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Soil erosion in northern Lao PDR

An evaluation of the RUSLE erosion model

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An evaluation of the RUSLE erosion model

A Minor Field Study

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Abstract

Soil erosion is a problem throughout the globe, as it reduces the fertility of arable land. As population increases the pressure on agricultural land increases, resulting in overgrazing of rangelands, shorter fallow periods and forest clearing. This reduces the protective vegetation cover and exposes the soil to rainfall and runoff erosion.

The aim of this master thesis is to evaluate the usefulness of the RUSLE (Revised Universal Soil Loss Equation) erosion model at a district level in Lao PDR. The model uses rainfall, land use, soil properties, slope length and slope steepness as parameters to calculate an estimate of soil erosion. The uncertainties of some of these parameters were measured by fieldwork in Laos, and the total effect of these uncertainties on the RUSLE erosion estimate was calculated. Slope length and slope steepness is indirectly dependant on elevation, which was the parameter measured during the fieldwork. Because of this Monte Carlo, simulations were used to determine how elevation uncertainty affects slope length and slope steepness.

Erosion calculations were also made when omitting land use. These produces an estimate of potential erosion without human influence, which may be useful when planning for land use changes.

Additionally, villagers in Laos were interviewed to get the farmers perspective on erosion. The results of these interviews were compared with the RUSLE erosion estimates to see if there were any correlations.

The result shows that the data and methods used produce a very high erosion estimate, 81 ton ha^{-1} y^{-1} average and 311 ton ha^{-1} y^{-1} on agricultural land. These are high values as other studies in Southeast Asia indicate erosion rates to be up to 40 ton ha^{-1} y^{-1}. The average uncertainty was calculated to be ±234 ton ha^{-1} y^{-1}, indicating the results to be useless for estimating erosion rates. When calculating the potential erosion uncertainties were lower, average 1400 ±1218 ton ha^{-1} y^{-1}. Thus the potential erosion may be useful for comparative purposes even though it is too insecure for numerical estimates. When comparing village interviews with modeled erosion, no clear relation could be found when using the Wilcoxon-Mann-Whitney test. The lowest P-values were achieved when comparing interviews and potential erosion, with P-values of 0.079 and 0.107.

The conclusion is that the low accuracy of the available data makes RUSLE unable to predict erosion rates on an acceptable level in Lao PDR districts. The largest contributor of uncertainty is land use, which to some extent depends on how the uncertainty is calculated.

Sammanfattning

Jorderosion är ett stort problem på många platser på jorden. Ökad befolkning och brist på jordbruksmark leder till försämrad produktion och tvingar bönderna att öppna upp skogar, överbeta betesmarker, övergödsla och odla på branta sluttningar. När vegetationstäcket sedan är undanröjt är marken mer utsatt för regn. Detta leder till erosion eftersom jordpartiklarna inte längre kan hållas kvar av växtlighet. Att åkermarken ligger i träda allt kortare tid kan också öka erosionen eftersom vegetationen inte hinner återhämta sig.

Syftet med denna studie är att undersöka hur användbar erosionsmodellen RUSLE (Revised Universal Soil Loss Equation) är i Laos, på distriksnivå. I modellen används nederbördsdata, markanvändningsdata, höjddata och jordartsdata. För att dessa data ska kunna fungera i modellen och eftersom väder- och klimatförhållandena i Laos är annorlunda än vad modellen är skapad för behövdes justeringar av modellen göras. Noggrannheten på datan, förutom nederbördsdata, utvärderades genom fältmätningar i distriktet Vieng Phoukha i norra Laos. Monte Carlo-simuleringar gjordes för att analysera hur osäkerheten i höjddata påverkar resultatet. Tillsammans användes osäkerheterna för att utvärdera hur pålitligt RUSLE är. Likaså gjordes intervjuer för att jämföra modellens resultat med bönders uppfattning om erosion.

Resultatet av erosionsmodellen visar att den genomsnittliga erosionen för hela distriktet är 81 ton ha^{-1} $år^{-1}$ och 311 ton ha^{-1} $år^{-1}$ för jordbruksmark. Dessa värden är höga jämfört med tidigare studier i Asien som visar en erosion på 40 ton ha^{-1} $år^{-1}$. Osäkerheten är beräknad till ±234 ton ha^{-1} $år^{-1}$, vilket visar på hög osäkerhet hos resultatet. Förklaringen till detta kan vara dels att den digital data som använts är otillräcklig och att förenklingarna av modellen inte är tillräckligt bra eller båda kombinerade. Modellens resultat och intervjuerna är inte korrelerade, dvs. det finns inga trender eller överensstämmelser mellan böndernas uppfattning av erosion och den beräknade erosionen.

Slutsatsen är att noggrannheten på den digitala datan är alldeles för dålig för att RUSLE ska kunna användas vid beräkningar av erosion i Laos på en acceptabel nivå. Osäkerheten i de olika parametrarna är för hög, med markanvändning som den faktor som påverkar resultatet mest.

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A thanks also goes to Margareta Hellström and Carl Bergman for technical support and help with problem solutions.

Abbreviations

Organizations:

DAFO	District Agriculture and Forestry Office
IRD	L'Institut de Recherche pour le Développement
IWMI	International Water Management Institute
LSUAFRP	Lao-Swedish Upland Agriculture and Forestry Research Program
MSEC	The Management of Soil Erosion Consortium
NAFRI	National Agricultural and Forestry Research Institute
NARES	National Research System
NISF	National Institute for Soils and Fertilisers
SIDA	Swedish International Development Cooperation Agency

RUSLE-parameters, objective functions and prefix:

θ_e	Slope steepness for cell *e*
σ_A	Uncertainty of the calculated erosion
σ_X	Uncertainty estimate of *x*
A	Average annual soil loss
a, b, c, …, i	Elevation values of DEM
A_e	Aspect of cell *e*
$A_{i,j\text{-}in}$	Area draining water into raster cell i,*j*
Ap	Potential erosion
$\beta i,j$	Slope gradient in the *i,j* directions
C	Cover management factor
CC	Canopy cover sub factor
cellsize_X,Y	Width of cells in direction *X* or *Y*
D	Raster resolution
DEM	Digital Elevation Model
D_g	Geometric mean particle diameter
D_i	Distance from weather station *i* to cell *e*
dX	Distance between the centers of two cells
dX_i	Distance between the centres of the mid cell and the cell in the *i* direction
dZ	Elevation difference between two cells
dZ/dX	Slope in the east-west direction
dZ/dY	Slope in north-south direction
EI_{30}	Precipitation during the 30 most intensive minutes
f_i	Primary particle size in *i* fraction
Fi_x	Fourier index for month *x*
i	Particles sizes (sand, silt and clay)
i,j	flow directions, or raster cell coordinates
K	Soil Erodibility factor
L	Slope Length factor
m	Exponent based on the ratio of rill- to interrill erosion
m_i	Arithmetic mean of particle size limits for size *i* (mm)
M_x	Precipitation during month *x*
n	Directions of adjacent cells with the same elevation as the centre cell
P	Support practice factor
P_y	Yearly precipitation
PLU	Prior land use sub factor
R	Rainfall-runoff erosivity factor
R^2	Coefficient of determination
R_e	R value at the raster cell *e*
R_i	R value at weather station *i*
RMSE	Root mean square error
S	Slope Steepness factor
SC	Surface cover sub factor
Sg	Slope gradient between two cells
SLR	Soil loss ratio for given conditions
SM	Soil moisture sub factor
SR	Surface roughness sub factor

t	Time periods with individual EI_{30}-values *X* RUSLE factors [R, K, L, S, C]
x	Months from January 2003 to December 2005
$x_{i,j}$	Length of the cell edge for raster cell *i,j*

Other:

Arc Map	Component of ESRI´s ArcGIS Geographical Information System (GIS)
a.s.l.	Above Sea Level
Lao PDR	Lao People's Democratic Republic
LPRP	Lao People's Revolutionary Party
MC	Monte Carlo
NTFP	Non Timber Forest Production
RTKGPS	Real-Time Kinematic GPS
RUSLE	Revised Universal Soil Loss Equation
USGS	United States Geological Survey
USLE	Universal Soil Loss Equation
VPK	Vieng Phoukha district

Table of content

1. Introduction

Lao Peoples Democratic Republic is a small country in Southeast Asia currently trying to reform and develop its agriculture by introducing new crops and farming practices. To aid in this the National Agriculture and Forestry Research Institute (NAFRI) is providing help and advice to farmers, by coordinating domestic and foreign research and helping farmers to put research conclusions into practice.

One of many things to consider when adapting to new farming practices is the impact on soil erosion. Until recently most of the farming in northern Laos, an area characterized by mountainous terrain and steep slopes, has been rice paddies on flat land and slash and burn agriculture on the hillsides. After clearing a forested area and growing crops, the soil was put into fallow for up to 20 year allowing the forest to regrow. Now, due to land reallocation and increased demands, the time span allowed for fallow has often been shortened to only a few years. This reduces the fertility of the soil since it has less time for recovering and nutrient accumulation, and also reduces the amount of regrowing vegetation.

In order to identify areas with higher erosion potential, where it may be appropriate to take extra care before applying changes to farming practices or even introduce erosion-preventing methods such as terracing, computer-based erosion models may be used. In this master thesis is the uncertainty of the RUSLE (Revised Universal Soil Loss Equation) erosion model and the data for Laos being evaluated.

1.1 Study objectives

The overall aim of this master thesis is to evaluate the usefulness of the RUSLE erosion model for use on a district level in Lao PDR using the input data currently available. This overall aim is subdivided into 3 objectives:

- Objective 1

Evaluate the accuracy of RUSLE erosion estimates in Lao PDR on a district scale. This will be done by estimating the uncertainty of the different input data used to calculate the RUSLE factors: rainfall, soil composition, land use, elevation and slope steepness, and then calculate how this affects the RUSLE factors and finally the RUSLE erosion estimate.

- Objective 2

Evaluate the influence of DEM (Digital Elevation Model) uncertainty when calculating the slope length factor of RUSLE, by using Monte Carlo (MC) simulations.

- Objective 3

To help evaluate the usefulness of RUSLE erosion estimates, interviews will be done in villages in Vieng Phoukha to compare the erosion model estimates with farmers' opinion of erosion.

2. Background

2.1 Overview of Lao PDR

Lao PDR is a country located in South East Asia (figure 1) and has an area of 236 800 km^2. The country has no coast and borders Burma and China in the north, Vietnam in the east, Thailand in the west and Cambodia in the south. Laos has about 6.1 million inhabitants and the capital city is Vientiane with a population of 200 000. The country is a socialist republic, with the Lao People's Revolutionary Party (LPRP) as only legal political party. The current president is Choummaly Sayasone, who is also secretary-general of LPRP (Nationalencyklopedin, 2008-01-05).

The main religion in Laos is Buddhism, practised by a vast majority of the people and well anchored in common-day life. Laos consists of roughly 40 ethnic groups, where some only consists of a few thousand individuals. Official statistics divide the population into three main groups (Nationalencyklopedin, 2008-01-05). The largest group is named Lao Loum or lowland Lao. The second group is Lao Theung, also called the upland Lao and the third group is Lao Soung or the highland Lao who lives mainly in the northern highlands. The official language is Lao, which is related to the languages spoken in Thailand and is spoken by about half the population. About one million speaks Mon-Khmer language and there are several other minority languages as well.

The transport network in Laos is limited. There are no railways and less than 50 percent of the roads are made of asphalt (Landguiden, 2007-09-26). Some roads are only passable during the dry seasons, isolating parts of Laos during the rainy summer.

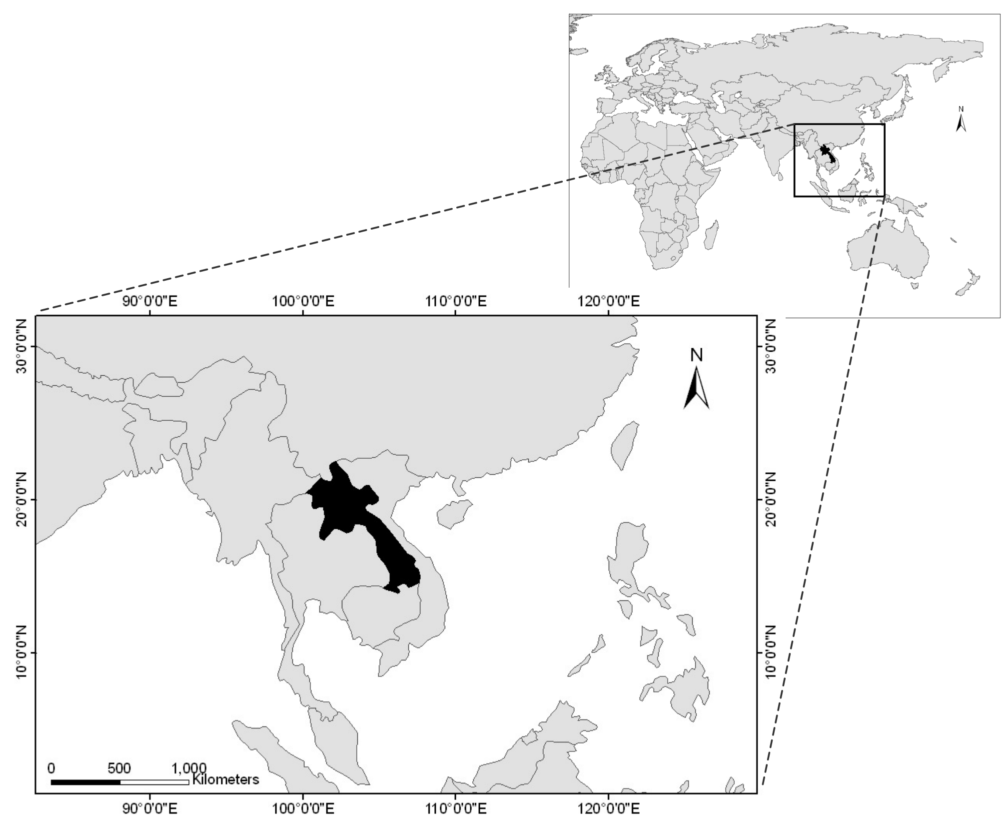


Figure 1: Location of Lao PDR

Laos consist mainly of highland, with several mountain ranges crossing the northern parts. The Annam mountain range runs from the marches near northeast Vietnam all the way down to the southern parts of the country (Landguiden, 2007-09-26). The tableland Plain of Jars takes up the northern parts of Laos and in the south is the fertile Boloven plateau. About half of Laos is covered by forest, with rainforests grooving in the northern highlands and along the Mekong River. The river runs through the west side of the country along the border to Thailand, and east of the river are large fertile plains. Besides the Mekong River there are several smaller watercourses, which together with the Mekong are important for both fishing and transport.

2.1.1 Climate

The weather in Laos is characterised by two main monsoon systems: the southwest monsoon from late May to October and the northeast monsoon ranging from November to March. The southwest monsoon brings heavy rainfall, 1300 – 2300 millimeters of precipitation (Nationalencyklopedin, 2008-01-05). At some locations the rainfall is even higher; the Boloven plateau for example receives about 4100 millimetres per year. The northeast monsoon usually characterizes relatively dry and stable conditions. The hottest period is from March through April, where the temperature exceeds 30 ºC. During the rainy season the temperature stays about 27 ºC, while during the dry season, November to March, it varies between 16 to 21 ºC. The temperature also varies with elevation as much as it does with the season changes.

The relief affects the climate in several ways (Landsberg, 1981). The most important effect of relief on air currents is the orographic precipitation on the windward side with rain-shadow on the leeward side. Mountain ranges can become sharp climatic dividers when the rain-bringing winds come mainly from one direction. As elevation increases, so does precipitation in the area, but only to a certain level where it thereafter decreases.

2.1.2 Social and economic situation

Laos is one of the least developed countries in the world. Human Development Reports list (Human Development Report, 2008-01-21) over developing levels ranked Laos as 130 of total 177 countries. The tangible poverty has decreased over the years, and the proportion of the population that is considered poor has according to the Lao government decreased from 46 percent 1992/1993 to 32 percent 2002/2003 (Regeringskansliet, 2004). At the same time the income disparity has increased, with people living in the cities and by the Mekong River profiting more from the country's development (Landguiden, 2007-09-26). The difference between cities and countryside, majority population and ethnic minorities is escalating and becoming a problem for the government to deal with. For the highland population, social indicators such as school, reading ability and expected lifespan are not as good compared to the rest of the population.

Undeveloped infrastructure and lack of skilled labor have caused natural recourses in Laos to remain unexploited. The clothing and textile exportation, mine industry, tourism and electricity production are the most important sources of influx of foreign money, but Laos is still in need of development aid and loan from foreign countries (Landguiden, 2007-09-26). The aid covers the unfavourable trade balance as well as a lack of money in the country's budget.

2.1.3 Farming practices

The majority of the inhabitants are farmers. Rice is the most dominant food product, often grown for personal use only. Cassava, corn, non-timber forest products (NTFP), sweet potato, cotton, tobacco and bean are also being produced and coffee is the only product that is exported in larger quantities (Landguiden, 2007-09-26). Trade and export are mainly limited by inadequate infrastructure, although the government is working to improve this.

Shifting cultivation, or slash and burn agriculture is widely used in the highlands due to the sparse population and poor conditions. The natural vegetation is cut down and burned, causing accelerated decomposition and release of nutrients as well as killing weeds and pests (Gansberghe, 2005). After farming the plot for one or a few years, it is left in fallow to allow the soil to recover and natural vegetation to reclaim it. The longer the fallow period is, the higher the fertility of the soil becomes. In most areas fallow periods are only three to five years, but in remote areas the fallow can extend for more than ten years. There are two ways of shifting cultivation: rotational and pioneering. The most common type in Laos is the rotational technique. This works by keeping the village at the same spot, while the cultivated plots are shifted according to the crop-fallow cycle. Pioneering on the other hand implies that the entire village is moved from one settlement to another after several years since the nearby forest has become worn out.

2.2 Study area

Vieng Phoukha (VPK) is a highland district in the southwest of the Luang Namtha province in northwestern Laos (see figure 2). The total area is 1949 km^2 and it is situated within 20° 19' to 20° 59' north latitude and 101° 49' to 101° 20' west longitude ranges. The district has boarders with Sing District, Nalae District and Long District.

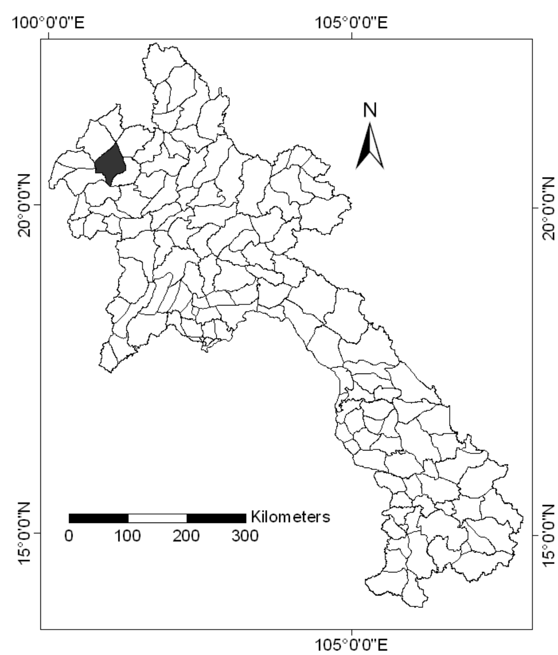


Figure 2. Location of the Vieng Phoukha district.

The mean temperature varies between 16.5 and 28.9 ºC throughout the year, and the total annual rainfall is about 2195 mm (NISF and NAFRI 2007). The highest peak is 1976 meter above sea level and located in the north of the district. The lowest is 551 meters in the centre of the district. Most areas of the district are situated in high mountainous regions with average elevation of 800 meters. The topography can be divided into three different types (NISF and NAFRI 2007). One is high mountains, where the mountain ranges are 1000 meters or higher. These are located mostly in the north and the east of the district and mainly covered by primeval or regenerating forest.

Secondly, there are the highland areas, where the surface is relatively flat and the dominant land covers are regenerating forests, shrubs and in some places upland rice and crops. The third type is consisted mainly of low hills, narrow valleys and plains, situated below 700 meters a.s.l. with relatively flat areas. Cultivation of rice paddies, perennial crops and remains of thin forest mixed with shrubs and grass covers most of the area.

In the centre of the district is the small town of Vieng Phoukha, the centre of commerce and communication in the district. Throughout the district runs a newly built road going from Thailand to China. The road has much improved the accessibility and transport potential in the district, and is starting to influence the agriculture in the area with more potential for trading cash crops and exports to China.

In the southeast part of the district lays the Nam Ha National Biodiversity Conservation Area, and in this area trekking routs and eco tourism is expanding and starting to bring tourists to the district.

2.3 NAFRI and their work

The National Agriculture and Forestry Research Institute (NAFRI) was established in Laos 1999 (NAFRI, 2008-03-03). NAFRI is an establishment working with research in order to coordinate research and provide recommendations to support agriculture, forestry and fishery. The assignments consist among other things of cooperating with national and international organizations. This is to improve information sharing, organize natural resources assessments and manage plant and animal genetic resources. NAFRI consist of nine discipline specific research centers, which are sited all round Laos. The institute also has three research support divisions based at the NAFRI headquarters.

Laos is currently undergoing a change towards a more market-oriented economy, and as a part of this the farming system is being reorganized (National Agriculture and Forestry Research Institute, 2008-03-03). Part of NAFRIs work is to supervise and evaluate the results of these changes on the environment and the livelihood of rural population.

2.4 Soil erosion

Soil erosion is defined as the removal and transportation of soil particles from an area by water, wind, mass movement and/or ice (Kearey et al., 1993). The most common process is the impact of raindrops striking the ground and flow of runoff, but human impact in the form of tillage and livestock trampling also accounts for much erosion in inhabited areas.

The rate of soil loss depends upon the erodibility of the soil and the degree to which it is covered by vegetation, rocks and boulders. Several other factors such as slope, topography and human influence affects soil loss as well (Kearey et al., 1993).

Ever since the land was first cultivated, erosion of soil by wind and water has been a problem (Morgan, 1995). The effects on-site are particular important on agricultural land. The rearrangement of soil within a field, soil loss from the field, breakdown of soil structure and the decline in organic matter and nutrients affect the arable soil depth and soil fertility negatively. Drought-tendency conditions are the consequence of reduced soil moisture that is caused by erosion.

Sedimentation downwind or downstream will result in off-site problems. This decreases the capacity of drainage and rivers ditches, which enhances the risk of flooding, blocks irrigation canals and deteriorates reservoirs (Morgan, 1995). Because sediment also is a pollutant, as chemicals are absorbed to it, it can increase the levels of nitrogen and phosphorus in water bodies and result in overfertilization.

2.5 RUSLE

RUSLE is one of the most widely used methods for predicting soil loss (Renard et al., 1997). It was developed by the U.S. Department of Agriculture and derives from the USLE (Universal Soil Loss Equation) model, which was established 1958 for American agriculture. USLE quantifies soil loss as the product of six factors representing rainfall and runoff erosiveness, soil erodibility, slope length, slope steepness, land cover management and support conservation practices. The idea is that a single number represents each factor, as calculated by different equations. RUSLE uses the same basic formula as USLE, but with improved equations for calculating the different factors. These consist of a time-varying approach for soil erodibility factor, a new equation to reflect slope length and steepness, a sub factor approach for estimate the cover management factor and new support conservation-practice values. The modifications resulted 1997 in the RUSLE model and it is now being used to estimate erosion in several parts of the world (Kinnell, 2007; Lu et al., 2004; Hartcher and Post, 2008; Diodato, 2006; de Asis and Omasa, 2007). RUSLE can be expressed using equation 1:

$$A = R \times K \times L \times S \times C \times P \qquad \text{(Equation 1)}$$

A = Computed soil loss per area per time unit (ton·ha^{-1}· yr^{-1})

R = Rainfall-runoff erosivity factor (MJ·mm·ha^{-1}·h^{-1}·yr^{-1})

K = Soil erodibility factor (ton·h·MJ^{-1}·mm^{-1})

L = Slope length factor (dimensionless)

S = Slope steepness factor (dimensionless)

C = Cover management factor (dimensionless)

P = Support practice factor (dimensionless)

There are several different ways of calculating the RUSLE factors, depending on where the modeled area is located and what data is available. Since RUSLE was originally developed for use in USA, a majority of the equations are specialized for use under American conditions. Much work is now being done worldwide to adapt RUSLE to suit local conditions, resulting in new and slightly altered equations.

2.5.1 Definitions of RUSLE factors

The explanations and definitions in this section are from the handbook completed by Renard et al. (1997)

The rainfall-runoff erosivity factor, R

The rainfall erosivity factor is the product of total storm energy and the maximum 30-minute storm intensity. The factor reflects the effect of raindrop impact as well as the amount of runoff associated with the rain. The equations used to calculate R are equations 12, 13, 14 and 15 in section 3.2.2.

The soil erodibility factor, K

The soil erodibility factor stands for the effect of soil properties and soil profile characteristics on soil loss. The K-factor is estimated by using the soil properties that are most strongly correlated with soil erodibility. These are soil texture, soil structure, permeability and content of organic matter. The value of K thus represents how easily the soil erodes. K can be calculated using equations 18 and 19 in section 3.2.4.

The slope length factor, L, and the slope steepness factor, S

Slope length and steepness factors represents the effect topography has on soil erosion. Erosion increases as slope length increases, and this is measured by the L-factor. The definition of slope length is the horizontal distance from the origin of overland flow to the point where either the slope gradient decreases enough that deposition begins or runoff becomes concentrated in a defined channel (Wischmeier and Smith, 1978). Both the L- and the S-factor are not absolute values but referenced to a value of 1 at slope length of 72.6 feet and 9% slope steepness.

The L-factor is calculated using equation 2 on page 17, and the S-factor is calculated using equations 10 and 11 in section 3.2.1.

The cover management factor, C

The cover management factor represents the effects of cropping and management practices on erosion rates. It includes the interrelated effects of cover, crop sequence, cultural practices, residue management and rainfall distribution. The C-factor also points out how the soil loss potential will be distributed over time during crop rotations, construction activities or other management schemes. The evaluation of the factor is difficult as there are many cropping and management systems. Crops can be rotated with other crops or grown continuously and the tillage of the soil may vary. Equations for calculating C are found in section 3.2.3 (equations 16 and 17), but for this thesis pre-calculated values were used and can be found in table 1 on page 25. C-values are dimensionless and relative a value of 1 for a barren plot with no land use.

The support practice factor, P

The support practice factor is the ratio of soil loss with a specific practice as compared to the soil loss without it. The support practice factors usually included are contouring, strip-cropping, terracing and subsurface drainage. Every factor has a fixed value describing how much it influences erosion, and P is calculated by multiplying the values for all relevant support factors.

2.5.2 Potential erosion

Potential erosion is the soil loss from an area without land use or support practice factors. It is used to compare the potential soil loss from different areas assuming the same land use is applied to both. This is desirable for example when planning for a land use change, as it helps to identify places where soil erosion may assume especially high values and thus extra care may be needed.

Potential erosion is not described in the RUSLE handbook. It is calculated using the RUSLE equation as usual but by excluding the C- and P-factors that describe human influence. The result is not an actual measure of erosion but a comparative number describing the proportional erosion between or within sites with identical land use. Since the C-factor is the highest influencing factor in the RUSLE equation, with values differing by more than a factor 10^2, a high potential erosion value does not necessarily indicate a high amount of erosion.

In order to separate potential erosion from real measurable erosion, the two will be referred to as potential- and actual erosion respectively. If no specific type of erosion is mentioned it is assumed to be actual erosion.

2.6 Related studies

The Management of Soil Erosion Consortium (MSEC) was established in 1997 as one of four consortia created by the Consultative Group on International Agricultural Research (CGIAR). The aim is to develop and support sustainable land management options for sloping uplands. As a first phase a network of 34 catchments and sub catchments in six countries in Asia (Indonesia, Laos, Nepal, Philippines, Thailand and Vietnam) was established (Maglinao and Valentin, 2003). The project was provided as a facility for research of water management and integrated land. Results showed that the current land management practices had some impact on the amount of soil erosion in the sub catchments within the catchments. According to Maglinao andValentin (2003) did the soil loss in 2001 vary for the different land use and countries and ranged within 0.8- 20.0 ton ha^{-1} for Indonesia, 0.0- 2.8 ton ha^{-1} for Laos, 0.1 ton ha^{-1} for Nepal, 0.1-53.9 ton ha^{-1} for Philippines, 0.1- 1.6 ton ha^{-1} for Thailand, but no result for Vietnam. In 2002 soil loss was between 0.2- 10.2 ton ha^{-1} for Indonesia, 0.0- 4.7 ton ha^{-1} for Laos, 0.0- 0.4 t ha^{-1} for Nepal, 0.0-28.3 ton ha^{-1} for Philippines, 0.1- 2.5 ton ha^{-1} for Thailand and 0.5- 1.9 ton ha^{-1} for Vietnam. The result from the Laotian catchment Ban Lak Sip, (10 km south of Luang Prabang) showed that the largest proportion of rotating land gave no erosion and the highest soil loss was found in the sub catchments with the smallest proportion of rotating land.

The second phase in the MSEC idea is a project that is mainly governed by IRD (L'Institut de Recherche pour le Développement), IWMI (International Water Management Institute) and NARES (National Research System) researchers. The study site is the same used in Laos for phase one. Students from both Europe and South East Asia cooperate with local farmers to measure erosion rates during rainfall and the impacts of different soil conservation policies. The measurements are confined to a single watershed with 27 catchments and sub catchments, where erosion is measured as soil captured in water basins. This has been done continuously since 2002. The erosion rates at Ban Lak Sip are measured to be 11.3 t ha^{-1} in 2005(Valentin et al., 2006).

3. Methodology

The objective of this thesis is to evaluate the usefulness of the RUSLE erosion model in Laos on a district level. This was done by estimating the uncertainty of the different input data used to calculate the RUSLE factors: rainfall, soil composition, land use, elevation and slope steepness, and then calculate how this affects the RUSLE factors and finally the RUSLE erosion estimate. The process is described in figure 3.

Most of the data used for calculating the erosion estimates was obtained from the NAFRI GIS Centre, as they have digital data covering all the Lao districts. The baseline for RUSLE calculations is described in the RUSLE manual (Renard et al., 1997), but since the procedures described there are based on American agriculture alternative methods for calculating the R-, C- and L-factors were used.

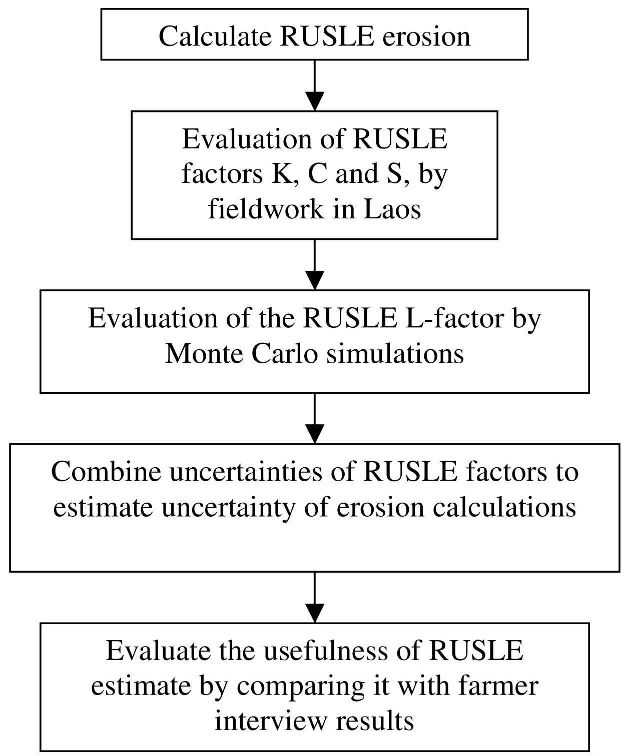


Figure 3: Methodology overview.

The accuracy of the digital data provided by NAFRI was evaluated by fieldwork in VPK. Land use, soil clay content, elevation and slope steepness were measured at 61 sample points. The results of these measurements were compared with the NAFRI data, and the RMSEs (Root Mean Square Error) were used as uncertainty estimates.

The L-factor is not directly calculated by elevation values, but instead depends on drainage areas that in turn are derived from the DEM (Digital Elevation Model). Monte Carlo (MC) simulations were used to determine how uncertainties in the DEM affect the L-factor.

The MC simulations were performed using two different water flow models to calculate drainage areas. For each flow model, five different uncertainty estimates for the DEM were used to see how the performance of each flow model varies with changed DEM uncertainty.

The results from the fieldwork and the MC simulations were used to determine the uncertainty of the RUSLE factors. These uncertainties were then combined to produce an uncertainty estimate of the RUSLE erosion calculations.

Finally, the RUSLE results were compared with answers from interviews of farmers in VPK to test the applicability of RUSLE. Using interview answers each village's erosion problem was estimated and given a numeric value of 0, 1 or 2. These values were then compared with the RUSLE erosion estimates using the Wilcoxon-Mann-Whitney test (Olsson et al., 2005).

3.1 Data used

The following data was used for calculating RUSLE erosion estimates:

- Precipitation data: Monthly precipitation during 2003-2005 for 9 weather stations situated in Laos, China and Thailand, see figure 4. The precipitation for Lao PDR was acquired from Lao Meteorological Institute, and for the other countries from the Tutiempo website (Tutiempo, 2006).
- Soil data: GIS layer containing soil percentage of clay, silt and sand. Data originating from a land suitability survey in VPK (NISF and NAFRI, 2007), provided by the NAFRI GIS Centre.
- Land use information: Also from the land suitability survey in VPK (NISF and NAFRI, 2007). Provided by the NAFRI GIS Centre.
- Digital elevation data: Raster data with 50 meters × 50 meters resolution, covering the VPK district. Provided by the NAFRI GIS Centre.
- GIS point layer with village positions: Provided by NAFRI GIS Centre.

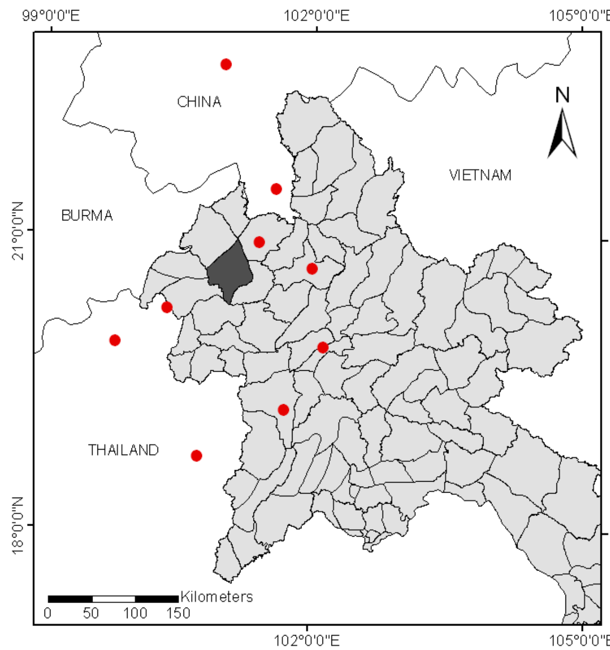


Figure 4: Location of weather stations (red dots).

All data obtained from the NAFRI GIS Centre were stored in WGS 1984 UTM Zone 48N. The precipitation data was obtained as UTM 48 Indian 54, but projected in ArcGIS to WGS 1984 UTM Zone 48N before any calculations.

3.2 RUSLE modeling

The RUSLE equation consists of six different factors, each representing the influence of environmental conditions on erosion: precipitation, soil erodibility, slope length and steepness, land use and support practices. These are calculated as described in figure 5, using the input data available. The support practice factor was excluded in the calculations, since no information about a coherent use of support practices could be found and thus making it impossible to include on a district level. The remaining five RUSLE factors were multiplied to produce estimates of both actual and potential erosion. Since the support practice factor has already been excluded its only the inclusion of the land use factor C that separates the calculations of actual erosion from potential erosion (see section 2.5.2 for a description of potential erosion).

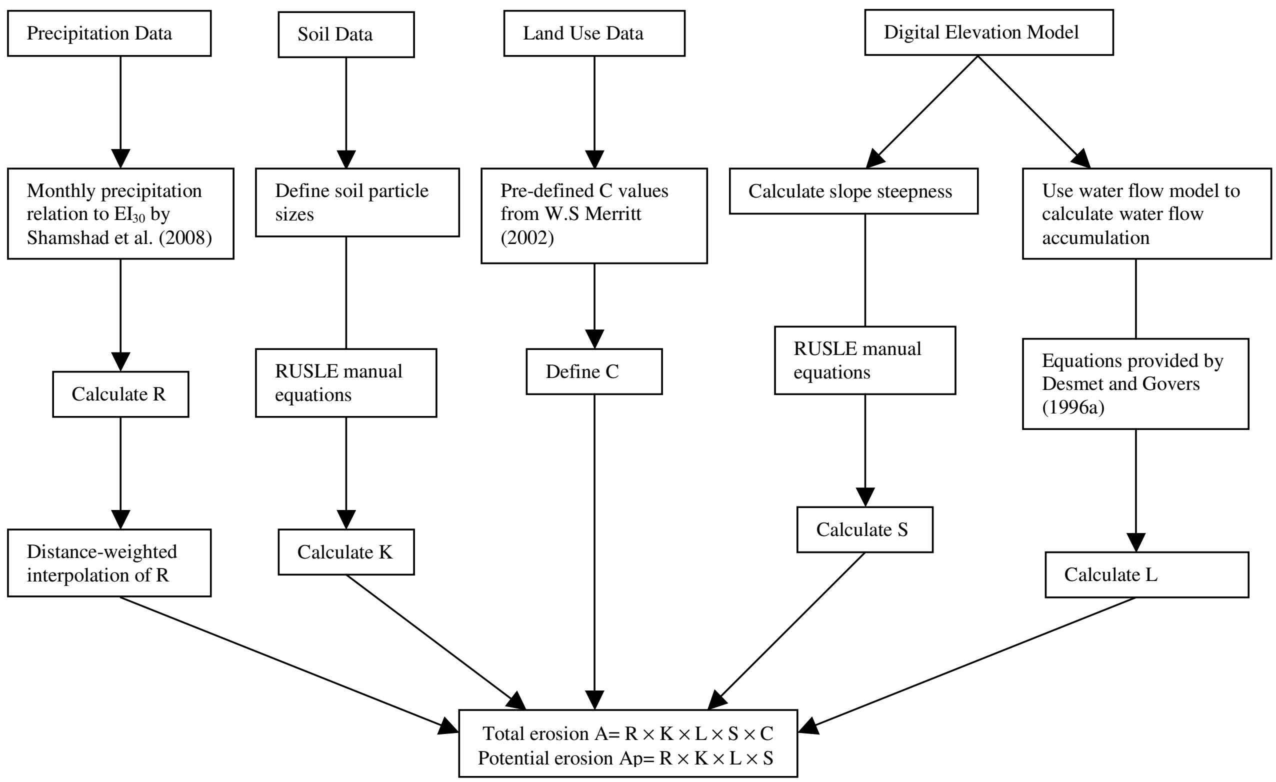


Figure 5. Flow chart for RUSLE modeling.

3.2.1 Calculation of slope length (L) and slope steepness (S) factors

According to Renard et al. (1997) the L-factor is calculated by using slope length, defined as the runoff horizontal flow length until deposition begins or runoff becomes concentrated into a channel (figure 6). However, this definition does not take into account the accumulation/distribution of runoff on non-uniform slopes where water flow may intensify or disperse depending on topography. On concave slopes the water flow concentrates resulting in increasing erosion rates. Contrary, on convex slopes the water is dispersed over a larger area, reducing the erosion intensity. To incorporate this in the RUSLE calculations Desmet and Govers (1996 a) suggest replacing the slope length unit with a unit contributing area. Using equation 2, the L-factor is calculated based on water drainage areas instead of slope length (Desmet and Govers 1996 a). When using a raster DEM for calculating L, the L value for a single raster cell thus depends on the amount of other raster cells draining water into it.

$$L_{i,j} = \frac{(A_{i,j-in} + D^2)^{m+1} - A_{i,j-in}^{m+1}}{D^{m+2} \cdot x_{i,j}^{m} \cdot (22.13)^{m}} \qquad \text{(Equation 2)}$$

$L_{i,j}$ = RUSLE L-value in the raster cell

i,j = Raster cell coordinates

$A_{i,j\text{-}in}$ = Area draining water into raster cell i,j (m^2)

D = Raster resolution (m^2)

$x_{i,j}$ = Length of the cell edge the water path is crossing (m)

m = Exponent based on the ratio of rill- to interrill erosion

The m-exponent is dependent on the steepness of the slope. The method to calculate m suggested by Renard et al. (1997) is preferable only for slopes with a low gradient. Instead a value of m = 0.5 was chosen for equation 2 based upon the results of Liu et al. (2000) who consider this value to be appropriate for terrain with slopes steeper than 30%.

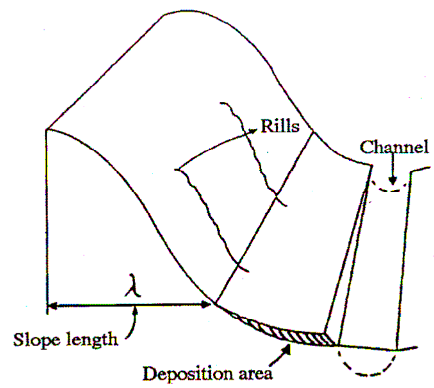


Figure 6. Slope length. Figure from Renard et al. (1997).

There are several ways to calculate the amount of runoff draining into a raster cell when using a raster DEM. In this thesis two different methods were used for calculating the flow directions: a single- and a multi-flow model. Both models assume that each raster cell initially receives 1 unit of precipitation, which is then distributed among the 8 neighbouring cells according to elevation differences. This distribution is repeated until all water flows have either passed the edge of the DEM, or reached an area from which it cannot flow since the entire surroundings have higher elevation (such an area is known as a "sink" and is described more detailed later).

The main difference between the two flow models used is the number of adjacent cells receiving runoff. The single-flow model allows water to flow only into one of the eight adjacent cells. The receiving cell is determined by calculating the slope between the centre cell and its neighbours, as described in equation 3:

$$Sg = \frac{dZ}{dX} \qquad \text{(Equation 3)}$$

Sg = Slope gradient between two cells

dZ = elevation difference between the cells (m)

dX = distance between the centers of the two cells (m)

The neighboring raster cell with the highest slope gradient receives all the runoff from the centre cell. In case two or more adjacent cells have the same slope gradient the receiving cell is determined by the aspect of the centre cell as calculated by equation 4:

$$A_e = 90° - \arctan\left(\frac{g+h+i-a-b-c}{a+d+g-c-f-i}\right) \qquad \text{(Equation 4)}$$

A_e = aspect of cell *e* (see figure 7 about cell handles)

a, b, c, …, i = elevation values of DEM cells around the active cell (m)

If the aspect of the centre cell is facing any of the possible flow directions then water flows to that neighbour. Otherwise, the centre cell is treated as a sink.

In the multi-flow model, water is distributed between all adjacent cells with elevation lower than the centre cell. The proportion of water each neighbour receives is calculated by equation 5:

$$f_i = \frac{\tan \beta_i}{\sum_{j=1}^{8} \tan \beta_j} \qquad \text{(Equation 5)}$$

a	b	c
d	e	f
g	h	i

Figure 7: Raster cell handles. e is the active cell for which an attribute is being calculated.

f_i = flow proportion in the *i* direction

i,j = flow directions from the mid cell (from *a* to *i*, see figure 7)

$\beta i,j$ = slope gradient in the *i,j* directions

This allows cells to receive fractions of unit runoff, as opposed to the single flow model where runoff accumulation always consists of integers. If all neighbouring cells have equal or higher elevation compared to the centre cell, the water flow is distributed as described by equation 6:

$$f_i = \left(dX_i \cdot \sum_n \frac{1}{dX_n} \right)^{-1} \qquad \text{(Equation 6)}$$

dX_i = distance between the centres of the mid cell and the cell in the *i* direction (m)

n = directions of adjacent cells with the same elevation as the centre cell

Since the multi-flow model is assumed to give a more realistic description of flow directions in mountainous terrain (Desmet and Govers 1996 b), this model was used for the calculation of L in the RUSLE equation. In the MC simulations (section 3.4), both models were used in order to compare their sensitivity to changes in DEM uncertainty.

3	3	3	3
4	2	2	4
5	2	2	5

Figure 8: Example of contradicting flow directions. The numbers in the cells represent DEM elevation values. According to the equations governing flow directions, the two centre cells will be assigned opposite flow directions. To solve this water flow between the two cells are prohibited. In the single-flow model this turns the cells to sinks, whereas in the multi-flow model all the runoff is distributed between the remaining cells with elevation = 2.

For both types of models there are a few exceptional situations that needs to be addressed, when water flow cannot be determined by standard rules:

- Sinks. When a flat area of one or more cells has a lower elevation than its surroundings, water flow cannot find an exit path and is halted. This may be a natural formation, but is often an artificial result of interpolations when creating the DEM. Standard procedures is often to either fill the sink, or in the case of larger sinks to find a place where the water outlet is blocked by a few cells with higher elevation and lower them to create an outlet. In this study only single cell sinks were filled before water flow calculations, with the remaining sinks left to end water flow when it reaches them.

- Contradicting flow directions. On flat areas water flow directions may contradict each other (figure 8) disrupting the model. This is solved by prohibiting water flow in the contradictory directions, which may cause sinks if those directions are the only outflow directions from the cells.

By definition, runoff stops contributing to the L factor when it "becomes concentrated into a defined channel" (Renard et al., 1997). To incorporate this factor when using water drainage area instead of slope length for calculating L, an upper limit of the drainage area need to be set. This is to prevent L from rising to extreme values, as the water flow does not stop until it reaches the edge of the DEM or a sink. According to Renard et al. (1997) slope length in reality hardly ever exceeds 300 meters (1000 ft), corresponding to a maximum value of L = 3.71. This value is too small when using a DEM resolution of 50 meters as it limits the maximum drainage area to two raster cells. We chose instead to use a limit of 20 cells, or 50 000 square meters, resulting in an upper limit of the L-factor equal to 9.96. Choosing such a high limit will probably give unrealistically high numerical values of the erosion estimate, but may make the estimates more accurate for comparative purposes.

The flow models were programmed as described above using MatLab, The MathWorks, Inc. The entire code can be found in appendix B.

The S-factor is strictly dependant on slope steepness. Slope steepness was calculated in Arc Map using the DEM. The elevation values of neighbouring cells were used to calculated the slope of raster cells according to equations 7, 8 and 9:

$$\frac{dZ}{dX} = \frac{(c + 2f + i) - (a + 2d + g)}{8 \cdot cellsize\_X} \qquad \text{(Equation 7)}$$

$$\frac{dZ}{dY} = \frac{(a + 2b + c) - (g + 2h + i)}{8 \cdot cellsize\_Y} \qquad \text{(Equation 8)}$$

$$\theta_e = \arctan\left(\sqrt{\left(\frac{dZ}{dX}\right)^2 + \left(\frac{dZ}{dY}\right)^2}\right) \qquad \text{(Equation 9)}$$

θ_e = slope steepness for cell e (degrees)

a, b, c, …, i = elevation values of DEM cells around the active cell (figure 7) (m)

cellsize_X,Y = width of cells in direction X or Y (m)

The slope steepness was then used to calculate S according to the equations suggested by Renard et al. (1997):

$$S = 10.8 \cdot \sin(\theta) + 0.03 \qquad S < 9\% \qquad \text{(Equation 10)}$$

$$S = 16.8 \cdot \sin(\theta) - 0.5 \qquad S \geq 9\% \qquad \text{(Equation 11)}$$

3.2.2 The R factor

The R factor is defined as being the yearly average of EI_{30} indices throughout the time for which erosion is being calculated. EI_{30} is calculated for every rainstorm event, and is a product of two factors: E that is the total storm energy and I_{30} that is the maximum 30 minutes intensity of the storm. Thus in order to calculate R then highly detailed precipitation data throughout the year is needed. Data, which is not available in Laos on a district scale.

Shamshad (2008) has examined relations between the Fourier index (Fi) and EI_{30} in Malaysia. The Fourier index is a relation between monthly and yearly precipitation as described by equation 13. The relationship between EI_{30} and Fi as derived by Shamshad is described by equation 12:

$$Fi_x = \frac{M_x^2}{P_y} \qquad \text{(Equation 12)}$$

$$EI_{30,x} = k \cdot Fi_x^{0.584} \qquad \text{(Equation 13)}$$

Fi_x = Fourier index for month x (mm)

M_x = Precipitation during month x (mm)

P_y = Yearly precipitation (mm)

$EI_{30,x}$ = EI_{30} for month x ($MJ \cdot mm \cdot ha^{-1} \cdot h^{-1}$)

k = 227 ($MJ \cdot ha^{-1} \cdot h^{-1}$)

As calculations of Fi only require monthly precipitation data, it is possible to use this relation for calculating R in Laos. Using equation 12 and 13, EI_{30} values were calculated at the nine weather stations located around VPK (see figure 4). R-values were then calculated as yearly averages of the EI_{30} values (equation 14). After calculating R for every weather station the values were interpolated to cover the VPK district, using inverse distance weighted interpolation with a power of 2 (equation 15):

$$R = \frac{1}{n} \cdot \sum_{x=jan03}^{dec05} EI_{30,x} \qquad \text{(Equation 14)}$$

$$R_e = \frac{\sum_{i=1}^{9} \frac{R_i}{D_i^2}}{\sum_{i=1}^{9} \frac{1}{D_i^2}} \qquad \text{(Equation 15)}$$

n = number of years

x = month from January 2003 to December 2005

R_e = R value at the raster cell e ($MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$)

R_i = R value at weather station I ($MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$)

D_i = Distance from weather station i to cell e (m)

3.2.3 The C factor

The C-factor, which represents the influence of land cover on erosion, is a combination of several sub factors. It is calculated according to equations 16 and 17 (Renard, 1997):

$$SLR = PLU \cdot CC \cdot SC \cdot SR \cdot SM \qquad \text{(Equation 16)}$$

SLR = Soil-loss ratio for given conditions (dimensionless)

PLU = Prior land use sub factor (dimensionless)

CC = the canopy cover sub factor (dimensionless)

SC = Surface cover sub factor (dimensionless)

SR = Surface roughness sub factor (dimensionless)

SM = Soil moisture sub factor (dimensionless)

The final C value is obtained by using the SLR values for different time periods and weighting them with the EI_{30} values of the same periods (equation 17). This causes vegetation cover during rainy seasons to have greater impact on the C-factor than vegetation during dry seasons when little erosion occurs.

$$C = \frac{\sum_{t=1}^{n} SLR_t \cdot EI_{30,t}}{EI_{30,tot}} \qquad \text{(Equation 17)}$$

t = time periods with individual EI_{30}-values

n = number of different time periods

As it takes extensive and time-consuming fieldwork to determine the sub factors required for calculating SLR, it was decided to instead use pre-calculated C values in this thesis. The C values for a certain land use is dependent on climate and farming practices as well as crop type. Because of this it is important to use C values that were calculated in similar conditions as those where they are intended to be used. No such calculations could be found for Laos, but conditions in northern Thailand were judged to be similar enough to use C factors from the Thai government (Merritt, 2002). The land use types from Merritt were interpreted to match the land use types for the data received from NAFRI. The different land use classes are listed in table 1, along with their assigned C-values.

Table 1: Land use classes and corresponding values of the C-factor.

Land use from NAFRI	Land Use from Merritt (2002)	C-value from Merritt (2002)
Rural Resident land	Urban City	0
Primeval Forest Lands	Deciduous	0.001
Bare Rocky Mountain land	Forest	0.02
Regenerate Forest of High Trees land	Forest	0.02
Thin Forest, Regenerate Shrub land	Grass/Shrub	0.048
Regenerate Sapling Forest land	Forest Plantation	0.088
Perennial Industrial Crops	Perennial	0.15
Upland Rice	Upland Rice	0.25
Lowland Rice	Paddy Rice	0.28
Flat Land Annual Crops	Field Crops	0.34
Upland Annual Crops	Field Crops	0.34

3.2.4 The K factor

To calculate the K-factor we chose to use equations 18 and 19 (Renard et al., 1997), which are based on soil particle size distribution. These equations seemed best suited since they are based on global soil data rather than being specific for American soils, and thus applicable in Laos without modifications.

Soil particle sizes for sand, silt and clay were defined in accordance with the Swedish Geographic Society (Stål, 1972), differing only slightly from international standards when defining the limit between silt and sand (0.06 mm according to Stål 1972, 0.063 mm according to FAO 2006). Using soil data from the VPK field survey, an average particle distribution between sand, silt and clay were determined for each soil type and added to the GIS soil data layer. Equation 18 calculates the geometric mean diameter of the soils particles, and this value was then used in equation 19 to get a final value of K.

$$D_g = \exp\left(0.01 \cdot \sum_{i=sand}^{clay} f_i \cdot \ln(m_i)\right) \qquad \text{(Equation 18)}$$

$$K = 7.594 \cdot \left(0.0034 + 0.0405 \cdot \exp\left(-0.5 \cdot \left(\frac{\log(D_g) + 1.659}{0.7101}\right)^2\right)\right) \text{(Equation 19)}$$

i = particle sizes (sand, silt and clay) (mm)

D_g = Geometric mean particle diameter (mm)

f_i = Primary particle size i fraction

m_i = Arithmetic mean of particle size limits for size i (mm)

3.2.5 Calculating actual and potential erosion

The total erosion was calculated by multiplying the factors accordingly equation 1, but without using the P-factor due to reasons stated in the beginning of section 3.2. The calculation for potential erosion is identical but without using the C- and P-factors. The results are stored as 50 meters x 50 meters rasters, as this is the highest resolution of the input data used for the calculations.

3.3 Fieldwork in the Vieng Phoukha district

Fieldwork was conducted in the VPK district during 10-20th November 2007, in order to evaluate the digital data provided by NAFRI and to perform interviews in local villages. Besides the two authors of this thesis, the fieldwork was carried out by 3 additional persons:

- Mr Sompan, who is an employee at NAFRI in Laos and served as an interpreter between English and Lao as well as providing knowledge about Lao agriculture and traditions
- Mr Deth who is an employee at NAFRI and served as driver
- Mr Saisamon who is working at the district agriculture and forestry office (DAFO) in VPK and served as a local guide and interpreter between Lao and some of the native dialects.

The time for the fieldwork was chosen to be at the start of the dry season in Laos. This is the time when roads are most likely to be traversable, as this is a problem in some of the remote parts of the countryside where villages may be isolated for several months during the rainy season. Had it not been for accessibility problems it might have been preferable to conduct field work during the rainy season, as it is the time when most of the erosion takes place and it is also before the harvesting begins which makes it easier to identify crops and land use.

There were 2 main goals of the fieldwork:

- On randomized sampled points, do measurements of variables used for calculating the RUSLE factors, in order to evaluate the uncertainty of the digital data.
- Interview villagers in 15 different villages and use their answers to make an estimate of the village’s problem with erosion.

3.3.1 Interviews

Interviews were conducted in 15 different villages in VPK. These were chosen in agreement with VPK DAFO district staff based on the following criteria:

- Accessibility: The villages had to be accessible by car.
- Availability: Several of the villages were harvesting rice at the time of the fieldwork. During harvest, the villagers may be away for several days working and sleeping on the fields or transporting rice and crops back to the village. Villages where the village leader was likely to be away were excluded.

- Distribution: The villages should be evenly distributed across the district.

The village chiefs were interviewed, sometimes with part of his staff such as the village deputy present as well. In case the village chief was unavailable another person recommended by the villagers was interviewed, often the village deputy or the son of the village chief. The questions were related to problems with erosion, see appendix A, to get the farmers perspective on the erosion problem and a rough estimate of the amount of erosion in the village fields. Questions often had to be asked about soil fertility and runoff as well as about direct soil movement and erosion, to make sure the topic was understood. This makes the process of evaluating the erosion problems of the villages less objective as the questions asked at each interview varies, but in the end the results are likely to be more accurate and less dependable on the vocabulary of the interviewee. An average interview lasted roughly 1 hour, sometimes more if the interviewee had good knowledge about erosion.

The locations of the village centres were measured with GPS. Since some of the villages had been recently moved or renamed, this made it easier to identify and locate the village and its surrounding fields.

3.3.2 Sample points

Sample points were placed along the roads from the interviewed villages and back to the town of Vieng Phoukha, with 2 kilometres equidistance. The positions of the sample points were not pre-determined, but measured using the cars milometer starting at the village centres.

A total of 61 sample points were measured. At each sample point five different parameters were measured:

- Position
- Elevation
- Land use
- Surface slope
- Soil clay content

Position and elevation was recorded at the road using a GPS. The position was stored in WGS84 degrees.

The sample points were always placed upslope of the road, since surface slope measurements often were impossible in the down slope direction due to streams and rivers.

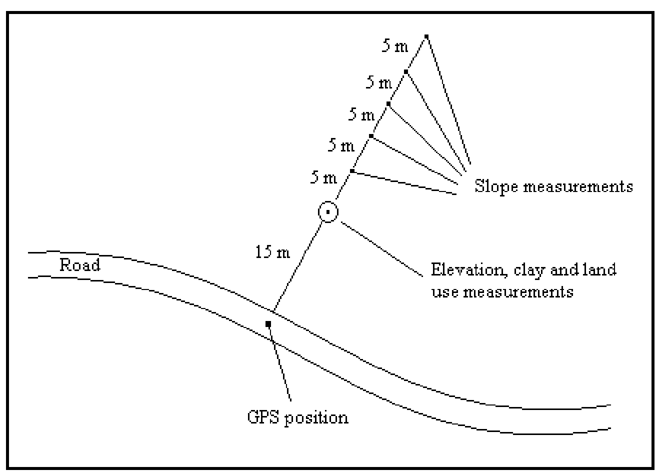


Figure 9: Sample point overview.

Land use and soil measures were made 15 meters from the road (see figure 9). Land use was noted and photographed, and later interpreted as one of 11 categories, see table 1. Soil samples were taken at 25 centimetres depth and used to measure clay content by using a soil-rolling method (Talme and Almén, 1975).

Surface slope was measured with a clinometer at five times 5 meters in a straight line perpendicular to the road, starting at the same spot as where the soil- and land use measures were made. If the measures started in a rice paddy, slope measurement was ignored and the slope was assumed to be zero since the paddies usually were filled with water.

Of the 61 sample points nine were not fully measured due to inaccessibility or because of animal incursion. Land use was measured at all 61 sample points. Surface slope was measured at all points except five: one was aborted because of wild animals, one as it was inside a town and one as it was located at a coalmine, and 2 points that were to steep to access and where only average slope was measured. Soil clay content was not measured at the points described above, and was also excluded at water filled rice paddies. In order to maximise the amount of sample points used for analyses, all points were still used for land use evaluation even though some lacked surface slope and clay content measurements.

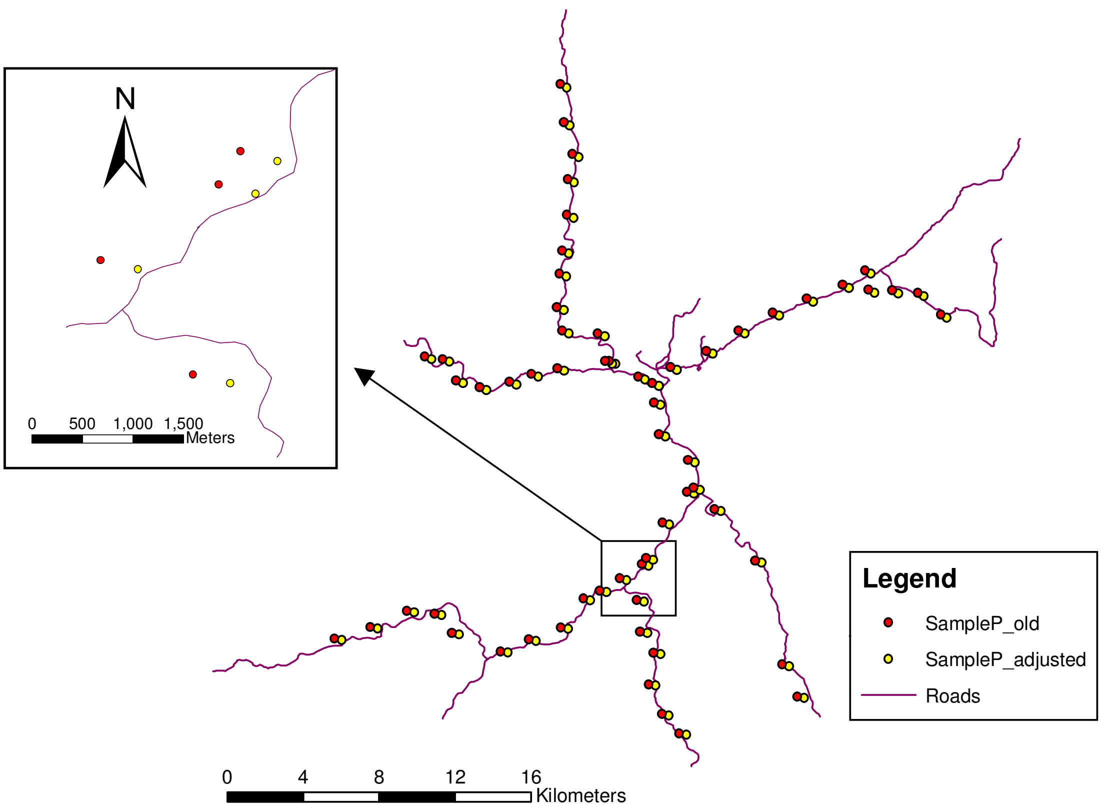


Figure 10: Spatial dislocation of sample points.

When digitized, the 61 sample points and the 15 village locations proved to be placed roughly 500 meters west-northwest of their expected locations (figure 10). This displacement could be seen by comparing the location of the sample points and the GPS position of the interviewed villages with the road- and village GIS layers. There are two likely sources for this error. Either the data layers containing road and village positions are wrong, perhaps due to some transformation error since all the displacements are in the same direction, or there has been some error when using the

GPS to get the coordinates of the sample points. To reduce the influence of this error on the uncertainty calculations, we tried to move the sample points closer to their expected locations. Using the average difference between the village GPS positions and the villages' location in the GIS data layer as a basis for displacement links, all the sample points were moved using the Arc Map "Spatial Adjustment" command. This does not place all sample points within 15 meters from the roads, but it does move them closer and it improves the accordance between values measured at the sample points and the values of the digital data from NAFRI.

3.4 Monte Carlo simulations

The goal of the MC simulations is to determine the impact of DEM uncertainties on water flow accumulation and in the end on the RUSLE slope length factor (L). This was done by using the flow models described in section 3.2.1 to repeatedly calculate drainage areas, each time adding a different layer of randomised errors to the DEM. The resulting drainage areas are then compared with calculations based on the original DEM (without adding random errors), and the average differences are used as an estimate of the DEM uncertainties impact on RUSLE calculations.

The first step of the simulation is creating a layer of random values to add to the DEM. For every run of the simulation a new layer is created, with values between the pre-decided uncertainty limits. The uncertainty of the DEM is believed to be spatially correlated, and this was represented when creating the random layer by not allowing two neighbour cells to differ more in value than by 10% of the value range. This makes it important in which order the cells are assigned values, as spatial patterns will occur. For example, when assigning values from left to right, top to bottom, diagonal patterns occurs (figure 11a) as every cell being assigned a new value will be influenced by the values of its four neighbours to the top and left.

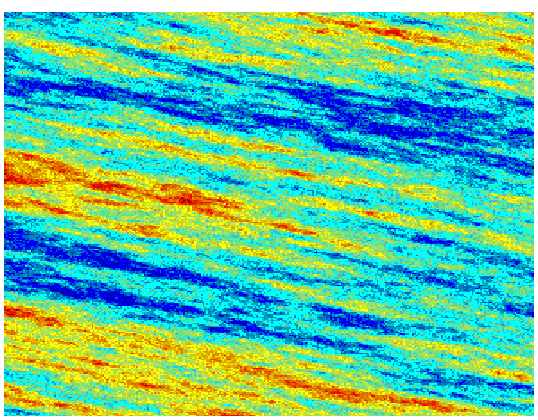


Figure 11a: Spatial pattern of a random number layer created from left to right, top to bottom.

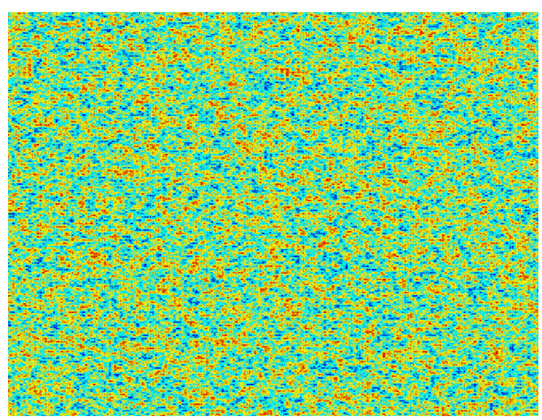


Figure 11b: Spatial pattern of a random number layer created at fixed intervals.

After trying different ways a method was chosen where an initial grid was created with independent random values every 10th cell (as the maximum difference between two cells are 10 %, they need to be at least 10 cells apart to be able to be independent). Next the mid cells in between were assigned random values, while making sure their values did not conflict with the closest neighbour in each direction.

This was repeated until every grid cell had been assigned values. This method minimizes the spatial extent of patterns due to creation methods as no cell is indirectly influenced by an existing value from more than 10 cells away (figure 11b).

When estimating the uncertainty of the DEM, no information could be obtained from NAFRI other than that the DEM was created mainly based upon American topographic maps with a scale of 1:50000. Based upon evaluations of other DEMs created from topographic maps with the same resolution, the RMSE seems to be around 10 meters, but may sometimes exceed 18 meters (Widayati et al. 2004, Zerger, 1999 and Holmes et al. 2000). In order to see how the result from the different flow models are affected by DEM accuracy, the MC simulation was made using hypothetical DEM RMSEs of 5, 10, 15, 20 and 25 meters. Thus, for a RMSE of 5 meters the values of the random fields created were allowed to vary between 5 and –5 meters, with a maximum spatial variation of 0.5 meters between neighbour cells.

After creating the random field, it was added to the elevation values of the DEM and water flow calculations were made using both models described in section 3.2.1. RUSLE slope length values were calculated and saved, and then the DEM was restored. This process was repeated a 100 times for each DEM uncertainty value for a total of 1000 water flow calculations (5 uncertainty values ×100 times × 2 models). See appendix B for complete Matlab code for the MC simulations.

3.5 Estimating the uncertainty of RUSLE

There are several factors contributing to the total uncertainty of the calculated RUSLE erosion, but not all of them are used in this thesis. First of all, the erosion estimate of the RUSLE function would not correspond 100% to reality even if the input data were perfect, since it is an empirical relation derived at several different locations and now applied at yet a different one. Second, when calculating most of the factors several approximations and simplifications are made that adds further to the uncertainty. Third, the input data always includes some uncertainty depending on the care and precision of the sampling. In this thesis we aim to quantify how much the uncertainty of input data affects the erosion estimate, and thus the other uncertainty contributors are ignored.

Uncertainties for the different factors were estimated using the following methods:

- Precipitation (R):

The quality of the measured precipitation at the weather stations used to calculate R is unknown, since no information on the measurement procedures could be obtained. Because of this, only the estimated uncertainty of R due to interpolation was considered for evaluating the RUSLE model.

The interpolation was evaluated by comparing interpolation results with actual R-values at the weather stations. Nine new interpolations of R were made, and during each new interpolation one of the weather station was excluded. The R-value of the omitted weather station was compared with the R-value of the interpolation at the same location, and the RMSE of these comparisons for all nine weather stations was used as a measure of uncertainty for the R interpolation over VPK. This method may result in an overestimation of the R uncertainty, since all the stations are located in a rough circle around VPK (see figure 4). Thus, if one is removed and R is interpolated, it instead becomes more of an extrapolation.

- Slope length (L)

The uncertainty of the L-factor was determined by the MC simulations (section 3.4). The elevation uncertainty of the DEM used for the calculations of the L-factor was unknown, so the RMSE value from the MC simulations with a DEM uncertainty of 20 meters was used. The choice was based on the work of Holmes et al. (2000) who has concluded that even though generally lower, the differences between RTKGPS (Real-Time Kinematic GPS) measurements and USGS (United States Geological Survey) 30-meter DEMs sometimes exceed 18 meters.

We chose not to use the results from the fieldwork to evaluate the DEM since the measurements indicated an unrealistically high uncertainty of the DEM, probably due to the displacement of the sample points (as described in section 3.3.2) and the low accuracy of our GPS for measuring elevation values.

- Slope steepness (S)

Slope steepness uncertainty was measured by comparing the steepness values calculated in ArcGIS (section 3.2.1) with the values measured during the fieldwork. The total uncertainty of the S-factor is equal to the RMSE of slope steepness at all the sample points.

- Soil (K)

Uncertainty of the K-factor was calculated using the fieldwork results (section 3.3.2). During fieldwork, soil clay content was measured at the sample points. Values of K were recalculated at every sample point using field values of clay percentage and equally adjusted values of silt and sand (i.e. if clay contend is 10 % higher according to the field samples, then sand and silt values are each considered to be 5 % lower) from the NAFRI data. The values calculated using field values were compared to the values calculated using NAFRI data, and the RMSE of all the sample points were used as an uncertainty estimate of the K value.

- Land use (C)

Land use at every sample point was classified as one of the categories in table 1. The C-values of those categories were compared with the C-values of the land use in the GIS layer provided by NAFRI, and the RMSE of those comparisons were used as the uncertainty estimate of the C-factor.

- Actual erosion (A) and potential erosion (Ap)

The total uncertainty estimate of the RUSLE erosion values, σ_A is calculated according equation 20 (Eklund, 2003) assuming all the RUSLE factors are uncorrelated:

$$\sigma_A = \sqrt{\sum_{X=R}^{C} \left(\frac{A \cdot \sigma_X}{X} \right)^2} \qquad \text{(Equation 20)}$$

A = RUSLE erosion (ton·ha^{-1}· yr^{-1})

σ_X = Uncertainty estimate of x

X = RUSLE factors [R, K, L, S, C]

3.6 Comparing village interviews with modelled erosion

Based upon their interview answers, the estimated erosion problem of each village was categorised as either zero or one. A value of zero was assigned to villages in which the village chief stated they had no problem whatsoever with erosion. One was assigned to villages were the village chief clearly stated they had a recognizable problem with erosion, and/or a plan to deal with erosion-related problems. Two villages neither stated having or lacking erosion, and these were excluded from the tests.

In order to quantify modelled erosion for the villages, a buffer zone was created in Arc Map around each village with the same area as the village fields (based upon interview answers, see appendix E). Three different methods were used to quantify the erosion inside these buffer zones, and each method was applied to both actual and potential erosion:

- Method 1 summarizes the total erosion within each village buffer.
- Method 2 calculates the average erosion in each village buffer.
- Method 3 summarizes the area above a certain threshold value in each village buffer. The threshold value is equal to the mean erosion in VPK plus one standard deviation.

To test the similarity of the RUSLE erosion and the interview results, a Wilcoxon-Mann-Whitney test was used. The Wilcoxon-Mann-Whitney test is a two-tailed, non-parametric test (Olsson et al., 2005) used to see if the RUSLE erosion estimates are higher at villages with erosion problem according to the interviews. The null hypothesis is that there are no erosion differences between the two village categories. A 0.05 level of statistical significance was used.

4. Results

4.1 RUSLE erosion modeling

The output of the RUSLE erosion calculations results in two 50 meters x 50 meters rasters, showing actual and potential erosion (figures 12 and 13). Calculated erosion rates vary between 0 and 2500 ton ha^{-1} y^{-1}, with an average of 81 ton ha^{-1} y^{-1}. The average erosion rate on agricultural land is 311 ton ha^{-1} y^{-1}.

When calculating potential erosion, values range between 1 and 9500 ton ha^{-1} y^{-1} with an average of 1400 ton ha^{-1} y^{-1}. The main differences between actual and potential erosion are located in the centre of VPK, where most of the agricultural land is situated.

The estimated uncertainties of these calculations are listed in section 4.4.

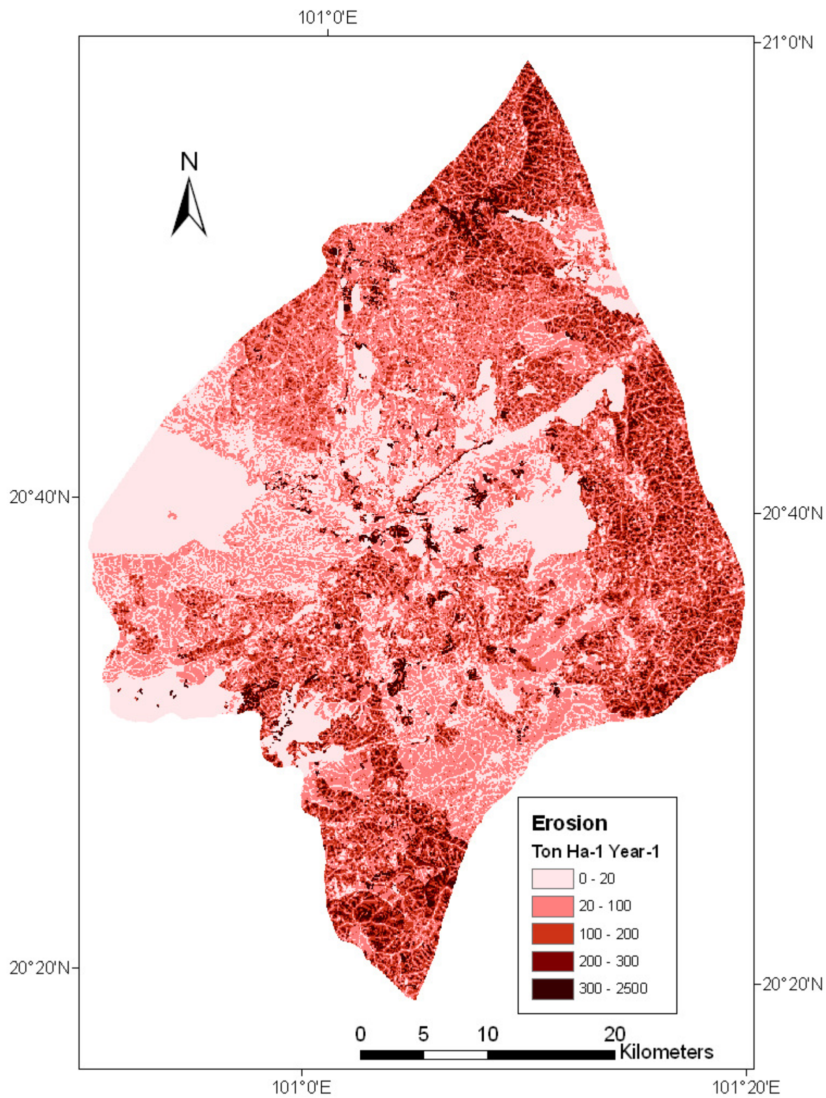


Figure 12: RUSLE calculated actual erosion.

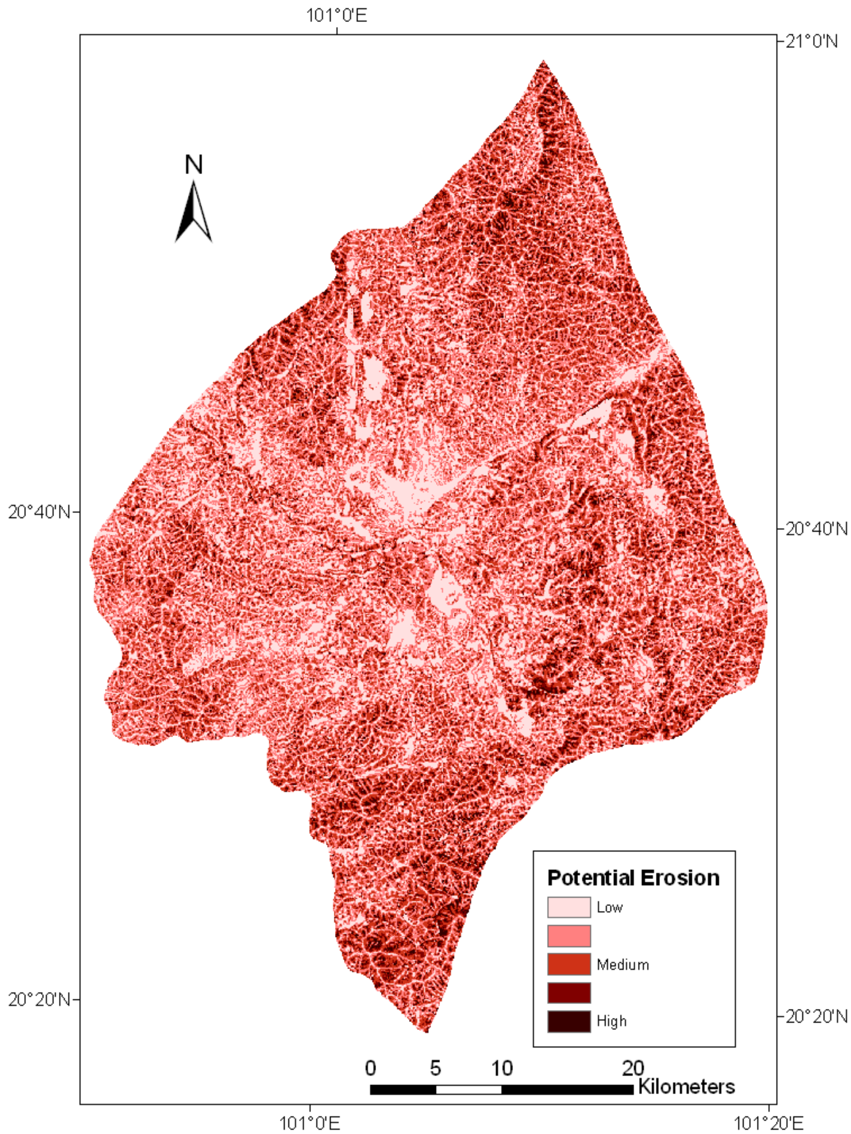


Figure 13: RUSLE calculated potential erosion.

4.2 Monte Carlo simulation

Table 2 and 3 show the result of the MC simulations by describing the differences between the MC output and the original L-values obtained by using the unmodified DEM. All the results listed in the tables are means over the 100 simulations performed for each configuration. Since the maximum change in L is the same for all simulations, dL_{max} = 1.3657, instead the number of cells experiencing maximum change is noted.

The RMSE of the single flow model is more than 50 percent higher than the RMSE of the multi flow model for every DEM uncertainty, although the difference decreases as uncertainty increases. Also, the variation in L is more evenly distributed across the area in the multi-flow model, with fewer cells experiencing maximum or no changes in L.

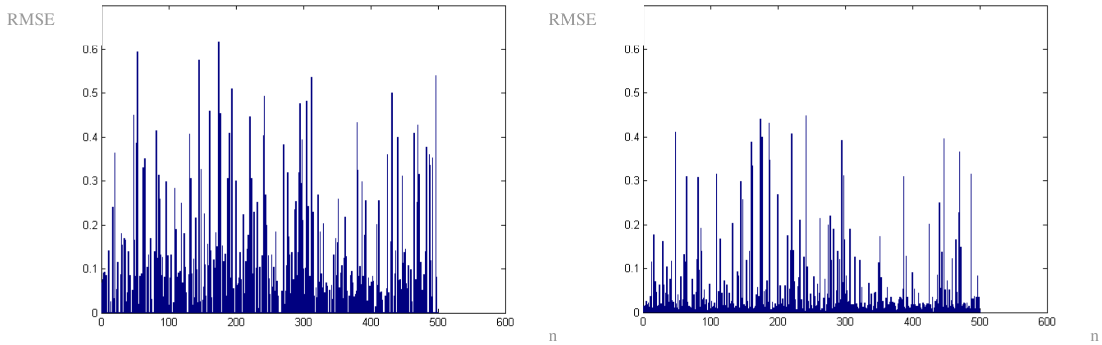
Table 2: Average result of Monte Carlo Simulation, single flow model.

DEM uncertainty	**5 m**	**10 m**	**15 m**	**20 m**	**25 m**
Cells with max diff. in L	1168	1886	2465	2911	3276
Cells with no diff. in L	596550	492670	427110	382640	351340
RMSE of L	0.1882	0.2520	0.2953	0.3281	0.3537
Average difference in L	0.0688	0.1145	0.1494	0.1772	0.1997
807614 cells total, maximum difference in L= 1.3657					

Table 3: Average result of Monte Carlo Simulation, multi flow model.

DEM uncertainty (m)	5	10	15	20	25
Cells with max diff. in L	11.13	19.51	27.22	32.29	37.69
Cells with no diff. in L	72445	63930	56953	50999	45873
RMSE of L	0.1074	0.1598	0.1993	0.2319	0.2598
Average difference in L	0.0384	0.0690	0.0956	0.1195	0.1412
807614 cells total, maximum difference in L = 1.3657					

Figures 14a and 14b shows the RMSE of the calculated L value at 500 different cells, during the MC simulation using a DEM uncertainty of dE = 20 meters. In accordance with the tables above these figures show that the single flow model has more cells experiencing extreme changes, either very high or no changes at all, whereas for the multi flow model the changes are lower and distributed more evenly across the cells. The reason for this is the basic workings of the models. In the single flow model you can change the elevation value of a cell without affecting the flow at all, but once you reach a certain threshold the entire flow will change direction at once.



Figures 14a and 14b: RMSE of the L value at 500 different cells, for the MC runs with dE = 20 meters. Figure 13a (to the left) show RMSE when using the single flow model and figure 13b (to the right) show RMSE using the multi flow model.

4.3 Field work

The results of the fieldwork can be found in Appendix C. The lists contain the measured values of land use, elevation, soil clay content and surface slope, along with sample point number and measured GPS position.

4.4 Estimating the uncertainty of RUSLE

Table 4 shows our estimated uncertainty of the RUSLE factors and the calculated erosion. The uncertainty of A and A-potential is individual for every map cell, so the values given in table 3 are averages for the entire VPK area. The uncertainty of the calculated erosion is ±234 ton ha^{-1} y^{-1}, a value higher than the average calculated erosion of 81 ton ha^{-1} y^{-1} indicating very high uncertainty. The uncertainty of the calculated potential erosion is ±1218 ton ha^{-1} y^{-1}, slightly less than the average value of Ap = 1400 ton ha^{-1} y^{-1}.

In table 5 is listed the uncertainty contribution of the different factors for when calculating total erosion. The C- and S-factors are the main contributors of uncertainty, together accounting for 96.5 % of the total uncertainty with the C factor alone contributing with 84.9 % of the uncertainty. This dominancy of the C factor explains why the relative uncertainty of the potential erosion is so much smaller than for actual erosion.

Table 4: Estimated uncertainty of RUSLE factors.

R	621 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$
K	0.0683 $ton \cdot h \cdot MJ^{-1} \cdot mm^{-1}$
L	0.23190
S	3.0466
C	0.1507
A	234 ton ha^{-1} y^{-1}
Ap	1218 ton ha^{-1} y^{-1}

Table 5: Estimated uncertainty contribution of RUSLE factors (%).

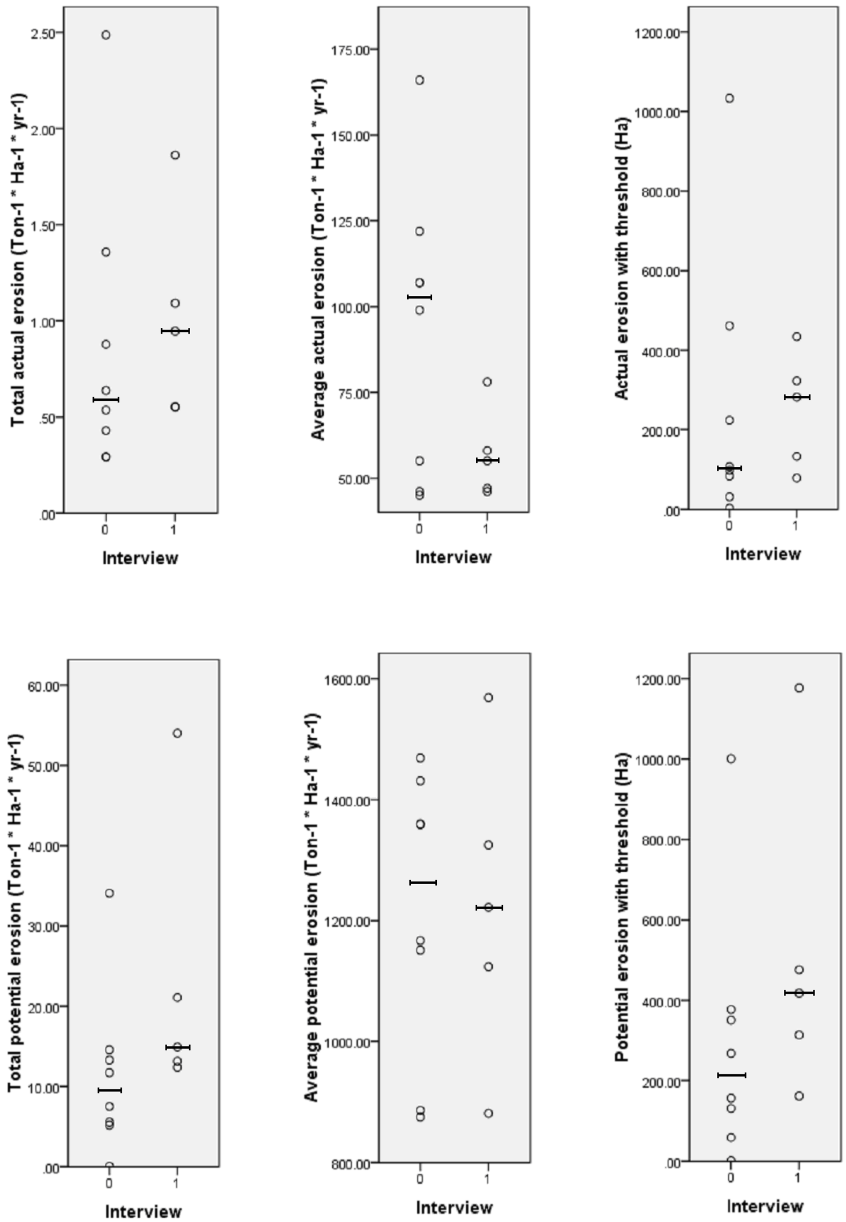
R	0.07
K	1.02
L	2.5
S	11.6
C	84.9

4.5 Comparing interview results with erosion modelling

Figure 15 a to 15 f show the calculated RUSLE erosion values for villages with no erosion according to the interviews (0) compare with those with erosion (1). The figures also show the median RUSLE erosion for villages in each category, shown as a horizontal line. The median was chosen instead of mean since a few villages had very high erosion values, which strongly influences the result. See appendix D for more precise values. For both average actual and potential erosion, (figures 15b and 15e), the medians are higher for villages that stated that they have no erosion. The highest value in the diagrams comes from different villages.

As can be seen in the figures there is no clear relation between modelled erosion and interview estimates. Table 6 shows the P-values from the Wilcoxon-Mann-Whitney test. All P-values are above 0.05, which was chosen as the required level of significance, which means that the null-hypothesis cannot be rejected. The lowest P-values were 0.079 and 0.107 for total potential erosion and potential erosion above a certain threshold respectively.

See appendix E for the villager's answers on the interview questions asked.



Figures 15a-f illustrates the distributions of the erosion values compared with villages answers for a: total actual erosion, b: average actual erosion, c: actual erosion with threshold, d: total potential erosion, e: average potential erosion, and f: potential erosion with threshold. Villages with no erosion according to interviews are marked 0 and villages with erosion are marked 1. The horizontal lines show the median values of erosion.

Table 6. Values from the Wilcoxon-Mann-Whitney's test.

Test Statistics

	Total actual erosion	Total potential erosion	Average actual erosion	Average potential erosion	Actual erosion with threshold	Potential erosion with threshold
P-value	0.306	0.079	0.240	0.884	0.464	0.107

5. Discussion and conclusion

5.1 Interview results

The interview answers are depending on several factors other than the actual erosion. The knowledge about erosion for example seemed to vary strongly between different village representatives depending on village size and the position of the interviewee. If the interviewees have low knowledge about erosion they might be less likely to see it as a problem and be prone to focus more on visible problems such as drought or wild animals. This might still serve as an indicator of erosion levels though, as villages with high erosion rates are more likely to have good knowledge about it. Another influencing factor is the time aspect of the interviewees' knowledge of erosion. Some villagers described how their problem with erosion had changed over time, for example by the construction of the new road going through the district, while others seemed to omit recent fluctuations and only focused on the present situation.

A major problem when performing interviews was the language barriers. The questions and answers had to be translated at least once from English to Lao, but often a second time as well by another translator from Lao to the local language or dialect. This makes it hard to determine how much the villagers have understood of the intentions with the questions, especially since the theoretical knowledge about erosion was low for both villagers and the person performing the second part of translation. In order to reduce this problem and make it easier to evaluate the answers, the interviews were performed more as discussions than series of predefined questions and answers.

Comparisons between the interview results and modeled erosion show no correlation at all. This is not unexpected, considering the large uncertainty of the RUSLE results and the problems discussed in this section.

5.2 RUSLE factors

5.2.1 Rainfall

The RUSLE rainfall factor was interpolated using data from nine weather stations. Since no precipitation data from Burma could be obtained, the interpolation lacked points in the northwest direction (figure 4). This is not optimal condition for interpolation, but the impact on the final erosion result is small compared to other error sources as R is estimated to contribute with only 0.07 percent of the total error.

The interpolation gives a smooth surface as result, with R varying with less than 10% within VPK. This is not the case in reality where factors such as local topography and vegetation affects rainfall pattern. There are models that incorporates these elements to produce a rainfall surface more detailed and realistic than by interpolation, but these were not used in this study due to lack of time and knowledge.

The R-factor was calculated using relations derived by Shamshad (2008) in Malaysia. Shamshad concludes the correlation between EI_{30} calculated with equation 8 and values calculated using rainfall gauges to be $R^2 = 0.81$ for Malaysia. But since rainfall patterns throughout the year varies between Laos and Malaysia, the R^2 values might be lower for Laos.

5.2.2 The S-factor

The S-factor is fully dependent on slope steepness. When using a DEM to calculate slope steepness, there is sometimes a smoothing of the result, as the surface shape between elevation values is unknown. This smoothing effect occurs when the slope changes direction between two adjacent elevation points, as can be seen in figure 16.

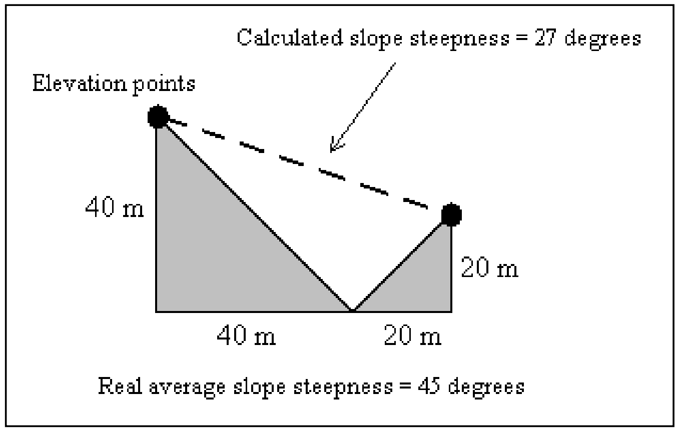


Figure 16: Example of slope underestimation when calculated using elevation points.

The end result is a raster with lower slope steepness than in reality, an error that increases with coarser cell size as the percentage of cells with changing slope direction increases.

During slope measurements at our 52 sample points, the slope changed direction at 5 locations. The average slope underestimation at these 5 locations ranges between 13 - 44 percent or 1.1 - 5.1 degrees over 25 meters.

5.2.3 The L-factor

- Flow models

There are several other flow models available for calculating the drainage area to each raster cell. The more advanced models are hybrid models that switch between single- and multi-flow depending on the topography, choosing the single flow version if the landscape is concave as this cases the water flow to be concentrated into a single channel. An example of a hybrid model is described in (Pilesjö et al., 1998).

When programming the flow models, a few solutions were made simple due to lack of time and insufficient programming skills. For example, the water flow over flat areas sometimes results in sinks if the flat area is large enough. This could have been avoided by an algorithm to define the flow over the flat area towards lower elevation. Spending more time to solve problems like this might produce slightly more realistic flow results.

5.3 Comparisons with related studies

Results from field measurements of erosion in other studies show that erosion rates in South East Asia normally lies between 0 – 40 ton ha^{-1} y^{-1}, while the results of the RUSLE model predicts average erosion rates of 311 ton ha^{-1} y^{-1} on agricultural land. This is almost certainly an overestimation of the actual erosion, with a few of the factors responsible. The main factor likely to contribute to an overestimation is the slope length L-factor. Due to the coarse grid size of the DEM, the values of L easily get very large. L also has a minimum value of 1.5 due to its grid size, a value that realistically should have been much smaller and thus increases the mean calculated erosion. Also, the upper limit of the water contributing area was chosen higher than the recommendations by Renard et al. (1997). Choosing a lower limit might result in more realistic values, but would reduce the ability to use the results for comparative purposes since a large part of the area would receive a maximum L-value.

Other contributing factors to the high values of erosion may be the steep terrain in VPK, resulting in a high model estimate that is not necessarily wrong, and the exclusion of the P-factor, which increases erosion estimates on agricultural land.

5.4 Conclusions

With the low accuracy of the input data presently available in Laos, RUSLE is unable to predict actual erosion amounts on any larger scale. The main reason for this is the unpredictability of land use combined with its large influence on erosion estimates, causing the RUSLE land use factor to contribute with 85 % of the uncertainty of RUSLE erosion estimates. This uncertainty in land use is mostly due to the shifting cultivation practised by farmers in Laos. The individual variations in length of fallow and farming practises combined with changing village borders and repeated land redistribution makes it virtually impossible to predict land use and ensures that any land use survey made will be outdated sooner or later. In the interviews some of the village leaders said they were trying to make farming practises in their villages more centralised, a reform which is currently also encouraged by the Lao government in its attempts to increase the output of Laotian agriculture. This centralization will reduce the unpredictability of land use slightly if adopted by all the villages, but as long as the shifting cultivation remains land use uncertainty will continue to be a large contributor to RUSLE uncertainty. This is a problem that arises from our way of evaluating the RUSLE model. We aimed at estimating erosion values for today by using data that is about 5 years old. If the aim instead had been to make an estimate of the amount of erosion five years ago, at the time the land use map was made, the accuracy probably would have been much better. But this would have needed an accuracy estimate of the input data from the time it was made, especially for the land use since it is the factor most likely to change over time.

Since land use is the largest contributor to erosion uncertainty, calculations of potential erosion instead are much more accurate. The uncertainty is still large enough to make numerical estimates invalid, but calculated potential erosion may be useful for comparative purposes.

Looking at the results of the MC simulation, the multi-flow model is less dependant on DEM uncertainty producing more consistent results (figure 13). The difference in consistency between single- and multi flow models remained constant with increasing DEM uncertainty. Using the multi flow model the variation was distributed more evenly among the cells compared to the single flow model. The RMSE of the water flow simulations, given a DEM uncertainty of 20 meters, were 0.3281 for the single flow model and 0.2319 for the multi flow model. This is to be compared with the values of L that ranges between 0.213 and 1.58. All these results confirm the choice of the multi flow model for use in Laos.

In order to produce reliable results with the RUSLE model, several improvements need to be made. The most important improvement is the DEM, which needs a higher spatial resolution. Preferably the DEM should have at least 5 meters resolution, to make it suitable for water flow and steepness calculations. The R-factor should be calculated from EI_{30}-Fi relations derived in Laos, or even preferably by using detailed precipitation data to calculate EI_{30} directly. The soil data is probably hard to improve without heavy investment costs. Nevertheless the improvements above might be enough to give accurate values of potential erosion and, assuming information about support practice factors can be obtained, also valid numerical estimates of erosion.

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146 af Wåhlberg, O. (2008): Tillämpning av GIS inom planering och naturvård - En metodstudie i Malmö kommun.
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151 Lyshede, Bjarne Munk (2008): Rapeseed Biodiesel and Climate Change Mitigation in the EU.
152 Sandell, Johan (2008): Detecting land cover change in Hambantota district, Sri Lanka, using remote sensing & GIS.
153 Elgh Dalgren, Sanna (2008): vattennivåförändringar I Vänern och dess inverkan på samhällsbyggnaden I utsatta städer
154 Karlgård, Julia (2008): Degrading palsa mires i northern Europe: changing vegetation in an altering climate and its potential impact on greenhouse gas fluxes.

Appendices A – E

A. Village interview questions

1. Village name and coordinated, date of interview, name and title of person to be interview.
2. How big is the village population?
3. How big is the land area?
4. What different crops are being grown?
5. Are any crops prioritized?
6. Are you selling outside the village?
7. Is erosion a problem?
8. Has the erosion gotten worse during the last 10 years?
9. Is the erosion visible?
10. Rate the impact of drought, crops diseases, land shortage and erosion, by the most affecting first.
11. Is anything done to prevent erosion?
12. How is erosion affecting the village?

B. Matlab code

MonteCarlo.m

(Performs the Monte Carlo Simulations)

```
repetitions = 100;
for uncert = 5:5:25


    m(1) = uncert;
    m(2) = -uncert;
    dE = uncert * 2/5;

    for q = 1:repetitions

    clc;
    filnamn = 'c:\tempdata\matlab-kod\dem_vpk.txt';
    lines = 6;

    fid=fopen(filnamn);
    rows = textscan(fid, '%s %f',lines);
    DEM_raw = textscan(fid,'%f','HeaderLines',1);
    DEM = DEM_raw{1};
    DEM = reshape(DEM,rows{2}(1),rows{2}(2));
    fclose(fid);

    sinks
    DEM_random
    Single_flow
    Multi_flow

    add2 = '';
    add1 = '';
    if q<10
        add2 = '00';
    elseif q<100
        add2 = '0';
    end
    if m(1)<10
        add1 = '0';
    end

    namn(q,:,1,uncert/5) = ['c:\tempdata\Matlab-kod\MCs\' 'Sf' add1
int2str(m(1)) '_' add2 int2str(q) '.mat'];
    save(namn(q,:,1,uncert/5),'flowmod')

    fid = fopen(namn(q,:,1,uncert/5),'w+t');
    for x = 1:6
        fprintf(fid,'%-14s%-14.12g\n',char(rows{1}(x)),rows{2}(x));
    end
    for x = 1:length(flowmod(1,:))
        fprintf(fid,'%d ',flowmod(:,x)');
        fprintf(fid,'\n');
    end
    fclose(fid);

    namn(q,:,2,uncert/5) = ['c:\tempdata\Matlab-kod\MCs\' 'Mf' add1
int2str(m(1)) '_' add2 int2str(q) '.mat'];
```

```
    save(namn(q,:,2,uncert/5),'flowmod2')

    fid = fopen(namn(q,:,2,uncert/5),'w+t');
    for x = 1:6
        fprintf(fid,'%-14s%-14.12g\n',char(rows{1}(x)),rows{2}(x));
    end
    for x = 1:length(flowmod2(1,:))
        fprintf(fid,'%d ',flowmod2(:,x)');
        fprintf(fid,'\n');
    end
    fclose(fid);

    end
end
antal = repetitions;
save('namn','namn','antal')
clear
```

DEM_random.m

(Creates a layer of random errors to add to the DEM during the MC calculations)

```
size(1) = rows{2}(1);
size(2) = rows{2}(2);

fel = zeros(size(1),size(2));
steps = ceil((m(1)-m(2))/dE);

add = fix(steps/2);
odd = steps-2*add;
steps = steps + odd;
add = steps/2;

for x = 0:fix(size(1)/steps)
    for y = 0:fix(size(2)/steps)
        valu = normrnd(0,m(1)/3);
        while (valu < m(2) || valu > m(1))
            valu = normrnd(0,m(1)/3);
        end
        fel(x*steps+1,y*steps+1)= valu;

    end
end

for x = 0:fix(size(1)/steps-1)
    for y = 0:fix(size(2)/steps-1)

            maxi = min([fel(x*steps+1,y*steps+1)+dE*add,
fel((x+1)*steps+1,y*steps+1)+dE*add,
fel(x*steps+1,(y+1)*steps+1)+dE*add,
fel((x+1)*steps+1,(y+1)*steps+1)+dE*add, ]);
            mini = max([fel(x*steps+1,y*steps+1)-dE*add,
fel((x+1)*steps+1,y*steps+1)-dE*add, fel(x*steps+1,(y+1)*steps+1)-
dE*add, fel((x+1)*steps+1,(y+1)*steps+1)-dE*add, ]);
            if maxi > m(1)
                maxi = m(1);
            end
            if mini < m(2)
                mini = m(2);
            end
            fel(x*steps+1+add,y*steps+1+add)= rand*(maxi-mini)+mini;
    end
end


for x = 1:fix(size(1)/steps-1)
    for y = 1:fix(size(2)/steps-1)

            maxi = min([fel(x*steps+1,y*steps+1)+dE*add,
fel((x+1)*steps+1,y*steps+1)+dE*add,
fel(x*steps+1+add,y*steps+1+add)+dE*add, fel(x*steps+1+add,(y-
1)*steps+1+add)+dE*add, ]);
            mini = max([fel(x*steps+1,y*steps+1)-dE*add,
fel((x+1)*steps+1,y*steps+1)-dE*add,
fel(x*steps+1+add,y*steps+1+add)-dE*add, fel(x*steps+1+add,(y-
1)*steps+1+add)-dE*add, ]);
            if maxi > m(1)
                maxi = m(1);
```

```
            end
            if mini < m(2)
                mini = m(2);
            end
            fel(x*steps+1+add,y*steps+1)= rand*(maxi-mini)+mini;

            maxi = min([fel(x*steps+1,y*steps+1)+dE*add,
fel(x*steps+1,(y+1)*steps+1)+dE*add,
fel(x*steps+1+add,y*steps+1+add)+dE*add, fel((x-
1)*steps+1+add,y*steps+1+add)+dE*add,fel(x*steps+1+add,y*steps+1)+dE*
add, fel(x*steps+1-add,y*steps+1)+dE*add]);
            mini = max([fel(x*steps+1,y*steps+1)-dE*add,
fel(x*steps+1,(y+1)*steps+1)-dE*add,
fel(x*steps+1+add,y*steps+1+add)-dE*add, fel((x-
1)*steps+1+add,y*steps+1+add)-dE*add,fel(x*steps+1+add,y*steps+1)-
dE*add, fel(x*steps+1-add,y*steps+1)-dE*add ]);
            if maxi > m(1)
                maxi = m(1);
            end
            if mini < m(2)
                mini = m(2);
            end
            fel(x*steps+1,y*steps+1+add)= rand*(maxi-mini)+mini;

    end
end

a = add;
b = 0;
while a > 1
    b = b+1;
    a = fix(a/2);
end
    w1 = fix(size(1)/steps-1);
    w2 = fix(size(2)/steps-1);
    add2 = steps;

for u = 1:b
    odd2 = add2 - 2*fix(add2/2);
    odd = add - 2*fix(add/2);
    add2 = add;
    add = fix(add/2);
    steps = add2;
    w1 = fix(size(1)/steps-2);
    w2 = fix(size(2)/steps-2);

        for x = 1:w1
        for y = 1:w2
            x2 = x+fix(0.5*x*odd2);
            y2 = y+fix(0.5*y*odd2);
                maxi = min([fel(x2*steps+1,y2*steps+1)+dE*add,
fel(x2*steps+1+add2,y2*steps+1)+dE*(add+odd),
fel(x2*steps+1+add2,y2*steps+1+add2)+dE*(add+odd),
fel(x2*steps+1,y2*steps+1+add2)+dE*(add+odd),fel(x2*steps+1+add,y2*st
eps+1-add-odd)+dE*add2,fel(x2*steps+1-add-
odd,y2*steps+1+add)+dE*add2]);
                mini = max([fel(x2*steps+1,y2*steps+1)-dE*add,
fel(x2*steps+1+add2,y2*steps+1)-dE*(add+odd),
fel(x2*steps+1+add2,y2*steps+1+add2)-dE*(add+odd),
fel(x2*steps+1,y2*steps+1+add2)-
```

```
dE*(add+odd),fel(x2*steps+1+add,y2*steps+1-add-odd)-
dE*add2,fel(x2*steps+1-add-odd,y2*steps+1+add)-dE*add2]);
                if maxi > m(1)
                    maxi = m(1);
                end
                if mini < m(2)
                    mini = m(2);
                end
                fel(x2*steps+1+add,y2*steps+1+add)= rand*(maxi-
mini)+mini;

                if odd == 1
                maxi = min([fel(x2*steps+1,y2*steps+1)+dE*add,
fel(x2*steps-add,y2*steps-add)+dE, fel(x2*steps+1-add,y2*steps-
add)+dE, fel(x2*steps-add,y2*steps+1-add)+dE,
fel(x2*steps+1+add,y2*steps-add)+dE*2*add,fel(x2*steps-
add,y2*steps+1+add)+dE*2*add]);
                mini = max([fel(x2*steps+1,y2*steps+1)-dE*add,
fel(x2*steps-add,y2*steps-add)-dE, fel(x2*steps+1-add,y2*steps-add)-
dE, fel(x2*steps-add,y2*steps+1-add)-dE, fel(x2*steps+1+add,y2*steps-
add)-dE*2*add,fel(x2*steps-add,y2*steps+1+add)-dE*2*add]);
                if maxi > m(1)
                    maxi = m(1);
                end
                if mini < m(2)
                    mini = m(2);
                end
                fel(x2*steps+1-add,y2*steps+1-add)= rand*(maxi-
mini)+mini;

                maxi = min([fel(x2*steps+1,y2*steps+1)+dE*add,
fel(x2*steps+1+add2,y2*steps+1)+dE*(add+1),
fel(x2*steps+1+add,y2*steps+1+add)+dE*2*add, fel(x2*steps+1-
add,y2*steps+1-add)+dE*2*add, fel(x2*steps+1+add,y2*steps-
add)+dE,fel(x2*steps+2+add,y2*steps-add)+dE]);
                mini = max([fel(x2*steps+1,y2*steps+1)-dE*add,
fel(x2*steps+1+add2,y2*steps+1)-dE*(add+1),
fel(x2*steps+1+add,y2*steps+1+add)-dE*2*add, fel(x2*steps+1-
add,y2*steps+1-add)-dE*2*add, fel(x2*steps+1+add,y2*steps-add)-
dE,fel(x2*steps+2+add,y2*steps-add)-dE]);
                if maxi > m(1)
                    maxi = m(1);
                end
                if mini < m(2)
                    mini = m(2);
                end
                fel(x2*steps+1+add,y2*steps+1-add)= rand*(maxi-
mini)+mini;

                maxi = min([fel(x2*steps+1,y2*steps+1)+dE*add,
fel(x2*steps+1,y2*steps+1+add2)+dE*(add+1),
fel(x2*steps+1+add,y2*steps+1+add)+dE*2*add, fel(x2*steps+1-
add,y2*steps+1-add)+dE*2*add, fel(x2*steps-add,y2*steps+1-add)+dE]);
                mini = max([fel(x2*steps+1,y2*steps+1)-dE*add,
fel(x2*steps+1,y2*steps+1+add2)-dE*(add+1),
fel(x2*steps+1+add,y2*steps+1+add)-dE*2*add, fel(x2*steps+1-
add,y2*steps+1-add)-dE*2*add, fel(x2*steps-add,y2*steps+1-add)-dE]);
                if maxi > m(1)
                    maxi = m(1);
                end
                if mini < m(2)
```

```
                    mini = m(2);
                end
                fel(x2*steps+1-add,y2*steps+1+add)= rand*(maxi-
mini)+mini;

                end

        end
    end
    for x = 1:w1
        for y = 1:w2
            x2 = x+fix(0.5*x*odd2);
            y2 = y+fix(0.5*y*odd2);
                maxi = min([fel(x2*steps+1,y2*steps+1)+dE*add,
fel(x2*steps+1+add2,y2*steps+1)+dE*(add+odd),
fel(x2*steps+1+add,y2*steps+1+add)+dE*add,
fel(x2*steps+1+add,y2*steps+1-add)+dE*(add),
fel(x2*steps+1,y2*steps+1-add)+dE*add,
fel(x2*steps+1+add2,y2*steps+1-add)+dE*(add+odd)]);
                mini = max([fel(x2*steps+1,y2*steps+1)-dE*add,
fel(x2*steps+1+add2,y2*steps+1)-dE*(add+odd),
fel(x2*steps+1+add,y2*steps+1+add)-dE*add,
fel(x2*steps+1+add,y2*steps+1-add)-dE*(add),
fel(x2*steps+1,y2*steps+1-add)-dE*add,
fel(x2*steps+1+add2,y2*steps+1-add)-dE*(add+odd)]);
                if maxi > m(1)
                    maxi = m(1);
                end
                if mini < m(2)
                    mini = m(2);
                end
                fel(x2*steps+1+add,y2*steps+1)= rand*(maxi-
mini)+mini;

                maxi = min([fel(x2*steps+1,y2*steps+1)+dE*add,
fel(x2*steps+1,y2*steps+1+add2)+dE*(add+odd),
fel(x2*steps+1+add,y2*steps+1+add)+dE*add, fel(x2*steps+1-
add,y2*steps+1+add)+dE*(add), fel(x2*steps+1+add,y2*steps+1)+dE*add,
fel(x2*steps+1-add,y2*steps+1)+dE*add]);
                mini = max([fel(x2*steps+1,y2*steps+1)-dE*add,
fel(x2*steps+1,y2*steps+1+add2)-dE*(add+odd),
fel(x2*steps+1+add,y2*steps+1+add)-dE*add, fel(x2*steps+1-
add,y2*steps+1+add)-dE*(add), fel(x2*steps+1+add,y2*steps+1)-dE*add,
fel(x2*steps+1-add,y2*steps+1)-dE*add]);
                if maxi > m(1)
                    maxi = m(1);
                end
                if mini < m(2)
                    mini = m(2);
                end
                fel(x2*steps+1,y2*steps+1+add)= rand*(maxi-
mini)+mini;

                if odd == 1

                    maxi = min([fel(x2*steps+1,y2*steps+1)+dE*add,
fel(x2*steps-add,y2*steps+1)+dE, fel(x2*steps+1-add,y2*steps+1-
add)+dE*add, fel(x2*steps+1-add,y2*steps+1+add)+dE*(add),
fel(x2*steps+1,y2*steps-add)+dE*(add+odd),
```

```
fel(x2*steps+1,y2*steps+1+add)+dE*(add),fel(x2*steps-add,y2*steps+1-
add)+dE*(add),fel(x2*steps-add,y2*steps+1+add)+dE*(add)]);
                    mini = max([fel(x2*steps+1,y2*steps+1)-dE*add,
fel(x2*steps-add,y2*steps+1)-dE, fel(x2*steps+1-add,y2*steps+1-add)-
dE*add, fel(x2*steps+1-add,y2*steps+1+add)-dE*(add),
fel(x2*steps+1,y2*steps-add)-dE*(add+odd),
fel(x2*steps+1,y2*steps+1+add)-dE*(add),fel(x2*steps-add,y2*steps+1-
add)-dE*(add),fel(x2*steps-add,y2*steps+1+add)-dE*(add)]);
                    if maxi > m(1)
                        maxi = m(1);
                    end
                    if mini < m(2)
                        mini = m(2);
                    end
                    fel(x2*steps+1-add,y2*steps+1)= rand*(maxi-
mini)+mini;

                    maxi = min([fel(x2*steps+1,y2*steps+1)+dE*add,
fel(x2*steps+1,y2*steps-add)+dE, fel(x2*steps+1-add,y2*steps+1-
add)+dE*add, fel(x2*steps+1+add,y2*steps+1-add)+dE*(add),
fel(x2*steps+1-add,y2*steps+1)+dE*add,
fel(x2*steps+1+add,y2*steps+1)+dE*(add),fel(x2*steps+1-add,y2*steps-
add)+dE*(add),fel(x2*steps+1+add,y2*steps-add)+dE*(add)]);
                    mini = max([fel(x2*steps+1,y2*steps+1)-dE*add,
fel(x2*steps+1,y2*steps-add)-dE, fel(x2*steps+1-add,y2*steps+1-add)-
dE*add, fel(x2*steps+1+add,y2*steps+1-add)-dE*(add), fel(x2*steps+1-
add,y2*steps+1)-dE*add, fel(x2*steps+1+add,y2*steps+1)-
dE*(add),fel(x2*steps+1-add,y2*steps-add)-
dE*(add),fel(x2*steps+1+add,y2*steps-add)-dE*(add)]);
                    if maxi > m(1)
                        maxi = m(1);
                    end
                    if mini < m(2)
                        mini = m(2);
                    end
                    fel(x2*steps+1,y2*steps+1-add)= rand*(maxi-
mini)+mini;

                end
            end
        end
    end
```

sinks.m

(Finds and fills all single raster cells that are surrounded by cells with higher elevation values)

```
c = 0;
clear rast;
rast = zeros(length(DEM(:,1))-2,length(DEM(1,:))-2,9);
maxX = length(rast(:,1,1));
maxY = length(rast(1,:,1));
totXY = maxX*maxY;

for x = -1:1
    for y = -1:1
            c= c+1;
            rast(:,:,c) = DEM(x+2:x+end-1,y+2:y+end-1);
    end
end
rast = reshape(rast,totXY,9);
rast(:,10) = min(rast(:,[1 2 3 4 6 7 8 9]),[],2);
x2 = find(rast(:,10) > rast(:,5));
rast(x2,5) = rast(x2,10);
rast = reshape(rast,maxX,maxY,10);
DEM(2:end-1,2:end-1) = rast(:,:,5);
```

Single_flow.m

(Calculate drainage areas using the single flow model)

```
c = 0;
rast = zeros(length(DEM(:,1))-2,length(DEM(1,:))-2,9);
maxX = length(rast(:,1,1));
maxY = length(rast(1,:,1));
totXY = maxX*maxY;

for x = -1:1
    for y = -1:1
        if  x*y~=x+y
            c= c+1;
            rast(:,:,c) = DEM(2:end-1,2:end-1) - DEM(x+2:x+end-
1,y+2:y+end-1);
        end
    end
end

rast = reshape(rast,totXY,9);
rast(:,[1 3 6 8]) = rast(:,[1 3 6 8])/sqrt(2);
rast(:,9) = max(rast(:,1:8),[],2);

lut(:,1) = rast(:,1) + rast(:,2) + rast(:,3) - rast(:,6) - rast(:,7)
- rast(:,8);
lut(:,2) = rast(:,8) + rast(:,5) + rast(:,3) - rast(:,1) - rast(:,4)
- rast(:,6);

x2 = find(lut(1:end-maxX,2) == 0 & lut(1:end-maxX,1) == 0);
lut(x2,2) = -(rast(x2-maxX-1,1) + rast(x2-maxX-1,4) + rast(x2-maxX,4)
+ rast(x2-maxX+1,4) + rast(x2-maxX+1,4)) + (rast(x2+maxX-1,3) +
rast(x2+maxX-1,5) + rast(x2+maxX,5) + rast(x2+maxX+1,5) +
rast(x2+maxX+1,8)) ;
lut(x2,1) = rast(x2-maxX-1,1) + rast(x2-maxX-1,2) + rast(x2-1,2) +
rast(x2+maxX-1,2) + rast(x2+maxX-1,3) - (rast(x2-maxX+1,6) + rast(x2
- maxX + 1,7) + rast(x2 + 1,7) + rast(x2 + maxX +1,7) + rast(x2 +
maxX + 1,8));

x2 = find(lut(:,2) ~= 0);
rast(x2,10) = atan(lut(x2,1)./lut(x2,2));

x3 = find(rast(x2,10) < 0);
rast(x2(x3),10) = 2*pi + rast(x2(x3),10);

x3 = find(lut(x2,2) < 0 & lut(x2,1) > 0);
rast(x2(x3),10) = rast(x2(x3),10) - pi;

x3 = find(lut(x2,2) < 0 & lut(x2,1) < 0);
rast(x2(x3),10) = rast(x2(x3),10) + pi;

rast(x2,10) = int16(rast(x2,10) * 4/pi);

x2 = find(lut(:,2) == 0 & lut(:,1) ~= 0);
rast(x2,10) = 4 - 2*(lut(x2,1)./abs(lut(x2,1)));

x2 = find(lut(:,2) == 0 & lut(:,1) == 0);
rast(x2,10) = 9;
```

```
tempy = rast(:,10);
for x = 0:9
    x2 = find(tempy == x);
    switch x
        case 0
            rast(x2,10) = 5;
        case 1
            rast(x2,10) = 3;
        case 2
            rast(x2,10) = 2;
        case 3
            rast(x2,10) = 1;
        case 4
            rast(x2,10) = 4;
        case 5
            rast(x2,10) = 6;
        case 6
            rast(x2,10) = 7;
        case 7
            rast(x2,10) = 8;
        case 8
            rast(x2,10) = 5;
        case 9
            rast(x2,10) = 0;
    end
end

clear tempy;
clear lut;

rast(:,11) = 0;
for x = 1:8
    rast(:,11) = rast(:,11) + (rast(:,x)==rast(:,9));
end

problem = rast(:,11)>1;
problem2 = rast(problem,1:8);
for x = 1:8
    rast(:,x) = rast(:,x)==rast(:,9);
end
felkoll = rast(:,11)-sum(rast(:,1:8),2);

for x = 1:8
        rast(problem,x) = (rast(problem,10)==x).*(problem2(:,x)>0);
end

rast = reshape(rast,maxX,maxY,11);

     g = zeros(4,1);
    c = 0;
    rast(:,:,11) = 0;
    for x = -1:1
        for y = -1:1
            if x+y ~= x*y
                if x == -1
                    g(1)=2;
                else
                    g(1)=1;
```

```
                end
                 if x == 1
                    g(2)=maxX-1;
                else
                    g(2)=maxX;
                 end
                if y == -1
                    g(3)=2;
                else
                    g(3)=1;
                end
                if y == 1
                    g(4)=maxY-1;
                else
                    g(4)=maxY;
                end
                c = c+1;

                rast(g(1):g(2),g(3):g(4),11) =
rast(g(1):g(2),g(3):g(4),11) + (2 == ( rast(g(1):g(2),g(3):g(4),c) +
rast(g(1)+x:g(2)+x,g(3)+y:g(4)+y,9-c) ));
            end
        end
    end
    rast = reshape(rast,totXY,11);

problem = rast(:,11)>0;
rast(problem,1:8) = 0;

rast = reshape(rast,maxX,maxY,11);
flowmod = DEM;
flowmod(:,:) = 1;
rast(:,:,11) = 0;

tempy = flowmod(2:end-1,2:end-1);
while sum(sum(tempy)) ~= 0
    c = 0;
    rast(:,:,11) = flowmod(2:end-1,2:end-1);
    flowmod(:,:) = 1;
    for x = -1:1
        for y = -1:1
            if x+y ~= x*y
                c = c+1;
                flowmod(2+x:end-1+x,2+y:end-1+y) = flowmod(2+x:end-
1+x,2+y:end-1+y) + rast(:,:,11).*rast(:,:,c);
            end
        end
    end
    tempy = flowmod(2:end-1,2:end-1) - rast(:,:,11);
    fel2 = find(tempy~=0);
     length(fel2)

end
```

Multi_flow.m
(Calculate drainage areas using the multi flow model)

```
c = 0;
rast = zeros(length(DEM(:,1))-2,length(DEM(1,:))-2,9);
for x = -1:1
    for y = -1:1
        if  x*y~=x+y
            c= c+1;
            rast(:,:,c) = DEM(2:end-1,2:end-1) - DEM(x+2:x+end-
1,y+2:y+end-1);
        end
    end
end

maxX = length(rast(:,1,1));
maxY = length(rast(1,:,1));
totXY = maxX*maxY;
rast = reshape(rast,totXY,9);

rast(:,[1 3 6 8]) = rast(:,[1 3 6 8])/sqrt(2);
rast(:,9) = max(rast(:,1:8),[],2);

x2 = find(rast(:,9) > 0);
for x = 1:8
    x3 = find(rast(x2,x) < 0);
    rast(x2(x3),x) = 0;
end

summan = sum(rast(x2,1:8),2);
for x = 1:8
    rast(x2,x) = rast(x2,x)./summan;
end

x2 = find(rast(:,9) == 0);
tempy = zeros(length(x2),8);
for x = 1:8
    tempy(:,x) = rast(x2,x) == rast(x2,9);
end
rast(x2,1:8) = tempy;
clear tempy

summan = sum(rast(x2,1:8),2);
for x = 1:8
    rast(x2,x) = rast(x2,x)./summan;
end

rast = reshape(rast,maxX,maxY,9);
g = zeros(4,1);
tempy3 = rast(:,:,1:8);
    c = 0;
    rast(:,:,10) = 0;
    for x = -1:1
        for y = -1:1
            if x+y ~= x*y
                if x == -1
                    g(1)=2;
                else
                    g(1)=1;
```

```
                    end
                     if x == 1
                        g(2)=maxX-1;
                    else
                        g(2)=maxX;
                     end
                    if y == -1
                        g(3)=2;
                    else
                        g(3)=1;
                    end
                    if y == 1
                        g(4)=maxY-1;
                    else
                        g(4)=maxY;
                    end
                    c = c+1;
                    tempy =  rast(g(1):g(2),g(3):g(4),c)>0 &
(rast(g(1)+x:g(2)+x,g(3)+y:g(4)+y,9-c)>0) ;

                    tempy2 = rast(g(1):g(2),g(3):g(4),c);
                    tempy2(tempy) = 0;
                    tempy3(g(1):g(2),g(3):g(4),c) = tempy2;
                    clear tempy2
                    clear tempy
                end
            end
        end
rast(:,:,1:8) = tempy3;

flowmod2 = DEM;
flowmod2(:,:) = 1;
rast(:,:,11) = 0;
tempy = flowmod2(2:end-1,2:end-1);

while sum(sum(tempy)) ~= 0
    c = 0;
    rast(:,:,11) = flowmod2(2:end-1,2:end-1);
    flowmod2(:,:) = 1;
    for x = -1:1
        for y = -1:1
            if x+y ~= x*y
                c = c+1;
                flowmod2(2+x:end-1+x,2+y:end-1+y) = flowmod2(2+x:end-
1+x,2+y:end-1+y) + rast(:,:,11).*rast(:,:,c);
            end
        end
    end
    tempy = flowmod2(2:end-1,2:end-1) - rast(:,:,11);
    fel2 = find(tempy~=0);
          length(fel2)
end
```

C. Sample point values from fieldwork

Sample point	Staring at	Distance from start (km)	Latitude (dec. deg.)	Longitude (dec. deg.)	Elevation (m)	Land use	Direction (deg)	Degree (0-5m)	Degree (5-10m)	Degree (10-15m)	Degree (15-20m)	Degree (20-25m)	Soil roll (mm)	Clay content (%)	Erosion indicator
1	Don May	2	20.553	100.905	647	Woodland	360	28.8	24.2	33.0	28.8	26.6	1.5	27	
2	Don May	4	20.559	100.923	704	Woodland	360	15.6	16.7	13.0	22.8	20.3	1.4	30	
3	Don May	6	20.567	100.941	761	Woodland	360	13.5	11.3	2.9	14.6	28.8	2	18	
4	Don May	8	20.566	100.955	910	Woodland	350	16.2	19.3	19.8	19.3	13.0	1.2	37	
5	Don May	10	20.557	100.964	1010	Upland rice	5	-2.9	9.6	14.6	14.0	3.4	1.5	27	
6	Thong Napene	2	20.512	101.080	984	Woodland	185	21.3	18.8	20.8	18.8	19.8	1.3	33	
7	Thong Napene	4	20.521	101.071	846	Woodland	25	27.9	35.0	33.8	31.0	29.2	1.5	27	Gully
8	Thong Napene	6	20.535	101.064	794	Forest	95	5.1	2.9	1.1	1.7	1.1	2	18	Gully
9	Thong Napene	8	20.550	101.066	778	Forest	20	25.2	27.0	28.4	25.2	25.6	1.8	21	
10	Thong Napene	10	20.560	101.059	740	Forest	100	13.0	9.6	9.1	25.6	33.0	1.2	37	
11	Thong Napene	12	20.575	101.057	716	Forest	115	14.6	18.8	19.8	22.8	20.3	2	18	
12	Sakon	2	20.592	101.059	684	Mine, coal	120	Flat area							
13	Nam Seur	2	20.595	101.116	716	Fallow	60	-2.9	5.7	2.3	9.1	7.4	-		
14	Nam Seur	4	20.619	101.095	698	Fallow	75	6.8	6.3	4.0	6.8	16.2	1.8	21	
15	Nam Seur	6	20.629	101.084	671	Paddy field	105	0.0	0.0	0.0	0.0	0.0			
16	Nam Vang	2	20.714	101.207	1182	Woodland	245	27.5	25.6	20.3	22.3	21.8	1.2	37	
17	Nam Vang	4	20.724	101.195	1154	Woodland	210	8.0	1.7	7.4	12.4	8.0	1.6	25	
18	Nam Vang	6	20.725	101.182	985	Bushes	305	9.6	6.8	4.6	1.1	-2.9	3.5	8	
19	Nam Vang	8	20.725	101.170	851	Woodland	40	Animal attacks							
20	Nam Vang	10	20.734	101.168	852	Paddy field	360	0.0	0.0	0.0	0.0	0.0			
21	Hoay Hok	2	20.801	101.014	765	Forest	30	25.6	28.4	28.8	26.6	24.2	2	18	
22	Hoay Hok	4	20.786	101.019	743	Fallow	100	21.8	24.2	24.2	23.3	25.6	2.5	13	
23	Thalyang	2	20.729	101.014	776	Tree plantation	160	20.8	26.6	27.5	19.3	17.7	1.8	21	
24	Nam kap	2	20.713	101.013	755	Tree plantation	110	32.6	27.9	23.3	21.3	22.8	1.8	21	
25	Thong Lat	2	20.819	101.012	847	Bushes	210	8.0	14.0	13.5	10.8	10.8	1.2	37	
26	Hoay Hok	6	20.774	101.017	729	Forest	110	19.8	27.9	32.2	33.0	33.4	1.8	21	
27	Hoay Hok	8	20.757	101.017	732	Fallow	20	27.5	27.9	25.2	17.2	10.8	0.9	56	
28	Hoay Hok	10	20.740	101.015	793	Woodland	180	14.6	16.2	14.6	13.5	6.8	1.9	20	
29	Hoay Hok	12	20.702	101.016	717	Upland rice	225	13.5	14.0	7.4	4.0	7.4	1.7	23	
30	Hoay Hok	14	20.701	101.034	712	Tree plantation	190	17.7	15.1	19.8	22.3	23.7	1.9	20	
31	Hoay Hok	16	20.688	101.040	710	Tree plantation	190	20.3	20.8	20.8	21.3	18.8	1.3	33	
32	Pahk Khane	2	20.688	100.947	698	Tree plantation	270	-16.7	-20.3	-27.9	-31.8	-37.2	1.2	37	

Sample point	Staring at	Distance from start (km)	Latitude (dec. deg.)	Longitude (dec. deg.)	Elevation (m)	Land use	Direction (deg)	Degree (0-5m)	Degree (5-10m)	Degree (10-15m)	Degree (15-20m)	Degree (20-25m)	Soil roll (mm)	Clay content (%)	Erosion indicator
33	Pahk Khane	4	20.687	100.956	696	Forest	165	12.4	8.0	6.3	8.0	17.2	1	48	Exposed roots
34	Pahk Khane	6	20.677	100.963	696	Forest	100	10.8	9.6	18.3	29.7	33.8	1	48	
35	Pahk Khane	8	20.674	100.975	674	Fallow	350	10.2	13.0	11.3	14.0	15.1	1.1	42	
36	Pahk Khane	10	20.677	100.990	709	Mixed Crops	160	6.8	9.6	7.4	9.1	9.6	1.6	25	
37	Pahk Khane	12	20.681	101.001	661	Upland Rice	240	36.9	35.0	28.8	27.9	27.5	2	18	
38	Nam Panam	1	20.684	101.014	705	Fallow	110	18.8	20.8	24.2	24.7	19.3	1.5	27	
39	Nam Panam	3	20.688	101.038	701	Tree plantation	200	-13.0	14.0	14.0	8.0	8.5	2.1	17	
40	Nam Panam	5	20.681	101.055	674	Paddy field	10	0.0	0.0	0.0	0.0	0.0	1.8	21	
41	Konthoo	2	20.531	101.139	714	Forest	20	29.2	26.6	19.3	11.9	5.7	2	18	Minor soil slide
42	Konthoo	4	20.546	101.131	779	Woodland	265	8.0	14.6	13.5	9.1	2.3	1.6	25	
43	Main road *	2	20.549	100.989	984	Upland rice	270	16.7	18.8	15.6	17.7	18.3	2.2	16	
44	Main road *	4	20.555	101.003	862	Woodland	130	24.2	24.7	25.2	23.3	16.7	3	10	
45	Main road *	6	20.561	101.019	820	Fallow	310	40.0	To steep to climb, only one steepness measurement and no soil sample						
46	Main road *	8	20.575	101.030	743	Woodland	90	29.7	33.8	31.8	33.4	32.2	2.7	12	
47	Main road *	10	20.579	101.038	713	Woodland	300	57.5	To steep to climb, only one steepness measurement and no soil sample						
48	Main road *	12	20.585	101.048	687	Paddy field	90	0.0	0.0	0.0	0.0	0.0			
49	Main road *	14	20.595	101.061	693	Tree plantation	150	11.9	13.5	14.6	9.1	6.8	2.1	17	
50	Main road *	16	20.612	101.069	682	Woodland	120	5.7	6.3	6.8	9.6	13.5	2.2	16	
51	Main road *	18	20.627	101.081	664	Paddy field	130	0.0	0.0	0.0	0.0	0.0	1.1	42	
52	Main road *	20	20.642	101.081	666	Bamboo woodland	75	18.3	26.1	32.6	28.8	27.9	1.4	30	
53	Main road *	22	20.654	101.066	669	Tree plantation	40	14.0	17.7	18.3	15.1	13.5	0.9	56	
54	Main road *	24	20.669	101.063	687	Fruit tree	290	35.0	32.6	30.1	30.5	24.2	1	48	
55	Main road **	2	20.727	101.157	742	Bamboo woodland	340	21.8	14.0	20.3	20.8	22.8	1	48	
56	Main road **	4	20.720	101.139	707	Paddy field	340	0.0	0.0	0.0	0.0	0.0	1	48	
57	Main road **	6	20.713	101.122	697	Fallow	340	14.6	19.8	24.2	25.2	22.8	1	48	
58	Main road **	8	20.704	101.105	684	Paddy field	320	0.0	0.0	0.0	0.0	0.0	1.8	22	
59	Main road **	10	20.694	101.089	678	Tree plantation	330	4.0	-1.1	31.0	27.5	20.3	1.2	37	
60	Main road **	12	20.686	101.071	681	Fallow	360	-18.3	2.3	-9.1	-18.3	7.4	1.2	37	
61	Main road **	14	20.678	101.062	682	Urban area	265								

* is towards Vieng Phoukha village centre from west

** is towards Vieng Phoukha village centre from east

D. Data used for statistical calculations

Village	Interview	Actual erosion (Ton × Ha^{-1} × yr^{-1})	Potential erosion (Ton × Ha^{-1} × yr^{--1})	Average actual erosion (Ton × Ha^{-1} × yr^{-1})	Average potential erosion (Ton × Ha^{-1} × yr^{-1})	Actual erosion with threshold (Ha)	Potential erosion with threshold (Ha)
Nam Kieng	0	0.637898	0.05	166	886	3	1
Nam Wang	0	2.486138	34.07	99	1359	1033	1001
Nam Kap	0	0.291603	7.51	45	1167	31	157
Thonglat	0	0.429803	5.19	122	1469	107	131
Huay Hok	0	0.877789	11.73	107	1431	224	351
Nam Panam	0	0.293091	5.56	46	875	84	59
Konthoo	0	0.535864	13.29	55	1360	98	377
Nam Chedri	0	1.357686	14.59	107	1151	461	268
Don May	1	1.861415	53.99	46	1325	434	1177
Thong Napene	1	0.551631	14.94	58	1569	133	476
Phoulet	1	1.091569	12.39	78	881	323	162
Thalyang	1	0.552844	13.14	47	1124	79	314
Nam Eng	1	0.946372	21.09	55	1222	282	418
Sakon	2	0.333438	4.2	59	743	70	46
Park Khane	2	0.81971	41.17	22	1107	69	723

E. Village interview answers

1. **Don May**, 20; 32.954 N and 100; 53.619 E, 2007-11-09, Mr Somsig - Village Headman
2. 898 individuals, 174 families
3. Total 12140 Ha, Conservation forest 1730 Ha, Protected area 1811 Ha, Forest 1184 Ha, Used forest 420 Ha, Production forest 4607 Ha,
4. Rice paddies, upland rice, corn, jobs tears, vegetables
5. Company has invested in equipment for corn production. The company then buys the corn.
6. Corn and rice. Rice is barter.
7. Not so much erosion in agriculture land, but much outside the village. A lot of landslides.
8. Yes, forest openings (cutting trees) have highly led to increased erosion. Building of new road has contributed to erosion.
9. Landslides, soil slides. Runoff is visible during heavy rain.
10. Drought, crop diseases, land shortage, erosion
11. Plan to convince people to stop slash and burn and to protect the forests
12. Soil erosion causes the soil less fertile giving lower yields. It also reduces the growing area forcing some families to move or break new land.

Comments: Large village and lack of land, which is a problem.

———

1. **Thong Napene**, 20; 30.079 N and 101; 05.181 E, 2007-11-10, Mr Khamman-Village Headman
2. 52 household, 58 families, 246 people
3. Total 2381 Ha, Conservation forest 1248 Ha, Protection forest 346 Ha, Production forest 150 Ha, Afforestation 421 Ha, Village 3 Ha, Agriculture 634 Ha
4. Rice, upland and paddy. Vegetables (corn, chilli, eggplant)
5. Upland rice from the village, paddy from other villages
6. Selling rice to other villages, some for money. Roof was once traded for rice. Difficult road makes is difficult to transport and sell crops.
7. Not so big problem in upland rice. Main problem is runoff near rice paddies.
8. More erosion now. Mainly due to less forest cover, which generates more runoff. Also increased rainfall.
9. Some crops destroyed. Knowledge about erosion was weaker with this village leader.
10. Erosion, drought, crop disease, land shortage
11. Some terracing and tree planting. Only at some places and does not always stop runoff.
12. Corn and some crops can be destroyed if grown around river or stream.

Comments: Generally crops are not growing well in this area, there is however no land shortage. The village has plenty of land and few inhabitants. The villages have just finished dame construction giving water paddy fields.

———

1. **Nam Kieng,** 20; 36.862 N and 101; 05.960 E, 2007-11-10, Mr Clrosy – Deputy
2. 47 households, 54 families, 265 people
3. Total 2094 Ha, Reserved forest 961 Ha, Protected forest 214 Ha, Improved forest 79 Ha, Produced forest 48 Ha, Agriculture 645 Ha, Paddy rice 13 Ha, Village 14 Ha
4. Corn and rice
5. Receive corn seeds from investors
6. Selling corn and NTFP (Non Timber Forest Product). Exports to China. Selling for cash making.
7. No problem with erosion at the time, but they would like to increase their upland production but have not enough land for sustainable expansion.
8. –
9. –
10. Land shortage, Drought, Crop diseases, Erosion
11. –
12. –

Comments: Drought is a big problem, as well as land shortage for growing paddy rice. Drought affects paddy fields and farmers wish to expand their production, but cannot afford leasing seeds from outside investors to whom they sell their corn.

———

1. **Sakon**, 20; 34.688 N and 101; 03.536 E, 2007-11-11, Mr Sengkeo – Village Headman
2. 82 household, 86 families, 369 people
3. Total 1425 Ha, protected forest 605 Ha, Production forest 85 Ha, Village 6 Ha, Paddy field 22 Ha, Agriculture upland 711 Ha, stream 1 Ha
4. Rice, corn, vegetables and home gardens
5. Corn seeds from Lao company (extension corn and sesame), Chinese Power Company is buying cassava.
6. NTFP, corn. Selling for money. Selling price is increasing because of transport.
7. Not much, a few families are experiencing erosion in the crop area.
8. –
9. Soil slides along hill slides.
10. Land shortage, Crop disease, Drought, Erosion
11. No practise of anything
12. –

Comments: Before there was more agriculture, now it is mining. New road is very comfortable for transport. Road is very good, they can sell more products.

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1. **Phoulet**, 20; 36.463 N and 101; 06.194 E, 2007-11-11, Mr. Ai Kham- Village Headman, Mr. Lang Ai - Deputy, Mr. Kamkor - Second Deputy
2. 87 households, 93 families, 448 total
3. Total 3512 Ha, Forest conservation 1800 Ha, Protected area 97 Ha, Reforestation 440 Ha, Used forest 120 Ha, Agriculture 1030 Ha, Paddy field 12 Ha, Village 9 Ha
4. Rice, corn and NTFP
5. Wish for the village to expand their paddy, provides corn seeds
6. Corn, rice, NTFP, some animals (goat, chicken, peak, buffalo). Crops for cash, animals for trade.
7. Some paddy fields and upland have erosion. Landslide.
8. Much less erosion now because efforts to stop slash and burn and forest clearing has been successful. Land allocation and sustainable land. Uses fallow instead of slash and burn. Before there were more openings and cutting trees.
9. Land slide at paddy fields
10. Crop disease, Drought, Erosion, land shortage
11. Bamboo fence and wooden sticks to stabilize the soil and slow the water flow
12. –

Comments: Every family have 3 plots of land, they use them for shifting cultivation. First year is good, second year is reduced and third year lies in fallow.

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1. **Nam Wang**, 20; 43.051 N and 101; 12.705 E, 2007-11-12, Mr. Ja er – Village Headman
2. 97 household, 175 families, total 904 people
3. Total 6531 Ha, Production forest 380 Ha, Protection forest 2284 Ha, Agriculture 1896 Ha, Forest conservation 796 Ha, Deforestation 292 Ha, Afforestation/improved forest 868 Ha, Paddy field 10 Ha, Village 5 Ha
4. Rice and corn and vegetables (chilli, eggplant, pumpkin, cucumber)
5. No outside influence
6. Only cabbage, animals and NFTP. NTFP and animals for cash
7. No serious problem. 10 year crop rotation/fallow
8. –
9. –
10. Crop disease, land shortage, erosion and drought same
11. No
12. –

Comments: Problem with crops, white pigs eat rice and corn. No farming system, making it difficult to control land use. 2 ethnic groups are there in the village. There is a lack of land area to rebuild. Road to village is very bad, making it hard to sell their products. During the dry season is the road closed.

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1. **Nam Kap**, 20; 43.431 N and 101; 00.856 E, 2007-11-14, Mr Ja Per – Village Headman
2. 39 Households, 57 families, 277 total
3. T otal 3932 Ha, Agriculture 766 Ha, Lowland rice 7 Ha, Conservation for 1399 Ha, Afforestation 789 Ha, Production for 35 Ha, Protection forest 605 Ha, Village 13 Ha
4. Rice and cassava. Eggplant and sweet corn for household
5. Cassava and maybe corn next year. Company introduced to grow corn and cassava but the villagers don't know why
6. Cassava and cabbage for cash
7. Nothing
8. –
9. –
10. Drought, crop disease, land shortage, erosion
11. –
12. No problem with runoff

Comments: Moving city

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1. **Thalyoung**, 20; 44.600 N and 101; 01.069 E, 2007-11-14, Mr Tai – Village Headman
2. 22 household, 29 families, total 211 people
3. Total area 2917.75 Ha, Agriculture 596 Ha, Paddy 46 Ha, Conservation forest 880.75 Ha, Protected forest 1080. 5 Ha, Production forest 12 Ha, Upforestation 189,5 Ha, Village 6 Ha
4. Rice, corn, and cabbage
5. Corn. Investor from outside - trading company for feeding animals. NTFP - no one invest
6. Corn, cabbage, NTFP and some rice. Most is for exchange, rest is for money
7. Close to stream. Water makes erosion, close to canal and paddy field. No landslide.
8. Right now it is worse than before because people do agriculture land in upper water area and they open more area. A lot of soil decreasing
9. Stream erosion.
10. Crop disease, erosion, drought, land shortage- (have no problem at all)
11. At some places they have bamboo fences. They are trying to make a dame and change water direction. If to much water it is hard to stop.
12. Destroyed paddy fields, but only some are destroyed.

Comments: -

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1. **Thonglat**, 20; 50.163 N and 101; 00.565 E, 2007-11-14, Mr Ma Hor – Village Headman
2. 49 households, 62 families, total 297
3. Total 3081 Ha, National conservation forest 1611 Ha, Village conservation 426 Ha, Protection forest 271 Ha, Afforestation 288 Ha, Production forest 96 Ha, Village 7 Ha, Paddy 7 Ha, Agriculture 375 Ha
4. Rice and cassava
5. Cassava, company introduce and sometimes they give training
6. Rice and cassava for both money and trade
7. No erosion. Effect from animals instead. White peak and monkeys witch are dangerous.
8. Same problem with animals 19 years ago
9. –
10. Drought, erosion (in the future), land shortage, crop disease
11. –
12. –

Comments: Using preventive methods to keep monkeys away: gas for smell, which is making the monkeys afraid. Monkey problem affects villagers, less food and they cannot harvest.

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1. **Huay Hok**, 20; 49.204 N and 101; 00.650 E, 2007-11-15, Mr. Ai Pe – Son of Village Headman
2. 28 households
3. Total 2272 Ha, National zone and Conservation for 80 Ha, Conservation forest 520 Ha, Protection forest 771 Ha, Production for 78 Ha, Afforestation 462 Ha, Village 7 Ha, Agriculture 354 Ha
4. Rice, Vegetables
5. –
6. No
7. No
8. –
9. –
10. Only problem is animal attacks on crops, the village does not have any other problem
11. –
12. –

Comments: The village elder was sick at the time of the visit, so we interviewed his son instead. His son did not seem to know all that much about erosion, which explains why we only got no as an answer to many of the questions.

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1. **Park Khane**, 20; 41.740 N and 100; 55.916 E, 2007-11-16, Mr Maen – Village Headman, Mr Son pet – First Deputy, Mr Lang - Village agriculture technican
2. 140 households, 151 families, 814 inhabitants
3. Total 9304 Ha, Conservations forest 5129 Ha, Protected Forest 3109 Ha, Agriculture 792 Ha, Production forest 108 Ha, Village area 66 Ha
4. Rice, Corn, Vegetables
5. The Son Hua Company will invest in rubber and timber plantations in the village. They will also improve the road to the village in order to improve transportation
6. Rice, NTFP, Building Material
7. Upland rice areas only very little, paddies areas may become flooded. No other erosion
8. –
9. –
10. Crop disease, land shortage, (drought and erosion)
11. –
12. –

Comments: The village is very new, founded 2003. The village is expanding its rice paddy areas, but lack of irrigation water is limiting the possible expansion. Former it was the village Sobkhan.

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1. **Nam Panam**, 2007-11-17, 20; 41.052 N and 11; 00.644 E, Mr LawSa – Village Headman
2. 22 household, 49 families, 232 total
3. Total 1589 Ha, Conservation for 239 Ha, Protection forest 293 Ha, Production forest 130 Ha, Afforestation 410 Ha, Village 8 Ha, Agriculture 475 Ha
4. Rice upland, cassava.
5. Cassava, sesame.
6. Cassava, pig, cardamom, bloom grass
7. No
8. –
9. –
10. Crop disease, shortage, erosion, drought
11. –
12. –

Comments: Interesting to grow corn but the land is not suitable. There is erosion especially in the paddy fields, but there is also runoff. They are clearing areas, burning and collecting grass and further reburning. Thereafter they are planting rice and crop. If some families get good area they can replant next year. Change land 5-6 years.

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1. **Konthoo**, 20; 31.381 N and 101; 08.774 E, 2007-11-17, Mr Lajaer – Village Headman
2. 74 household, 80 families, total 404
3. Total 2442 Ha, Conservation forest 699 Ha, Protection for 494 Ha, Afforestation 423 Ha, Production for 144 Ha, Village 4 Ha, Agriculture 678 Ha
4. Rice, corn, sesame, some families cultivate cassava
5. Planting rubber, corn, upland and lowland rice
6. Corn, rice, NTFP, bloom grass, sesame, mushroom
7. No
8. –
9. –
10. Drought, crop disease, erosion, land shortage
11. –
12. –

Comments: Plenty of land, some families have 20 plots. They have no idea on how to control runoff. No system for crop growing.

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1. **Nam Eng**, 20; 43.298 N and 101; 08.524 E, 2007-11-18, Mr Tong Keo – Village Headman
2. 83 households, 87 families, 432 people
3. 4315 Ha total, Conservation forest 1558 Ha, Protection forest 1195 Ha, Afforestation 538 Ha, Production forest 338 Ha, Village 45 Ha, Agriculture 558 Ha, Lowland rice 8,148 Ha, Upland field 75 Ha
4. Rice, corn, cassava
5. Ginger, cardamom
6. Cassava, bitter bamboo, corn, bloom grass, NTFP - for money
7. A lot, especially low land area was reduced because if flooded out. Upland field - not destroyed by erosion, but by animals
8. Worse with heavy rain. Only this year was less rain than other years.
9. –
10. Land shortage, crop disease, drought, erosion
11. –
12. –

Comments: No money to buy dame or canal for lowland. They have no knowledge on how to control runoff. Rotate with 7-10 years. If they only use 3-4 years, fallow will cause lots of vegetation, which is difficult to control.

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1. **Nam Chedri**, 20; 33.322 N and 101; 00.924 E, 2007-11-19, Mr Sompon – Village Headman
2. 80 households, 89 families, total 424
3. Total 3169 Ha, Protected forest 92 Ha, Village 4 Ha, Agriculture 1361 Ha, paddy field 3 Ha, Conservation forest 1581 Ha, Production forest 38 Ha, Afforestation 88 Ha, Road 1 Ha, Stream 1 Ha
4. Rice, corn, cassava, rubber, vegetable
5. Rubber, cassava, corn - company invest
6. Rice, corn, cassava for money
7. No
8. –
9. –
10. Crop disease, drought, land shortage, erosion
11. –
12. –

Comments: No runoff problem. More positive effects than negative with the new road. Road is convenient for travelling and transport. Water supply is much better. Negative with new road: More than 10 households had to move. Land, such as agriculture and construction area is destroyed. Cultivation: Before they used 10-year rotation, now 3 year