaya. Against this backdrop, a series of methodological steps were taken to face the mentioned problems and to highlight future management options. Apart from this environmental challenge, the thesis attempted to investigate the applicability of a process based soil erosion model (WEPP/GEOWEPP) to investigate soil erosion hot spots in a medium sized agricultural watershed in Lower Austria.

The methodological approach presented allowed to examine the WEPP/GEOWEPP model for the underlying problem and to test the delineation of sediment-yield-hotspots for the whole watershed and flow paths for different target areas. WEPP/GEOWEPP based modelling facilitates the identification of areas with potentially high sediment yield. These locations can be used for target-oriented management.

Simulation of sediment yield hotspots in the Fugnitz catchment showed potentially affected subcatchments across the whole catchment area. Comparison of model results and information obtained via field surveys indicates broad agreement. Although conducted validation method based on field survey checklists for a limited area and at one point in time constitutes an insufficient validation method. Therefore model predictions need to be treated with caution.

Modeling of soil loss on target-area-level showed some deficiencies with re-

gard to the influence of microtopographiy features on flow path delineation. At target area A (8.3 ha), modeled flow paths and observed erosion rills coincided quite well. At the smaller target areas B (3.7) and C (2.3) erosion rills in the field were mainly governed by plough lines and deposition areas were found at the slightly elevated field boundaries. WEPP/ GEOWEPP was not able to capture the influence of microtopographic features at this spatial scale.
A main virtue of the rather complex, process-based model WEPP/GEOWEPP was shown during scenario modeling in this study. In respect to the backdrop of this thesis, it was possible to simulate different land use scenarios in order to provide environmental managers information on possible mitigation strategies.
The present thesis suggested a set of mitigation steps and provides the Thayatal National Park with maps for localization of potentially affected areas. Nevertheless, further research is needed in order to calibrate the WEPP/GEOWEPP model and to subsequently refine hotspot areas in the Fugnitz catchment. In terms of soil erosion modeling the challenge of different spatial scales was highlighted. Future modeling approaches need to combine easy-to-use applications like GEOWEPP with modern high-resolution data in order to provide environmental managers tools that are able to handle the complexity of large catchments on different spatial scales

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