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Estimation of Potential Soil Losses on a Regional Scale: A Case of Abomey-Bohicon Region. Benin Republic

[1]Olanrewaju Lawal, [2]Gaiser Thomas and [3]Nuga Babatunde
[1]Centre for Geo-Information Studies, UEL Barking Campus, Longbridge Road, Dagenham, Essex
[2]Institute of Soil and Land Evaluation, University of Hohenheim, 70593, Stuttgart, Germany
[3]Department of Crop and Soil Sciences, Faculty of Agriculture, University of Port Harcourt, P.M.B.5323, Port Harcourt, Rivers State, Nigeria

Abstract: The rapid erosion of soil by wind and water has been a problem ever since land was first cultivated, onsite effect include breakdown of soil structure, loss and redistribution of soil (from and from field), and decline in organic matter and nutrient which results in reduction of cultivable depth, soil fertility and soil moisture. The net effect is a loss of productivity, which at first restricts, what can be grown and results in increased expenditure on fertilizers to maintain yield but later threatens food production and lead to land abandonment. Land degradation and soil fertility depletion are considered as the major threats to food security and natural resource conservation in SSA. Various studies on land degradation in Africa have shown that besides nutrient depletion through lack of fertilizer and nutrient management, water and wind erosion are the main causes of degradation. This continued degradation reduces the capacity to increase food production. Although, large areas of forests, wetlands, river valley bottoms and grassland savannah have been put under food crops, the food gap keeps on growing. Therefore there is need for a quick and reliable estimation of potential soil losses before land use plans are made. The research uses the modified USLE equation to estimate the potential for soil losses by rainfall and runoff in a GIS environment. The equation was divided into two parts namely the potential part B which consists of the relatively constant attributes of the soil and landform while the second part (modifying part) consists of the cover and management factor and the conservation or support practice factor. The equation is applied to the Abomey-bohicon region in Benin Republic (West Africa), which is presently characterised by soil degradation, scarcity of forest cover and low agricultural yields this further highlights the need for quick assessment of potential soil losses thereby providing decision makers and resource users with information for land use planning to check further decline of the resource base. The objective is to present a simple and quick method of assessment of water erosion making use of available information thus making decision making process easier and quicker.

Key wards: Redistribution, soil fertility, nutrient, degradation, USLE

INTRODUCTION

The rapid erosion of soil by wind and water has been a problem ever since land was first cultivated. Onsite effects include breakdown of soil structure, loss and redistribution of soil, and decline in organic matter and nutrients which results in reduction of cultivable depth, soil fertility and soil moisture. The net effect is a loss of productivity, which at first restricts, what can be grown and results in increased expenditure on fertilizers to maintain yield but later threatens food production and lead to land abandonment.

Land degradation and soil fertility depletion are considered as the major threats to food security and natural resource conservation in SSA. The Abomey-Bohicon region is an example of such area B it is presently characterized by soil degradation, scarcity of forest cover and low agricultural yields. Various studies on land degradation in Africa have shown that besides nutrient depletion through lack of fertilizer and nutrient management, water and wind erosion are the main causes of degradation. This continued degradation reduces the capacity toincrease food production even though; large areas of forests, wetlands, river valley bottoms and grassland savannah have been put under food crop production.

The Abomey plateau is heavily influenced by its history as central territory of a formerly important kingdom. It has over the years witnessed a significant change in landuse. According to Vodougnon and

Corresponding Author: Olanrewaju Lawal, Centre for Geo-Information Studies, UEL Barking Campus, Longbridge Road, Dagenham, Essex

Vennemann[1] the plateau between 1954 and 1982 witnessed an increase from 1% to 6% in settlements area. And according to the population census in 1992 the population density of this region stands around 225 inhabitants per square kilometre which is among the highest in Benin. It was also reported that there was a decrease in woodland and tree savanna coverages (35% and 12%, respectively). It was observed that development of new settlement occurred in close proximity to already existing agricultural land. The decrease in woodland and tree savanna are attributed to the practice of slash and burn which is related to charcoal production and demand for fire wood as well as wood carving activities.

With all these changes taking place there is a growing need to provide decision makers with adequate information to enhance their capability to institute appropriate land use planning based on the potential of the area under question to generate erosive material which could lead to loss of fertility and consequently land degradation. The Universal Soil Loss Equation (USLE) is an empirical model that has been used widely all over the world for the assessment and prediction of soil erosion due to water runoff. And in many cases outside the US (where the equation was originally developed) satisfactory results were reported[2-4] but it is necessary to adjust the factors to the specific location to obtain reliable results[5,6]. While several attempts have been made to modify and further develop the USLE[7,8], but the original USLE still remains the most widely used due to its simplicity.

With the recent development in GIS techniques and availability of high quality digital elevation models estimation of potential soil losses could be carried out quickly and reliable estimation could be obtain to guide future land use plans. The research uses the modified USLE equation[8] to estimate the potential for soil losses by rainfall and runoff in a GIS environment.

MATERIALS AND MATHODS

In the USLE, annual soil loss A ($t\,ha^{-1}$) is a product of the rainfall erosivity (R), the soil erodibility (K), an index of slope length and slope steepness (LS), the cover and crop management factor (C) and the conservation or support Practice factor (P)[9]. In this research this equation was divided into two parts namely the potential part B which consists of the relatively constant attributes of the rainfall, soil and landform (R, K and LS factors) while the second part (modifying part) consists of the C and P factors.

The rainfall erosivity factor R is a principal factor for the USLE equation; it is the combined function of rainstorm intensity and duration, and the mass, diameter and velocity of rainfall. Many methods have been proposed by studies in the tropics for calculation of the USLE R factor, and although annual R index is not directly linked to annual rainfall, in West Africa Roose[10] have shown that the mean annual R (over ten years) is equal to mean annual rainfall multiplied by factor >a=.
Where a = 0.5 in most cases ±0.05

- 0.6 near the sea (>40 km)
- 0.3 B 0.2 in tropical mountain areas
- 0.1 in Mediterranean mountain areas

Other equations examined include: Morgan[1] sModified Fournier Index[12] as presented by Renard and Friemund. The rainfall data used for the computation (Table 1) was obtained from the FAOCLIM[13] database and the average of the two weather stations located in this region was used (Abomey and Bohicon). The monthly values are 30 years averages for both stations (1961 B 1990).

The Soil erodibility factor depends on the organic matter and texture of the soil and is influenced by its permeability and profile structure. This index varies from 70/100 for most fragile soil to 1/100 for the most stable soil. Adopting a suitable estimation method could present a problem but the aim here is to keep it simple and practical. Three methods/equations were initially suggested: Mulengera and Payton[14] USLE nomograph[15] and Williams[16]. The K values are calculated for each SOTER unit within the study area, a SOTER unit is composed of unique combination and pattern of terrain, terrain component and soil component[17].

The LS factor or topographic factor depends on length and gradient of the slope. This factor was computed from the 90m SRTM[18]. In order to incorporate the impact of flow convergence, the modified equation for computation of LS factor was used as derived by Van Remortel *et al.*[19].

The conservation or support practice factor (P) is set to the highest level of 1. Values for the C factor were derived from the Land use/cover map of 1988[20].

Table 1: Mean monthly rainfall data for the Abomey and Bohicon weather stations.

Months	Abomey	Bohicon	Average
January	5	4	4.5
February	25	28	26.5
March	79	75	77
April	131	125	128
May	147	153	150
June	187	176	181.5
July	157	142	149.5
August	105	112	108.5
September	157	141	149
October	109	118	113.5
November	25	22	23.5
December	9	14	11.5
Annual total	1136	1110	1123

RESULTS AND DISCUSSION

The R factor was computed using all the four methods (Table 2) stated earlier. And for this study the Modified Fournier Index method as presented by Renard and Friemund[10] was selected. For this study the average of the Roose[10] equation and the Modified Fournier Index B MFI (as presented by Renard and Freimund) The was done since these two estimations are closer to measured R factor in obtained in other studies in the tropics and also reports showing their significant correlation with mean annual R for different climatic regions[12,21]. Values for the Morgan equation and Foster *et al.*, were considered to be too small and as such were not used for further computation.

In the estimation of the soil erodibility factor the Nomograph[15] was deemed inappropriate due to various studies[14,22,23] that have reported its inadequacy when used on soils significantly different to the ones from which the nomograph was developed. The equation proposed by Mulengera and Payton was rejected as noted by the authors that it may not give accurate results on soils with very low content of silt which is the case in the study area and also it has not been extensively tested.

The equation of Williams[16] was eventually selected as its estimation (Table 3) of erodibility is strongly influenced by texture-related soil characteristics and the components of the equation corrects the soil erodibility values for factors like high coarse-sand content, little sand content, high clay:silt ratios and high organic carbon content. Using the Williams[16] equation for erodibility gave values which are in agreement with results from Roose[24] and Roose and Sarrailh[25] and generally the soil shows a low K-value because of their high clay (BJ20 and BJ21) and high sand content (other mapping units). The high clay content makes the soil resistant to detachment while the high sand content despite easy detachment generates low runoff. Accordingly at the level of the present regional assessment it was deemed appropriate to use these values as it represents the average annual erodibility of these soils.

The execution of the AML of Van Remortel *et al.*,[19] produces the grid for L, S and LS factor of the RUSLE equation (Fig. 1b, c and d). The Abomey B Bohicon region has an elevation ranging from 7.5m to 264.5m, the S constituent ranges from 0.05 to 3.13, with a mean of 0.22 and a standard deviation of 0.12. A range of 1.02 to 3.85 was obtained for the L constituent and 1.25 and 0.23 as mean and standard deviation respectively. The LS factor ranges from 0.05 to 6.98 with a mean of 0.29 and a standard deviation of 0.23.

Table 2: Computed R factor from the long-term mean monthly rainfall data

Months	Roose[10]*	Renard and Freimund (1994)**	Average Eqn1 and Eqn2	Foster *et al.* (1981)	Morgan[11]
January	38.93	30.53	34.73	0.93	4.76
February	229.23	179.78	204.50	5.49	28.02
March	666.05	522.37	594.21	15.94	81.43
April	1107.20	868.35	987.78	26.50	135.36
May	1297.50	1017.60	1157.55	31.05	158.63
June	1569.98	1231.29	1400.63	37.57	191.94
July	1293.18	1014.21	1153.69	30.95	158.10
August	938.53	736.06	837.29	22.46	114.74
September	1288.85	1010.81	1149.83	30.84	157.57
October	981.78	769.98	875.88	23.49	120.03
November	203.28	159.42	181.35	4.86	24.85
December	99.48	78.02	88.75	2.38	12.16
R-Annualtotal	9713.95	7618.42	8666.18	232.46	1187.58

* a = 0.5, Renard and Freimund[10]. Equation for MFI>55 mm, Eqn 1and Eqn2=> Roose[10]

Table 3: Representative soil physical properties and estimated K factor

Mapping Unit	Org. C content	Sand	Silt	Clay	Williams[6]	Mulengera and Payton[14]
BJ19	4.7	78.5	10.8	10.7	0.131	0.024
BJ20	26.7	16.3	22.8	60.9	0.143	0.022
BJ21	28.5	21.5	18.5	60.0	0.131	0.018
BJ22	4.7	78.5	10.8	10.7	0.131	0.024
BJ26	8.7	57.8	14.3	27.9	0.144	0.025
BJ27	8.7	57.8	14.3	27.9	0.144	0.025
BJ28	8.7	57.8	14.3	27.9	0.144	0.025
BJ14	5.9	70.7	4.9	24.4	0.110	0.009

The C factor was computed using the tables compiled by Morgan[6] from various studies. Weighted C values (Table 4) was calculated for each month using the percentage contribution of each month = s rainfall to total annual rainfall multiplied by average monthly C value. This is done to better reflect the dynamics which exist among plant growth, soil cover and rainfall amount. In the final calculation the weighted values were used.

Examining the 1988 Land use map it was found that about 77% of the total area of the region is used as Farm and Fallow while Shrub Savanna and Settlements (urban/rural human dwellings) covers 10 and 6% respectively. Other Land use classes such as the Oil Palm plantation, Gallery forest, Tree Savanna and Woodland covered an area between 1 and 3% (Fig. 2).

The estimated potential soil losses were grouped into 5 Eight SOTER units were identified in the area. The units BJ26 and BJ14 occupied about 50 and 32%, respectively of the total area (Fig. 3). BJ21 has the lowest percentage contribution which is about 0.3 percent while BJ19, BJ20, BJ22, BJ27 and BJ28 covered 4.6, 2.4, 3.3, 2.1 and 5.3%, respectively of the study area. The description of these SOTER units is well covered by Weller[26]. Classes (Table 5) namely low, moderate, high, very high and

Fig. 1: Zooned view of Grids for Abomey-Bohicon Region (a) Digital Elevation, (b) S-Constituent, (c) L-Constittuent and (d) LS factor

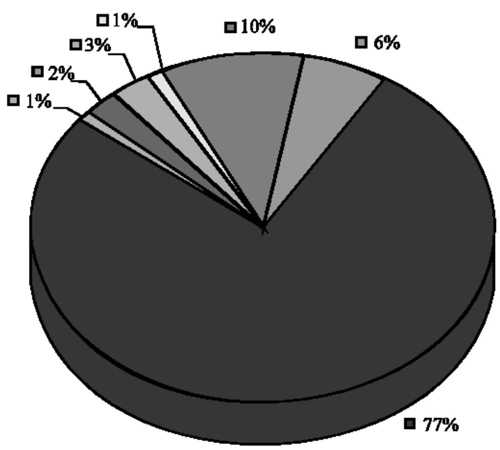

Fig. 2: Landuse Classes and their percentage coverage in the Abomey-Bohicon region.

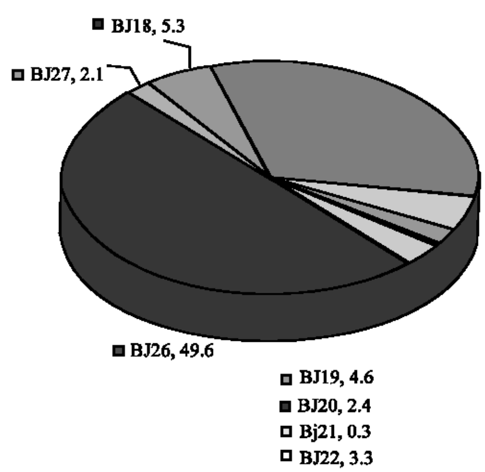

Fig. 3: Soter units in the Abomey-Bohicon region

severe (Fig. 5). About 46% of the total area of the plateau has a potential for generating moderate sediment yield, and 11 percent shows a potential for low sediment generation. 25% of the area was also found to exhibit high potential for sediment generation. It was discovered that the very high and severe potential class are found around river valleys (Fig. 4) with each of then occupying about 17 and 0.7% of the total area of the Abomey-Bohicon region, respectively. These areas realistically could be referred to as areas prone to gully formation or channel erosion (i.e. areas classified as very high and severe). The distribution of the potential for soil loss is mainly influenced by the LS factor as observed in the correlation analysis (r = 0.84).

Table 4: Estimated USLE Annual Crop management factor for the Land Cover/Use for Abomey-Bohicon Region.

Land cover Types	Settlement	Farmland/Fallow	Wood-land	Gallery forest	Tree Savanna	Shrub Savanna	Oil-palm plantation
Average C	0.030	0.403	0.167	0.003	0.167	0.267	0.005
Weighted C value*	0.030	0.551	0.145	0.003	0.128	0.228	0.006

Fig. 4: Map of Abomey-Bohicon region showing potential annual soil loss classes

The potential soil loss map (Fig. 4 and Table 5) shows areal distribution of potential for soil loss in the Abomey-Bohicon region and from this it could be seen that very high and severe soil loss classes are usually occurring at river/stream valleys (both permanent and temporary). In the north to northwestern part of the region the potential is dominated by the low and moderate potential. The fringes (west and east) of the plateau where the hydrological networks of the Abomey region connects to the Zou and Couffo rivers shows a very high annual potential as the dominant class for this area. From the central part to the furthermost south a more or less mixture of moderate to very high potential could be observed. The southeastern most corner of the region also displayed a characteristic which is similar to that observed in the northern part.

The estimation of the monthly R-factor could provide an insight into the contribution of each month's rainfall characteristics to the erosion potential. This estimation (Table 6) revealed that the months of November to February contributed to about 6% to the erosion potential while in March a factor of about 7% was computed. The highest (combined) contribution occurred between April and July with a value of about 54%. A 10% contribution was estimated for August and a total of 23%. The monthly contribution followed the rainfall pattern (bi-modal), and highlights the months in which much care needs to be taken. With this information farmers/resource users or planner could also implement operations at times with lower contribution or target times with higher contribution

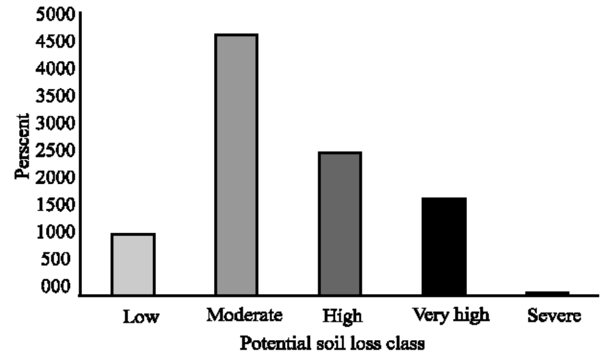

Fig. 5: Percentage area of coverage for potential annual soil loss classes in the abomey-bohicon region

Table 5: Estimated Potential Soil Loss Classes and percentage area coverage

Potential Loss Class	Estimated Potential Soil Loss (ton ha^{-1}/annum)	Area coverage (%)
Low	> 100	11.10
Moderate	100-300	45.88
High	300-500	25.15
Very High	500-1500	17.21
Severe	>1500	0.65

Table 6: Estimated Annual Soil loss with 1988 Landuse types in the Abomey-Bohicon Region.

Landuse types	Annual Mean (ton ha^{-1})	Standard Deviation
Farm/Fallow	182.5	153.7
Shrub savanna	62.1	50.8
Woodland	58.3	60.6
Tree savanna	48.9	55.4
Settlement	27.3	66.3
Gallery forest	18.5	68.2
Plantation	10.6	45.7

to implement control measures thereby reducing the erosion potential.

The Erosion potential map generated was further analysed to understand the within and across group distribution of erosion classes among the major land use types of 1988.

Farmland and Fallow has the highest coverage in all the five potential soil loss classes having a percentage ranging from 73% - 84% of the total area in each class (Fig. 6). Shrub savanna shows percentage coverage in the classes which ranges between 0.3 and 12 percent while settlement contributes about 5 – 7%. Around 4% of the total area in the very high potential class was occupied by Gallery forests and 7% of the class was also found to be occupied by Oil-palm plantation. Another 5% of the area under Oil-palm plantation was also found to be on at locations classified as having severe erosion

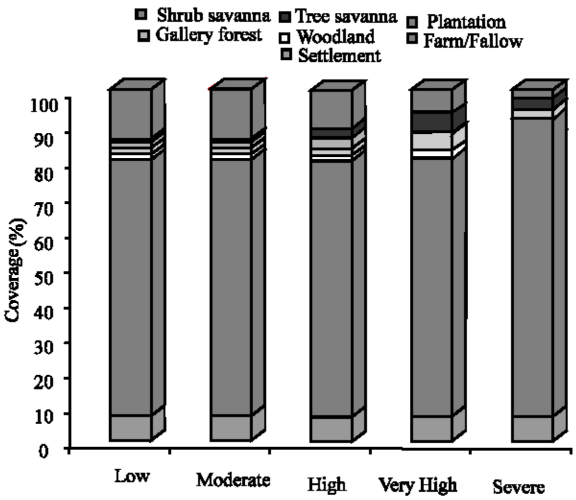

Fig. 6: Distribution of Land use types within potential soil loss classes

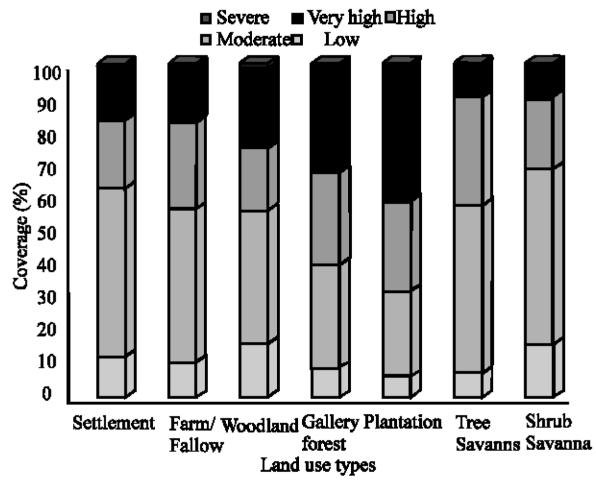

Fig. 7: Distribution of potential Soil loss Classes within Land use types of 1988

potential. Other land use types generally display a very low percentage distribution in relation to the potential soil loss classes. This distribution further highlights the significance of cropland and land clearing in soil erosion generation in this region. It also shows that farmlands/croplands are located irrespective of the potential of the topography to generate erosive soil loss and since in most case there are no erosion control practices, the problem are often pronounced.

Overlaying the Landuse map of 1988 and the potential soil loss classes provide and analysis of distribution of land use types among potential soil loss classes. From the analysis about 12%, 50% and 21% of the settlement could be found on low, moderate and high soil loss potential classes respectively while about 16% could be found on very high potential class. The farmland/fallow are mainly found on moderate and high potential (46 and 26%, respectively) but about 17% was also found in the areas with very high potential class while 10% are found in the low potential class. The second most prominent land use type-Shrub savanna was mainly found on areas with moderate soil loss potential class (53%) while about 21% occurred also on area with high potential. This land use type could also be found in area with low (16%) and very high (10%) potential soil loss and absolutely none in the severe potential class (Fig. 7).

Gallery forest was found to have about 91% of its area of coverage to existing on location with moderate to severe potential soil loss while the remaining 9% could be found at location with low potential. 40% of areas under Woodland exist at location with moderate potential and about 24% are at areas with very high potential. This land use type also has 16 and 19% of its coverage at location

Table 7: Distribution of monthly R-factor across the year

Months	Computed R-factor	Contribution to Annual potential Erosion (%)
January	34.73	0.40
February	204.50	2.36
March	594.21	6.86
April	987.78	11.40
May	1157.55	13.36
June	1400.63	16.16
July	1153.69	13.31
August	837.29	9.66
September	1149.83	13.27
October	875.88	10.11
November	181.35	2.09
December	88.75	1.02
Total	8666.18	100.00

with low and high potential respectively. A very small area (1%) under Oil-palm plantation was also found to exist at locations with severe potential while 40% (of the total Oil-palm plantation coverage) was found to exist at locations with very high potential. 7%, 25%, and 27% are located at area with low, moderate and high soil loss potential respectively. Tree savanna was found to have 50% of its coverage located in areas with moderate soil loss potential while 32% of its coverage is located in areas with high potential. This land use type also has 10% of its coverage at location with very high potential and about 8% exist at location with low potential for soil loss.

The product of the annual potential soil loss and weighted USLE Crop factor gives the annual USLE soil loss for this region based on the land use of 1988.

Farmland/fallow recorded the highest mean annual soil loss (Table 7) followed by Shrub savanna with about 62 ton ha^{-1}/year soil loss. While the other land use types generated an estimated mean soil loss ranging between 11 and 59 ton ha^{-1}/year. A high variation in annual soil loss was exhibited by Farm/fallow (154 ton ha^{-1}) followed by Gallery forest (68 ton ha^{-1}). The lowest variation is recorded from Oil-palm plantation with value of about 46 ton ha^{-1}. These mean values reflect the rate of the erosion (and soil degradation) in this region this is further highlighted by the degree of variation (standard deviation) indicating higher erosive losses which are part of the problems that need to be addressed for future land use planning.

The estimation of the potential made it quite easy to analyze the likely generation of erosive material when planned or current land use is overlaid, therefore allowing a quick assessment of the impact of the land use distribution on soil erosion in the region/area of interest. With this approach current land use could be assessed and proposed changes could be evaluated to see their impact on estimated of soil loss. In this way decision makers/planners will have to make decision on which land use types, crop management and support practices can be used to reduce the erosion potential in an area to the tolerance level.

CONCLUSION

Although the USLE model applies to sheet erosion, it could be seen that with adequate adjustment it is possible to use it to model the potential soil loss on a regional scale. The model generates high values for areas with flow concentration which normally correspond to areas with very high soil loss in reality. These areas could also be classified as areas with potential for gully formation or channel degradation.

The study has demonstrated that the preparation of the potential soil loss map could be done easily and quickly with available data (soil maps, long-term rainfall data, DEM etc) and these estimations could be used as a base map on which land use types can be overlaid thus giving an idea of the likely erosive soil loss which may occur in an area.

The input parameters for the model are subjected to considerable uncertainty but for this case study since estimates are derived from observed data we could reliably conclude that the estimates are robust enough at the regional scale for planning purposes.

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