Master thesis

Developing a procedure for erosion risk evaluation
concerning slopes with depression lines
for the Hochsauerlandkreis administration

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Science Pledge

By my signature below, I certify that my thesis is entirely the result of my own work. I have cited all sources I have used in my thesis and I have always indicated their origin.

(Place, Date) (Signature)

Abstract

Soil erosion is a very complex process. In science the modeling is either handled empirically with the Universal Soil Loss Equation (USLE) or based on physical theories (physical models). In the daily work of the lower soil protection agency of the Hochsauerlandkreis (HSK) the empirical approach is used, since it is the standard approach in the administration of North Rhine Westfalia (NRW).

Slopes with depression lines represent a gray area in erosion risk assessment because the amount of erosion is underestimated by the USLE. In this thesis field data obtained from twelve erosion events in nine investigation areas and calculations conducted with a Geographic Information System (GIS) are used to start to close the gap left by the USLE.

A 1 m raster Digital Elevation Model (DEM) derived from high resolution LiDAR data was used to calculate flow accumulation values for slopes with depression lines. The tool adds up all cells of the raster along the path of the surface runoff. Through the creation of weight rasters it is possible to model the influence of various factors on the erosion process.

The Bundesverband Boden (BVB), a society of soil experts, defined a risk threshold for slopes with depression lines in 2002. Feldwisch et al. (2005) turned the simple threshold into three classes. This evaluation method relies on four of the six factors from the USLE.

In the evaluation system used today in NRW each agriculturally used area (AUA) is regarded individually. It is assumed that no inflow from external areas takes place. This point of view is practical but not realistic, because more often than not AUA are not completely protected from inflow.

The GIS procedure for risk calculation for single fields is complicated. Because of its size it is not possible to do so for every AUA in the HSK. In order to get an overview of all slopes with depression lines so called slope maps are created, which rely on less factors and are thus easier to compute.

The comparison of slope maps with field data of charted erosion events showed regularity. The severity of the erosion events correlated strongly with the amount of flow accumulation/ surface runoff in the depression line. With a minimum of 25.000 m² that discharge into a depression line linear erosion with considerable amount of soil erosion is very likely to develop. The slope gradient as the second most important factor influencing the erosivity of surface runoff was taken into account via the respective factor of the USLE (S-Factor). A threshold was defined, if it is surpassed the erosion risk on that slope must be regarded as critical.

In the next step the AUA from those areas that are evaluated as critical on the slope map are evaluated individually. The AUA maps where calculated using the four USLE factors R (local rain erosivity), S, L (effective slope length) and K (soil erodibility). All investigation areas except one fall into the most critical category for slopes with depression lines. The developed procedure meets the requirements of the hardware capacities of the HSK administration and the existing evaluation system for erosion risk in NRW and takes into account the experience from local erosion prevention work. It is a good first step to close the gap in erosion risk evaluation for slopes with depression lines.

Preface

Erosion is a natural process. The loss of fertile soil has occurred since the dawn of agriculture. With the advent of industrialization field size increased and with the technical advances barriers like steep slopes began to crumble away. For example Christmas trees are planted by machines on slopes with a slope gradient of 45 %.

On top of the advances and changes in agriculture various circumstances demand attention. First there are climatic changes with longer dry periods and more intense precipitation which lead to higher erosion risk, second the population in the country shows less acceptance of erosion as part of nature but demands that actions are taken against it, third the residential areas of towns and villages expand in areas which are critical with regard to erosion and third the technical advances in agriculture lead to higher stress for the soil which in turn is more easily eroded. To effectively treat these problems new paths have to be taken, new tools have to be used.

Geographic Information Systems bear great potential towards solving space related problems. To use a GIS properly several aspects have to be considered. Not only the knowledge of the problem to be solved but also the knowledge of the tool that is used to solve it is necessary. As with all new tools the possibilities are vast and so is the frustration that comes with the hours spend on getting the tool to work. In the course of this thesis the joy exceeded the annoyance. The wonder of finding something new and good was worth the trouble.

Acknowledgements

No product is the work of single hands. I wish to thank Dr. Hiller for his time, expertise and reassurance. My wife Jutta supported me as did my tutor Dr. Adrijana Car. I would also like to thank the whole UNIGIS team for their kindness and support. The data used in this thesis was kindly provided by the Hochsauerlandkreis administration and the Bezirksregierung Köln.

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List of abbreviations

AUA	–	Agriculturally used areas
BBodSchG	–	Bundesbodenschutzgesetz (federal soil protection law)
BbodSchV	–	Bundesbodenschutzverordnung (federal soil protection act)
BMVEL	–	Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft
BVB	–	Bundesverband Boden
DEM	–	Digital Elevation Model
DSM	–	Digital Surface Model
DVWK	–	Deutscher Verband für Wasserwirtschaft und Kulturbau e.V. (now DWA Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall)
GIS	–	Geographic Information System
HSK	–	Hochsauerlandkreis
K-Factor	–	Soil erodability factor of the USLE
KOSTRA	–	Kordinierte Starkniederschlags-Regionalisieruns-Auswertungen (soft ware to assess the frequency of heavy precipitation for each region in Germany)
LABO	–	Bund-/Länderarbeitsgemeinschaft Bodenschutz (soil protection work group of the states of Germany)
L-Factor	–	Slope length factor of the USLE
LWK	–	Landwirtschaftskammer (administrative agency for agriculture)
NRW	–	North Rhine Westfalia, one of the sixteen states of Germany
ReiBo	–	Reichsbodenschätzung (soil assessment for taxation)
R-Factor	–	Rain erosivity factor of the USLE
S-Factor	–	Slope gradient factor of the USLE
UBB	–	Untere Bodenschutzbehörde (Lower soil protection agency in charge of erosion prevention)
USLE	–	Universal Soil Loss Equation

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1. Introduction – Soil erosion in the Hochsauerlandkreis

Erosion risk assessment and the prevention of harm caused by erosion is part of the administrative work of the lower soil protection agency (UBB) of the Hochsauerlandkreis (HSK). This thesis is based upon the field work of the author, the LiDAR data set provided by the Bezirksregierung Köln and the land use data of the HSK both of which are administrative departments of North Rhine Westfalia (NRW). The data sets are used in a GIS, in this case ArcMAP by ESRI. The goal of this thesis to find a way to evaluate erosion risk on slopes with depression lines, since they represent a gray area in risk evaluation.

Figure 1: The village of Mülsborn lies in direct prolongation of the depression line. Around 100 linear erosion forms developed on the slope with a combined soil loss of 170 tons.

Depression lines act as natural drainage systems, they bundle the water from the surrounding slopes (see figure 1) and discharge it at their lowest point at best into a manmade drainage system, in the worst case into a residential area or onto a road. In depression lines the surface runoff is bundled. The effect on the amount of erosion can be extreme. The same precipitation can cause sheet erosion on the slope contributing to the depression line and linear erosion in the depression line with much larger impact on the soil, as the amount of eroded material and thus the onsite and offsite damage is greater. Linear erosion sets in faster and has a greater extent when the slope steepens and the catchment area waxes.

The form of the depression line is not limited to deep incisions like creeks with water currents. Much smaller, shallower and thus less obvious forms bundle sufficient water to create linear erosion. While these curved slopes are seldom overlooked, their impact is very easily underestimated. Either the slope gradient or the catchment area is not assessed correctly. Another reason that a tool/map is needed is that in some places unfavorable conditions concerning erosion risk prevail, like highly susceptible soils and statistically more heavy rainfall events, both conditions are not easily determined.

The effect of depression lines on erosion is not doubted but the degree of influence on the erosion event is difficult to assess. Erosion in itself is a complex process; erosion in a depression line is even more complex due to the amount of surface runoff and the physical processes in this temporary water flow. Therefore the aim of this thesis is not to predict the

amount of erosion, but to evaluate the risk for considerable erosion of a whole slope respective individual agriculturally used area (AUA).
At the moment the evaluation methods are either concerned with retaining the fertility of a field or a slope is defined as critical after erosion events took place and if it is likely that erosion will occur again. Both classifications are not satisfying, since the first does not include severe single case events and the second can hardly be called erosion prevention.
Until a few years back the topic erosion was not perceived as a problem by the communities. Therefore urban planners in the HSK placed residential areas in direct prolongation of critical depression lines. Either the erosion risk was not incorporated in the planning or vastly underestimated. This has lead to immense costs for communities for single events but also on a regular basis. There have been several larger erosion events in the past five years, which were in part mapped by the UBB (see chapter 4.3). These caused thousands of Euros damage in cleanup work and even more if the spoiled property of the residents is taken into account. In one case the cost did go up to more than 20.000 Euros (50.000 Euros if the construction costs for street and canal work is added that ensued after the erosion event (Meisen, 2011a)) for the relevant agencies or communities. Apart from monetary damages, the quality of life of the residents is greatly reduced and their resentment focuses on the farmers as the actual cause of the mud flow.
In 2011 the amount of erosion was strongly influenced by the adverse weather conditions. A long dry period in spring lead to the degradation of the soil aggregates and in turn to faster soil crusting, so that even ordinary precipitation which happens every few years was enough to cause considerable erosion.
Due to the climatic change these and other adverse conditions like an increase in frequency of heavy rain falls are likely to happen in the future (Neuhaus et al., 2010; LABO, 2010). This is the result of climate model calculations commissioned by the Landesamt für Natur, Umwelt und Verbraucherschutz in 2010, the magnitude of the erosive rain events will increase. The Länderarbeitsgemeinschaft Bodenschutz (LABO) made a statement concerning soil and climate change in 2010, there will be a greater amount of heavy rain falls and winter precipitation.
Changes in legislature or market force or encourage farmers (both forest and agriculture) to change their production habits. In the case of the HSK this means that with the boom in Christmas trees and the subsidies for renewable energies along with more weather proof corn breeds a wide spread change of agriculture into Christmas tree production and the intensive cultivation of corn set in.
Both plants are planted in rows and therefore are very critical with regard to erosion; the large interspaces between the rows and thus the large amount of naked soil in the field present the direst circumstances. The naked soil in combination with steep slopes and the silty soils form the basis for the high soil erosion risk in the HSK. These three factors are amplified by a depression line.
The involved agencies use an evaluation system that is quite well established and works fine for homogeneous slopes. For curved slopes though it is not appropriate because the effect of depression lines cannot be calculated with the used formula. Thus slopes with depression lines are per se underestimated in the evaluation system (see chapter 3.1). Urban planners as well as soil protection agencies need a tool to evaluate the erosion risk for slopes with depression lines to have a basis to work with. This tool or the first step towards it is provided by this thesis. A threshold system is defined which shows the risk evaluation of a slope with concern to erosion.

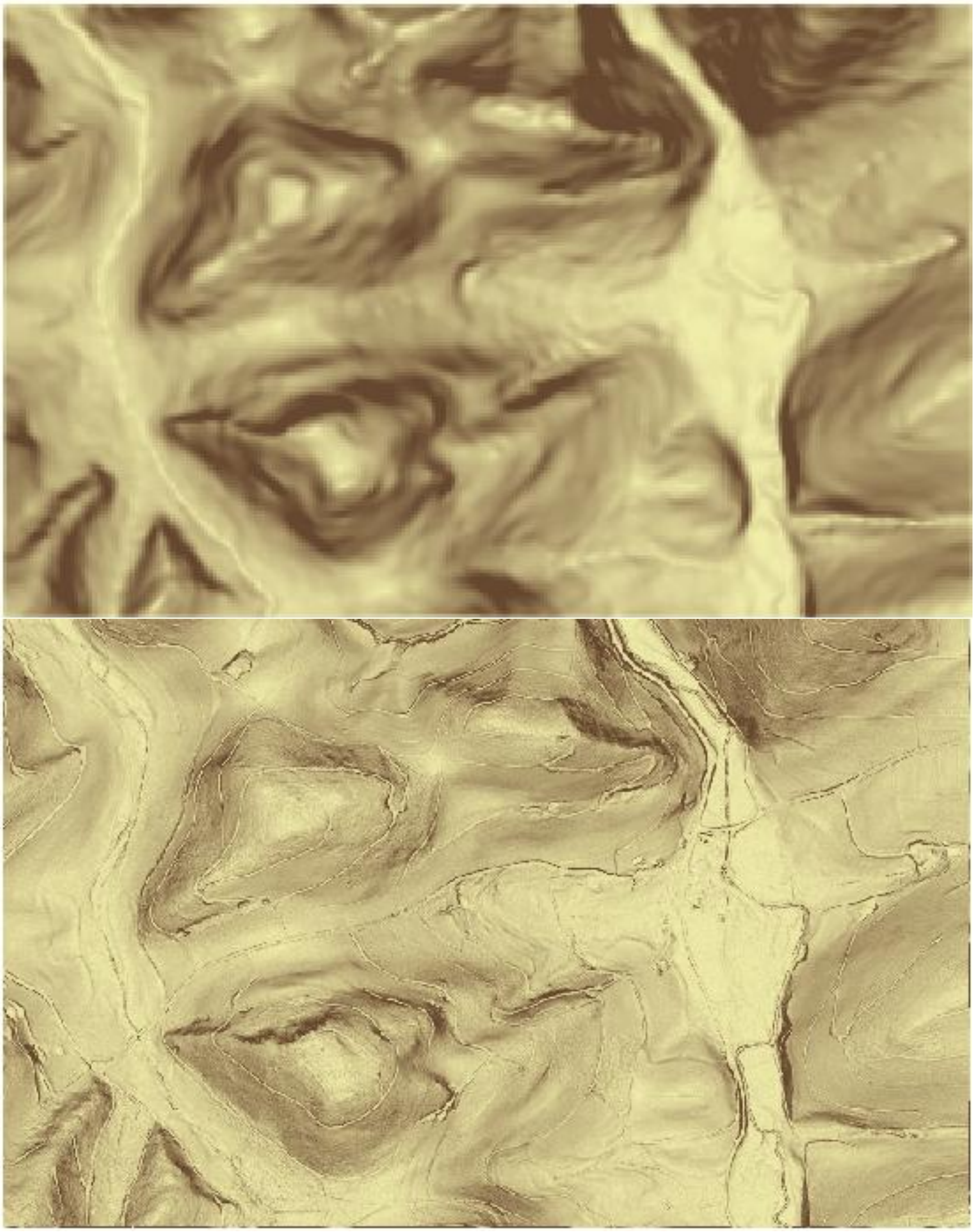


Figure 2a: Slope gradient of 10 m Raster of the area Berghausen1.11. Figure 2b: Slope gradient of 1 m Raster of the area Berghausen1.11.

Heavy erosion in depression lines and its underestimation are the motivation for this work. The advent of high resolution LiDAR data made this work possible. The resolution of a 1 m raster is needed to catch roads, large ditches and small dikes and other parts of a slope that influence the surface runoff. Comparing figure 2a and 2b it is obvious that the 10 m raster is not suited for calculation of surface runoff. If the path of the surface runoff is the object of interest, many forms that influence surface runoff like ditches or small ridges disappear in the 10 m raster while they show in the 1 m raster.

The tool to help devise a procedure for erosion risk evaulation is a geographic information system (GIS). It is used to work on a DEM derived from LiDAR data with a 1 m raster and field data of erosion events function as a means to control the results and help define threshold values. The idea for this thesis was born when the author first heard that a high resolution surface model was available for the whole HSK. The use of a high resolution DEM in combination with hydrology tools of a GIS bears great potential for the evaluation of erosion risk potential of a slope. The hydrology tools can be used to show in detail the area draining into each cell of a raster and they can also show the distance the water has traveled. The slope and surface runoff data obtained from the DEM can be combined with soil and land use data contained within the GIS of the HSK to incorporate other factors influencing erosion, like soil erodibility and infiltration/interception. The results of the GIS calculations are then compared to field data of the before mentioned mapped erosion events and used to answer the following questions:

1. Is the risk of significant erosion given on a slope?
2. Where do the critical slopes lie in the HSK?
3. Are there simple countermeasures to minimize this risk?

The result of this thesis is a GIS procedure to evaluate erosion risk for slopes with depression lines. It is to be used by personnel of urban planning who are in most cases laymen on the field of soil erosion and by soil protection agencies which experience difficulties concerning erosion and depression lines. An urban planner should consider the worst case before allowing the residential use of an area. The worst case with regard to erosion is a catastrophic precipitation event which only occurs once in hundred years. This time span seems long on the first view but considering the life span of residential areas it is not. By placing areas which are to be built with permanent structures in the path of surface runoff the question is not if a mud flow will hit the buildings but how often. In other words how much risk is acceptable, which repetition times for precipitation should be taken into account. If the approach of the Bundesbodenschutzgesetz is used every event with a repetition time of less than ten years must not be allowed to cause considerable erosion.
The question how to develop erosion risk threshold numbers is not easy to answer. Since it cannot be the goal of this thesis to predict the amount of erosion from depression lines, the threshold numbers cannot be based on exact rates of erosion. They must be derived from the probability with which considerable soil erosion can happen on a slope. Considerable in this case means enough soil has to be transported from the field unto the underlying areas to cause nuisance, disturbance or danger for the individual or the general public. Based on the experience of the administrative work and the information from citizen who live in areas where erosion happens more or less regularly some of the mapped sites can be taken as archetypes for critical conditions. These are Mülsborn area 1 and 4, Amecke, Enkhausen and Mielinghausen, since on all sites erosion happened on an almost regular basis.
There are very few definitions for critical conditions regarding the erosion susceptibility of a slope. The Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft (BMVEL) publicized the following figures in 2002. Any slope which exhibits one or more of the following characteristics can be considered critical with regard to erosion:

1. Slope gradient > 4 %
2. Soil is a loamy sand, sandy loam or silt
3. Precipitation of more than 7,5 mm total or > 5 mm in one hour
4. Slope length > 50 m
5. Absence of soil cover

Almost every slope in the HSK exhibits the first, second and the fourth of these characteristics. Point three is also true for great parts of the HSK with mean annual precipitation of 900 to 1200 mm. These figures obviously cannot be used to define erosion risk thresholds for slopes in the HSK not to speak of slopes with depression lines.
The danger of soil erosion on slopes with depression lines was classified via thresholds by the Bundesverband Boden (BVB). In the jurisdiction of NRW concerning soils there is no

classification of slopes with depression lines. The derivations of recommendations or assessment values are overdue. Assessment values are used to evaluate the harmfulness of a potential danger which has its roots in the soil either as a contamination or as a result of unfavorable physical properties of the soil, for example the potential of mud flows. This kind of value is defined in the federal soil protection act or Bundesbodenschutzverordnung (BBodSchV) and is a threshold value. If it is surpassed, the case has to be evaluated individually; if the measured value lies below the assessment value the danger is negligible. An assessment value represents a worst case value, which means that unfavorable conditions are assumed. This procedure makes it less likely to miss a critical area.

The thresholds defined by the BVB and Feldwisch in 2004 and 2005 respectively are much stricter than those of the BMVEL but nevertheless any investigation area falls into the highest category. Of course all investigation areas did show critical erosion in the past but while some of them can be handled by simple erosion countermeasures others like Mülsborn area 4 could not be mitigated by anything less than conversion into pasture or woodland.

Even with an excellent tool like a GIS the generated information is only as good as the underlying data. There are several uncertainties due to annually changing crop, conversion of pasture into field and vice versa, deforestation, reforestation (see chapter 3) or road construction. This has to be kept in mind when the erosion risk is calculated. It is not possible to create a GIS layer with permanently valid erosion risk classes; especially the changes in the land use woodland and pasture have dramatic effects on erosion. Also the kind of crop sown on a field can make the difference between no erosion and gully erosion.

The cost for capturing LiDAR data and GIS user licenses is immense, but Reutebuch (2003) states that the potential for a DEM to locate high risk erosion sites justifies the greater cost. After the completion of this thesis the statement is found to be true.

On the following pages the author will first give an overview of the literature and data used and move on to describe the regional and legal conditions concerning erosion. Then single erosion events will be discussed with regard to their use. In a third section the approach including theory, tools and data will be presented. Three ways of classifying erosion risk for slopes with depression lines were followed in subprojects. Each subproject has an individual data set and procedures. Of these three the best approach or combination of approaches will be defined and its impact on the administrative work explained. All important information will be repeated in a summary after that and a chapter on future work marks the end point of this thesis.

2. Scientific background and theories

2.1 Predicting the amount of soil erosion

There are two ways to predict the amount of soil erosion. First there are the physical models in which relevant physical parameters like soil moisture, soil aggregates, slope, infiltration rate, etc. are used to calculate the amount of erosion and deposition and second there is the Universal Soil Loss Equation (USLE), a formula based on empirical knowledge about erosion derived from field tests. As the name of the formula says it can only be used to calculate soil loss not deposition.

There are several aspects in disfavour for the use of a physical model. First it is not practical since the data needed for the model are very difficult to obtain and the benefit-cost-analysis is negative. Second the physical model is used to calculate the amount of erosion and sedimentation of a single erosion event. If the physical model is to be used in large scale erosion prevention, general assumptions about infiltration capacity, rain duration and intensity, interception and so on had to be done. Once again the determination of these factors is costly and impractical considering the size of the HSK (1961 km²) and the range in each value.

For this and other reasons the USLE is used in this thesis. The most important other reason is that the USLE has a broad acceptance in the administration of Germany. Thus an attempt to classify erosion risk based on the USLE has a better chance to be incorporated into the system of erosion risk management in North-Rhine Westfalia.

The USLE is a product of six factors: Slope gradient (S-Factor), slope length (L-Factor), soil erosion resistance (K-Factor), rain erosivity (R-Factor), coverage factor (C-Factor) and protection factor (P-Factor). The first four factors are easily determined since there are DEM's and maps available from which they can be extracted. The coverage factor is determined by the crop that is planted and the planting technique, it varies drastically. The protection factor covers the erosion protection activities. If the cultivation occurs at right angles to the slope the erosion risk can be reduced if a critical slope length is not exceeded. But given the large slope gradients and the great slope lengths this factor is negligible in the HSK. Of the six factors only the first four will be used following the evaluation concept of the BVB (2004) and Feldwisch et al. (2005).

2.2 Most relevant literature

Concerning the prospected use of this thesis as part of the work in the administration of the HSK, literature that was approved or contracted by the administration of North-Rhine Westfalia is most important. There are three works in particular which heavily influence this thesis:

1. MALBO Band 19 which is about the measures to reduce erosion (Feldwisch et al., 2004)
2. BVB Handlungsempfehlungen zur Gefahrenabwehr bei Bodenerosion durch Wasser (BVB, 2004)
3. Leitfaden zur Ausweisung von Bodenschutzgebieten (Feldwisch, 2005)

These works contain information about the evaluation of erosion risk on slopes with depression lines as well as important findings concerning erosion processes. Feldwisch et al. (2004) investigated an AUA on a slope with a depression line with regard soil erosion. The soil, slope gradient and slope length are comparable to the AUA found in the HSK. Four years of measurements of precipitation events and subsequent soil loss were conducted. Ten events caused over 95 % of the erosion on the plot. One event caused around 66% of the soil loss. Feldwisch et al. (2004) also state that the mulch is a very good countermeasure.

2.3 Limitations of the USLE

The BVB (2004) and other sources (Thomas, 1986) state that the USLE is not suited to calculate the amount of erosion from linear erosion forms. The BVB (2004) also states that on slopes with lengths of 100 to 300 meters or more the overland flow bundles and linear erosion results, thus again bringing the USLE to its boundaries of use. Therefore no calculation using the USLE can accurately predict erosion rates for slopes with a depression line.

2.4 Single events vs. mean soil loss

Figure 3: Gully erosion on a slope near the village of Mülsborn. From this gully alone 61 tons of soil were eroded.

Looking at the works of Návar et al. (2000) and Feldwisch et al. (2004) it becomes clear that the amount of erosion is not evenly distributed among the precipitation events. In single drastic events the ratio of amount of soil erosion to amount of precipitation is much higher than the ratio for the many smaller precipitation events over the course of the year. This circumstance is problematic (see 2.2). These single drastic events are not covered by the USLE. It is used to calculate the mean annual soil loss. Using the USLE to evaluate slopes with length of several hundred meters is not realistic. Erosion is underestimated, thus the results implicate a protection from mud flows caused by single events which does not exist. In this evaluation system the larger erosion events are perceived as outliers, as something that cannot be prevented. The precipitation leading to great soil loss can have a repetition time of less than ten years and thus countermeasures have to be taken against them by the farmers. Considering that these events cause most of the erosion, they should be incorporated into the erosion prevention work and not left aside. Small events usually do not

have the potential to cause either irreversible damage or the feared mud flows that ruin property.
The larger events in which tens or even hundreds of tons of soil are eroded (see figure 3) are most often caused by either soil treatment mistakes, adverse conditions like heavy rains after a long dry period or by natural catastrophes. On slopes with depression lines these larger events happen more often because of the amplifying effect of the depression line. The ephemeral gullies or more correctly ephemeral rills (see table 1) disappear with the next soil treatment and as long as no residential area or main road is directly affected the problem is not perceived as such.
The processes regarding ephemeral gullies were explained by Thomas (1986). There are several factors which lead to the formation of ephemeral gullies in depression lines. First of all the amount of water that runs through the channel is much larger than that on an even slope. As a consequence the amount of infiltration is reduced faster and the water no longer flows laminar, i.e. as a layer, but turbulent with small eddies and in general more kinetic energy.
As a second point the soil in a depression lines tends to be more easily eroded since it was brought there by tillage after the last ephemeral gully incision. Because of this the gully evolves faster at comparably lower surface runoff values and erodes the “fresh” soil. The underlying soil has a much higher erosion resistance and is considered a nonerodible layer. Thus the gully commonly develops a shallow and wide form, this can be seen after the erosion event in Mülsborn area 4. Thomas states that the amount of erosion in an ephemeral gully can make up as much as 50 % of the total slope erosion.

2.5 Development of rain erosivity

A study contracted by the Landesamt für Natur, Umwelt und Verbraucherschutz (LANUV) came to the conclusion that the precipitationn erosivity is increasing (Neuhaus et al., 2010). The frequency of heavy precipitation will increase while the amount of precipitation will not. There will be an increase in risk for the month June and July as well as October. Affected by this change are corn, potatoes and winter cereals like rape. In the concerned moths this crop is sown and the soil is vulnerable because of the soil treatment and the low soil coverage after the use of the plough.
The position paper of the Länderarbeitsgemeinschaft Bodenschutz (LABO) towards climatic change contains the information derived from climatic models. It is said that the frequency of heavy rainfall will grow higher in the 21st century and the temperatures will rise. This is accompanied by longer dry periods. In 2006 and 2011 this was already the case. Adverse weather conditions in combination with the soil type and slope gradients in the HSK bear a great risk for substantial soil loss with all negative aspects accompanied by it. It is recommended to devise and implement an erosion control mechanism, in the form of a monitoring program. The form of this program is up to the UBB's of NRW.

2.6 Influence of DEM resolution on the USLE factors

The resolution of a DEM has direct influence on the proposed erosion rates (Chisholm, 2008) if the USLE used. If the resolution is upgraded the calculated soil loss after USLE grows. This happens because of the great influence of the slope gradient. Through the plus in cells there is a much greater chance of capturing the highest and lowest point on the slope and thus greater slope gradients. For example in a 10 m raster there are 100 height values in a hectare, for a 1m raster there are 10.000 values. The difference in height, i.e. the slope gradient, is reflected much more realistic in the 1 m raster.

3. Legal and regional situation concerning the evaluation of erosion

3.1 Erosion prevention work flow

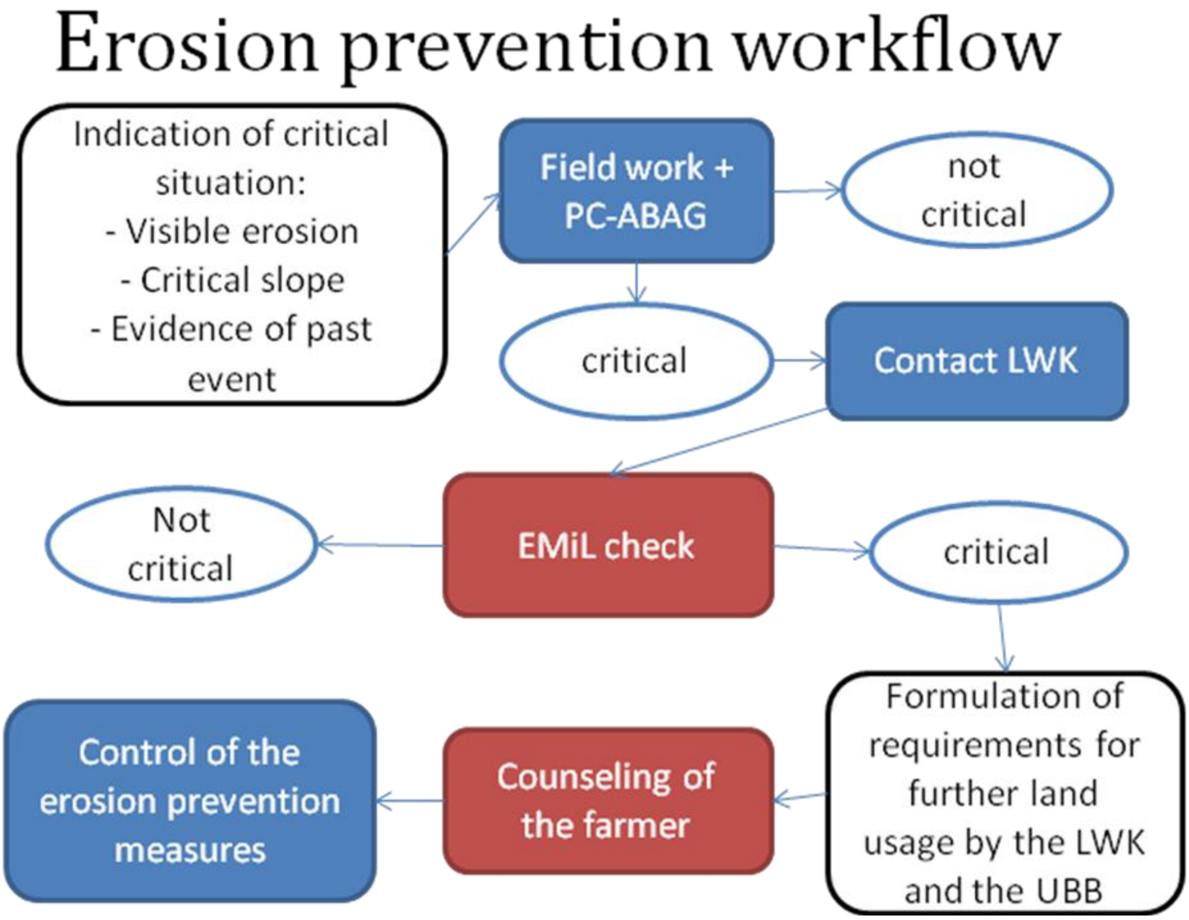


Figure 4: Work flow of erosion prevention in the HSK. Blue fields stand for HSK duties, red fields for LWK duties during the process.

The Bundesbodenschutzgesetz (BbodSchG, 1998, soil protection law) and the Bundes-bodenschutzverordnung (BbodSchV, 1999, soil protection act) form the basis for the administrative work of the UBB of the Hochsauerlandkreis. The soil is to be preserved and its functions are to be maintained or enhanced. Every person or company using an area has the duty to act in a way that no danger, nuisance or disturbance for a single person or the public can come from this area. The law and the act are formulated in a way that makes clear that a certain amount of erosion is to be tolerated.

Erosion in a noteworthy amount takes place almost exclusively on agriculturally used areas. In the two legal acts mentioned above it is written that the agency which handles agricultural issues is to be consulted before requirements or rules are declared in any case where AUA are concerned. In Northrhine-Westphalia this agency is named the Landwirtschaftskammer (LWK).

In union with the LWK the UBB assesses the risk and possible countermeasures for erosion on AUA on which almost all significant erosion takes place. The LWK counsels the farmers in many areas including erosion prevention. Its counselors use the software 'Erosion Management in der Landwirtschaft' (EMiL) to predict the erosion on a plot. This software was developed by several federal agencies and external professionals and is based upon the Universal Soil Loss Equation (USLE). While this software works fine in general, there is one critical drawback to it. It cannot be used to calculate linear erosion, i.e. visible rills and gullies. This leads to differences in the evaluation of the erosion risk for plots with depression lines or longer plots (> 100 m). The goal of this thesis is to close this gap.

3.2 More than one field on a slope/in a water shed

If the water shed of a depression line is large it is possible even with the great field sizes today that more than one field lies in the flow path. This means that very different soil coverage factors could exist in this water shed. To evaluate the erosion risk the worst case should be assumed, if there is more than one field crop succession could be organized in a fashion to reduce the risk. This is usually the case if the fields are used by one farmer. But with two or more involved farmers miscommunication or lack of communication could lead to for example the planting of corn or rape on the whole slope/in the whole water shed. This would result in a very high erosion risk for that year. The field size has increased very much. Usually one slope (up to the trees that populate the crest) is taken up by one field or managed by one farmer.

3.3 The soil on the slopes of the Hochsauerlandkreis

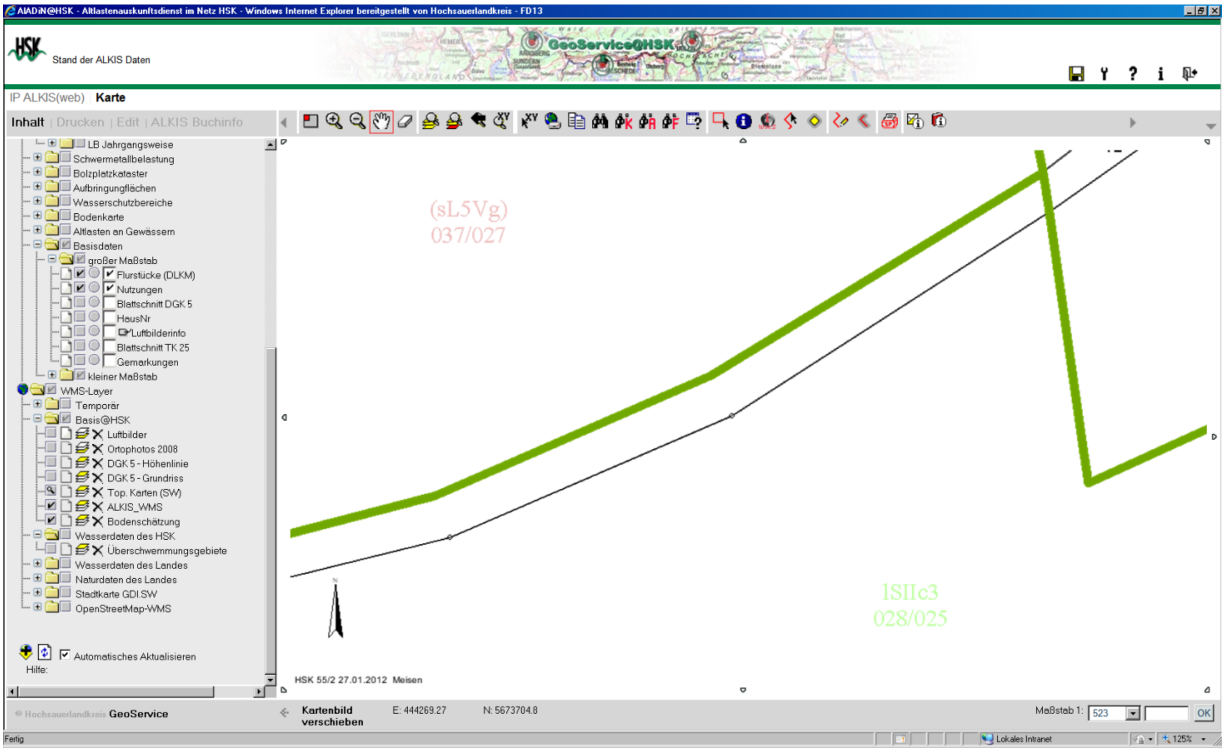


Figure 5: Soil classification layer of the Geoserver of the HSK. The green line is the boundary between two soil classes. The reddish text is the classification for land use field, the greenish text for land use pasture.

Most of the slopes in the HSK are dominated by weathered silt stone. This leads to the formation of silty loams or loamy silts with a varying amount of silt stone fragments. Whereas this is common knowledge, there are two points of view as to how the soil erodibility is described.

Two soil maps could be used to define the soil erodibility, the geological map and the map on which the taxation of AUA's is based, the so called Reichsbodenschätzung or ReiBo. The latter is biased since it is created for a specific purpose, it is used to estimate the potential harvest and thus factors like a change of grain size in deeper parts of the soil that are not

directly influencing the erosion resistance of the soil are blended into the result. In the ReiBo classification sand includes stones.
The geological map on the other hand is in theory better suited to calculate erosion risk, since it only records the distribution of grain sizes on the surface. Unfortunately there are three drawbacks to this map.

1. There have been several areas where the stone coverage of the soil (grain size between 2 mm and 6.3 cm) was not taken into account. The stone fraction is very important in assessing the erodibility of a soil. Due to their mass stones are unaffected by the impact of the rain drop and the infiltration is greater.

2. The resolution is only half as good.

3. Much more important; the map is not accessible due to financial considerations.

Figure 6: Erosion rill in a plant row of a Christmas tree culture. Please note the lack of vegetation due to herbicides and the destroyed soil structure.

For these reasons the ReiBo is used, which is also used by the LWK. The disadvantage of the ReiBo is that there are only values for AUA and not for example woodland. The soil erodibility factor K of the USLE would have to be interpolated for these land uses by using ReiBo layer of the Geoserver (GIS) of the HSK and look for AUA next to the woodland or the soil type has to be assessed in the field.
After the ReiBo there are mainly two types of soil on the slopes of the HSK, very loamy sands and sandy loams. There are a few loams and loamy sands but their number is very small. Loams are usually bound to flat areas and so are loamy sands, because the fine grain sizes are more easily eroded and sediment on flat areas. Thus due to erosion processes there is a fractionation of grain sizes in as much as the coarse sizes in this case mostly the stones are more often found on the slopes, because they are not easy to move by the surface runoff. This effect is reduced with the steepness of the slope, because the energy it takes to move the stones decreases.
The two characteristic soil types have nearly the same erodibility (K-Factor of 0.25 and 0.3) this is very advantageous for this thesis since it allows the generalization of this factor and hence the risk calculations based solely on catchment area and slope (slope maps) are much more reliable.
Of course there are exceptions to this uniformity of the soil. First there is the presence of very stony soils, which have a lower K-Factor and second on the areas where hurricane Kyrill blew down most of the trees the soil is milled up to a depth of 25 cm, destroying the aggregates and worm holes (important for infiltration) thus lowering erosion resistance. This

milling is done to create a plain area that is required for the planting machines to work on. There have been several erosion events on such areas. There is no known literature on the effect of this milling on the K-Factor of the soil, considering the fast onset of linear erosion on these slopes the effect can be called drastic.

3.4 Soil crusting

Feldwisch (2004) states that single events of intense rains cause much more erosion than the sum of low intensity rains in one year. The worst cases of erosion happen when heavy rains fall on dry, recently tilled soil. Especially dangerous conditions exist if the soil has been prepared for rape or another crop requiring fine grained soil or has been milled deeply, because the grains are more readily loosened from the aggregates.
After the infiltration capacity is surpassed, surface runoff begins and the loosened fine grains settle in the pores on the surface of the soil. In consequence water can no longer infiltrate (see figure 6). This effect is greatest with the silt grain size. Because of the large portion of silt soils in the HSK soil crusting leads to large amounts of soil loss. This countered by leaving mulch on the field or by undersown crops, which help to stabilize the soil and reduce the kinetic energy of the rainfall.

3.5 Problematic agricultural crops

At the moment there are three crops sown or planted in the HSK which for two reasons negatively influence the erosion risk.
Corn and Christmas trees are planted in rows. Most commonly Christmas trees are planted parallel to the slope, so that the surface runoff is channeled in the interspaces of the rows. The ground is treated with herbicides so that the sapling can grow undisturbed. If the ground was covered well enough the residue of the dead plants suffices to protect the soil against erosion. But often the soil cover is marginal and erosion occurs unnecessarily. Corn is often planted at right angle to the slope. Unfortunately the slopes are seldom completely homogeneous. There are almost always one or more parts that curve. In these parts it is impossible to plant the corn in a fashion as to hinder the bundling of surface runoff and once there is a bundled stream it has the tendency to grow and cause linear erosion.
Another problematic plant is the winter rape. The soil needs to be fine grained for the winter rape to grow. The sowing time lies in the summer so that heavy rainfalls are not uncommon. For several weeks the soil is only protected by mulch if there is any. The fine grained soil speeds the formation of soil crusts and thus drastically enlarges the danger of soil erosion.

3.6 Changes in land use

Conversion of pasture into fields is a common practice in North Rhine Westfalia since pastures that are not tilled for more than five years count as permanent pastures and cannot be tilled without permission of the Untere Landschaftsbehörde. To prevent this bureaucratic act and the impending compensation farmers plow pastures that might be used as fields every four years.
The land use layer of the Geoserver of the HSK is not up to date concerning these conversions. Since there is a great difference between the land use pasture and the land use field with regard to erosion risk the information in the land use layer cannot be used without on-site inspection.
Also since the catastrophic storm Kyrill the weighing with concern to influence on erosion of the different land uses is no longer as easy. Large devastated areas in the HSK were in part turned into Christmas tree plantations. Those have the opposite effect on erosion compared with forest/ woodland. On the other hand it is impractical to check every land use polygon for its present state of actual land use.

3.7 Field observations

Figure 7: Ephemeral gully in area Wormbach 3.87. Obvious is the large discrepancy between the erosion in the depression line and on the rest of the slope.

1. The threshold which marks the boundary between sheet and rill erosion to gully erosion is often surpassed in the depression line. This can be seen in the cases where linear erosion only took place in the depression line. In these cases the soil on the slopes outside the depression line showed only few signs of sheet erosion like damaged plants or small erosion rills (<2 cm depth) whereas the erosion rill in the depression line was deeper than 10 cm (see table 1). With further study this threshold could be correlated to the value of flow accumulation in ArcGIS. The existence of such a threshold is logical but the evidence of it clarifies the need to calculate it, in the context of the danger and the inconveniences that are implicated for the society and the individual citizen by the greater amount of erosion due to linear erosion.

German classification after DVWK	Depth	English	Depth
Sheet and rill (flächenhafte) erosion	Up to 2 cm	-	-
Rillenerosion	2 to 10 cm	Rill erosion	Up to 30 cm
Rinnenerosion	10 to 40 cm	Gully erosion	More than 30 cm
Grabenerosion	Above 40 cm	-	-

Table 1: Classification of erosion forms in relation to depth.

2. Shortly after the tillage the soil can be easily eroded. This is especially true for milled soils (see

figure 8) and soils that were tilled for plants like winter rape which need a fine grained seed bed to prosper. In the HSK these two conditions are found quite often.

These soil treatment techniques should only be used with appropriate erosion countermeasures. Whereas the fine grained soil required for rape can be protected by mulch, the milled soil has experienced much more destruction of valuable structure (aggregates, earthworm tunnels) hence the grains are more easily swept off even if a soil cover of more than 70 % exists. The infiltration rate is reduced greatly due to soil crusting. This can only be countered by the planting of fast rooting plants. If the soil is more stable due to roots and stabilized aggregates deep rills cannot develop or can only develop if the surface runoff has a much higher kinetic energy, as can be seen on the slopes in Ebbinghof.

3. The planting of corn and Christmas trees on more than slightly inclined slopes (> 5 %) is critical. In spring 2011 very little precipitation occurred, hence the soil was dry and after rain falls with repetition times of less than five years massive erosion took place. In one case less severe erosion occurred at least twice in the years before. Always involved were corn fields and in one case a strawberry field, i.e. plants that are sowed in rows. The interspaces of which act as runoff channels and leave a large quantity of the soil without plant cover during a long time of the year where the rain conditions are more critical.

Figure 8: Steep slope (25 %) with milled soil and linear erosion. Please note the large amount of surface cover (stones, plant residue).

4. The ratio of lost soil in the depression line to lost soil from rills on the slope (in the watershed of the depression line) was found to be between 1 : 2,5 and 1 : 3. The portion of the total erosion amount is lower if the sheet erosion is taken into account but sheet erosion is very difficult to quantify. On the other hand in the depression line the onset of linear erosion is reached much sooner than on the rest of the slope, therefore the risk of considerable erosion rates is much higher on slopes with depression lines.

5. The formation of rills depends very much on the direction of tillage. If the tillage was done parallel to the slope several rills will form, because the tillage rows bundle the surface runoff.

If the tillage was done perpendicular to the slope the formation of rills is more likely to be limited to the depression line and not the contributing slopes, increasing the risk and amount of linear erosion in it. If the field is planted with corn or another crop sowed in a row terraces will develop perpendicular to the slope. These terraces are an obvious sign for sheet erosion the extent of which is very difficult to know.

3.8 Mapping erosion events

After erosion took place it is possible to map linear erosion forms. This is conducted after the official instruction by the Deutscher Verband für Wasserwirtschaft und Kulturbau e.V. (DVWK). In regular distances measurements of width and depth are taken. The length and number of the linear erosion forms is measured. Assuming an oven-dry density of 1.4 g/cm³ the calculated volume is transformed into a mass of eroded soil. Because there is no adequate graphic design software the map is a sketch made in the field.

4. Underlying data: Digital elevation model and investigation areas

4.1 Vertical accuracy of the DEM

The DEM created from LiDAR data is the result of an interpolation process in which the statistically distributed LiDAR data points are “pressed” into a raster. One to four points were measured per square meter. This has to be kept in mind, when the correct depiction of forms with an extent smaller than one meter is regarded.
The official vertical accuracy of the LiDAR data is +/- 0.2 m. With a raster of 1 m this leads to large amplitudes in the slope calculation. If there are only small changes in altitude, as for example on roads the digital elevation model (DEM) might show a faulty tilt of the road and in consequence the flow direction is not depicted correctly, leading to false flow accumulation calculations.
The correct depiction of roads is very important, because roads bundle surface runoff. When they are not parallel or perpendicular to the slope they can bundle the surface runoff, it stays on the road as long as the road does not tilt downslope at which point the surface runoff of a large area is released as a torrent onto the area below.
This effect can be observed on an asphalt road after heavy rain where the runoff track is traced by a band of wetness crossing the road. The bundled release of surface runoff onto a field can cause severe linear erosion. To check whether the DEM can depict these points of inflow the vertical accuracy of the LiDAR data has to be scrutinized.
The Bezirksregierung Köln Dezernat 74 - Geodatenzentrum, Geodateninfrastruktur, which is in charge of capture and provision of digital surface data, provided a statistical analysis concerning the vertical accuracy of the LiDAR data (Bezirksregierung Köln, 2007). 25 sports fields were examined by ground control and compared to the LiDAR data of those fields. Two out of these 25 areas express mean errors of 10 cm and more. It can be argued that those values are outliers since they lie outside of the twofold amount of standard deviation of 5.08 cm.
The mean height error of the LiDAR data is +3.8 cm. This number shows that the height was overestimated in general. One of the 1511 control points showed an error of 21 cm, this lead to the official accuracy statement. The author believes that a much better accuracy can be attested to the data. At least the above mentioned standard deviation of 5.08 cm can be used when considering the vertical accuracy. If the above mentioned areas with mean errors of 10 cm and more are not taken into account, the mean error drops to +3.0 cm and the standard deviation to 4.42 cm. Whether 5.08 or 4.42 cm is correct, the vertical accuracy for this data set can be considered to be +/- 10 cm (twofold standard deviation) or better.
The question arises whether the vertical accuracy and the amount of detail caught by the 1 m LiDAR raster is sufficient for the GIS to calculate the surface runoff pathways accurately enough for the purpose of this thesis.
Any feature with a diameter of one meter and more like roads, large dikes or wide ditches were depicted accurately enough to simulate their effect on surface runoff (see figure 9).

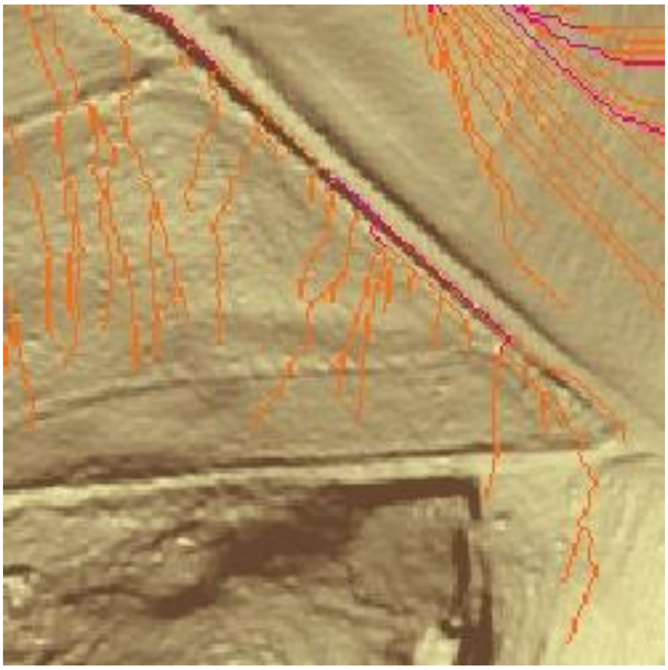


Figure 9: Flow accumulation map detail.

Small ditches or even the height differences on a dirt road where the wheel tracks are usually considerably lower than the banquette and the strip in the middle were not captured. That means that the flow direction is only shown correct in the AUA maps for their surface is by definition without hindrances. Since the object of interest of this thesis are depression lines this fault is not that grave for in the end all surface runoff runs into the depression line, but like all models or interpolations there is the trading of realism against practicality. Since every cell only enters the calculation one time the amount of surface runoff stays the same. Only the flow length differs from the reality, but with 10.000 and more cells the flow length differences are likely to equilibrate.

4.2 Topographic development or the half-life of the LiDAR data

The landscape is not masoned in stone, it is changing. Events like the hurricane Kyrill fundamentally change the earth's surface in a very short time. Drastic changes in surface characteristics like interception of precipitation and hence surface runoff are the consequence. New developments in land use with the corresponding changes in physical and chemical properties also ensue, since some of the areas that were devastated by Kyrill were turned into Christmas tree cultures.

The LiDAR data are a snap shot, a moment in time. If for example an area was subject to construction on the day of the data capture the results of the area that was worked upon after the laser signal was reflected is not depicted right (as is the case in the Enkhausen example, where the area to the north-west of the critical field (see figure 18) is part of a soil improvement measure and elevations and thus slope have changed). Whereas the vast majority of the soil was in a state that is comparable to the status quo there are several processes like Kyrill or the conversion of forest into field and vice versa that take place which are not contained in the LiDAR Data. Therefore every result has to be verified. The more so the older the LiDAR data set becomes. The current set was captured in 2007. Starting in 2012 the data will be updated every six years.

The most important changes are those that directly affect the surface runoff like drainage rills on rural roads or the removal of a hedge. The surface runoff reaches the field bundled and hence linear erosion starts sooner and in consequence the amount of erosion is greater. Unfortunately the drainage rills or small dykes on roads are not caught by the LiDAR system. The same is true for hedges since they are removed in the creation of the DEM.

4.3 Investigation areas

Below are presented the nine investigation areas which were used in this thesis. All areas have once or more been subject to erosion in the past five years. Erosion events which happened in 2011 have been charted by the author who took up work in erosion prevention at the end of 2010. The charting was done according to the official field manual of the DVWK and estimations of soil loss were conducted. Please note that some depression lines are quite obvious while others are far less so but still important due to large water sheds contributing to it (for example Mielinghausen).

The erosion events fall into two categories. First there are the catastrophic events with massive erosion and large damage from multiple linear erosion forms and sheet and rill erosion (Mülsborn, Amecke, Enkhausen, Mielinghausen, Menkhausen, Ittmecke) and second there are those events with only a single linear erosion form in the depression line (Wormbach3.87, 2.143 and 8.133). From the first case areas we can get a feeling for the amount of erosion that can take place. From the second case areas we can try to derive the threshold after which sheet erosion turns into linear erosion. With Ittmecke as an exception precipitation with a repetition time of less than ten years led to the erosion events.

Ittmecke

This area lies in Meschede, which is a small town which has used up most of the space in the Ruhr valley and has “climbed” up the slopes. Unfortunately a residential area was set into the Ittmecke valley. The narrow valley was like all valleys a natural drainage system. Today it is a high density residential area with little infiltration potential and no countermeasures against mud slides. In 2007 there was heavy precipitation with around 60 mm/h and a repetition interval of 17 years.

Soil from a three year old Christmas tree culture was eroded and entered a depression line that leads to the Ittmecke valley. The mud flow passed a pasture of around 80 meter length and flowed along the depression line across a field road into a 40 meter wide and quite steep strip of forest. A deep rill or gully was eroded into the forest floor and the mud flow hit the Rehweg five meters distant from the first residential house. There is a foot path that goes straight up the depression line. Obviously the possibility of a mud slide down the depression line was not foreseen as the Rehweg was planned. There is no countermeasure installed. Actions on the AUA where the Christmas tree culture stood have been taken. In 2011 the field was again planted with Christmas

trees.
This area of investigation shows that things in nature are interconnected but human being sometimes cannot or would not see it.

Mielinghausen

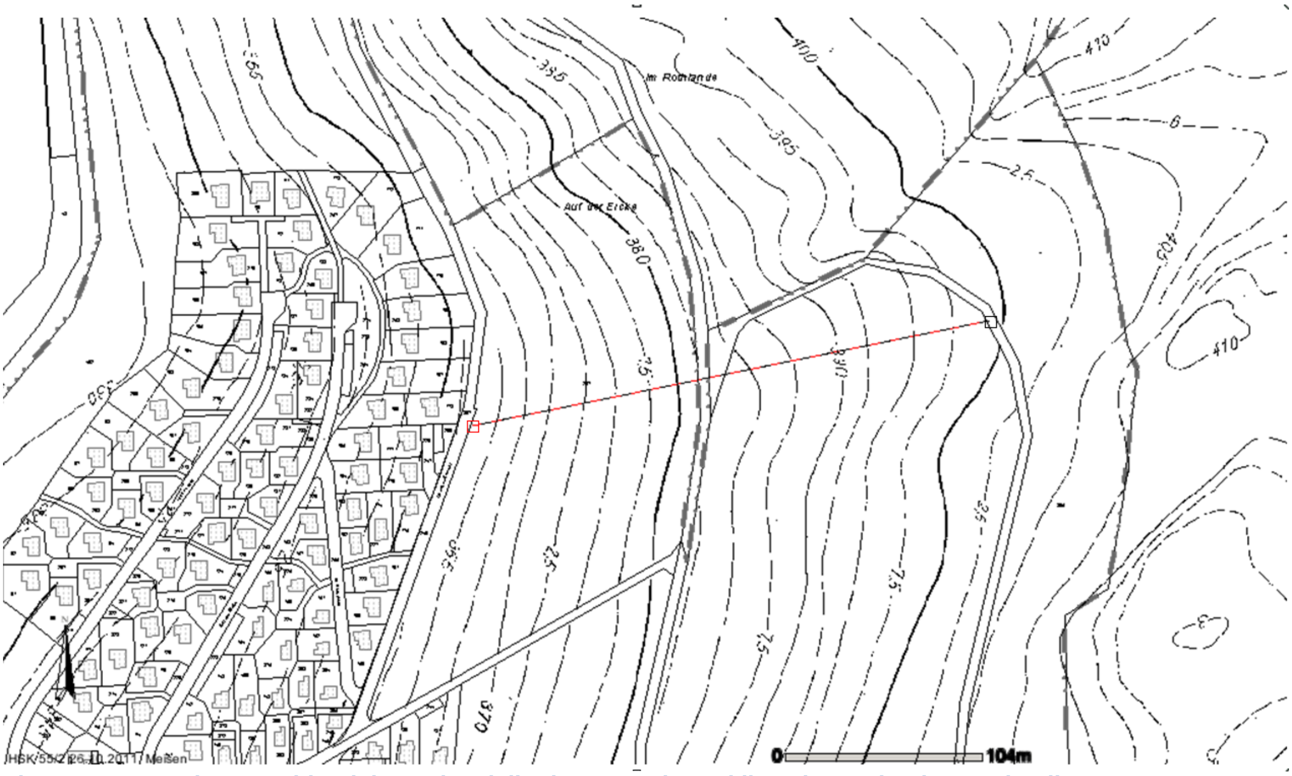


Figure 10: AUA above residential area in Mielinghausen. The red line shows the depression line.

This area encompasses woodland, AUA and real estate used for vacation and permanent living lying directly below the AUA. There is a depression line in the AUA which points toward the real estate (see figure 10). In 2000, 2006 and 2011 erosion events took place. The first in summer 2000 led to the displacement of large amounts of soil from the AUA into the settlement. The upper two roads that run perpendicular to the slope had to be cleared. On the roads and in the gardens the deposition had a thickness of about 20 cm. The farmer supposedly plowed parallel to the slope. This harsh mistake would fit well with the amount of erosion.
In summer 2006 only the area directly below the depression line was affected. In spring 2011 the melting of snow in concurrence with a warm rain caused linear erosion in the depression line. This area is a very good example for the selectivity brought into the erosion process by depression lines. While the area offset from the depression line was not subjected to a mud flow or at least not enough to cause concern the area in prolongation of the depression line was at least hit up to the second row of houses. Another insight this example can give is that the effect of the depression line is easily underestimated. At first look the field does not look that critical. The area contributing to the depression line is relatively small and the woodland in the north (see figure 10) seems to mitigate the erosion risk because of the reduced inflow of water onto the field.
The slope gradient is 15 % and the slope length crossing two AUA in the depression line is around 280 m. These two figures are quite high values and in union with the depression line offer enough explanation for the three erosion events. There is a road which runs parallel to the contour lines dividing the AUA in half. The crest of the hill is used as woodland respectively Christmas tree cultures. It is possible that the amount of interception is reduced in the Christmas tree cultures for the trees do not yet have a large surface. This could have led to a greater amount of surface runoff and hence made the erosion events more probable.

Menkhausen

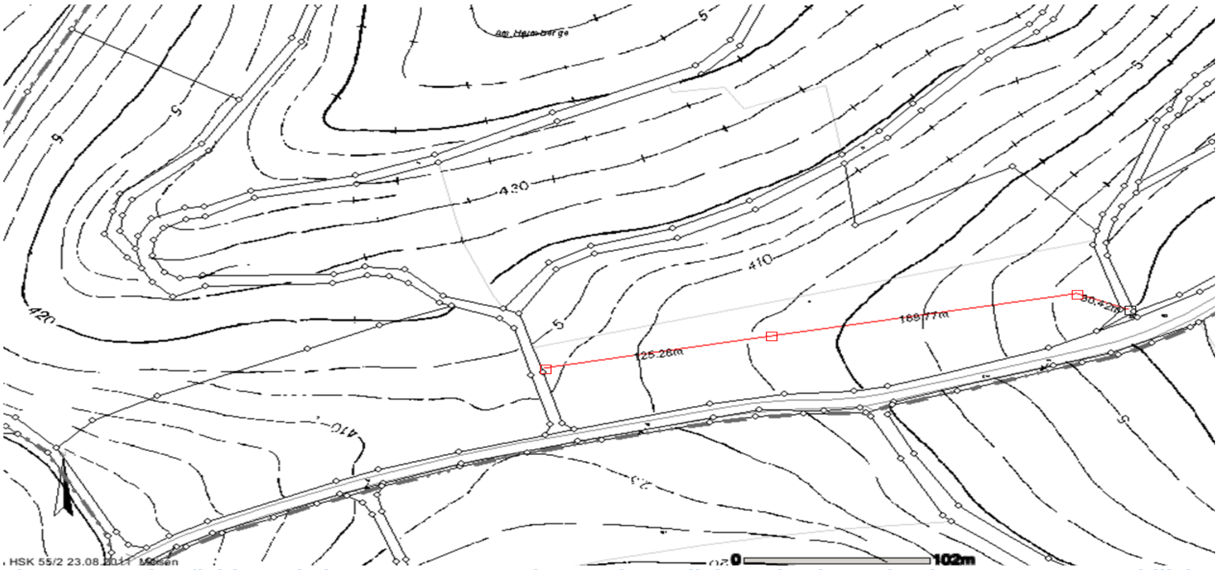


Figure 11: The field road that connects to the road parallel to the investigation area goes uphill before it connects to the larger road, hence all surface runoff must flow either onto the left or the right field. The red line marks the depression line.

Not danger to life and private property but soil degradation and the clogging of ditches are the focus in this area. The depression line discharges onto a field road and in consequence into a ditch along the road to Menkhausen. The slope length is around 335 m with a slope gradient of 9 %. Because of the form of the AUA and its position on the slope the soil treatment is done parallel to the slope. The depression line is not very distinct in the field, but the contour lines make it obvious. At least once in 2009, twice in 2011 and once in 2012 erosion events took place. Each of the events was characterized by linear erosion forms parallel to the depression line and the direction of soil treatment. The amount of erosion lay somewhere between ten and twenty tons of soil per event although the second event in 2011 was less strong with only around five tons of eroded soil. In the early years of the last decade the lower part was grassland, effectively stopping the mud flow and preventing the discharge of soil into the ditch along the road.

Figure 11 is a good example of how roads can enlarge the effective water shed. Please note how the road above the field connects the area northwest of the field to it. This has two adverse effects, first the amount of water running over the field is greater and second the inflow does not happen evenly distributed along the road but enters the AUA bundled on the spot where the slope of the road dips towards the field. This bundled surface runoff has led to linear erosion on the field which in turn leads to greater soil loss.

Ebbinghof

In the greater area around the small village of Ebbinghof there are three areas of investigation each with a depression line but with differently sized water sheds and pathways for water inflow.

1. Wormbach 8.133

The AUA in question runs parallel to a road. Upslope land use is woodland and one Christmas tree culture. A single erosion rill developed in the depression line in spring 2011 and winter 2012, probably due to moderately developed grass growth which held back the soil the slope outside the depression line showed only little signs of erosion.

This is a good example of a case where the contour lines do not show a small depression line which ends in the larger one (the short red line in figure 12 lies in this small depression). The soil type in the sedimentation area is a colluvisol, a soil created by sedimentation pointing to the fact that erosion is a natural process and at this location happens often enough to create a soil layer.

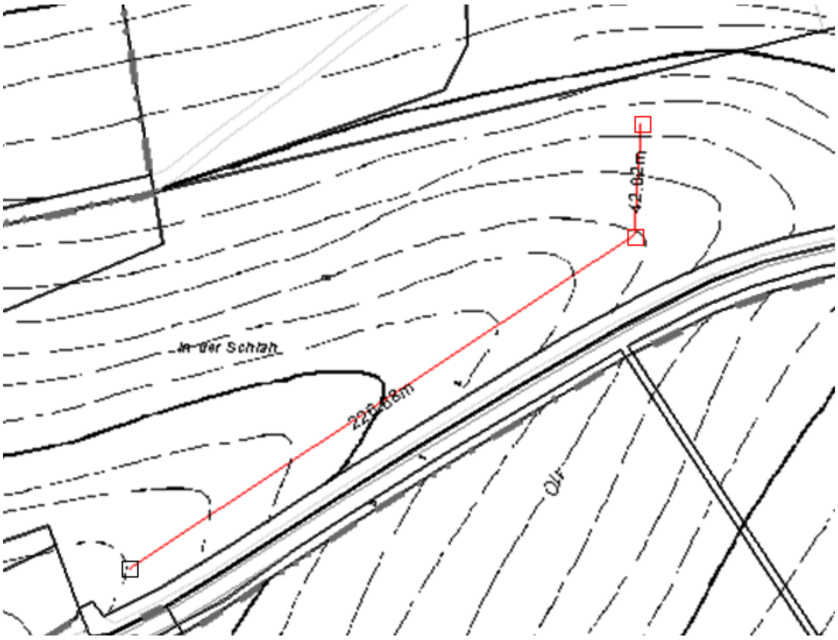


Figure 12: Area Wormbach8.133. The red line represents the ephemeral gully erosion with a length of 270 m.

2. Wormbach 3.87

Figure 13: Area Wormbach3.87. The red line retraces the ephemeral gully with a length of 250 m. The gully developed in spite of a moderately developed pasture.

This area is characterized by a 20 ha water shed which consists mainly of AUA (see figure 13), a depression line of 770 m and a mean slope gradient of 9 %. On the aerial image it looks as if the slope was only used as pasture but that is not the case. The fields underlie a rotation system with pasture as one part.

In an erosion event in early 2011 an ephemeral gully with a mean depth of 17 cm, a mean width of 25 cm and a length of 250 m developed in the depression line that was fed by another smaller erosion rill. With the last erosion event around 15 tons of soil were eroded, some of which deposited in the lower part. Considering the size of the water shed the amount of erosion is relatively low. This is the consequence of the land use pasture.

3. Wormbach 2.143

The depression line has a length of approximately 190 m and the slope is 10 %. Approximately 7.5 ha discharge into the depression line. In the aerial image the soil in the depression line and around the ephemeral gully (red line figure 14) is obviously different from the surrounding soil. The amount of soil eroded in early 2011 was around 15 tons from an area of 1.4 ha. The gully started very close to the edge of the field. This indicates that the erosion is greatly influenced by the inflow of water from the road.

Figure 14: Aerial image of area Wormbach2.143. The dark patches in the depression line hint at a regular process.

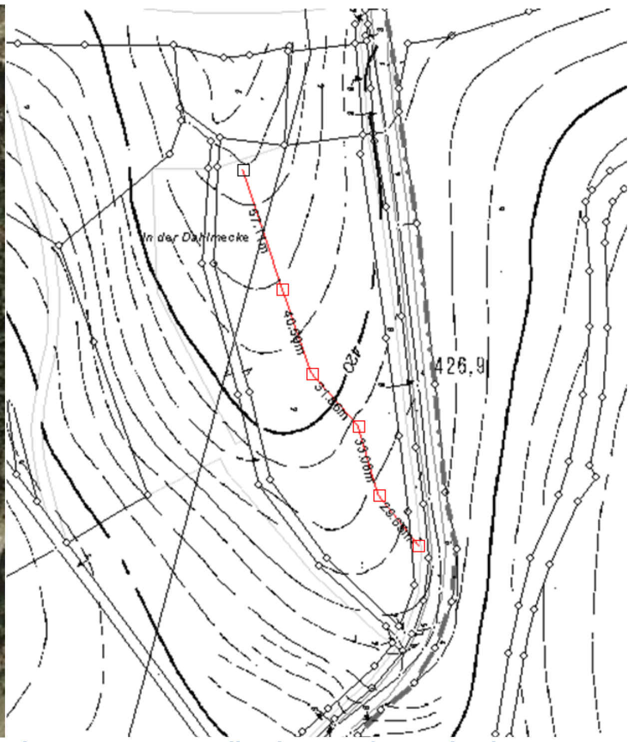


Figure 15: Contour line image of Wormbach2.143. The red line shows the ephemeral gully erosion with a length of 190 m.

Sundern Amecke

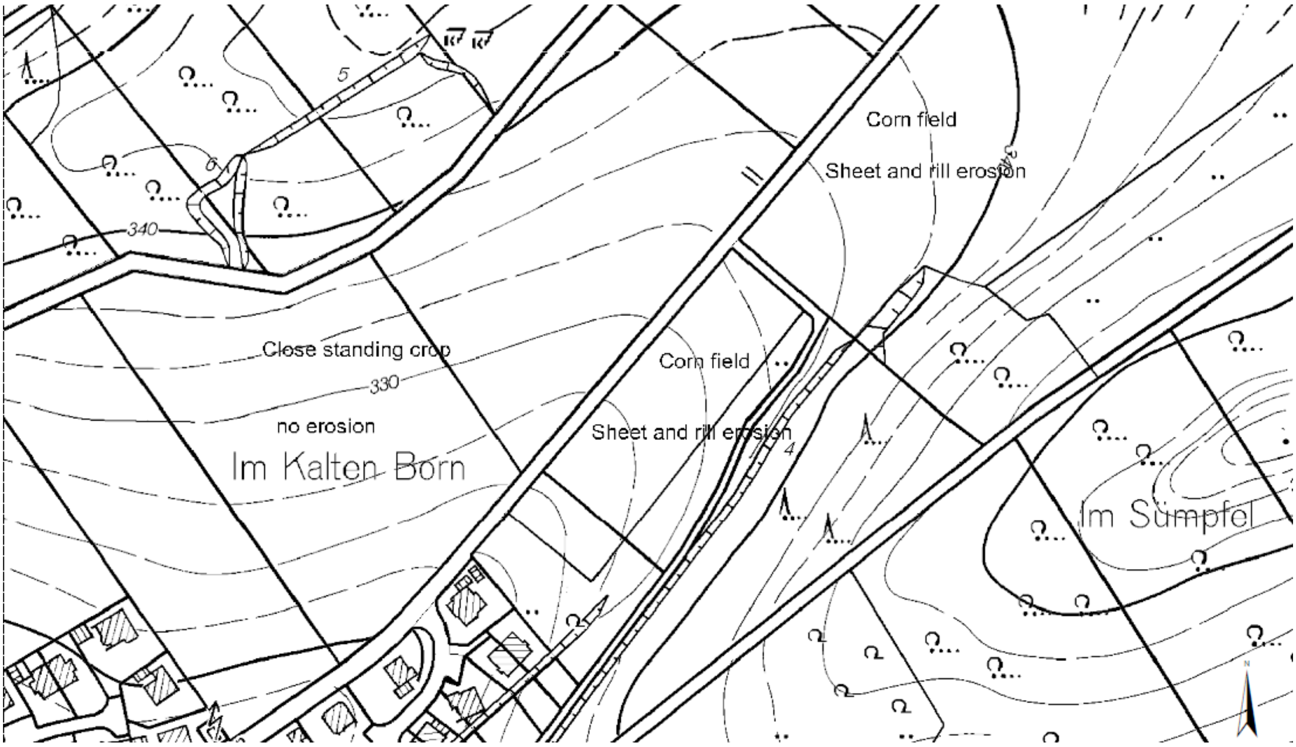


Figure 16: AUA in a valley above residential area. If no countermeasures are taken, damage to property is inevitable.

On June 5th 2011 moderately heavy rain falls led to erosion on several corn fields in the area of Sundern Amecke. The real estate of residents and companies was subjected to mud flows. The precipitation that led to the great amount of erosion happened at a time when the corn plants were small thus the soil had no protection from the impact of the rain drops. Loosened soil particles led to soil crusting and in consequence to large erosion rates which are very hard to quantify since most of the erosion was sheet and rill erosion which is impossible to measure accurately. Around 230 tons of soils had to be moved from ditches, roads and private property (backyards, doorways, etc.). On top of that an unknown amount of soil deposited in areas where it went unnoticed or was transported away by river into Lake Sorpe.

Six fields were affected with differing degrees of erosion. One field has a distinct depression line (see figure 17); the other five appear more or less homogeneous or express very shallow depression lines. From this field a large amount of soil was eroded which deposited in an unused plot of the commercial area at the end of the depression line.

The linear erosion on the slope with the depression line consisted of two shallow and broad rills with a combined length of 275 m, a mean width of 30 to 90 cm and a mean depth of 5 to 20 cm. A rough approximation of amount of erosion in linear forms is 29 tons. The corn stood perpendicular to the slope. Sheet erosion sculpted the field into terraces on which erosion and deposition took place. A very rough approximation comes to

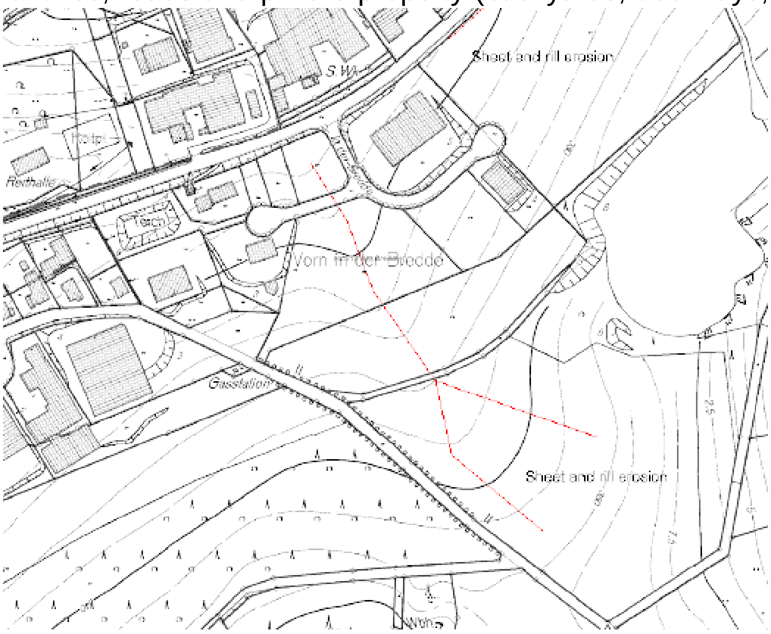


Figure 17: The red lines show linear erosion. In general the corn fields were subject to sheet and rill erosion.

170 tons from sheet erosion. At least 30 tons were deposited either in the rows or in the changeover from the field to the row of trees and bushes.
Around 35 l/m² of rain fell in about 90 minutes. Statistically this happens once a year, a document of the Deutsche Wetterdienst gives proof of that. All precipitation that would statistically happen once in eleven or more years count as an act of nature beyond control, but in this case farmers should have prepared their fields so that the amount of erosion was not considerable. As was mentioned in the introduction there was a very dry spring in 2011 and soil crusting started much sooner than under "normal" weather conditions. This example shows that it is very difficult to force the complex process of erosion into a rigid evaluation system. If erosion had only happened in 2011 the liability of the farmers would not have been easy to prove. Unfortunately for the residents erosion has also taken place in 2008, 2009 and 2010. Not always from the same fields and not nearly the rate of 2011 but it was enough that no farmer argued the necessity of actions to counter erosion.

Sundern Enkhausen

Also on the 5th of June 2011 around 20 km distant in Sundern Enkhausen erosion took place in a much smaller amount. Along a depression line gully erosion showed (two to three small gullies with depth between 10 and 20 cm and width between 10 and 90 cm). The erosion was enlarged by concentrated inflow from the soil enhancement measure above, on a plot of land (white area on figure 18) which is in the future to be used for agriculture, soil is deposited with the aim of facilitating the soil treatment. The elevation of the area has not yet been surveyed therefore it is a white spot in the contour line map.
During these earth works a small ridge was formed that ends in the depression line, hence water accumulated before the ridge and was then released into the depression line. The degree of influence this ridge had on the linear erosion is not clear but there were linear erosion forms in the depression line upslope of the ridge, so that it is unlikely that the ridge was not the cause for linear erosion on the field but only added to its extent.
Around 30 meters before the end of the corn field the depression line came upon a road. The sediment laden flow was in part captured in a drainage system. In the village below one resident had problems with sediment in front of his garage. Around four to five times in the last twenty years notable erosion took place, clearly showing that the area has a high erosion disposition. The field which was eroded is to be prolonged up to the crest of the hill. This merging of the soil enhancement area and the AUA

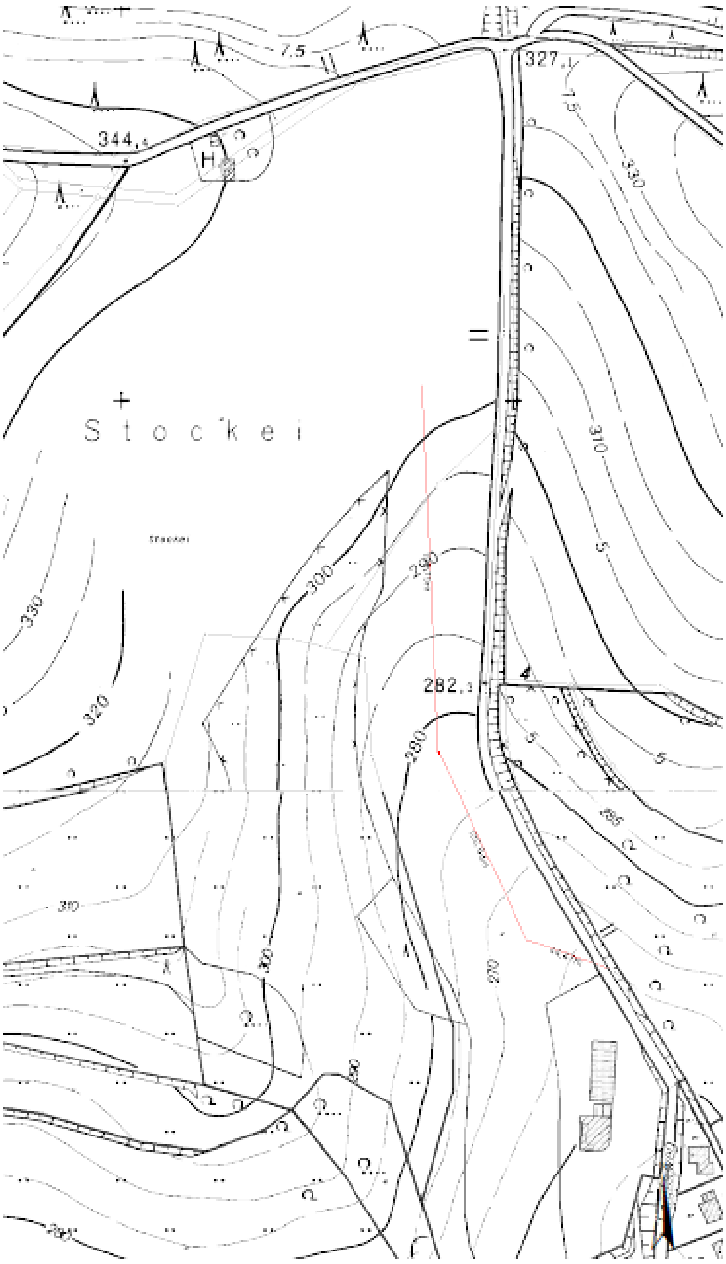


Figure 18: Contour line map of area Sundern Enkhausen. The thin red line (above the house to the south-east) shows the ephemeral gully erosion. The white area is a soil enhancement measure. It is supposed to be added to the AUA below.

would create even worse conditions than those that prevail now.
The image shows the usual allocation of land use: woodland on the ridges, farmland and pasture on the slopes. And another common sight the farmland below the forest is one plot (no roads divide it). This is an example where the UBB in union with the LWK has to take action to prevent erosion.

Meschede Mülsborn

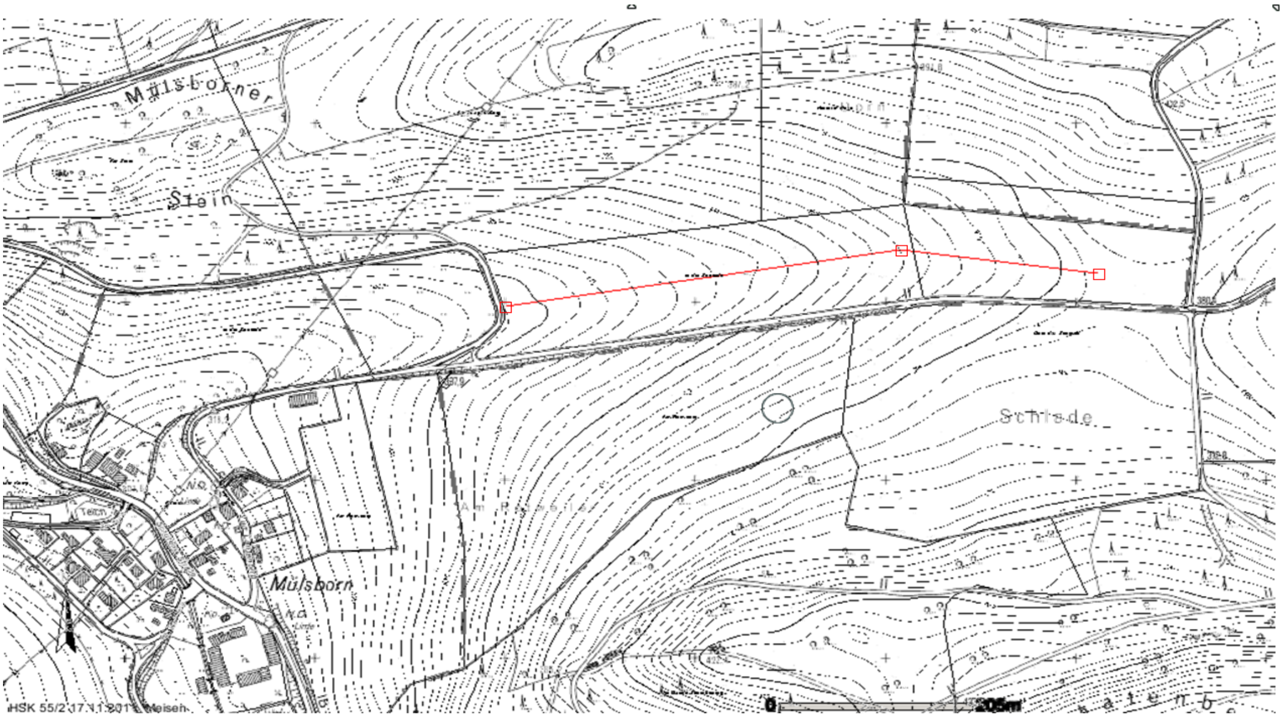


Figure 19: Contour line image of Mülsborn area 4. The red line shows the depression line with a length of 650 m.

The village of Mülsborn lies in a valley. Just like Meschede and other villages it gradually expanded “up the slopes”. Unlike in Ittmecke valley in Mülsborn the slope on either side bears a depression line the area in which is used agriculturally. On the south-western side the last twenty meters and on the north-eastern slope the last two hundred meters are pasture, building a barrier for the mud flows. Still the soil has more than once reached the centre of the village and caused considerable damage to private and public property.
In August of 2011 five erosion events in rapid succession occurred. Because of a previous erosion event in 2007 the population had prepared themselves with sand bags to guide the surface runoff away from their homes. Both times the erosion took place shortly after the sowing of rape with tremendous amount of erosion. In 2011 over 700 tons of soils were eroded from the AUA from linear erosion alone while around 100 tons deposited in more shallow parts onsite (see table X).
Three AUA were affected with an area of about 35 ha. One field on the eastern slope was divided into two areas because of two different topographies on this field. The amount of

Figure 20: Contour line image of Mülsborn area 1. The red line shows the depression line with a length of 250 m.

rain that started the onset of erosion was about 52 to 58 l/m² in 12 hours. According to KOSTRA the statistical software of the Deutsche Wetterdienst this precipitation event can happen every ten years. The following precipitation events measured no more than 5 l/m² but each one was rather short with fifteen to thirty minutes. After the five events the erosion rills measured between 6.5 and 18 cm in depth and between 17 and 120 cm in width. Most noteworthy were the two rills in the depression line on area 4 with each a length of about 380 m, a mean depth of 14.3 cm, a mean width of 87.4 cm and thus around 133 tons of eroded soil. Fortunately this field is separated from the residential area by over 200 m of permanent pasture in the depression line.
In total the erosion in the depression lines accounted for 23.5 % of the material eroded in linear erosion forms but only for 3.6 % of its rill length (compare table X). This ratio shows the drastic effect depression lines have on the amount of erosion.

	Size (ha)	Number of rills	Mean width and depth of rills (cm)	Mean length of rills (m)	Erosion (t)	Erosion total (Erosion – Deposition in t)	Deposition On-Site (t)
Area 1	6,5	58 40 1	17 x 8 12,5 x 6,5 120 x 10	85 110 200	92,8 50 33,6	126	~ 50
Area 2	9,1	54	19,6 x 9,5	190	282,2	237	~ 45
Area 3	8,5	30 1	33,1 x 12,0 57,3 x 18,0	115 210	191,8 30,3	217	~ 5
Area 4	11,8	18 2 5	59,1 x 12,0 87,4 x 14,3 28 x 10	160 380 50	285,9 132,9 9,8	127 to 227	~ 200 to 300

Table 2: Detailed list of the amount of erosion on the four areas concerned in Mülsborn.

5. Finding critical slopes with depression lines and evaluating their erosion risk

5.1 Introduction

The goal of this work is to evaluate erosion risk for slopes with depression lines, not to predict erosion rates for them. In a first step the critical slopes in the HSK have to be found and in second step the individual fields on the slope have to be evaluated (see chapter 3). For both steps threshold values are needed to classify the risk of erosion. There is the evaluation concept of the BVB (2004) and Feldwisch et al. (2005). For the whole slope this concept is not applicable for two reasons. First the there would be no real classification since the threshold for many slopes in the HSK would very easily be surpassed and second the size of the water shed contributing to the depression line by far surpasses the size for which these thresholds were developed. Instead the concept is applied to individual AUA, this way the USLE factors retain their validity.
To find the critical slopes via field work is impractical considering the size of the HSK of 1961 km² and the time needed to inspect an area. To overcome this problem a procedure is developed to automatically find these slopes with the help of a GIS. The GIS calculates the amount of surface runoff via flow accumulation. Required for this tool is a DEM, like the high resolution DEM from LiDAR data which is available for the administration of NRW. The flow accumulation data is calculated on known critical slopes. By deriving factors influencing the amount of erosion like slope gradient and rain erosivity it is possible to find thresholds which define a high risk for considerable erosion.
The most important tool of the GIS is the flow accumulation calculation in which the amount of cells that flow into each raster cell is determined. It is possible to put a weight raster into the flow accumulation process. This weight raster has a value which can be derived by any simple or complex mathematical function.
Once the critical slopes in the HSK are found the AUA maps come into play. These are maps in which the situation for each AUA is regarded individually. Every AUA is cut off from external inflow and thus the flow accumulation calculation with the four USLE factors of slope gradient, slope length, soil type and rain erosivity deliver values for each field as if it were detached from the rest of the slope. These are then compared to the thresholds defined by the BVB (2004) and Feldwisch et al. (2005).

5.2 Tools

The GIS used in this thesis is ArcGIS 9.3.1 by ESRI. Several of its tools were needed to calculate diverse layers. Most of these tools are part of the spatial analyst extension apart from that only conversion and data management tools were used. The following tools were used in particular:

Spatial analyst → Surface → Slope was used to calculate the S-Factor and to orientate. The image shows nicely the roads, lakes, the rough surface of woodland and the smoother surface of AUA.

Spatial analyst → Hydrology → Flow direction was used to calculate the path of the surface runoff. Every cell of the raster flows into one other cell of the raster. This does not represent natural conditions. The discrepancy between the aspect of the slope and thus the actual flow direction and the eight possible flow directions means that the flow is simplified. This can be neglected in the case of depression lines since the water will reach it in any case. The surface size is unchanged and thus the surface runoff amount can be estimated.

Spatial analyst → Hydrology → Flow length is the most disputable tool. See the L-Factor section below.

Spatial analyst → Hydrology → Flow accumulation is the most important tool. The advantage of this tool is that only those parts of the slope that drain into the depression line are caught. Hence the result depicts the real situation as good as possible (in the raster resolution). It was coupled with several weight raster which represented the different combination of different factors influencing erosion.

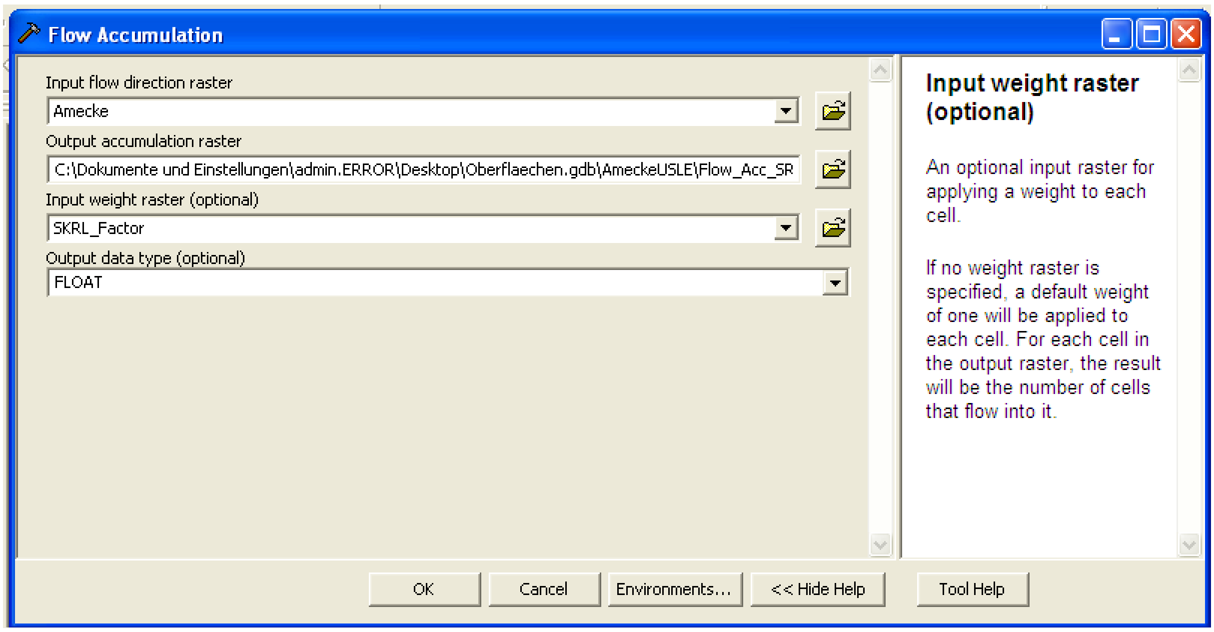


Figure 21: GUI of the ArcMAP tool flow accumulation. By defining input weight rasters the factors influencing erosion can be incorporated.

Spatial analyst → Map Algebra → Single Output was used to calculate the sine of the slope. The sine was needed for the S-Factor calculation.

Spatial analyst → Math → Times, Divide, etc. were used to calculate the individual factors.

Conversion → From raster → Raster to point and **Conversion → To raster → Feature to raster** were used to convert the data into the needed from.

The **Model Builder** was used to automate certain processes.

Another practical part of this thesis was the **field work**. More than ten erosion events were mapped, eight of which happened on slopes with depression lines. The mapping was conducted following the “Kartieranleitung zur Erfassung aktueller Erosionsformen” – mapping instruction for the catchment of recent erosion forms. This is the official instruction cited in the BBodSchV.

5.3 Flow direction and forced flow accumulation

The surface runoff tools used in this work make an abstraction of the process. By forcing the whole flow of one cell into just one other cell the bundling of the surface runoff is unnaturally enlarged. If the flow direction would be distributed according to the real surface, bundled flows could be split up, as can be seen seldom in the field. This cannot happen with this procedure; the flow accumulation value in one flow path will not drop until the slope ends.
Because the formation of bundled surface runoff is very important for this thesis this could pose a problem but it does not if it is viewed in the context of this thesis. First of all the results only refer to depression lines which bundle surface runoff by definition and second the observations in the field have shown that under dire circumstances rills develop rather soon and once a rill has developed it very rarely splits up. The bundled surface runoff caused by the forced flow direction shows a similar number of these preferred flow lines. Considering the fact that the surface of the AUA is not permanent, but on the contrary varies each year in the centimeter to decimeter range it is more than probable that the surface runoff is guided

into “channels” by the micro relief. The exact location of these preferred channels of the surface runoff is displaced with each soil treatment but the amount of lines should vary only little.

5.4 Weight raster zero values

All bodies of water represent end points of surface runoff. This will be implemented by choosing a factor of zero for the weight raster for the flow accumulation calculation for these areas.

5.5 Classifying water sheds for erosion potential

5.5.1 Slope maps

Threshold values can be derived from field data and the use of chosen factors influencing erosion like slope gradient and rain erosivity. The linear erosion on all eight slopes with depression lines sets in when the flow accumulation value exceeds 10.000 to 20.000 m².

5.5.2 AUA maps

In the BVB-Merkblatt Band 1 there is a suggestion of how to handle erosion on slopes with depression lines. The R-, K-, L- and S-factors and the water shed size can be used to estimate erosion risk. If the four factors of the USLE add up to a loss of soil of more than 100 tons/hectare*year and the water shed is bigger than 1 ha or if 200 tons/hectare*year are possibly lost from a water shed with a size between 0.5 and 1.0 hectare the erosion risk is high.

		Standörtliche Gefährdung durch flächenhafte Bodenerosion im Einzugsgebiet der Hangmulde (Produkt aus R·K·L·S-Faktoren)		
		50 bis 100	100 bis 200	größer 200
Größe des Einzugsgebietes der Hangmulde in ha [1)]	0,25 bis 0,5	1	1	2
	0,5 bis 1,0	1	2	3
	größer 1,0	2	3	3

Gefährdungsgrad:
1 = gefährdet; 2 = stark gefährdet; 3 = sehr stark gefährdet
[1)] Die Klassengrenzen der Einzugsgebietsgröße sind Festlegungen aufgrund von Expertenwissen. Sie bedürfen noch einer Verifizierung.

Table 3: Adopted from Feldwisch (2005): Erosion risk classification of an area with a depression line in relation to the water shed size in hectare (left hand side) and the product of the RKLS factors of the USLE (above).

5.5.3 Range of the four USLE factors R, K, L, S in the HSK

R-Factor: between 67 and 98
K-Factor: between 0.15 and 0.3
L-Factor: no longer than 300 m → between 1.0 and 3.72 (20 to 300 m erosive slope length)
S-Factor: between 0.5 and 5.0 (5 to 25 % slope gradient)
Product of the minimum values: 5 t/ha*a
Product of the maximum values: 546 t/ha*a

This range of possible values seems to fit well with the thresholds showed in table 2. There are however very few AUA with a slope length of less than 70 meters and the slope gradient often does rise above 10 %. If this is taken into account the product for the communities with the higher R-Factor for example Eslohe (87) the minimum value rises to around 60 t/ha*a, meaning every slope with a depression line is more or less critical.

5.5.4 Which factors of the USLE can be incorporated into the weight raster?

1. S-Factor: Is the second most important factor and easy to handle because of the availability at each cell.
2. K-Factor: Can only be incorporated in the On-site calculations, for the other areas it is unknown.
3. L-Factor: Is very critical because of the limitations of the USLE and the difficulties in the calculation which stem from the versatile topography respectively the non uniformity of the AUA.
4. R-Factor: Can easily be incorporated since it is not dependent on topography and makes a valuable statement about a physical parameter influencing erosion.
5. C-Factor: The coverage factor is most important and assumptions would have to be made according to the worst case approach. Given the discrepancies between the recorded land use (agriculture – field and agriculture – pasture) and the real land use, this factor is arguable.
6. P-Factor: Negligible, because of the field lengths and slope gradients.

5.6 Calculating/Setting the USLE Factors

5.6.1 L-Factor

It is difficult to calculate the correct length factor for the USLE. In this thesis the usual method of L-Factor estimation (laying a representative line onto the slope and measuring its length) is not possible since ArcGIS cannot decide which line describes the slope the best.
The flow length tool is the most appropriate tool to procure the length factor. It stays true to the high resolution approach in this thesis since the flow length is calculated for each cell. The tool either returns values as the upslope or the downslope distance along the flow path. In both cases the whole slope according to the flow direction is used in the calculation. That means that the tool cannot be used without further adjustments to evaluate single AUA, unless they lie on the highest point of the slope, which they usually do not.
Since this thesis has the goal to develop an erosion risk map for on- and off-site damage the whole slope and the individual AUA have to be regarded.
Regardless whether the flow length is measured up- or downstream it would reach values on almost every slope where the USLE is no longer valid (> 300 m). This is only important if the speed and amount surface runoff on these three hundred meters grows on a steady scale, i.e. if there are no hindrances like ditches or dikes that remove kinetic energy from the surface runoff. It could be argued that the woodland cells could remain in the flow length value. They are weighted much more lightly (12%) because of the lesser amount of surface runoff.
The direction of measurement is of no importance since values flow into the weight raster without exact spatial location. Every cell that is in the flow path is treated the same and since

the mathematical functions are addition and multiplication and the values are all positive it does not matter at which point on the slope the cell lies.

The L-Factor is calculated after DIN 19708 (DIN, 2005) by multiplying the flow length layer with 0.046 and setting this layer to the power of 0.5.

$L = (l \times 0.046)^{0.5}$

(With L = L-Factor and l = erosive length of slope)

For the AUA maps the individual fields have to be separated from the rest of the DEM. This is done by the following method:

DEM-Raise-Method:

11. Open the table of Nutzung.shp
12. Add field called AUA in which Nutzung Landwirtschaft-Ackerland+Brachland+Gartenland is set to 1. All other uses are set to 0.
13. Feature to raster → Nutzung.shp with field AUA to raster; output is called DEMRaise
14. DEM-Raise Plus DEM
15. Flow direction
16. Flow length
17. Flow accumulation

This way the AUA are one meter higher than the surrounding area. The flow direction layer leads the surface runoff around the AUA, thus the flow length and accumulation calculation is restricted to the AUA.

The actual L-Factor calculation can be done several ways. Each of the following methods has its advantages and disadvantages:

4. Flow length times 0.046 result power 0.5:
   If the pure flow length values are inserted into the L-Factor formula the resulting L-Factor is based on the mean flow length and not the erosive slope length. Thus the erosion risk is underestimated.
5. Flow length times 2 times 0.046 result power 0.5:
   By this method the mean flow length is doubled and on a homogeneous slope this would work very well. The cells that drain into depression lines are not necessarily evenly distributed on the slope depending on its topography. This way if much more of the cells that lie on the higher part of the field, i.e. at the start of the surface runoff, drain into the depression line the L-Factor is calculated too high (if the downstream method is chosen, vice versa with the upstream method). A more promising idea is to since the flow length lies around the former maximum value.
6. Max flow length per AUA:
   1. DEM-Raise
   2. Flow length
   3. Model builder: Extract by mask (polygons of land use agriculture - field), Zonal statistics maximum, create raster with maximum flow length
   4. Calculate L-Factor according to the formula

   If the L-Factor is defined as the maximum value the flow length algorithm generates on the individual AUA, unrealistic L-Factor values result. The AUA exhibit diverse to pographies like l shaped fields or the flow changes direction in the field as it does in Amecke and Mülsborn area 1. Thus the cells that flow into the flow accumulation process do not represent the mean erosive length of the field but an extreme value which would if used lead to an overestimation of erosion risk for the AUA.

5.6.2 S-Factor

The S-Factor is calculated after the following formula taken from the DIN 19708:

$S = -1.5 + (17 / (1 + e^{2.3-6.1\sin\alpha}))$

This can be done in ArcMAP with the Field calculator tool or the map algebra tool or with the individual math tools. The two latter are to be found in the spatial analyst tool box, the former in the drop down options menu in the attribute table.

5.6.3 R-Factor

There is one R-Factor for each of the twelve communities of the HSK. This number can simply be multiplied with the other factors. The table to the right shows the R-Factors for the communities of the HSK. It is obvious that the three eastern communities Hallenberg, Medebach and Marsberg lie in another climatic regime. Together they have 20 % of the area of the HSK.

Considering the high R-Factors and the great area of the HSK there are bound to be many critical areas. With the growing pressure on the AUA that comes from the renewable energy policy, the Christmas tree market and the local cow farmers, the erosion problems will grow.

The geological survey of NRW also hosts a map of the lines of equal rain erosivity. Financial considerations are the reason why this map is not available in the HSK administration.

Community	Area in km²	R-Factor
Arnsberg	193,44	79
Bestwig	69,36	88
Brilon	229,01	79
Eslohe	113,37	87
Hallenberg	65,36	71
Marsberg	182,02	67
Medebach	126,06	67
Meschede	218,5	84
Olsberg	117,97	89
Schmallenberg	303,07	92
Sundern	192,89	85
Winterberg	147,86	98

Table 4: Communities of the HSK with size and R-Factor.

5.6.4 K-Factor

The K-Factor represents the erodibility of the soil. It can be calculated via ReiBO classification which is available as a GIS layer or it can be set to 0.3 because of the uniformity of soils in the HSK. The former was done in cases where the latter was not true.

6. Projects: Developing different map types required to evaluate erosion risk on slopes with depression lines

To evaluate erosion risk on and off site, AUA maps and slope maps are produced. Both kinds will be created with the flow accumulation tool and weight rasters. AUA maps calculate the erosion risk of each individual plot following the rules of the USLE. Of course this proceeding is unrealistic since the AUA which are connected to their environment are artificially separated from it but this is how they are evaluated in NRW. Slope maps give an overview of the erosion risk for the whole slope. The theoretical background of these maps is not as good as that of the USLE and different factors will be combined and compared to the charted erosion events.

The following ideas and concepts flow into the evaluation of a slope/AUA:

6.1 The worst case approach

Since the consequences of a large scale erosion event are devastating not only for the soil but also for the local population, the worst case approach is chosen for the definition of erosion risk classes. That means that in any case were a factor stood on the brink, the side was chosen that enhances erosion. For example the effect of fields on the SRO-Factor is set to 1, i.e. all water flowing into one cell of a field also flows out. This stems from the fact that under certain conditions the soil forms crusts which are impenetrable for water.
Another example is the land use agriculture-field. These plots are often temporarily used as pasture. The SRO-Factor for fields which are tilled is 1, for pastures it is 0.1. Since there has not been a further subdivision of this land use for pasture and tilled land, the worst case approach demands that the factor stays at 1, a single case check has to be done. It would be possible to use remote sensing technology in combination with a GIS to differentiate between pasture and tilled field land use but since the farmers decide which plot is tilled and which can remain as pasture on a yearly basis this differentiation is not possible because the aerial photographies are not taken in the same interval, hence each case would have to be checked anyway.

6.2 Influence of land use on erosion

An overwhelmingly large part of soil erosion happens on AUA. Water sheds above residential areas only seldom consist solely of AUA; hence the erosion risk for other land uses has to be defined (see 6.5.2).

6.3 Severity of ephemeral gullies

Thomas (1986) says that the part of the total erosion caused by gully erosion can be as high as 50 %, from charted erosion events in the HSK it can be said that the part of the linear erosion eroded in the depression line can be as much as 30 %. Apart from the higher kinetic energy of the combined surface runoff the ephemeral gully has another effect. By tillage soil from the surrounding is deposited in the depression line. This soil is much more susceptible to erosion because of its loose structure and thus the gully has a wide and shallow form as the surface runoff hits the lower more resistant layer of soil. The energy of the water flow rebounds and further erodes the walls of the gully.
That means that the K-Factor of the soil in the depression line is higher. Since there is no scientific work concerning this higher K-Factor this circumstance will not find its way into this thesis but it has to be kept in mind.
Due to the turbulent water flow in a depression line which stems from the amount of water the downward erosion rate is an order of magnitude higher than in rills (Thomas, 1986).

6.4 Graphic design

Keeping in mind that the erosion risk map is to be used by persons with different knowledge standards the map must be kept simple. No more than four classes should be used since the viewer is unable to apprehend more than that and it is vital for this map to be easily readable. This fits well with the three official risk classes after Feldwisch et al. (2005, see 6.6).
The urban planner usually has other things than erosion in mind when they dedicate an area for a specific purpose or use. This has lead to some badly informed decisions in the past, when residential areas were planned in valleys which are used by natural drainage. Hence the cellars filled with mud and the residents are thunderstruck although the phenomenon is quite well known. Expensive measures are the consequence in which the eroded soil has to be removed from ditches, drainage systems have to be upgraded or the surface runoff is led into areas where it can do no harm if the circumstances allow this. This could have been prevented if the urban planner saw a bright red area on a map. At least countermeasures could have been set up. In some cases simple measures are enough to reduce the risk enormously.

6.5 Slope Maps

These are maps that contain statements for the whole slope and not the individual AUA.

6.5.1 Pure Flow accumulation

If the flow accumulation without the influence of land use and physical parameters is observed very important information shows up: The predefined pathways for the surface runoff and the area draining onto that path. The amount of water is a very important factor influencing the kinetic energy of the surface runoff and thus the erosion potential. The value in itself is not enough to define erosion risk for a slope since erosion nearly exclusively takes place on AUA but it shows the general discharge situation of the area/slope. Since it does not require much computing time the pure flow accumulation map could be used to make a list of slopes/areas in the HSK to be checked in more detail.

6.5.2 Flow accumulation with SRO-Factor (Land use)

There is a distinct effect of the land use on the amount of surface runoff. Infiltration and interception vary in no small amount between the different land uses. A combined infiltration/interception factor would have to be defined for every land use that is part of the flow path of surface runoff. This factor would have to include annual changes, for example leaves of trees and frozen soil. There are no regional studies covering these aspects.
The concerned land uses are woodland, pasture and fields. With respect to mean values the first two land uses have a much higher retention potential for precipitation. With the latent danger of soil crusting there is a much higher probability for critical amounts of surface runoff from fields. Unfortunately the intensity of soil treatment in form of tillage and the velocity of developing plant cover are much more difficult to evaluate. Therefore the SRO-Factor has to be a rough approximation. According to Navar et al. (2000) the amount of surface runoff from woodland and pastures is one order of a magnitude smaller than that from fields. This goes in accordance with the statement of the EPA that around 10 % of the precipitation that hits a forest leaves it as surface runoff (U.S. Environmental Protection Agency, 2003). Following the worst case approach the SRO value is set to 0.1 for the land uses woodland and pasture and to one for the land use field.

6.5.3 Flow accumulation with S-Factor

This map is very basic. But under these circumstances (little data, complex process) it can be argued that this is not a disadvantage but an advantage. According to Toy (2002) the slope

gradient and the amount of water primarily influence the erosivity of the surface runoff. These two factors are caught by this map. Thomas (1986) relates the slope gradient with the shear stress from the pure volume of the overland flow in that it comes into the equation to a power of two thirds, i.e. it is not as important as the amount of runoff but nearly as much.
The S-Factor of the USLE is used because the influence of the slope gradient on erosion is complex. For example the amount of infiltration is reduced the steeper the slope becomes. On the other sedimentation begins on slightly inclined slopes. These effects have been taken into account in the S-Factor. The use of the S-Factor on whole slopes is not undisputed as the S-Factor was derived from experiments on a slope with a length of 22 m.

6.5.4 Flow accumulation with S-Factor and SRO-Factor

Assuming that the amount of erosion is primarily dependent on the amount of surface runoff and the slope gradient of the slope this map gives a very good indication of problematic areas. It takes into account both parameters and adds the different interception and infiltration of fields and other land uses to the amount of surface runoff.

6.6 AUA maps

6.6.1 SKRL map

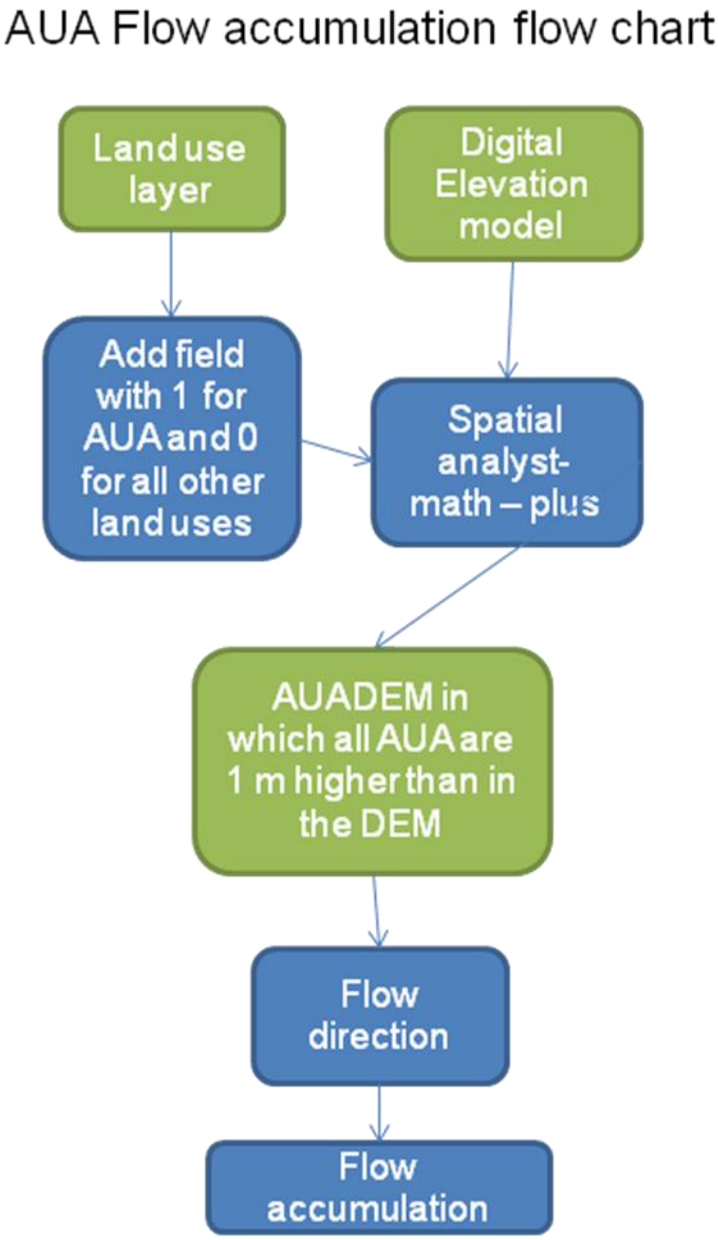


Figure 22: Flow chart AUA flow accumulation. Green fields stand for results and data layers. Blue fields stand for ArcMAP tools.

Table 2 shows the erosion risk classes if the USLE factors are used. If the flow accumulation values with the SKRL weight raster lie above the following thresholds the area is put into the respective erosion risk class:

Class 1: 125.000 at risk
Class 2: 500.000 at high risk
Class 3: 1.000.000 at very high risk

Once the factors are multiplied the size of the slope in question is needed. This size is contained in the flow accumulation. In most cases not all cells from an AUA flow into the depression line. That means that with the standard method in which the whole AUA size is used for evaluation the risk is overestimated.
The Flow accumulation tool often finds more than one flow paths in the depression line for example in Amecke. These have to be added up, since this reflects the real situation. To automate the procedure the flow accumulation raster can be converted into a point shapefile. From this shapefile all points within a buffer around the maximum have to be selected by location. The extent of the buffer has to be chosen in a fashion that only the flow lines from the AUA in question are selected. This way all points above a threshold are chosen, now the end points of the respective flow lines have to be found. So far no automation of this process has been developed, so that it has to be done by hand. In this case the author chose all lines that lay in the depression line and bundled more than 1.000 m².
Considering the problems that arose with the L-Factor calculation, it seems worthwhile to devise an alternative.

6.6.2 SKR map

If the difficult L-Factor calculation is shunned, it is possible to take it out of the equation by determining a standard field length and divide the threshold by the respective L-Factor. The L-Factor for proposed lengths is given in table 5. The choice of the mean slope length is very difficult because of the diverse extents of AUA in the HSK.

Slope Length in m	L-Factor	Class 1	Class 2	Class 3
50	1.52	32,89	65,79	131,58
100	2.14	23,36	46,73	93,46
150	2.63	19,01	38,02	76,05
200	3.03	16,5	33,0	66,0
250	3.39	14,75	29,5	59,0
300	3.71	13,48	26,95	53,91

Table 5: L-Factor in relation to slope length and the respective erosion risk classification.

200 m was chosen as the standard erosive slope length for two reasons. On one hand the validity of the L-Factor lessens between one hundred and three hundred meters and on the other hand it reduces the danger of missing areas with critically long slopes. The following risk classes result:

Class 1: Mean SKR value 16,5 = at risk
Class 2: Mean SKR value 33,0 = at high risk
Class 3: Mean SKR value 66,0 = at very high risk

Through the assumed L-Factor an uncertainty enters the process. The results have to be used with caution. All results will be double-checked in a single case examination, in which the erosive slope length will also be estimated. Viewed this way the SKR map can be used without prejudice. It is possible that very long slopes with less critical SKR factors slip through the net; at least they will be classified less risky.

6.6.3 Creating an erosion risk map

The SKRL or the SKR maps show flow lines for the surface runoff with the respective risk classification marked by a colour. This map is not easy to read since the field is not marked by a single class. To create an easy to read map each AUA needs to show the erosion risk class reached at the lowest point of the depression line on that AUA. This is done via the following steps:

The raster data of the respective flow accumulation layer has to be converted to a point shapefile, because the tool select does not work on raster layers.

With the tool select by attribute all points where the flow accumulation value surpasses a certain threshold (e.g. 1,000,000 for class 3 SKRL) are selected from the shapefile created in step 1.

To find the AUA (polygon shapefile) in which the threshold is surpassed another selection tool is used. With select by location it is possible to select all polygons which contain a point from another layer. It is possible to only use the selected points from step 2. Only AUA polygons can be used in this step because the values for the other land uses are not correct (see DEM raise method, 5.6.1).

In this step the polygons selected in step 3 are exported into a new layer.

In the last step the graphic design of the new found layer is defined.

By changing the selection value in step other classes can be depicted.

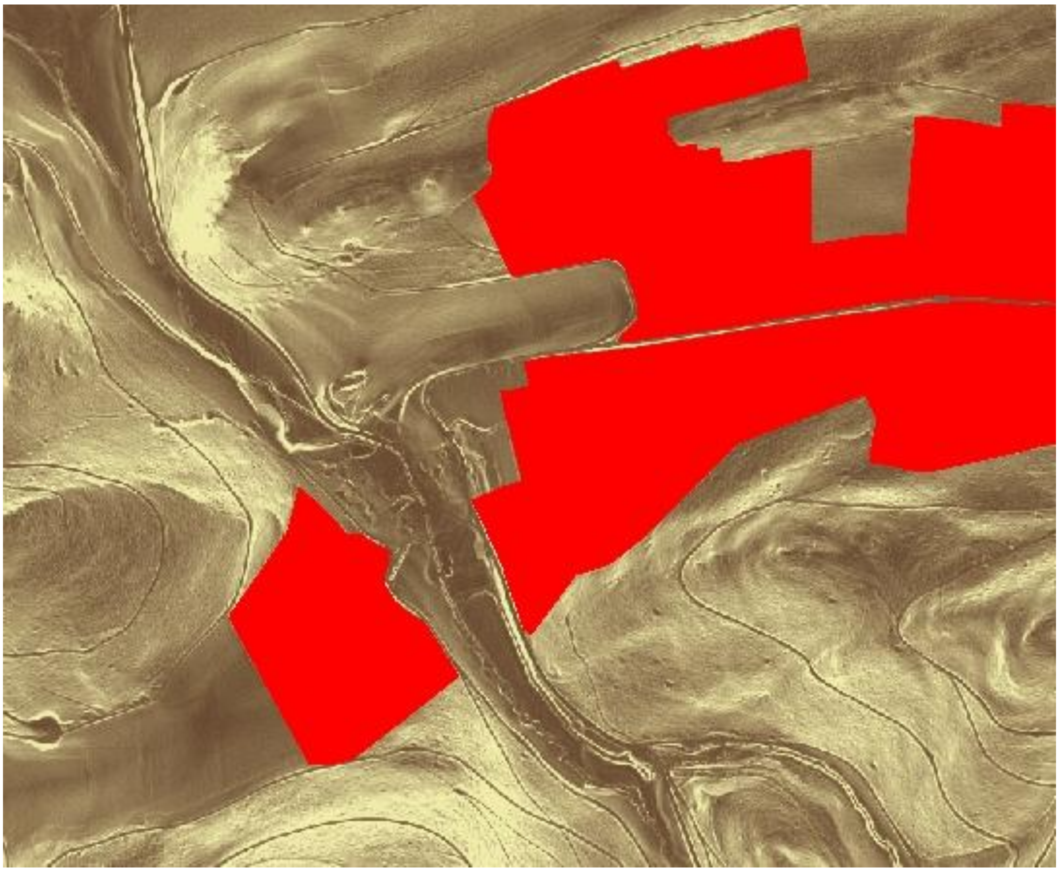


Figure 23: Erosion risk map of Mülsborn showing all areas with an erosion risk class of three according to Feldwisch et al. (2005).

7. Results

7.1 Slope maps

Location	Pure flow accumulation	SRO	S-Factor + SRO	S-Factor	SR-Factor
Wormbach3.87	339.620	227.472	3.254.233	764.413	70.325.520
Wormbach8.133	295.026	124.157	1.798.834	736.445	67.752.952
Mülsborn Area 4	233.481	186.019	368.827	508.516	42.715.360
Enkhausen	136.606	112.088	191.687	316.419	26.896.411
Mülsborn Area 1	87.004	24.500 (pasture)	86.177	256.423	21.593.571
Berghausen1.11	64.713	37.900	85.913	164.200	15.106.400
Amecke	62.116	36.058	56.083	100.981	8.583.591
Ittmecke Rehweg	38.073	25.080	-	92.330	7.756.003
Wormbach2.143	32.954	8.241 (pasture)	19.649	78.106	7.184.772

Table 6: Values derived from slope maps ordered after pure flow accumulation.

The slope maps unlike the AUA maps describe the whole slope. Every investigation area represents a critical slope, so the point is to find common factors among them. Looking at the unweighted flow accumulation it is obvious that all depression lines have a water shed bigger than 20.000 cells or 2 hectare. This goes up to as much as 33,9 hectare.

The SRO-Factor map shows the weighted amount of surface runoff to be expected. It is by definition smaller than the unweighted flow accumulation since the largest SRO-Factor is 1 (fields and roads). The greatest effect on this value stems from pastures and woodland. The comparison of the unweighted flow values and the SRO values indicates the ratio of fields to woodland and pasture since all other land uses seldom lie above a field. Unfortunately the land use data cannot be trusted. In two cases the AUA which suffered from erosion was incorrectly registered as a pasture (see table 6). Hence the SRO values are very small and these areas would fall into a very low erosion risk class. On the other hand if the land use entries are correct the ratio described above is a very good hint at the risk class of a slope. For example Mülsborn area 4 shows in comparison to the other areas only a slight diminution of the value and it is in fact the most critical slope with the largest charted erosion rates so far registered in the HSK. The Ittmecke area is another good example for the incorrect land use layer. A pasture is registered as a field thus the area seems much more critical than it really is if only the SRO values are viewed.

The SRO-S value suffers the same problems as the SRO value because of the unreliable land use data. Through the incorporation of the S-Factor the map gives a much better overview of erosion potential since the three most important factors are taken into account.

The S-Factor slope maps are more promising. The S-Factor slope map shows a much smaller range of values which can be used to derive threshold values. Maximum value divided by the minimum value equals 15.9.

The SR-Factor slope map does not deliver new inputs to finding threshold values because the difference in values is too small (R Factor: 84 to 92).

7.2 AUA Maps

Location	SRKL Flow	SRKL standard procedure	SRK Flow	SRK standard procedure
Mülsborn Area 4 (with 156.679 cells)	49.374.812	39.404.141 (R: 84; LS: 9,98; K: 0,3)	8.013.529	6.435.746 (R: 84; S: 1,63; K: 0,3)
Wormbach3.87 (with 60.293 cells)	7.418.330	4.792.569 (R: 92; LS: 2,88; K: 0,3)	1.873.191	1.331.269 (R: 92; S: 0,8; K: 0,3)
Wormbach8.133 (with 44.708 cells)	7.856.813	8.781.545 (R: 92; LS: 8,54; K: 0,25)	2.894.302	2.005.153 (R: 92; S: 1,95; K: 0,25)
Amecke (with 43.159 cells)	5.052.558	5.557.800 (R: 85; LS: 6,06; K: 0,25)	1.497.418	1.614.146 (R: 85; S: 1,76; K: 0,25)
Mülsborn Area 1 (28.984 cells)	6.302.814	5.746.831 (R: 82; LS: 8,06; K: 0,3)	1.361.942	1.283.411 (R.82; S: 1,8; K: 0,3)
Berghausen1.11 (with 17.811 cells)	2.997.880	2.703.709 (R: 92; LS: 5,5: K: 0,3)	738.751	732.459 (R: 92; S: 1,49: K: 0,3)
Enkhausen (with 15098 cells)	3.457.569 (LS: 9,36)	1.643.945 (R: 85; LS: 4,27; K: 0,3)	876.768 (S: 2,27)	538.998 (R: 85; S: 1,4; K: 0,3)
Wormbach2.143 (with 11.814 cells)	2.105.062	1.043.412 (R: 92; LS: 3,2; K: 0,3)	586.267 (S: 1,56)	371.715 (R: 92; S: 1,14; K: 0,3)
Mielinghausen (with 9571 cells)	1.641.451	1.145.648 (R: 84: LS: 4,75: K:0,3)	540.265	489.614 (R: 84; S: 2,03; K:0,3)
Ittmecke Rehweg	Not applicable since the AUA does not have a distinct depression line. The eroded soil accumulated in a depression line further downhill.			

Table 7: Values derived from SKRL and SKR maps compared to the values derived from the standard procedure. The cell values under location represent m².

Two points can be made by looking at table 7:

1. The standard procedure values are in general lower, meaning the amount of erosion is predicted to be lower

and

2. The range of values is immense considering the fact that each area was subject to one or more considerable erosion events. This fact is not represented by the range of values. SKRL max/min = 40 SKR max/min = 13.

7.3 Comparison of field observations and results

1. In Berghausen1.11 the results are very promising. Not only is the area that was already subject to erosion depicted accordingly, but a nearby area that seems very problematic shows only flow accumulation values that are one tenth the size of those on the problematic area.

2. The flow accumulation values in area Wormbach3.87 show a very good correlation with the linear erosion forms in the field. There is a sidearm outside the depression line that is positioned exactly where there is one in reality, although there is no obvious depression line.

3. A small depression line on area Wormbach8.133 is retraced by the flow accumulation values and it fits with the 10.000 cells threshold.

4. The number of class 2 erosion risk (after Feldwisch 2005) flow lines on the slope of

Mülsborn area 4 coincide with the amount of charted rills on that part of the slope. This might be chance but it was written before that rills develop on soils that are in bad condition due to milling or long dry periods. And there are other examples where the charted rills and the calculated flow lines coincide (see image below).

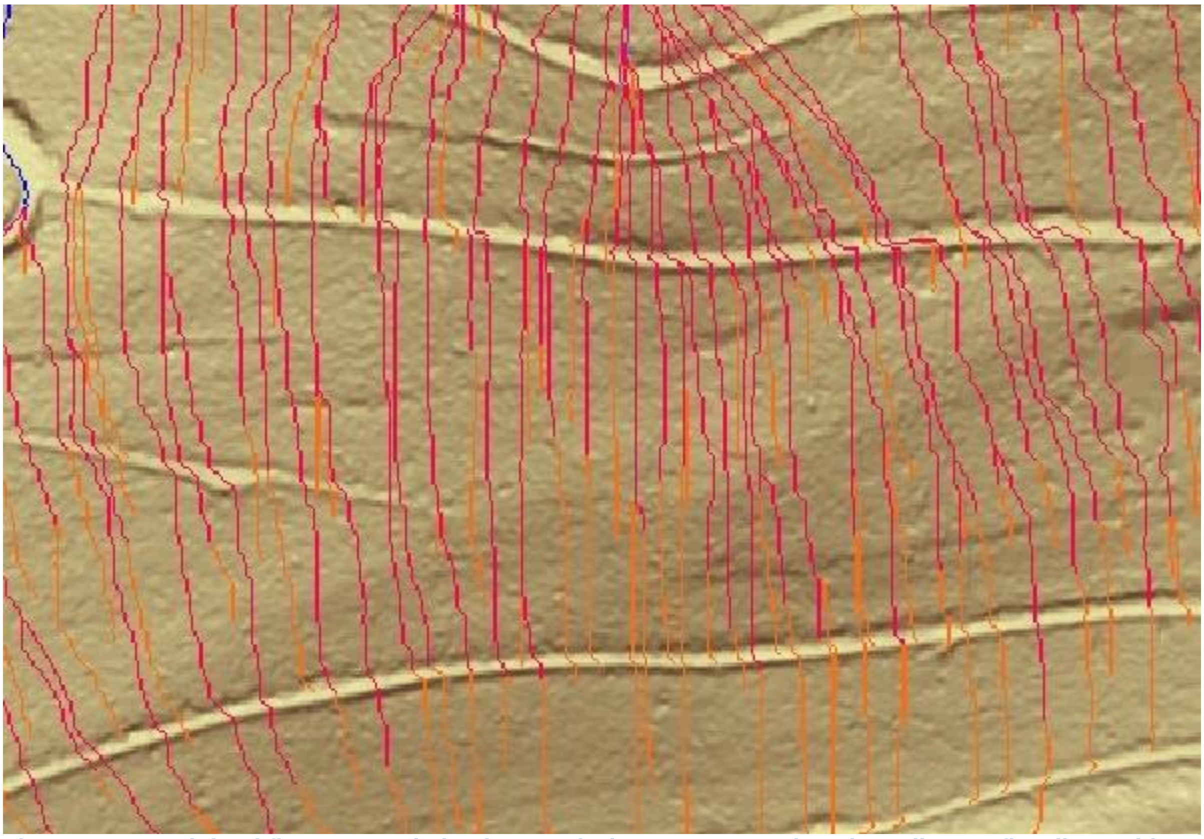


Figure 24: Unweighted flow accumulation image of a homogeneous slope in Wallen. 44 flow lines with an intake of at least 500 cells exist. The red lines represent intakes of at least 1000 cells. In an erosion event around 50 rills were charted.

7.4 Results of the SRKL- and the SKR-maps

Investigation area (size in ha)	SKRL	Risk level SKRL	SKR	Risk level SKR
Mülsborn Area 1 (2,90)	217,46	3	46,99	2
Mülsborn Area 4 (15,67)	315,13	3	51,15	2
Berghausen1.11 (1,78)	168,32	3	41,48	2
Mielinghausen (0,96)	171,50	2	56,45	2
Amecke (4,32)	117,09	3	34,70	2
Wormbach3.87 (6,03)	123,04	3	31,07	2
Wormbach2.143 (1,18)	178,18	3	49,62	2
Wormbach8.133 (4,47)	175,73	3	64,74	2
Enkhausen (1,51)	229,01	3	58,07	2

Table 8: Erosion risk classification of the investigation areas after Feldwisch (SKRL, 2005) and modified (SKR).

By dividing the flow accumulation by the cell number the products of the SKRL respective SKR are gained. In table 7 the numbers are shown with the respective erosion risk class. As was expected almost all investigation areas surpass the proposed maximum SRKL threshold value of Feldwisch (2005). The investigation areas are slopes with known erosion disposition. This result shows that the classification is realistic and all areas would have been caught by this method although Mülsborn area 4 exhibits implausible values due to its extreme extent. All areas except Mielinghausen fall into risk level 3.
This can be explained: The S-Factor rises with the resolution (see discussion). Also the flow length is longer, for the flow does not lead in a direct line across the field as the standard approach line does. It is a two segment line, one towards the depression line and the other in the depression line towards field boundary. Because of these two circumstances the SKRL values generated by ArcMAP tend to be higher than those of the standard procedure. That means that the risk classes need to be adjusted but there is as of yet not enough data to do so.
The SKR values lack official thresholds. It is obvious that the L-factor depends immensely on the form of the field and its position on the slope. Fields that lie parallel to the slope exhibit high L-Factors. This problem was overcome by setting the standard erosive slope length at a high value. Thus all critical areas are still evaluated as such, even if one level lower.
It is obvious that the range of values is more homogeneous in the SKR map. This will in part be caused by the faulty L-factor calculation that widens the range in the SKRL map and in part is logical since the L-factor was standardized.

Some results of the double flow length L-Factor calculation:

	Erosive slope length according to mean L-Factor in m	Representative line according to standard procedure in m
Amecke	320	270
Berghausen	381	393
Wormbach2.143	274	199
Wormbach3.87	281	291
Enkhausen	324	293

Table 9: Comparison of L-Factor standard approach and GIS procedure.

The discrepancy in the case of Amecke stems from a change of direction of flow in the southern corner of the field where the flow makes a 90° turn after around 50 meters.
In the case of Wormbach2.143 there is no satisfactory explanation yet. The values were checked five times but still the large L-Factor is inexplicable. The maximum flow length value lies around 255 m.
The Enkhausen depression line is fed mostly by the cells farther upslope, creating the difference of 30 meters, those cells have higher flow length values.

7.5 Difference in flow accumulation values between depression line and contributing slopes

Whereas the depression line is fed most often by more than 10.000 m², the flow accumulation values on the contributing slopes rarely reach the mark of 1.000. In combination with data about soil condition, formation of linear erosion forms and precipitation it could be possible to define a threshold for the formation of linear erosion forms (see figures 34 and 35).

7.6 Case studies

Mülsborn area 1 and 4

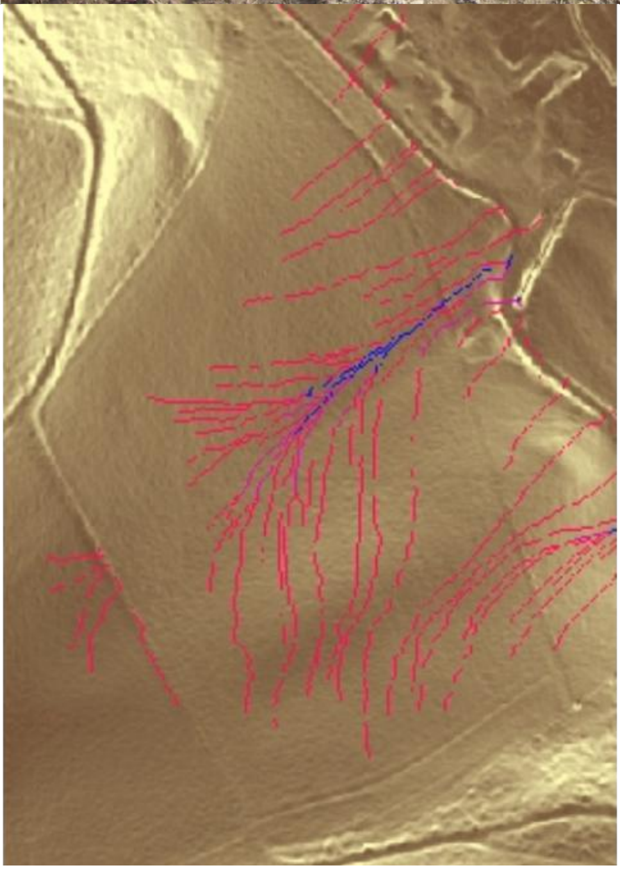
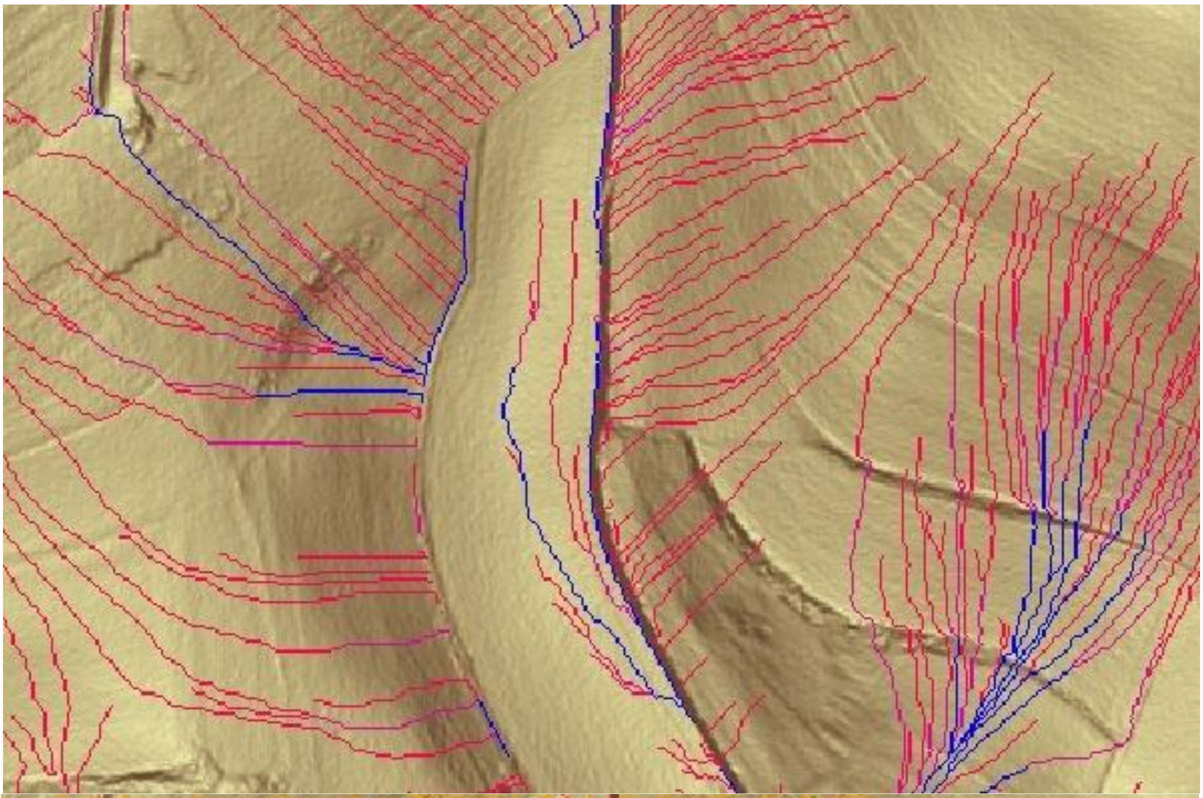


Figure 25: The image above shows the rills that drain into the depression line.
Figure 26: The SKRL flow accumulation map to the left exhibits very high risk values for the depression line of Mülsborn area 1 starting long before the end of the depression line.
Figure 27: The image below shows that the tillage can have a strong influence on the formation and direction of rills.

Mülsborn area 1 and 4 are good examples for the discrepancy of the standard evaluation system to that of the BVB for slopes with depression lines. The standard evaluation method comes to the conclusion that erosion rates are acceptable when sufficient mulch lies on the surface of the field at the time of sowing, i.e. the danger can be reduced to a bearable level with simple measures.
The SRKL map shows that the slope is at a very high risk (the most dangerous category). This evaluation seems to be more realistic considering the fact that considerable erosion has taken place at least three times in the last five years. It is very unlikely that the erosion risk can be reduced to a tolerable level with simple measures. Unfortunately there are no explanations what the different risk levels require to reduce the risk.
The discrepancy between standard approach and BVB/Feldwisch evaluation repeats itself on nearly every field on a slope with a depression line. Especially drastic is the discrepancy between the standard procedure and BVB method on Mülsborn area 4. Whereas the SRKL value is very high, the standard evaluation comes to the same conclusion as on Mülsborn area 1.

Enkhausen



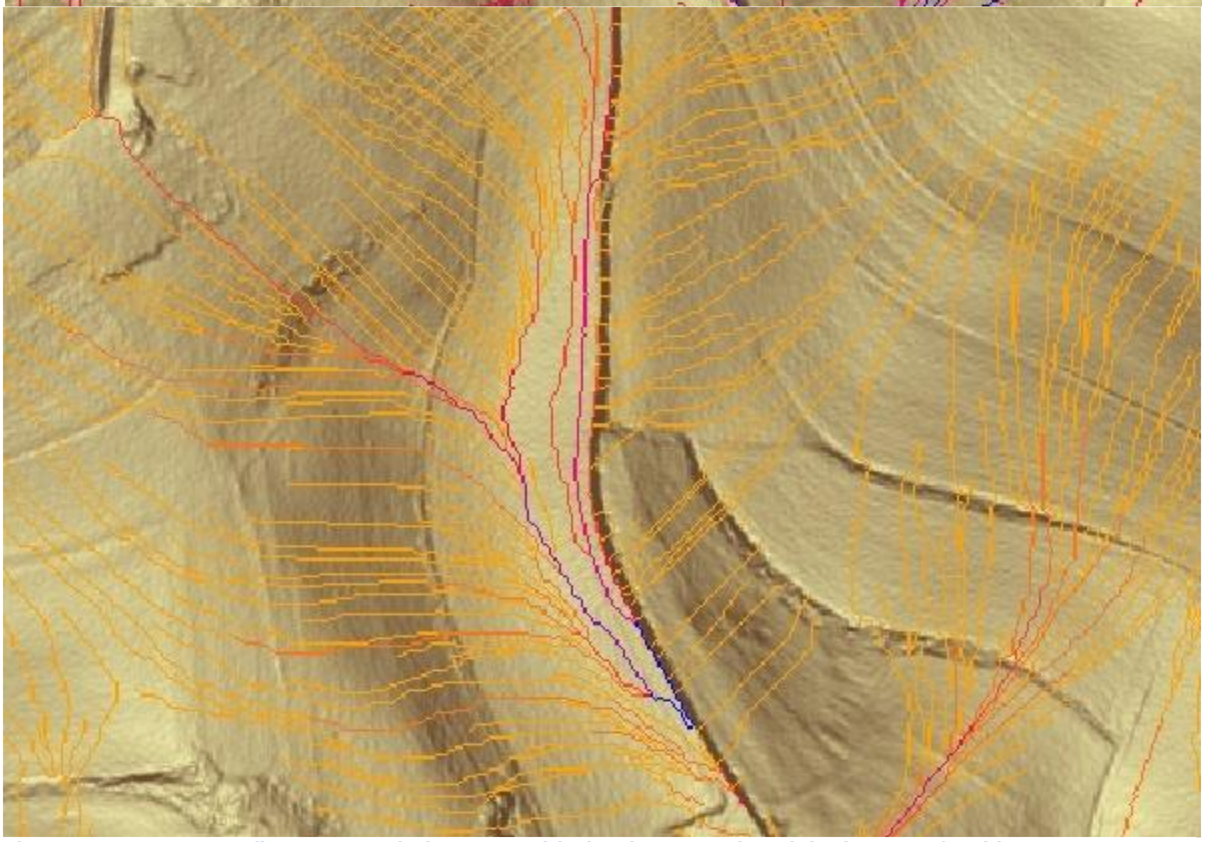


Figure 28: Top: SKRL flow accumulation map with the three erosion risk classes of Enkhausen.
Figure 29: Bottom: Flow accumulation with S- and SRO-Factor.

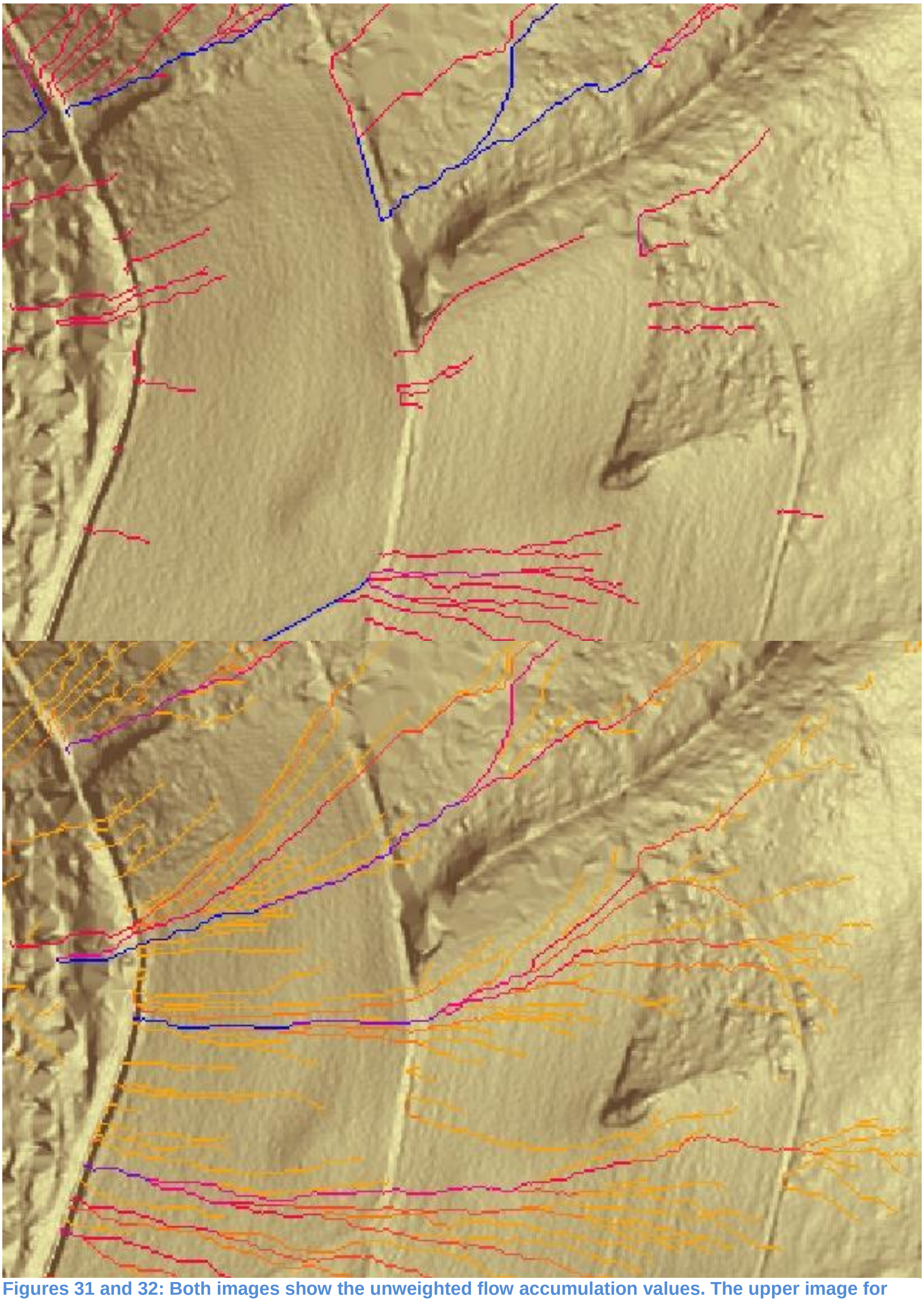
The peculiarity of this area is that the depression line runs through the AUA and does not flow through the whole length of the AUA but onto the parallel road. The mud flow is supposed to enter the ditch on the other side of the road which enters a pipe at the end of the critical AUA. Around 20 hectare drain through this road. The drainage system is not suited for this, the pipe has a diameter of 15 cm and clogs very fast because of the debris (leaves, twigs, etc.) that is flushed into it with heavy rain falls. Thus when a certain amount of water and soil amass the entry points are no longer able to accommodate the combined mass and the mud flow runs down the road. The maps could help make the involved persons see the magnitude of the problem and thus lead to a consensus in which the farmer and the community agree to do their part in erosion countermeasures.

Ittmecker Weg

Figure 30: Unweighted flow accumulation map of Ittmecke. There is a residential area to the far left. The lines are accumulation flow lines from 500 cells up (orange). Red lines start at 1000 cells and blue lines at 10.000. The blue line in the lower left corner runs atop roads. It is not critical with regard to erosion. This shows that the unweighted flow accumulation map can only be used to understand the general situation.

The area Ittmecker Weg is an example for a situation where the source of the soil loss lies far away from the residential area but is connected to it via a depression line. In figure 30 on the right hand side the AUA (smooth surface) are planted with Christmas trees and on the far left side the residential area begins. The blue line indicates an accumulated flow of over 10.000 m^2. The first house is five meters distant from the point at which the surface runoff of 38.000 m^2 hits a road. There are no drainage systems installed at this point. The surface runoff of nearly four hectare albeit with a lot of woodland land use is supposed to run across the road and into the canal. In summer 2007 several hundred m^3 of soil were deposited in the residential area. The mud flow had to pass 100 m of pasture and in succession eroded a foot path (coincides with the blue line) that led from the residential area up the depression line onto the field road above. Obviously this scenario was not foreseen by the urban planners.
Using this map erosion prevention measures could be devised. The effect of different measures could be simulated with a GIS. For example measures taken far up the depression line would reduce the input from the AUA whereas measures further down the depression line would reduce the amount of surface runoff flowing into the depression line.

Mielinghausen



Figures 31 and 32: Both images show the unweighted flow accumulation values. The upper image for each individual AUA and the lower image for the whole slope.

The AUA map shows a diffuse grid of not critical bundled surface runoff in contrast to that the slope map shows the effect of the depression line much more clearly (Figures 31 and 32). If the AUA are viewed individually the critical area does not have a flow accumulation value greater than 3700, only by depicting the real situation of inflow from the field above the risk is assessed correctly. On the other hand this means, that if the inflow is eliminated the problem will be eliminated too.
The comparison of the AUA and Slope flow accumulation maps is very enlightening. The real situation in the field is depicted by the Slope map and the comparison to the AUA map shows how much the risk can be reduced if the inflow in the depression line is stopped.

Ebbinghof area

The erosion forms in the three investigation areas around the village of Ebbinghof are characterized by little sheet erosion and one very distinct linear erosion form in the depression line. The surface of the AUA either consisted of bare soil or had a soil coverage of between 30 and 50 % by grass.
The pure flow accumulation value at the onset of the gully erosion reaches from 10.000 to 60.000 m². In the case of Wormbach8.133 the linear erosion starts at a hole in the ground where interflow reaches the surface, the same process led to the formation of the side arm gully on Wormbach3.87. In Wormbach2.143 the linear erosion starts on the rim of the AUA so that external inflow is the most likely cause. The area where the starting point of the main gully on Wormbach3.87 lay, expressed flow accumulation values of over 50.000 m² (see figure 34 and compare with figure 7).

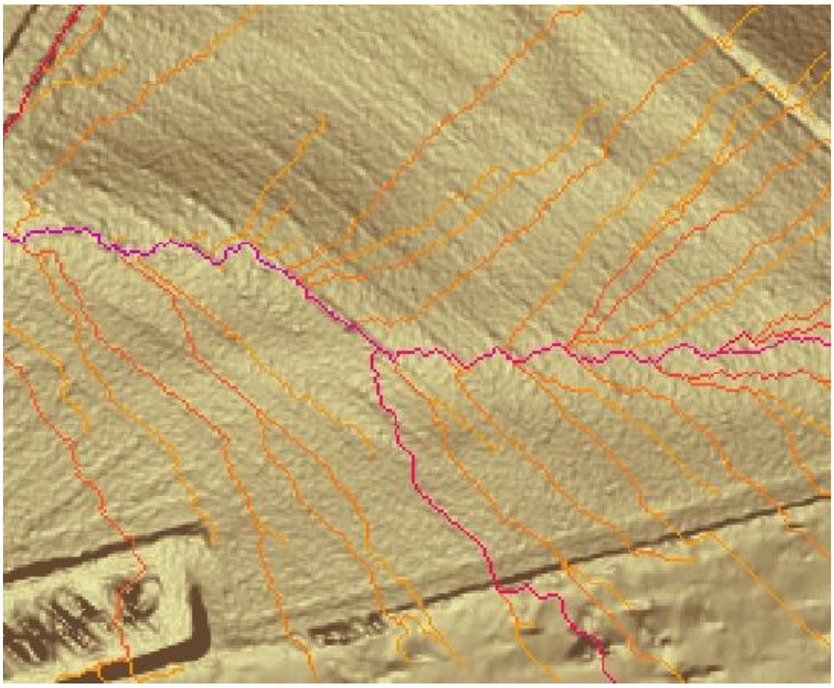


Figure 33: Slope map (pure flow accumulation) of Wormbach3.87.
The magenta coloured line starting from the right side of the image indicates flow accumulation of more than 50.000 cells.

The direction of soil treatment is the most important factor concerning the formation of linear erosion forms. This circumstance is not reflected in all slope maps since the resolution is not good enough to capture the lanes of the tractor, but the height difference in reality is enough to divert surface runoff (see figure 33). In some cases like Mülsborn area 1 this can lead to a prolongation of the linear erosion forms and thus to higher erosion rates.

8. Discussion

8.1 Comparison of the different evaluation methods

Of the seven possible evaluation methods those using the unreliable land use data are problematic in an automated erosion risk assessment. As was explained in chapter three the land use pasture underlies constant change. This makes the use of this information difficult. Aerial images could be an alternative if they were shot every year, but since that is not the case they are no more reliable than the land use layer of the Geoserver. Only the slope maps which incorporate the SRO-Factor are affected by this problem. There are two possible approaches:

1. Treat all agricultural areas as potential fields

or

2. rely on the land use layer.

The first option faces great problems in the cumulated flow since fields are treated with a very high SRO-Factor. While this would work well for the critical areas, a lot of pasture areas would also be marked as critical with this method. The second option bears the danger of missing critical AUA if they were registered as pastures. If the goal is to find all critical areas in the HSK the SRO-Factor seems to cause more problems than to make the risk evaluation easier. If an already known critical area is to be scrutinized the SRO-Factor can be helpful, by showing the effect of the land use on flow accumulation.

The UBB has to evaluate a whole slope in erosion prevention work. The slope map which only incorporates the S-Factor represents the best compromise between informative value, reliability and practicality.
Given the wide range of R-Factors in the HSK the introduction of it seems reasonable because it would have a decisive effect on threshold values. It has to be kept in mind though that the value was standardized for each community that means that the value describing the situation on the spot is unknown. Given the large differences in the communities (see table 4) this slope map can do more harm than good in places which lie close to a community boundary. With the currently available data set the R-Factor should not be used.
The definition of a local threshold value is the next step. This will be based upon the S-Factor slope map and the charted erosion events. That means that the areas with low factors define the lower boundary and vice versa.

S-Factor slope map value	Erosion risk class
50.000	At risk
200.000	At high risk
500.000	At very high risk

Table 10: Erosion risk classes for S-Factor slope map.

Following the present regulation each field has to be assessed individually. This can be done either by SKRL or SKR thresholds. The range of values in the SKRL procedure is vast. It is difficult to define threshold values. One point to argue over with the SKRL method is that the area size and thus the amount of surface runoff is overestimated since it is incorporated in the L-Factor and the flow accumulation. The slope length influences the amount and the velocity of surface runoff (Schwertmann et al., 1987).

Because of the limited number of mapped areas to base the threshold upon and the little facts known about the actual process in the depression line, it is chosen to use only those two factors that influence the process the most, i.e. amount of surface runoff captured by the flow accumulation value and slope gradient captured by the S-Factor of the USLE. The investigation areas do not come from the whole HSK but only from three of the twelve communities. Only four documentations exist where heavy erosion took place. The amount of duration of the precipitation that led to the events is only known for Ittmecke and Sundern Amecke.

Untersuchungsgebiet Oberaargau schlagbezogen

Einflussfaktoren (MUSLE87), aktuelle Erosionsgefährdung	*Berechnung MUSLE87 mit DHM100*		*Berechnung MUSLE87 mit DHM25*		*Berechnung MUSLE87 mit DTM-AV*	
	Mittelwert	Wertebereich	Mittelwert	Wertebereich	Mittelwert	Wertebereich
R-Faktor [$N*h^{-1}$]	97	93 bis 101	97	93 bis 101	97	93 bis 101
K-Faktor [$kg*h*N^{-1}*m^{-2}$]	0.43	0.35 bis 0.45	0.43	0.35 bis 0.45	0.43	0.35 bis 0.45
C-Faktor [dimensionslos]	0.03	0.02 bis 0.03	0.03	0.02 bis 0.03	0.03	0.02 bis 0.03
λ [erosive Hanglänge in m]	108 (Median: 100)	100 bis 209	80 (Median: 55)	25 bis 933	94.53 (Median: 61)	7 bis 674
L-Faktor [dimensionslos]	2.13	1.32 bis 3.80	2.37	1.04 bis 9.36	2.65	0.70 bis 8.08
S-Faktor [dimensionslos]	0.89	0.17 bis 3.39	1.72	0.23 bis 5.39	2.30	0.37 bis 5.71
P-Faktor [dimensionslos]	0.91	0.43 bis 1.00	0.83	0.44 bis 1.00	0.87	0.49 bis 1.00
Erosionsgefährdung [$t*ha^{-1}*a^{-1}$]	2.27 (Median: 1.83)	0.24 bis 11.75	4.82 (Median: 3.92)	0.30 bis 22.47	6.65 (Median: 5.77)	0.47 bis 33.90

Table 11: The development of the USLE factors S, L and P with respect to the resolution of the DEM (taken from Chisholm, 2008).

Erosion itself cannot be prevented. If the time span is long enough erosion will take place on a field with a high slope gradient. Depending on various factors the amount of soil which is eroded can reach from negligible to catastrophic. For the placement of residential or industrial areas in a direct prolongation of a depression line the question will not be if the cellars will be filled with mud but how often and in what time. The procedure developed in this thesis cannot answer this question but it gives a hint as toward the magnitude of the problem. The more m² that drain into a depression line, the more water can gather in it and the more kinetic energy can be built up by the surface runoff. Critical conditions start at the last with 25.000 m² draining into a depression line. Knowing this the problem can be tackled. Today this problem is not even acknowledged before it is too late.

8.2 The necessity of creating slope and AUA maps

There are two aspects in the erosion risk assessment; the on- and the off-site damage. The risk of on-site damage, i.e. the loss of fertile soil, can be evaluated with the USLE individually for each field. The off-site damage, i.e. deposition of soil outside the AUA it originated from and the discharge of agricultural chemical substances into bodies of water (either flowing or standing), cannot be evaluated realistically with the help of the USLE, because the surface runoff is not bound to the individual field but the whole slope. More often than not there are no ditches to direct the flow away from the next AUA, hence the whole slope has to be regarded. This is done with the slope maps. They show the real situation whereas the USLE maps are by legal definition restricted to the AUA. Erosion prevention measures are usually bound to one field or its vicinity. The disadvantage of only looking at the flow accumulation on the AUA is that the real situation is not taken into account. The SKRL or the SKR map and the flow accumulation map that regards the whole slope are needed in the administrative work. The first map is used to evaluate the field itself and the latter to find the points where external inflow gets into the field so that it can be stopped, if the SRO factor is included there is even a coarse guess how much water enters the field.

8.3 Flow accumulation and types of linear erosion

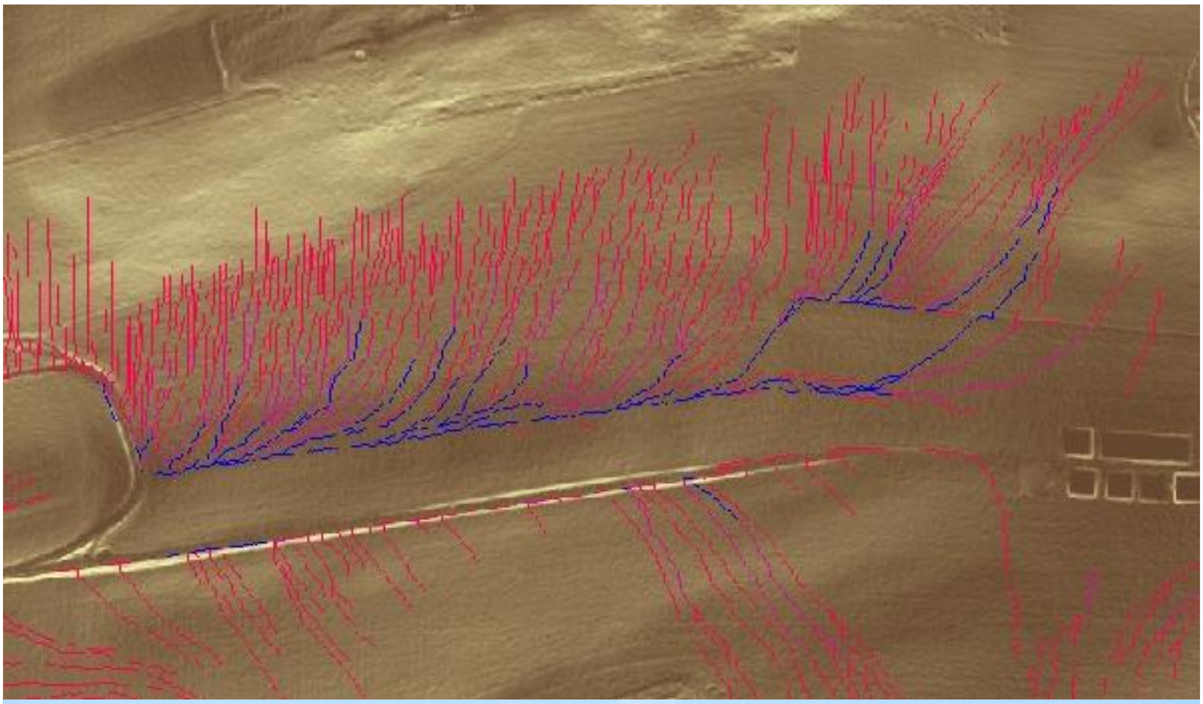


Figure 34 and 35: Top: SKRL flow accumulation of Mülsborn area 4. Red, purple, blue line = Class 1, 2, 3. Bottom: Photography of erosion event.

In every investigation area linear erosion set in when more than 10.000 cells drain into one channel. It is thus possible to accurately depict the risk of ephemeral gully erosion in depression lines with flow accumulation values greater than 10.000. Rills on homogeneous slopes with depth of up to 20 cm are not subject to such regularity. Their formation seems to depend on the structure of the soil, i.e. the predefined flow channels that stem from the soil treatment. As was indicated by the example of flow lines on the slope contributing to the depression line, the formation of rills can also be shown with the SRKL map (see figure 34 and 35).

The value of flow accumulation in depression lines goes up to over 200.000, i.e. 20 ha drain into the depression line. It can be observed that the flow does not always accumulate in one channel in the depression line but is split up. Instead of one gully or deep rill several deep rills form if the tillage was done parallel to the depression line.

8.4 The USLE factors

The USLE was derived in a time before raster resolutions of 1 m. The obvious increase in the S-Factor with the increasing resolution can be explained with the plus in detail. In the lower resolution the slope gradient is lowered by interpolation, because ridges are only caught if the DEM raster point lies on the ridge. The L-Factor increase is moderate compared to the S-Factor increase and it should very much depend on the raster cell size and the respective resolution.
A comparison of the standard to the automated procedure of S-Factor determination showed that the slope gradient on slopes with depression lines is estimated lower in the standard procedure.
The L-Factor calculation is problematic. The proposed methods have disadvantages because they depend on two assumptions. First the field form is regular, i.e. square or rectangle and second each part of the field drains into the depression line. If the surface runoff exits the field sideways the SKRL flow accumulation value which represents the mean value of all involved cells diverts strongly from the value reached with the standard procedure.
The maximum flow length method also strongly depends on the form of the field. The more the field form diverts from the rectangle with the depression line in the middle the less this maximum flow length value describes the mean erosive slope length. Considering the versatility of field forms which depend on the local circumstances this method seems less likely to create meaningful results. Because of the complexity of the erosion process all attempts to describe it can only be approximations. The goal must be to find the best fit, the method with the greatest agreement.
But are the other USLE factors suited for the classification of erosion risk? The S- and R-Factor are independent of flow length; their influence on the process is the same on every part of the slope. The flow length obviously cannot be used without uncertainty and the K-Factor is as immutable as is made believe by the USLE. It very much depends on climate, which does not show in the K-Factor and soil treatment which is not always incorporated in the C-Factor as for example in winter rape. Using the S-Factor and the flow accumulation tool a slope with depression line can be described very well with respect to erosion disposition. The two most important factors, amount of water and slope gradient, are dealt with.

8.5 External water inflow

The inflow of water in Amecke depicted by the pure flow accumulation slope map and the Pure flow accumulation AUA map differs by 40 %, i.e. there is a significant amount of inflow from external sources. If the SRO-Factor is taken into account the difference is reduced to 11 %.

The erosion in depression lines is part of the natural process. Due to the concentrated surface runoff the conditions are critical. In extreme cases erosion cannot even be prevented if badly developed pasture is present. For the administrative work this means that, as long as there is no danger to human beings the erosion in depression lines should be viewed as part of nature and thus as a process we have to live with.

8.6 Flow accumulation vs. standard procedure

The approach chosen in this thesis has one great advantage over the standard procedure. It is more precise, because it does not rely on human perception and mean values or at least not to such a large degree as the standard procedure. For example the slope gradient and thus the S-Factor is calculated for each m². This way there is no influence on the result according to the chosen slope line. The process is no longer averaged over the whole AUA but calculated for every square meter contributing to the depression line. This way the estimation errors that are brought into the calculation in the standard procedure do not occur,

but on the other hand not the whole AUA is taken into account (see figures 36 and 37).
This procedure is much more precise as long as there is a distinct depression line. There are areas like Mielinghausen or Amecke in which several more or less equal sized flow accumulation lines are found by ArcMap (see figures 36 and 37). In this case a threshold has to be chosen for the lines that are used, i.e. added up. For example every flow line of more than 1.000 cells is used. This method brings arbitrariness into the procedure. Considering the high threshold of 1.000 cells the degree of this arbitrariness is negligible.

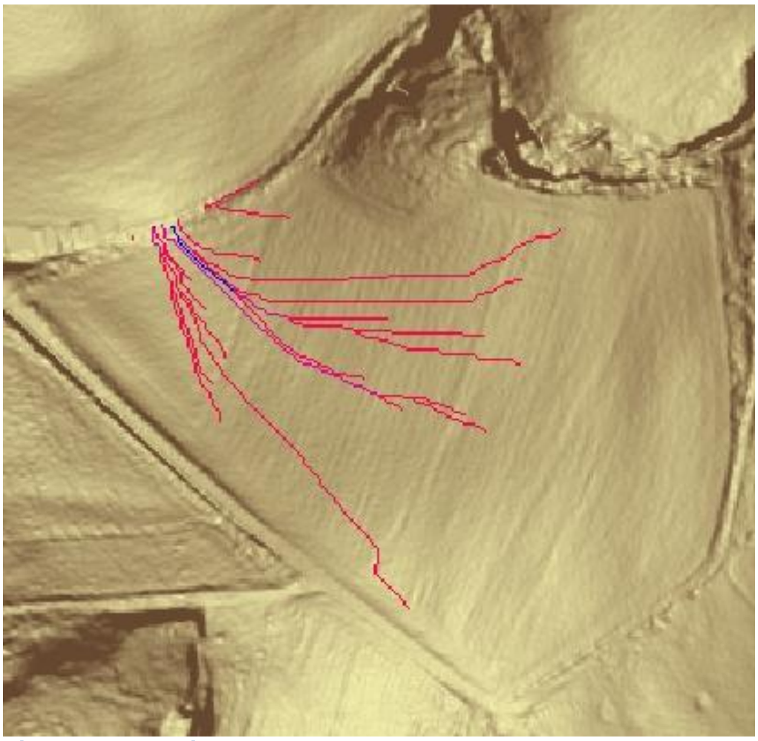


Figure 36: Amecke SKRL map.

The four used USLE factors do not all have a 1 m resolution or are otherwise unreliable or not well suited. The S-Factor and the R-Factor are reliable because of the large (1 m) respectively small scale (community) and the universal method behind its calculation. Given the smoothing the R-Factor has received because the mean value is taken for each community it should be neglected since it does not nearly reach the desired resolution.
The resolution of the K-Factor depends on the raster cell size of the ReiBo which is 50 x 50 m. There are soil maps of the geological survey with point distances of less than 100 m but this would not be a gain but a loss of accuracy. The K-Factor is only available for the AUA, therefore it can only be used in the AUA maps. As was mentioned before the range of values in the soil erodibility on the slopes in the HSK is not large. Considering these three facts the K-Factor should be used with caution. In some cases the depression line is only ten meters wide. One fifth of the ReiBo resolution is not adequate since the changes can be dramatic.
Depending on the method chosen the L-Factor calculation may be more error prone due to the extent of the individual AUA.

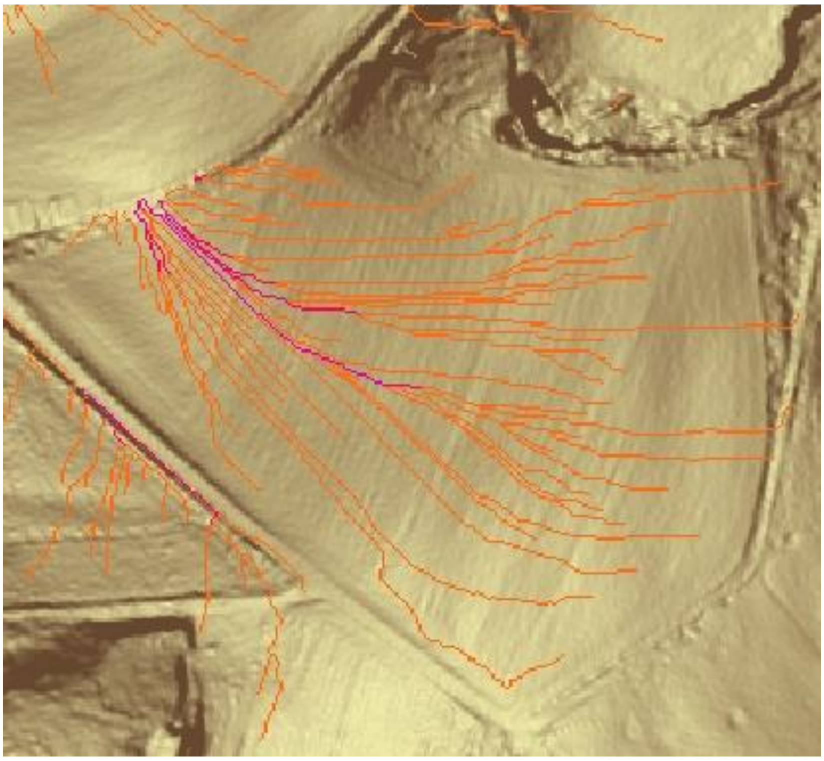


Figure 37: Amecke S-SRO slope map.

8.7 Discrepancies between GIS and standard procedure

1. The GIS procedure regards only the factors of the involved cells not the whole field like the standard procedure.

2. The Standard procedure relies on estimation (guessing errors), GIS procedure is a mathematical function (systematic error as for example in in L-Factor calculation).

9. Conclusions

In this thesis several methods were presented to evaluate the erosion risk for slopes with depression lines. The pure flow accumulation calculation without any weight factor gives an indication for erosion risk disposition. The great advantage of this number lies in the fact that it is unbiased. All other maps rely on empirical knowledge in form of USLE factors or arbitrary numbers like the SRO factor. The pure flow accumulation would be a good basis for an examination program. Regrettably the threshold of 10.000 cells that flow into one cell would lead to too many investigation areas. Many of which would lie in the middle of the forest or on permanent pastures; both land uses are not critical.

Thus the SRO-Factor was introduced to incorporate the different infiltration and interception attributes and in consequence the amount of surface runoff of the different land uses to filter out areas that lie in woodland or on permanent pastures. The threshold of 10.000 cells still works for all the known points where erosion took place, although the land use field is sometimes shown as pasture and vice versa. Maps in which the SRO-Factor is included deliver unreliable results and are thus neglected for the moment.

Next the slope factor the second most important factor influencing the kinetic energy of surface runoff after the amount of runoff was integrated. The resulting values were classified with respect to erosion risk. This slope map could be the first step in the process or maybe the second after filtering out all slopes without AUA. The addition of the rain erosivity factor R brought no further benefit for the definition of a risk threshold. It has to be kept in mind though that the R-Factor for the mapped sites only has a range of 84 to 92. Considering the large range of R-Factor values in the HSK (67 to 98) its incorporation would take the edge of slopes that would be marked as critical by the S-Factor slope map in the communities of Medebach and Hallenberg.

The flow accumulation depicts the dimension of the surface runoff bundling in the depression line and hence allows to work out solutions for the problematic inflow into AUA from other areas and puts a figure to the water shed size which can only be guessed during field work. In combination with USLE and SRO-Factors it creates an informative image of the situation, a point of view that would otherwise not exist or could only be reached with long field work. In short it offers a new tool that is suited to evaluate depression lines which are the cause for major erosion problems.

One disadvantage of the method is the large amount of storage a DEM with a 1 m raster requires. It is not possible to calculate an erosion map from the 1 m raster for the whole HSK without upgrading the available storage. Thus a procedure has to be developed which determines the slopes with a depression line and in a second step this area is analysed in the 1 m raster. Another option would be to calculate the communities one after another.

There are three different applications of the results of this thesis. First there is the evaluation of slopes as part of the day to day work of general erosion prevention of the HSK administration. Second there is the damage event after which solutions have to be found. Thirdly there is the involvement in urban planning. The data set of mapped erosion events is not large enough to define several classes, but it can be said that all slopes with depression lines and a S-Factor slope map value of 40.000 or greater are at a high risk of severe erosion if adverse weather conditions prevail or if critical crop is sown on the fields of the slope.

The slope and AUA maps are adequate tools to evaluate a slope with respect to erosion disposition. Not only is the estimation part of the whole evaluation process greatly reduced but also the comparison of the two map types gives clues where to start with the erosion prevention measures. And last but not least the classification of the BVB can be used effectively whereas this is very difficult with the standard procedure because of the great variance in the S- and L-Factor on slopes with depression lines. Despite the problems with the L-Factor calculation of the USLE equation this tool has great potential to close the gap left by slopes with depression lines in the erosion prevention duties of the HSK administration.

10. Future work

6. The following steps have to be taken to use the results of this thesis:
    1. Run the S-Factor slope map over the communities to detect critical slopes.
    2. Check the actual land use, so that the slope can either be disregarded or
    3. Create AUA SKRL maps for the AUA's.
    4. Contact local population. Ask for erosion events on the critical slope.
    5. Check if simple measures can be taken to reduce erosion risk, if that does not work
    6. Calculate the effect of taking a part of the slope out of the agricultural use.
7. With more charted erosion events a more detailed classification could be developed and the correlation of on-site parameters with flow accumulation values could be investigated.
8. The resolution of the R-Factor can be enhanced by incorporating the respective data layer of the geological survey of NRW. This is a financial problem.
9. The LWK has a much more accurate land use data set which is updated once per year, if it was possible to incorporate this set into the process the very important land use could be incorporated in the process. This would make it much easier to check the actual land use. If the data set is reliable the SRO-Factor could be used, automating number 1.3.
10. As the year 2011 has shown the tremendous influence of the climatic conditions prior to the soil treatment and bare soil phases need to be taken into account. This can either be done empirically or through physical models. The former method is time consuming, the latter very expensive. Apart from the prediction of exact rates, the knowledge about the influence of climatic conditions on erosion could be used to install an alarm system. If the climatic conditions are unfavourable The farmers are warned not to remove the residue of the crop, so that there is mulch on the field.

References (according to the Harvard referencing guide)

Bezirksregierung Köln, 2007, Kontrollflächen zur Höhengenauigkeit des 1-L DOM

Bodenkundliche Kartieranleitung, Hrsg.: Bundesanstalt für Geowissenschaften und Rohstoffe in Zusammenarbeit mit den Staatlichen Geologischen Diensten, 5. Aufl., 438 S.; 41 Abb., 103 Tab., 31 Listen, Hannover 2005

Bryant, 2005, LIDAR resolution, vegetation filters and preservation of topographic discontinuities, Symposium Poster

Bundes-Bodenschutzgesetz, 1998

Bundes-Bodenschutz- und Atlastenverordnung, 1999

Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft (BMVEL), 2002, Bund-Länder-Papier: Gute fachliche Praxis zur Vorsorge gegen Bodenschadverdichtung und Bodenerosion

Bundesverband Boden (BVB), 2004, BVB-Merkblatt Band 1: Handlungsempfehlungen zur Gefahrenabwehr bei Bodenerosion durch Wasser

Chisholm, M. 2008, Analyse der Bodenerosion mit der AVErosion-Extension für ArcView, Diplom-Arbeit, Universität Bern

Deutscher Verband für Wasserwirtschaft und Kulturbau (DVWK), 1996, Merkblätter 239/1996, Bodenerosion durch Wasser – Kartieranleitung zur Erfassung aktueller Erosionsformen

Deutsche Industrie Norm (DIN) 19708 , 2005, Bodenbeschaffenheit – Ermittlung der Erosionsgefährdung von Böden durch Wasser mit Hilfe der ABAG

Feldwisch, N. et al., 2004, Materialien zur Altlastensanierung und zum Bodenschutz Band 19: Maßnahmen zur Minderung von Bodenerosion und Stoffabtrag von Ackerflächen, Landesumweltamt Nordrhein-Westfalen

Feldwisch, N. et al., 2005, Leitfaden zur Ausweisung von Bodenschutzgebieten, Ministerium für Umwelt und Naturschutz, Landwirtschaft und Verbraucherschutz des Landes Nordrhein-Westfalen

Hudson N.W. 1973. *Soil Conservation.* Batsford, London, 320 p.

Julien, P. Y. 1998, Erosion and Sedimentation, Cambridge University Press

LABO, 2010, –Klimawandel– Betroffenheit und Handlungsempfehlungen des Bodenschutzes, Positionspapier der Bund-/Länderarbeitsgemeinschaft Bodenschutz, Rosenkranz, Einsele, Harreß, Ergänzbares Handbuch Bodenschutz

Mückenhausen, E., Mertens, H., Dübber, H.J., 1988, Die Bodenkarte 1:5000 auf der Grundlage der Bodenschätzung, Landesausschuß für landwirtschaftliche Forschung, Erziehung und Wirtschaftsberatung beim Ministerium für Umwelt, Raumordnung und Landwirtschaft des Landes Nordrhein-Westfalen

Návar, J., Synnott, J., 2000, Surface runoff, Soil erosion and land use in Northeastern Mexico, Terra Volumen 18 Numero 3

Neuhaus, P., Fiener, P., Botschek, J., 2010, Einfluss des globalen Klimawandels auf die räumliche und zeitliche Variabilität der Niederschlagserosivität in NRW, Landesamt für Natur, Umwelt und Verbraucherschutz, Nordrhein-Westfalen

Pirotti, F., Tarolli, P., 2010, Suitability of LiDAR point density and derived landform curvature maps for channel network extraction, Hydrological processes 24, John Wiley & Sons, Inc.

Reutebuch, S. E., McGaughey, R. J., Andersen, H. E., Carson, W.W., 2003, Accuracy of a high-resolution lidar terrain model under a conifer forest canopy, Can. J. Remote Sensing, Vol. 29, No. 5, pp. 527–535, 2003

Roose E. 1975. Natural mulch or chemical conditioner for reducing soil erosion in humid tropical areas. In: *Soil Conditioners.* SSSA Special publication 7(12): 131-137.

Schäuble, H. 1999, Erosionsprognosen mit GIS und EDV, Diplom-Arbeit, Geographischen Institut der Eberhard-Karls-Universität Tübingen

Schwertmann, U., Vogl, W., Kainz M., 1987; Bodenerosion durch Wasser – Vorhersage des Abtrags und Bewertung von Gegenmaßnahmen; Eugen Ulmer GmbH & Co., Stuttgart

Toy, T. J., Foster G. R., Renard, K. G. 2002, Soil erosion, John Wiley & Sons, Inc.

U.S. Environmental Protection Agency, 2003, Polluted runoff (Nonpoint Source Pollution), Urban fact sheet, EPA 841-F-03-003, http://www.epa.gov/owow/NPS/urban_facts.html