Rainfall Induced Landslide Probability Mapping for Central Province

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RAINFALL INDUCED LANDSLIDE PROBABILITY MAPPING FOR CENTRAL PROVINCE

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Abstract

Rainfall induced landslide hazards in Kenya represents a major challenge and remain an important issue in disaster management especially in Kenya's central province where the effects are very common with the onset of El niño rains. The main aim of this study is to develop a rainfall induced landslide probability map for Kenya's central province. In order to achieve this, process based methods were used to map landslide areas using the following factors: slope, rainfall, land cover change, Normalized Difference Vegetation Index (NDVI) change, Curvature, watershed, and soil characteristic including: type, texture, soil bulk density, Base Saturation, and Total Water Available Distribution Map. The minimum conditions were set for each factor for landslide occurrence.

Slope stability mapping was done to determine the stable areas and thus derive the probability of landslide occurrence. Statistical methods were then employed by means of weights of evidence to achieve the probability weights for each factor considered to cause landslides. The factors were then overlaid using the probability weights to obtain the probability map for landslide occurrence in central province.

The results of the study were landslide areas, Maps showing the stable and unstable areas and probability maps of landslide occurrence for central province for two epochs i.e. October 1997 – May 1998, and October 2009- May 2010. The probability weights of a factor causing landslide, showed Land cover change, Rainfall and NDVI change factors as very important for this study. It was observed that the probability map of landslide occurrence had the same pattern as rainfall distribution and that probabilities of landslide occurrence were higher with more rainfall.

1. Introduction

Rainfall-induced landsliding represents a major hazard not only in Kenya but also in other parts of the world. In Kenya, preliminary statistics show that most catastrophic landslide events have been associated with rainfall. Landslides drain years of economic gains and development through disruption of people's lives through displacements, destruction of livelihoods and property, deaths and injuries. Landslides are triggered by rapid saturation of the soil, which in turn reduces cohesion, surface tension and friction. The El Niño rains experienced in the epochs October 1997 to February 1998 and October 2009 to May 2010 exacerbated the landslide hazards, thus calling for an urgent need to set up early warning systems in Kenya.

This study therefore sought to develop a landslide probability map showing the probabilities of landslide occurrences in central province. Identification of areas prone to rainfall induced landslide is a fundamental component of disaster management and an important basis for promoting safe human occupation and infrastructure development in landslide prone areas considering the devastating impacts of such landslides. The study helped to investigate the characteristics, probabilities and intensity of rainfall induced landslide hazards and factors which determine the magnitude of a landslide disaster.

The main objective was to develop a rainfall induced landslide probability map for Kenya's central province. The specific objectives were: to identify areas susceptible to rainfall induced landslides; to find out if landslide activity in the study area is related to both intense, short duration precipitation events (1–30 days) and long-lasting rainfall episodes (1–6 months); to assess the dependency between rainfall induced landslide areas with respect to land use; generate probability maps of rainfall induced landslides in the study area; to familiarize the relationship of rainfall induced landslide hazard inducing factors.

2. Study area

The study area is central province which is one of Kenya's provinces and it ranges from longitude 36°15´00"E to 37°30´00"E and latitudes 0°7´00"N to 1°15´00"S. It has a highly rugged mountainous terrain with altitude varying from 1020m to 2890m above mean sea level. Kenya's major rivers originate in the study area and their major tributaries form a dendritic drainage pattern on the slopes of Mt Kenya and the Aberdare ranges. It has fairly reliable rainfall is fairly reliable, with two seasons, one from early March to May and a second during October and November. According to the 2009 population census results, the province had a total population of 4.4 million inhabitants for an area of 13,232 km^2.

According to The Kenya Natural Hazard Profile (2010), "in Murang'a district there are reports of whole families being buried in the long rains of April and May in 2002 and 2003". Some of the factors reported to aggravating landslides in this district include: the influence of topography, human activities i.e. cultivating, deforestation and construction which destabilize the already fragile slopes.

3. Slope Instability mapping

Approaches to assess susceptibility to landslides are either heuristic, deterministic (process based), or statistical (Regmi et al. 2010). Heuristic approaches require expert opinions/observations to estimate landslide potential from data on preparatory variables. Deterministic/ GIS process based approaches are based on slope stability analysis (Xie et al., 2004), and include the physical processes involved in landsliding and therefore can often better pinpoint causes of mass movement (Miller, 1995). They usually provide the most detailed results, expressing the hazard in absolute values as safety factors, or a probability of failure given a set of conditions (Barredo et al., 2000).

This study used both process-based landslide models and statistical approaches. The boundary conditions for upper and lower thresholds for possible slope failures were used to define stable and unstable areas. Unconditionally stable areas are areas predicted to be stable even when saturated and satisfy: $tan\theta \leq \left(\frac{C}{cos\theta}\right) + \left(1 - \frac{\rho_w}{\rho_s}\right) tan\emptyset \qquad (eqn1)$

Unconditionally unstable areas are areas predicted to be unstable even when dry and satisfy: $tan\theta > tan\emptyset + \frac{C}{cos\theta} \qquad (eqn2)$

Where: θ the local slope angle [°]; ρ_s wet soil bulk density [g cm+^{3}]; ρ_w the density of water [g cm^{-3}]; ϕ the effective angle of internal friction of soil [°]; and C the combined cohesion term made dimensionless relative to perpendicular soil thickness and defined as: $C = \frac{C_r + C_s}{D\rho_s g} \qquad (eqn\ 3)$

Where: C_r is root cohesion [N m^{-2}], C_s soil cohesion [N m^{-2}], D perpendicular soil thickness [L], and g the gravitational acceleration constant (9.81 m s^{-1}).

The susceptibility to landslides was assessed through GIS techniques using Bayesian theorem based on weights of evidence (WOE). For mapping susceptibility to landslides, the WOE method calculates the weight for each causative factor of a landslide based on the presence or absence of landslides within the area. It assumes that future landslides will occur under conditions similar to those contributing to previous landslides and that causative factors for the mapped landslides remain constant over time. It therefore has two probabilities i.e. the prior probability (which is the probability of an event, determined by the same types of events that occurred in the past, for a given period of time) and the posterior probability (which is the modified / revised prior probability using other sources of information or evidence).

Favourability of an incidence of landslide given the presence of the causative factor can be expressed by conditional probability (Bonham- Carter, 2002) as follows: $P\{L/F\} = \frac{P(L \cap F)}{P\{F\}} \qquad (eqn\ 4)$

Where: P (L/F) is the conditional probability of the presence of a landslide (L) given the presence of a causative factor, F. Similarly, the conditional probability of landslides based on factor F is: $P\{F/L\} = \frac{P(L \cap F)}{P\{L\}} \qquad (eqn\ 5)$

Combining equations (4) and (5), we obtain equation 6 below: $P\{L/F\} = P\{L\}\frac{P\{F/L\}}{P\{F\}} \qquad (eqn\ 6)$

This states that the conditional (posterior) probability of a landslide, given the presence of the factor F, equals the prior probability of the landslide P{L} multiplied by the factor P{F|L}/P{F}.

Dividing both sides of the Equation (6) by $P\{\bar{L}/F\}$ i.e. the probability that there is no landslide but there is a factor that cause a landslide, we obtain

$$\frac{P\{L/F\}}{P\{\bar{L}/F\}} = \frac{P\{L\}P\{F/L\}}{P\{\bar{L}/F\}P\{F\}} \qquad (eqn\ 7)$$

Similarly, the posterior probability of a landslide, given the absence of the factor, can be determined as:

$$P\left\{L/\bar{F}\right\} = P\{F\}\frac{P\{\bar{F}/L\}}{P\{\bar{F}\}} \qquad (eqn\ 8)$$

Similar to Equations (5) and (6), from the definition of the conditional probability is:

$$P\{\bar{L}/F\} = \frac{P\{\bar{L} \cap F\}}{P\{F\}} = \frac{P\{F/\bar{L}\}P\{\bar{L}\}}{P\{F\}} \qquad (eqn\ 9)$$

Substituting the value of P{L̅|F} in the right side of Equation (7), produces:

$$O(L/F) = \frac{P\{L/F\}}{P\{\bar{L}/F\}} = \frac{P\{L\}\,P\{F\}\,P\{F/L\}}{P\{\bar{L}\}P\{F\}\,P\{F/\bar{L}\}} \qquad (eqn\ 10)$$

Where: O{L|F} is the conditional (posterior) odds of L given F.

$$But, \quad \frac{Probability\ that\ an\ event\ will\ occur}{Probability\ that\ an\ event\ will\ not\ occur} = \frac{P\{L\}}{P\{\bar{L}\}} = O\{L\} \qquad (eqn\ 11)$$

From Equations, (10) and (11), it can be rewritten as: $O\{L/F\} = O\{L\}\frac{P\{F/L\}}{P\{F/\bar{L}\}}$ $(eqn\ 12)$

Where: O{L} is the prior odds of F.

$\frac{|P\{F|L\}}{P\{F|\bar{L}\}}$ is known as the sufficiency ratio abbreviated as LS (Bonham-Carter, 2002).

In WOE, the natural logarithm of the sufficiency ratio is W+. $W_i^+ = \log_e \frac{P\{F/L\}}{P\{F/\bar{L}\}}$ $(eqn\ 13)$

Thus, Similarly, taking the natural log of Equation (12) on both sides, produces: $W_i^+ = \log_e \frac{O\{L/F\}}{O\{L\}}$ $(eqn\ 14)$

Similar algebraic manipulation leads to the derivation of an odds expression for the conditional probability of L given the absence of the factor. Thus, $O\{L/\bar{F}\} = O\{L\}\frac{P\{\bar{F}/L\}}{P\{\bar{F}/\bar{L}\}}$ $(eqn\ 15)$

The term $\frac{P\{\bar{F}|L\}|}{P\{\bar{F}/\bar{L}\}}$ is known as the necessity ratio, LN (Bonham-Carter, 2002). W^- is the natural logarithm of LN. Thus,

$$W_i^- = \log_e \frac{P\{\bar{F}/L\}}{P\{\bar{F}/\bar{L}\}} \qquad (eqn\ 16)$$

Similarly, taking the natural log of Equation (15) on both sides gives: $W_i^- = \log_e \frac{O\{L/\bar{F}\}}{O\{L\}}$ $(eqn\ 17)$

LN and LS are also referred to as likelihood ratios. If the pattern is positively correlated, LS is greater than 1 (W^+=positive) and LN ranges from 0 to 1 (W^-=negative). If the pattern is negatively correlated, LN would be greater than 1 (W^-=positive) and LS ranges from 0 to 1 (W^+=negative). If the pattern is uncorrelated with a landslide, then LS=LN=1 (W^+=W^-=0) and the posterior probability would equal the prior probability, and the probability of a landslide would be unaffected by the presence or absence of the factor. When more than one factor occurs, it is necessary to combine weights of all the factors. For example, when two factors are present:

$$O\left\{{}^{L}/_{F_1} \cap F_2\right\} = O\{L\} + LS_1 + LS_2 \qquad (eqn 18), \quad Logit\ \left\{{}^{L}/_{F_1} \cap F_2\right\} = Logit\ \{L\} + W_1^+ + W_2^+ \qquad (eqn\ 19)$$

Therefore, the general expression for combining i=1, 2, …, n maps containing data on factors is:

$$Logit\ \left\{{}^{L}/_{F_1} \bigcap F_2 \bigcap F_3 \bigcap F_4 \dots \dots \dots F_n\right\} = Logit\ \{L\} + \sum_{i=1}^{n} W^+ \qquad (eqn\ 20)$$

4. Methodology

The methodology involves data collection, derivation of factors, determining and extracting conditions favourable for landslide event, overlaying and intersecting the dataset to map the areas, stability mapping, derivation of probability weights and their application to overlay the factors resulting in landslide probability maps.

4.1 Description of the Data and the derivation of factors

The following data was used: Rainfall data, Soil data, DEM / elevation, Land-cover change, NDVI change, Curvature, and Watershed. Landslide occurrence was observed under the following conditions: rainfall > 1160mm (in 8 months period), soil properties: soil texture= clayey & well drained, BULK[*] >1, TAWC >10 and BSAT >50, DEM derivatives: slope > 60º, curvature >1 and watershed >128, Land-cover change > ± 10% and NDVI change < 0%.

Landsat TM images for scenes: p168r060, p168r061& p169r060 taken in the month of February, for the years 1995, 2000 and 2002 were used. The scenes were mosaiced and subset for each year. Maximum likelihood supervised classification method was used to classify the Landsat images. The overall classification accuracy was 79%, 74% and 82% for the years 1995, 2000 and 2002 respectively.

Change detection was then performed for the epochs 1995-2000 and 2000-2002. NDVI for each of the images was calculated and the NDVI values range is as follows: 0.98 to -1, 1 to -1, and 0.80 to -1 for the years 1995, 2000 and 2002 respectively. The NDVI change was as shown in Table 1.

[*] BULK – Bulk density (density of the soil) , TAWC- Total Available water capacity, BSAT- Base saturation

Table 1: NDVI change

	1995-2000		2000-2002	
	Area in Km^2	Percent	Area in Km^2	Percent
Decreased	11712	88.4%	731.	5.5%
Some Decrease	1245	9.4%	3645	27.5%
Unchanged	6	0%	27	0.2%
Some Increase	211	1.6%	6818	51.5%
Increased	68	0.5%	2021	15.3%
Total	**13242**	**100%**	**13242**	**100%**

A 30m resolution DEM data from ASTER Data was used to derive slope, flow direction, curvature, upslope contributing area, flow accumulation, and watershed map. Slope angles ranged between 0º to 88º, curvature values ranged between -13 to 569, while watershed values ranged between 1 to 255. Rainfall data from 14 stations for the epochs October 1997 to May 1998 and October 2008 to May 2010 respectively were used. Kriging method was used with the rainfall data at the measured stations to interpolate the rainfall across the study area. The results are shown in figure 1. Soil properties affect landsliding by determining how much water the soil can retain, the rate of permeability and its erodibility factor. BSAT values were ranging from 0 to 100, BULK values: 0 to 1.47 and TAWC: 0 to 35. Figure 2 shows the area that satisfies soil conditions for landslide occurrence.

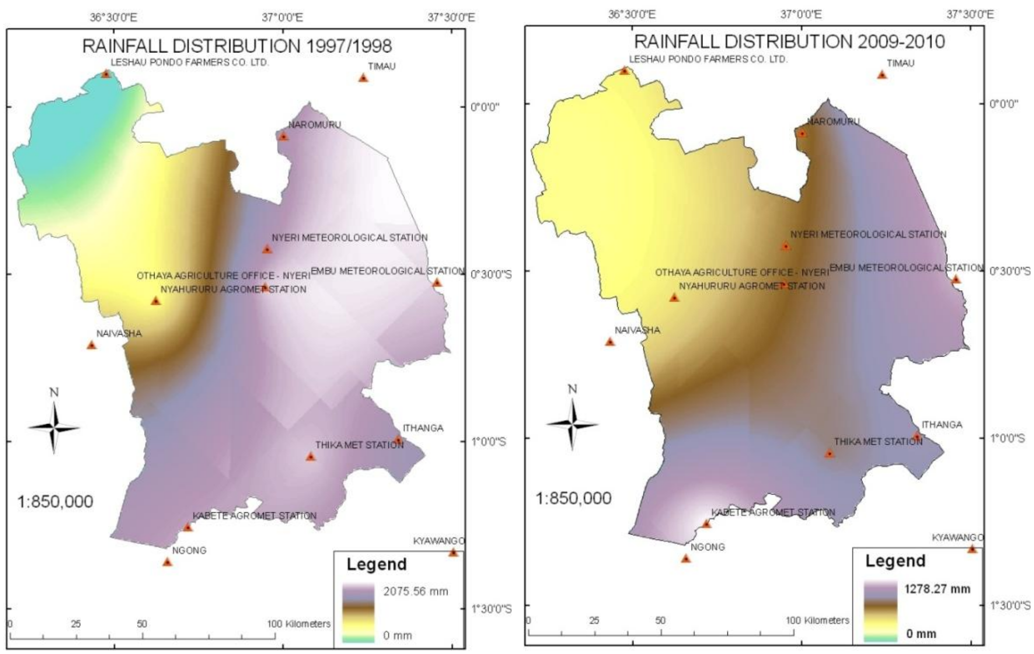

Figure 1: Rainfall distribution (a) October 1997- May 1998 and (b) October 2009- May 2010

4.2 Landslide areas and Results

The minimum condition for landslide occurrence for each of the factors described above in section 4.1 was applied on each of the factor by selection / extraction by SQL statements into a separate layer. Land-cover, NDVI and Rainfall factors were extracted for two epochs i.e. 1997/1998 and 2009/2010 and were overlaid with the other factors (with exception of Land-cover change) using equal weights. The result of this overlay is shown in figure 2a. Landslide areas were further combined with land-cover factor to obtain figure 2b.

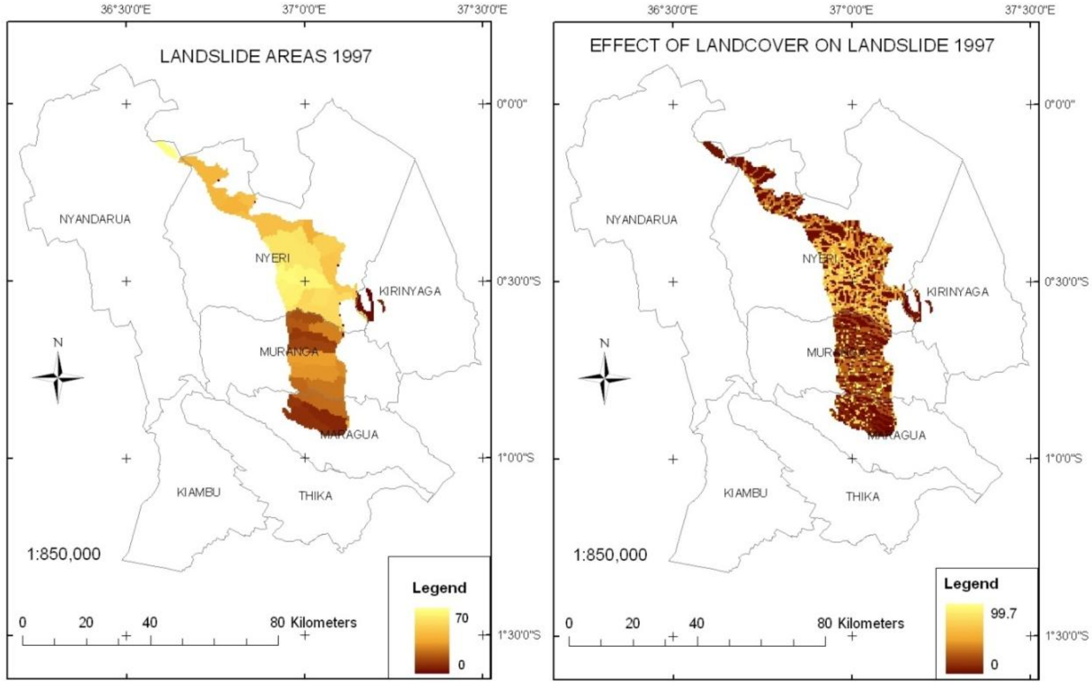

Figure 2: (a) Landslide areas (b) Landslide areas in relation to land-cover

4.3 Stability mapping and Results

Stability mapping procedure was done considering equations1 & 2 and using the following factors: slope angle θ, soil cohesion C, friction angle ϕ, bulk densityρ_s and water density ρ_w**.** To apply the two equations, all the factors were required as single themes in raster format. The right and left hand side of equations 1and 2 were then executed separately. The areas returned as true for equation 1 were unconditionally stable areas while those that returned true for equation 2 were unconditionally unstable areas as shown in Figure 3.

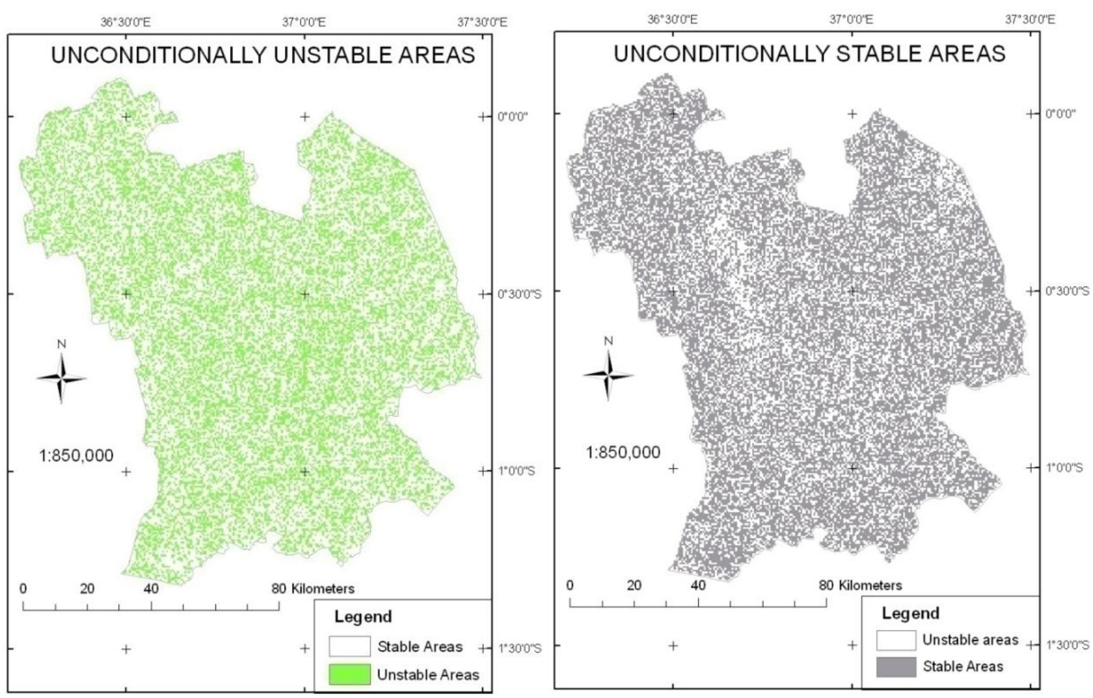

Figure 3: Unconditionally (a) stable areas and (b) Unstable areas

4.4 Derivation of Probability weights for Factors

The results obtained in section 4.3 above were used to determine the probability of landslide occurrence P(L) and the probability of no landslides P($\bar{L}$) for the whole central province. From definition of probability, then P(L) =0.389 and P($\bar{L}$) =0.611 from equation 21 below.

$$P(L) = \frac{\textit{The number of unstable cells}}{\textit{Total number of cells}} \qquad P(\bar{L}) = \frac{\textit{the number of stable cells}}{\textit{Total number of cells}} \qquad (eqn\ 21)$$

For each factor deemed to cause landslide, as described in section 4.1, the probability was calculated as shown in table 2. ***[Table 2 here]*** Similar weights were also calculated for landslide causing factors in the year 2009/2010 as shown in Table 2. ***[Table 3 here]*** For the two epochs, the probability of landslide due to land cover and NDVI changes were much higher than other factors.

Table 2: Weight of evidence for factors contributing to landslides in 1997/98

$P(L)$ = **0.389**			$P(\bar{L}) = 0.611$		W_i	
Factor	$P(F)$	$P(\bar{F})$	$P\left(\frac{F}{L}\right)$	$P\left(\frac{F}{\bar{L}}\right)$	$Log_e \frac{P(F/L)}{P(F/\bar{L})}$	**Scaled W$_i$**
Slope	0.0049	0.9951	0.9875	0.992	0.0046	0.0028
watershed	0.0128	0.9872	0.9681	0.9794	0.0117	0.0073
NDVI change	0.9995	0.0005	0.2802	0.3794	0.3032	0.1888
TAWC	0.1097	0.8903	0.78	0.8478	0.0833	0.0519
BSAT	0.1097	0.8903	0.78	0.8478	0.0833	0.0519
unstable	0.389	0.611	0.5	0.611	0.2005	0.1248
curvature	0.5383	0.4617	0.4195	0.5316	0.2369	0.1475
Rainfall 2009	0.9329	0.0671	0.2943	0.3958	0.2963	0.1845
Land Change	0.9967	0.0033	0.2807	0.3801	0.3029	0.1886
Bulk	0.1097	0.8903	0.78	0.8478	0.0833	0.0519
					1.6059	**1**

Table 3: Weight of evidence for factors contributing to landslides in 2009/10

$P(L)$ = 0.389			$P(\bar{L}) = 0.611$		**Wi**	
Factor	$P(F)$	$P(\bar{F})$	$P\left(\frac{F}{L}\right)$	$P\left(\frac{F}{\bar{L}}\right)$	$Log_e \frac{P(F/L)}{P(F/\bar{L})}$	**Scaled W$_i$**
Slope	0.0049	0.9951	0.9875	0.992	0.0046	0.0029
watershed	0.0128	0.9872	0.9681	0.9794	0.0117	0.0075
NDVI change	0.9979	0.0021	0.2805	0.3798	0.303	0.1939
TAWC	0.1097	0.8903	0.78	0.8478	0.0833	0.0533
BSAT	0.1097	0.8903	0.78	0.8478	0.0833	0.0533
unstable	0.389	0.611	0.5	0.611	0.2005	0.1283
curvarture	0.5383	0.4617	0.4195	0.5316	0.2369	0.1516
Rainfall 1997	0.6264	0.3736	0.3831	0.4938	0.2538	0.1624
Land Change	0.9909	0.0091	0.2819	0.3814	0.3023	0.1935
Bulk	0.1097	0.8903	0.78	0.8478	0.0833	0.0533
					1.5627	**1**

4.5 Application of the weights to overlay the factors and Results

The factors were overlaid using the scaled weights obtained in section 4.4 above. The result was then overlaid with the stable areas while applying P(L) and P($\bar{L}$) respectively. The final result is shown in Figure 4.

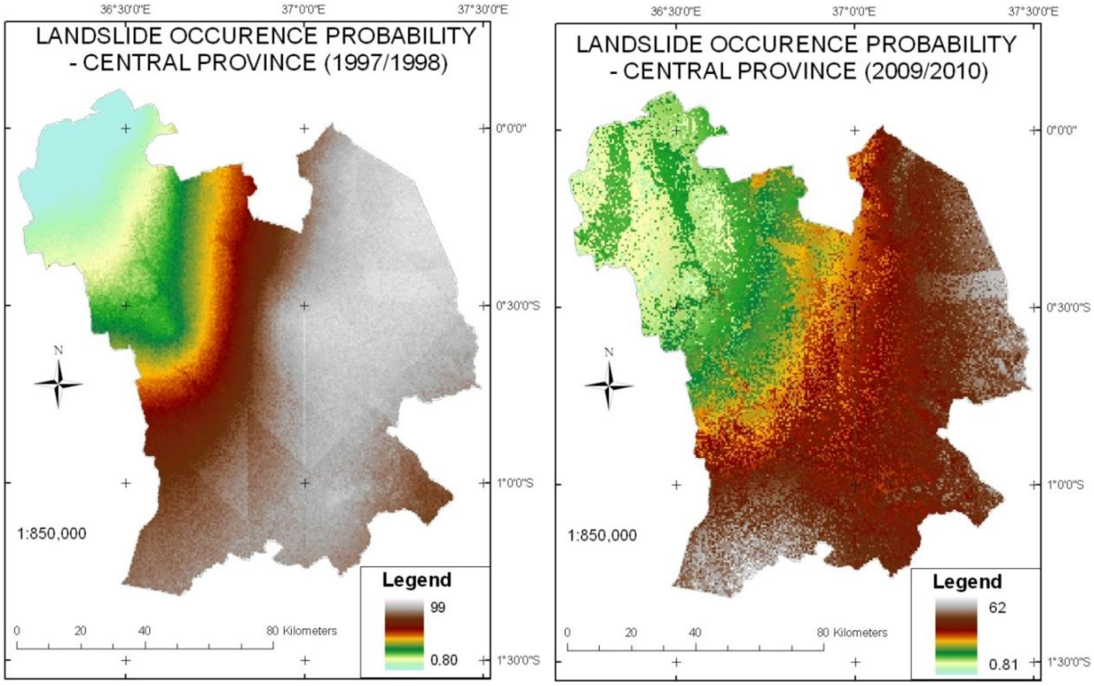

Figure 4: Landslide Probability Values for central province for (a) 1997/98 & (b) 2009/10

5. Discussion

Epochs 1997/1998 and 2009/2010 had similar scale ranges for both landslide areas with and without land-cover change i.e. 0-70 to 0-99.7 respectively. There was more emphasis on man-made developments which disturbs the soil greatly, such that areas with such developments were at a higher scale value than areas with no developments. The effect of land-cover change on landslide probabilities may be explained in table 4. ***[Table 4 here]*** The landslide areas obtained were compared with OCHA landslide regions and approximately 62.3% of the mapped area was within the landslide zone by OCHA. Villages reported to have suffered landslides in the recent past in Mathira and Mukurweini divisions were well within the mapped areas.

Table 4: Effect of Land-cover change on landslides Probabilities

				Land cover probability change						
Year	Crop Field	Intensive Agricult.	Dense Forest	L. D Forest	Thick Shrubs	Grass land	Swampy veg	Rock/ Barren Land	Settle-ments	Water Bodies
1995-2000	3.3%	5.5%	3.2%	3.5%	0.5%	1.8%	0%	8.9%	2.4%	0.3%
2000-2002	4.1%	1.8%	1.6%	0.7%	8.7%	5.9%	2.9%	2.8%	0.3%	0.5%

It can be noted from the stable and unstable areas, Figure 3 (a) and (b), that the classification results are almost identical in both cases. However the slight difference can be attributed to the condition of instability even at dry levels when triggering factors of moving water are absent.

The probability of landslide occurrence, Figure 4, in the epoch 1997/98 ranges from zero to 99%, while that of 2009/10 ranges from zero to 62%. That remarkable difference can be induced from rainfall which was much higher in 97/98 period than in 2009/10 period, and NDVI changes where the 97/98 period recorded a general decrease in NDVI while there was a general increase in NDVI values towards the year 2002.

6. Conclusions

The landslide probability map for the two epochs displays a similar pattern to rainfall distribution. The difference in probability values for epoch 1997/98 (0-99%) and 2009/10 (0-62%) can be attributed to the rainfall difference in the two epochs. It can be noted that the most important factors for landslide occurrence in central province are the amount of continuous rainfall and decrease of NDVI as a result of decrease in agricultural areas and forests.

Areas susceptible to rainfall induced landslide were successfully mapped and validated against OCHA landslide prone areas, of which 62.3% of the mapped area was within the OCHA landslide prone areas. It was also noted that most landslide activity is associated with heavy rainfall as north-East parts of the central province had the lowest probability of landslide occurrence and they registered the least rainfall.

Application of the weights of evidence on the factors causing landslides shows the relationships between the factors and can be used as basis for modeling. By varying the application of land cover change in the factors to map landslide areas, the results showed a remarkable difference implementing that land cover change should not be ignored in landslide studies. Also during the weights of evidence Land-cover and NDVI changes had the greatest weights and therefore their importance in determining landslide occurrence in Central Province.

It was also observed that slope instability mapping conditions for unstable and stable areas resulted in slightly different values of stable and unstable areas. This can be attributed to the fact that unconditional unstability condition predicts areas to be unstable even when it is dry. For the case of rainfall induced landslides, water flow facilitates movement of the land masses and therefore the difference between the values obtained using stable and unstable conditions.

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