CHAPTER II
LITERATURE REVIEW

2.1 Concept of soil erosion

Soil erosion is a natural geological process caused by several uncontrolled variables. Morgan (1995) defined that soil erosion is a two-phase process consisting of the detachment of the individual particles from the soil mass and their transport by water and wind. Junian and Katherine (1996) defined soil erosion as the wearing away of the land surface by the running water, the wind, the ice or the geological agents. Accelerated erosion is much more rapid than normal, natural, or geological erosion, occurring primarily as a result of the influence of human activities.

The factors controlling the soil erosion include the erosivity of the eroding agent, the erodibility of the soil, the slope of the land, and the nature of the plant (Hudson, 1995). The erosivity that relates to amount of the rainfall and its intensity is a measure of the detaching power of raindrops striking the soil surface and establishing the surface runoff. The soil erodibility is defined as the resistance of the soil to both the soil particle detachment and their transport. It is mostly affected by soil texture, soil structure, soil permeability and soil organic matter. The slope of the land also directly associates with the soil erosion because the soil loss increases with a rise in slope steepness and slope length as a result of respective increase in velocity and the volume of the surface runoff. The nature of the plant acts as a protective layer for the surface soil layer or the topsoil since it absorbs some of kinetic energy of the falling raindrops and the running water.

2.2 Soil erosion driving forces and its studies in the northern Vietnam

2.2.1 Driving forces of the soil erosion

Vietnam has a total area of 33 millions hectares, 71.5 % of those area are the steep land. The degraded land area has occupied nearly 50 % of the total land

(Environmental Database Division, 2002). The main driving forces of soil degradation in the upland areas of northern part of Vietnam are deforestation, slash and burn agriculture, the forest fires, the war-induced damage and the livestock grazing.

As a result of deforestation, the forest fires, the war-induced damage and the livestock grazing, the land cover in Vietnam was rapidly reduced from 1943 to 1998. Before 1943, Vietnam had about 14.3 millions hectares of forests that comprised 43 % of the country's natural land area. However, the total area of the forested land was rapidly dropped to 9.6 millions hectares in 1999 corresponding to its percentage of 28.8 % of country's total land area. The forest stands are recently remained at only 8.2 millions hectares and forest plantation area of 1.4 million hectares are recovered so far (Environmental Database Division, 2002).

The shifting cultivation, which was widely practiced in many upland areas in the northern part of Vietnam, referred as a second important cause that seriously resulted in the soil degradation. The seriously eroded land area at level of 100 tons ha^{-1} $year^{-1}$ covered an area of 17 % (Bat, 2001). A latest soil erosion report revealed that a large area of nearly 22.95 millions ha had the potential soil loss ranging from 50 to 4,500 ton ha^{-1} $year^{-1}$. The potential soil loss was increased to the rate of 250-300 ton ha^{-1} $year^{-1}$ in the food cropland. The totality of the soil loss was estimated roughly 10,141 billions tons $year^{-1}$ excluding areas of soil loss rate of less than 50 tons ha^{-1} $year^{-1}$ (Environmental Database Division, 2002).

As a consequence of deforestation and shifting cultivation, the onsite and offsite effects of soil erosion are urgently raising many concerns regarding the long-term erosion control strategies. In order to deal with such challenges, soil erosion studies are recently ranking as a first research priority of central and local government for the upland areas in the northern part of Vietnam.

2.2.2 Measuring the soil loss

Several field experiments were carried out to measure the rate of soil erosion and its effects on crop productivity under different cropping systems and soil conservation practices across the northern part of Vietnam.

Vinh *et al*. (2001) found that there was a variation of soil loss among cropping systems on the steep lands from 8 to 22^o in Luong Son district, Hoa Binh province. Rate of the surface runoff was proportional to the measured potential soil loss.

Another field experiments on 9-12 percent lands in Tam Dao, Phu Tho province revealed that cassava intercropping with peanut-hedgerow and high input was significantly reduced more than 50 percent of soil loss comparing with cassava-monoculture, cassava with peanut and low input, cassava with peanut-hedgerow and low input (Howeler *et al*. 2001). Experiments on 10 percent sloping land at the research station at Thai Nguyen University of Agriculture and Forestry (Loi, 2000) were also shown the same trend of the intercropping practices on potential soil loss.

The additional fertilizer and conservation practices were significantly decreased soil loss. Phien *et al*. (1997) reported that there was an effect of intercropping and fertilizing on soil loss in Kieu Tung village, Thanh Ba district, Phu Tho province on slopping land of 40 percent. He found that soil loss was larger within the treatments that hedgerow and fertilizer were not applied.

2.2.3 Measuring the losses of nutrients

Soil loss led to losses of basic nutrients that were one of consequences of the exhausted soil in the upland areas, especially where food crops were annually cultivated. Siem and Phien (1999) found that losses of nutrients under the cassava cultivation plots was higher those than under the tea cultivation plots and maize intercropping with peanut.

The losses of available nutrients were considerable under upland rice cultivation systems. Vinh *et al*. (1999) reported that nutrients were lost at very high rate under mono upland rice cultivated plots even though contouring practice was applied from 1996 to 1999 in Luong Son district, Hoa Binh province. While nutrients were lost at lowest rate under bare soil plots during that time.

2.2.4 Soil erosion modeling

Recently, soil erosion studies in the upland areas of Vietnam mostly aim to measure the rate of the soil loss and its related consequences at field level. Using soil erosion models were not widely practiced in the soil erosion studies (Hien *et al*. 2001). However, USLE was suggested as soil erosion estimation method in the northern Vietnam, which was well worked with real erosion system (Siem, 1999). Siem and Phien (1999) was estimated the rainfall erosivity index using 6,500 rainfall events with interval of every five-minute in Xuan Mai, Thuy An, Hoa Binh, Ba Vi, Thai Nguyen and Tay Hieu province in the northern Vietnam and they found that the erosivity index varied from 523 to 963 MJ ha $^{-1}$ year $^{-1}$ and they also mapped the rainfall erosivity index for the northern Vietnam at scale 1: 1,000,000. The equation, R = 0.548527 P - 59.9, was used for mapping. Furthermore, he estimated the soil erodibility index using the Nomograph for the northern provinces. He found that soil erodibility index varied from 0.09 to 0.31.

Phien *et al*. (2001) integrated the Revised Universal Soil Loss Equation within ILWIS 2.23 and MapInfo 5.0 to estimate the potential soil loss in Ninh Thuan province, Vietnam. The estimation indicated that the derived potential soil loss fell within the range from 50.1 to 870.12 tons ha $^{-1}$ year $^{-1}$. They were found that small amount of soil loss was occurred in areas with rainfall less than 1,000 mm year $^{-1}$ and flatted land. While large amount of soil loss was occurred in areas with slopes greater than 15 ^{o} and annual rainfall of 1,500 mm.

Regarding the soil erosion cost, Bui Dung (2001) estimated the onsite cost of soil erosion and analyzed the determinants of the choice of land use systems by upland farmers, Vietnam. Estimations indicated that fruit tree and eucalyptus-based systems were least cost while upland rice system was highest cost.

2.3 Model for soil erosion study

Field measurements, laboratory techniques and erosion models can be used to study the soil erosion process. Field experiments are the most accurate method but it is laborious and expensive. Laboratory techniques are used to determine a factor that affected soil erosion. Soil erosion models are generally developed for a specific location, but can be used for other areas with suitable modifications and validations.

Soil erosion models have been progressed from data collection to compare practices, to simple empirical models, to complex empirical models and most recently toward process based model. Models of the soil erosion can be grouped into empirical models and physically based models. An empirical model statistically determines relationships between the assumed important variables where a reasonable dataset is available. It is only based on observations or experiments. It fits the observed dataset and then let us to estimate what will happen in certain circumstances (Hudson, 1995). The reliability of an empirical model depends on the experienced dataset. An empirical model may be a simple approximate relationship or complex multiple regression equation.

Conversely, the knowledge of working of erosion processes is focused on the physically based-models. There are several mathematical equations that are developed to describe the separate physical processes involving in a model (Morgan, 1995). Because there are so many variables and computations, these models are only operated through the computer.

There is a greater concern with the on-site consequences of the soil erosion so that models development for runoff and sediment prediction on land surface is considerably made. However, the empirical models pose several limitations in solving those questions. They are not able to simulate the movement of water and sediment over the land. Instead, physically based models have met such objectives (Morgan, 1995).

In short, physically based models make an estimation of soil loss more exactly while a huge input dataset required is always not available. Conversely, empirical models require less data than physical ones. However, in developing countries like Vietnam, a limited existing dataset is a barrier to apply physically based models. Hence, three empirical models USLE, SLEMSA and MMF model were adapted to compare for estimating spatial distribution of soil loss under Ba Be, Bac Kan, Vietnam.

2.4 Roles of GIS technology in soil erosion studies

Lately, integration of soil erosion models within GIS package is widely practiced for the soil erosion studies around the world. Particularly, the empirical erosion models such as USLE, SLEMSA and MMF were integrated within a GIS package to estimate soil loss due to their simplicity.

Ankeney (1994) and Lufafa *et al*. (2002) stated that input dataset for soil erosion studies were easily digitized and efficiently stored in a GIS package. Therefore, data on different themes and from different sources are well incorporated and displayed in a well-structured format which users can easily visualize. Andrew *et al*. (1999) also indicated that GIS provided a robust soil conservation-planning tool readily manageable and assessable to land managers in Mexico. Ogawa *et al*. (1997) confirmed that traditional investigation for erosion studies was very expensive and laborious. In such conditions, land resource planning needed a complete and regular information system. GIS was referred as a useful aiding tool for assessing and monitoring the seriously eroded areas.

There were several applications of GIS-erosion model integration in soil erosion studies, particularly USLE. The USLE was efficiently incorporated in a GIS package to estimate soil loss in Khonkean and Udon provinces, Northeastern of Thailand (Mongkolsawat *et al*. 1994), the northern Pakistan (Ogawa *et al*. 1997), the Lake Victoria Basin, Uganda, Kenya (Lufafa *et al*. 2002), and the Upper Ewaso Ng'iro North basin of Kenya (Mati *et al*. 2000). The MMF model was also integrated in GIS enviroment to estimate soil loss in Indonesia, Nepal, Mediterranean areas and the Bas-Vivarais zone of Ardeche, Southern France (Morgan, 2001).

2.5 Universal Soil Loss Equation (USLE)

Universal Soil Loss Equation provides an estimate of the long-term average annual soil loss from each micro-area of the arable land under various cropping conditions. However, USLE was not designed to estimate the sediment yield from a watershed, soil loss from a single storm, soil loss from large rills and gullies, sediment movement into streams and deposition of eroded soil mass (Hudson, 1995). The USLE (Wischmeier and Smith, 1978) is expressed as the product of six causative factors

$$A = R \cdot K \cdot LS \cdot C \cdot P \qquad [2\text{-}1]$$

Where

A = mean annual soil loss (ton ha^{-1} $year^{-1}$)

R = rainfall erosivity index (J m^{-2})

K = soil erodibility index

LS = factors of slope length and slope steepness

C = cover management factor

P = conservation practice factor

The rainfall erosivity index (R)

The most widely used manner for estimating the erosivity factor is an index that is calculated using the EI_{30}, which is a product of kinetic energy (E) and maximum 30-minute intensity (I_{30}).

The kinetic energy is probably derived from the general relationship between the kinetic energy and the rainfall intensity. Since rainfall conditions vary from place to place; hence, the equations are fitted in the different forms.

Marshall and Palmer (1948) derived the equation for estimating the kinetic energy that represented a wide range of environments and its form was given as.

$$KE = 8.95 + 8.44 \log_{10} I \qquad [2\text{-}2]$$

Where

KE = kinetic energy ($Jm^{-2}\ mm^{-1}$)

I = rainfall intensity ($mm\ h^{-1}$)

Wischmeier and Smith (1958) obtained the equation for this relationship based on previous works of Laws and Parson reported in 1943 in the United States.

$$KE = 11.8 + 8.73 \log_{10} I \qquad [2\text{-}3]$$

For tropical rainfall regions, (1965) analyzed the rainfall data records and his derived equation was given as

$$KE = 29.8 - 127.5/I \qquad [2\text{-}4]$$

Another equation was derived from rainfall condition in Italy, Zanchi and Torri (1980) obtained a relationship between the kinetic energy and its intensity as follows.

$$KE = 9.81 + 11.25 \log_{10} I \qquad [2\text{-}5]$$

Onaga *et al*. (1988) found this relationship for Okinawa, Japan as follows

$$KE = 9.81 + 10.6 \log_{10} I \qquad [2\text{-}6]$$

Uson *et al*. (2001) reported two equations 2-7 and 2-8, one was for the rainfall intensity of less than 20 mm h^{-1} and the other for that was higher than 20 mm h^{-1}. If rainfall intensity was less than 20 mm h^{-1}, equation [2-7] was derived with a coefficient of determination of 0.92.

$$KE = 0.0065\, I - 0.0050 \qquad r^2 = 0.92 \qquad [2\text{-}7]$$

If rainfall intensity was more than 20 mm h^{-1}, equation was given as

$$KE = 0.0093\, I - 0.0517 \qquad [2\text{-}8]$$

All linear regression equations from 2-1 to 2-8 were developed to estimate the kinetic energy from its intensity of rainfall for calculating erosivity index. In many developing countries, the existing rainfall dataset is, however, often in short supply. An attempt can be made to find a more widely available rainfall parameters that significantly correlated to erosivity. Morgan (1974) used the rainfall records from ten stations of Malaysian Meteorological Service with autographic rain gauges and established the relationship between mean annual erosivity (R) and mean annual rainfall (P; mm) as follows

$$R = 9.28\, P - 8838.15 \qquad r = 0.81 \qquad [2\text{-}9]$$

This equation [2-9] was used for mapping the rainfall erosivity index from the mean annual rainfall data for the whole country in Malaysia.

Renard and Freimund (1994) found the relationship between erosivity and the annual rainfall in the mountainous rainfall regime of Mexico; equation was fitted as follows.

$$R = 587.8 - 1.219\ P + 0.004105\ P^2 \qquad [2\text{-}10]$$

Where

R = rainfall erosivity (MJ mm ha^{-1} h^{-1} $year^{-1}$)

P = annual precipitation (mm)

However, Andrew *et al*. (1999) found that the erosivity was strongly correlated with the annual precipitation in a mountainous tropical watershed in Mexico and was fitted in another form.

$$R = -\ 0.0334\ P_a + 0.006661\ P^2_a \qquad [2\text{-}11]$$

Where

R = erosivity factor (MJ mm ha^{-1} h^{-1} $year^{-1}$)

P_a = annual precipitation (mm)

Lufafa *et al*. (2002) determined the relationship between the EI_{30} and annual rainfall with deterministic coefficient r^2 = 0.72 in the Lake Victoria basin, Kenya. The equation was given as

$$R = 47.5 + 0.38\ P \qquad [2\text{-}12]$$

Where

R = rainfall erosivity (J m^{-2})

P = annual rainfall (mm $year^{-1}$)

Siem (1999) analyzed the existing rainfall dataset of all weather observation stations in the northern part of Vietnam; he gained the relationship between the rainfall erosivity index and the annual rainfall in the following form.

$$R = 0.548527\ P - 59.9 \qquad [2\text{-}13]$$

Where

R = rainfall erosivity index (MJ ha $^{-1}$ year $^{-1}$)

P = annual rainfall (mm)

The soil erodibility index (K)

The soil erodibility index refers as the susceptibility of soil to erosion. A soil with the high erodibility suffers more erosion than a soil with the low erodibility. It mostly depends on the soil texture, the soil structure, the soil infiltration capacity, the soil organic matter, and the topographic conditions. El-sway *et al.* (1982) reported that the soil erodibility index fell within the range from 0.06 to 0.48 in the tropical soils.

Several methods were developed for estimating soil erodibility index. Bouyoucos (1935) developed a simple formula, based on a laboratory analysis concerning with the soil texture, for calculating soil erodibility index.

$$Erodibility = \frac{\%Sand + \%Silt}{\%Clay} \qquad [2\text{-}14]$$

The Nomograph method (Wischmerier *et al*. 1971) requires data of the organic matter content, the soil structure, the soil texture, and the soil permeability. These were defined according to soil-mapping units.

An additional formula was established to estimate the soil erodibility index in United States (Wischmeier and Smith, 1978).

$$K = \frac{2.1 * 10^{-4} * (12 - OM) * M^{1.14} + 3.25 * (S - 2) + 2.5 * (P - 3)}{7.59 * 100} \qquad [2\text{-}15]$$

Where

K = soil erodibility factor, expressed in t ha h ha $^{-1}$ MJ mm $^{-1}$

OM = soil organic matter content

M = (% silt + % very fine sand) (100 - % clay)

S = soil structure code

P = permeability class

Besides equation [2-15], Wischmeier and Smith (1978) also reported that the soil erodibility index for a series of benchmark soils was obtained using data of direct soil loss measurements from fallow plots in many US states. An estimate for an unknown K was calculated from the regression equation 2-16.

$$K = 2.8*10 - 7*M^{1.14} (12 - a) + 4.3*10^{-3} (b - 2) + 2.3 *10^{-3} (c-3) \qquad [2\text{-}16]$$

Where

K = soil erodibility index

M = particle size parameter = (% silt + % very fine sand) (100 - % clay)

a = organic matter (%)

b = soil structure code (very fine granular = 1, moderate = 2, blocky = 3 and massive = 4)

c = profile permeability class (rapid = 1, moderate to rapid = 2, moderate = 3, slow to moderate = 4, slow = 5 and very slow = 6)

In relation to the soil condition, there is a difference between soils in United States and the other countries around the world; therefore, an approximation need to be made for this index, especially in tropical areas. Ogawa *et al*. (1997) used the scoring method for obtaining the soil erodibility index in Pakistan. This index was estimated by assigning the scoring value for each soil characteristic and then the total score of each soil type was summed up. The next step was the ranking of the soil erodibility factor according to the total score.

Slope steepness and slope length (L S)

Wischmeier and Smith (1978) determined that factors of slope length and slope steepness were combined in a single index which expressed the ratio of soil loss under a given slope steepness and slope length to the soil loss from the standard condition of a 5 ^{o} slope, 22 meter long. It was given by the equation

$$LS = (X/22.3)^{n} \ (0.065+0.045\ S+0.0065\ S^{2}) \qquad [2\text{-}17]$$

Where

LS = factors of slope length and slope steepness
X = slope length (m)
S = slope gradient (percent)
n is varied according to slope steepness

Moore and Burch (1986) derived an equation for estimating LS based on flow accumulation and slope steepness, which was given as

$$LS = (\text{flow accumulation*cell size}/22.13)^{0.4} \ (\sin \text{slope}/0.0896)^{1.3} \qquad [2\text{-}18]$$

Where

LS = factors of slope length and slope steepness
Slope expressed in radian

Mitasova *et al*. (1996) reported a continuous form equation for LS factor calculation at a point r (x, y) on a hill slope. The equation was applied for computation of the LS factor for a grid cell representing a hill slope segment. It was given in the form

$$LS(r) = (m + 1) [A (r) / a_o]^m [\sin b (r) / b_o] \quad [2\text{-}19]$$

Where

LS(r) = slope steepness and slope length at a point with coordinates (x, y)

A(r) = upslope contributing area per unit contour width

b = slope expressed in degree

m = 0.6, n = 1.3 for slope length less than 100 m and slope less than 14 degree

a_o = 22.1 m and b_o = 0.09

Desmet and Govers (1996) revised slope length calculation equation of Foster and Wischmeier (1974) for each grid cell as follows.

$$L_{i,j} = \frac{A_{i,j-out}^{m+1} + A_{i,j-in}^{m+1}}{(A_{i,j-out} - A_{i,j-in})(22.13)^m} \quad [2\text{-}20]$$

Where

$L_{i,j}$ = slope length factor for the cell with coordinates (i,j)

$A_{i,j-out}$ = contributing area at the outlet of the grid cell with the coordinates (i,j) (m^2)

$A_{i,j-in}$ = contributing area at the inlet of the grid cell with coordinates (i,j) (m^2 m^{-1})

m = slope length exponent

Nearing (1997) made a single continuous function for slope steepness in order to calculate the LS factor. The equation was given as

$$S = -1.5 + 17/(1+e^{2.3-6.1\sin\theta}) \quad [2\text{-}21]$$

Where

θ is slope in degrees of cell for which LS is to be determined.

Kinnell (2001) employed the slope length equation for grid cell with the sides of the length (D) with coordinate (i,j) was given as

$$L_{i,j} = (D_{i,j}/22.13)^{m} \qquad [2\text{-}22]$$

The values of m varied according to slope, m = 0.5, 0.4, 0.3, 0.2 corresponding the values of S > 5%, 3 % < S < 5%, S < 1%, respectively.

Under condition of tropical areas, there is a considerable variation in steepness. Therefore, Mati (2000) used LS-factor equations of McCool developed in 1987 for assessment of soil erosion hazard in Kenya.

$$LS = (\lambda /22.13)^{m} \ (10.8 \sin S + 0.03) \text{ for slope less than } 9\% \qquad [2\text{-}23]$$

$$LS = (\lambda /22.13)^{m} \ (16.8 \sin S + 0.03) \text{ for slope more than } 9\% \qquad [2\text{-}24]$$

Where

LS = Factors of slope length and slope steepness

λ = slope length (m)

S = slope (percent)

m = an exponent that depends on slope steepness, it is 0.5 for slope exceeding 5%; it is 0.4 for slope of 4% and it is 0.3 for slope of less than 3%.

Lufafa (2002) estimated LS-factor using two equations, one for slope below 21 % given as

$$LS = (L/72.6)\ (65.41\text{Sin}\ (S) + 4.56\ \text{Sin}\ (S) + 0.065) \qquad [2\text{-}25]$$

Where

LS = slope length and slope steepness factor

L = slope length (m)

S = slope expressed in radian

The cover management factor (C)

Wischmeier and Smith (1978)'s procedure retain to estimate crop management factor. In this procedure, percentage cover is multiplied with percentage rainfall erosivity for each period and finally C-factor is summed up for a year (Morgan, 1995). The cover management factor represents the ratio of the soil loss under a given crop to that from the bare soil. The C factor varies from 0.001 for forest, dense shrub and high mulch crops to 1.0 for bare soil (Wischmeier and Smith, 1978).

Conservation practice factor (P)

The conservation practice factor is estimated by comparing ratio of soil loss between with and without soil conservation practice. The P values vary according to types of the contouring and the strip cropping and the slope steepness as well Wischmeier and Smith (1978).

However, Wener (1981) suggested an equation for calculating the soil conservation practice in the following form.

$$P = 0.2 + 0.03\,S \qquad [2\text{-}26]$$

Where

S = slope expressed in percent

2.6 Soil loss Estimation Model for Southern Africa (SLEMSA)

Soil loss estimation model for Southern Africa was originally developed to estimate the soil erosion in the farming systems in Zimbabwe, which based on the principles of Universal Soil Loss Equation. In SLEMSA, the soil conservation factor is left out because the effect of the local conservation practice is included in the slope length or the slope factor within the topography or within the erodibilility factor in the soil system. The other factors are quantified by methods, which are simpler to calculate, or requires less data.

The equation (Elwell, 1978) was given as the product of three main factors as follows.

$$Z = K \cdot X \cdot C \qquad [2\text{-}27]$$

Where

Z = mean annual soil loss (tons ha^{-1} year^{-1}).

K = mean annual soil loss from a standard field plot (ton ha^{-1}) [20 meter long, 10 meter wide, at 2.5-degree for a soil of known erodibility (F) under a weed bare fallow]

X = a dimensionless combined slope length and steepness factor

C = a dimensionless crop management factor

K-factor

The K value was determined by relating mean annual soil loss to mean annual rainfall energy (E) using the exponential relationship as bellow

$$\text{Ln } K = b \text{ Ln } E + a \qquad [2\text{-}28]$$

Where

E = mean annual rainfall energy (J m^{-2})

The values of a and b are functions of the soil erodibility factor (F) that are calculated by the following equations.

$$a = 2.884 - 8.2109\ F \qquad [2\text{-}29]$$

$$b = 0.4681 + 0.7663\ F \qquad [2\text{-}30]$$

The value of F-factor was determined upon the soil texture that classified into groups of sands, loamy sands, sandy loams, sandy clay loam, clay loam, sandy clay, clay and heavy clay.

The values of F can be subtracted or added in certain conditions. The value of F is subtracted by 1 if soil is one of types that is described by following characteristics: light-textured soils consisting of mainly sands and silts, restricted vertical permeability within one meter of the surface, ridging up-and-down slope, deterioration in soil structure due to extreme soil loss in the previous year (more than 20 ton ha^{-1}). The values of F is subtracted by 0.5 if the soil is slight to moderate surface crusting or soil loss of 20 ton ha^{-1} in the previous years. The rating of F also be added by 1 if soil is one that is described as main characteristics: tillage techniques encouraging maximum preservation of water on the surface, high surface infiltration, maximum water storage and first season of no tillage in the profile. If soil is added with 2, characteristics of a soil are subsequent seasons of no tillage or a soil that has depth of more than 2 meter, well drained and light-textured.

X-factor

The topographic factor (X) adjusts the values of soil loss calculated for standard condition to that for the actual conditions of slope steepness and slope length, which is given as

$$X = L^{1/2} (0.76 + 0.53 S + 0.076 S^2) / 25.65 \qquad [2\text{-}31]$$

Where

L = slope length (m)

S = slope (percent)

C-factor

The C-factor adjusts the value of the soil loss for the standard bare soil condition to that from a cropped field. The C-factor depends on the percentage of the rainfall energy that is intercepted by the crop (i). For crops and natural grassland with i is less than 50%, the C-factor is given as

$$C = e^{(-0.06 i)} \qquad [2\text{-}32]$$

For the dense pasture and the mulches which i is more than 50%, the these relationship is obtained in the following equation

$$C = (2.3 - 0.01 i) / 30 \qquad [2\text{-}33]$$

Values of i is obtained by weighting the percentage crop cover in each period by percentage of the mean annual energy (E) occurring in that period and summing the C values. The crops cover values for calculating C-factor presented by Elwell and Wendelaar (1977) and Elwell (1978).

2.7 Morgan, Morgan and Finney model (MMF)

The Morgan-Morgan-Finney model (1984) is also an empirical model, which uses for estimation of the annual soil loss by the water from the field-sized areas on the hill slopes. It separates the soil erosion process into the water phase and the sediment phase. Model describes erosion as the detachment of the soil particles by the raindrop impact and the transport of those particles by the overland flow. However, the process of the splash transport and the detachment by the runoff is not included. The effects of the soil conservation practices can be added within the separate phases of the model through the changes in the evapo-transpiration, the interception by the crop, the rate of the detachment and the transport capacity. The model compares the soil mass detached by the rain plash and the soil mass transported by the overland flow in order to quantify the soil loss going beyond a field or a watershed. That is, the difference between two these values is assigned as the annual soil loss rate. If the soil loss by the detachment is less than that by the transport, it is actually a redistribution of the soil within a field or a watershed. If these two values are same, then the soil loss by the detachment is the annual soil loss.

In the water phase, there are two equations, one is used for estimating the kinetic energy of the rainfall and the other is used for estimating the volume of the overland. The equation for calculating the kinetic energy of the rainfall is given as

$$E = R\,(11.9 + 8.7 \log_{10} I) \qquad [2\text{-}34]$$

Where

E = kinetic energy of rainfall (J m $^{-2}$)

R = annual rainfall (mm)

I = typical value for intensity of erosive rain (mm h^{-1}) (use 11 for temperature climate, 25 for tropical climate and 30 for strongly seasonal climates)

In order to improve the equation [2-34], Morgan (2001) revised it as following form.

$$KE = DT\,(11.9 + 8.7 \log_{10} I) \qquad [2\text{-}35]$$

Where

KE = kinetic energy (J m $^{-2}$)

$$DT = ER - LD \quad [2\text{-}36]$$

Where

DT = kinetic energy of direct throughout rainfall (J m^{-2})

ER = total energy of effective rainfall (J m^{-2})

LD = kinetic energy of leaf drainage (J m^{-2})

LD = ER * CC, CC = % canopy cover

The equation for calculating the overland volume is given as

$$Q = R \,.\, \exp(-Rc/Ro) \quad [2\text{-}37]$$

Where

Q = volume of overland flow (mm)

R = annual rainfall (mm)

$$Rc = 1000 \,.\, MS \,.\, BD \,.\, RD \,.\, (Et/Eo)^{0.5} \quad [2\text{-}38]$$

Where

MS = soil moisture content at field capacity (% w/w)

BD = bulk density of topsoil layer (kg m^{-3})

RD = top soil rooting depth (effective hydrological depth, m)

E_t/E_o = ratio of actual to potential evaporation

$$Ro = R/Rn \quad [2\text{-}39]$$

Rn = number of rain days in a year

In the sediment phase, there are also two equations, one is used for estimating rate of detachment by raindrop impact and the other is used for estimating transport capacity by overland flow. For the rate of the detachment by the raindrop impact, it is given as

$$F = K \,.\, (E \,.\, e^{-aA})^{b} \,.\, 10^{-3} \quad [2\text{-}40]$$

Where

F = rate of soil detachment by raindrop impact (kg m $^{-2}$)

K = soil detachment index defined as the weight of soil detachment from soil mass per unit of rainfall energy

E = kinetic energy of rainfall (J m^{-2})

a = 0.05

b = 1.0

A = percentage of rainfall contributing to permanent interception as stem flow

However, in the revised version of MMF model, the soil detachment by the raindrop impact was revised as follows (Morgan, 2001)

$$F = K \,.\, KE \,.\, 10^{-3} \qquad [2\text{-}41]$$

Where

F = soil detachment by raindrop impact (kg m $^{-2}$)

K = erodibility of the soil (g J $^{-1}$); a guide values for K have been revised and now cover a range of soil texture

KE = kinetic energy (J m $^{-2}$)

For the transport capacity by the overland flow, it is given as

$$G = C \,.\, Q^{d} \,.\, \sin S \,.\, 10^{-3} \qquad [2\text{-}42]$$

Where

G = transport capacity by overland flow (Kg ha $^{-1}$)

C = crop cover management factor

Q^d = volume of overland flow (mm), d = 2.0

S = steepness of the ground slope expressed as degree

In addition, the revised version of MMF model (Morgan, 2001), a new component was added in the model. This component is to calculate the detachment of the soil particles by the runoff, which is a function of the runoff, steepness and the resistance of the soil. The equation is

$$H = Z.\ Q^{1.5}\ .\text{Sin}\ S\ (1 - GC)\ 10^{-3} \qquad [2\text{-}43]$$

Where

H = detachment by runoff (kg m^{-2})

Z = resistance of the soil

Z = 1/(0.5 * COH), COH = cohesion of the soil (K pa)

Q = volume of overland flow (mm)

S = slope (degree)

GC = ground cover (%)

2.8 Model comparison

Comparison between the estimated outputs and observations is an important step to test the model accuracy and locate the gap for further improvements. The correlation-regression approach is very common in fitting an empirical model to data obtained from experimental observations or surveys (Kazuhiko *et al*. 2000).

A comparison of the model output (Jamieson *et al*. 1998) was summarized by a statistic of the overall deviation, namely Root Mean Squared Error or Root Mean Squared Deviation (RMSD).

$$RMSD = \frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2 \qquad [2\text{-}44]$$

Where

x_i = measured values

y_i = estimated values

Retta *et al*. (1996) recommended equation [2-45] to describe the difference between the mean of the simulation and the observation or often called the bias. It was given in the following equation.

$$MD = \frac{1}{n}\sum_{i=1}^{n}(x_i - y_i) \qquad [2\text{-}45]$$

Lars (1995) developed an algorithm that defined as the confidence limit for the predicted values. The algorithm was given as

$$CI/R = (2.17/(n-2)+ 0.52) *(1-r^{2})^{0.5} \qquad [2\text{-}46]$$

Where

CI = 95% confidence interval for the predicted y value, expressed as fraction of the maximum y value, transformed as necessary to the most normal frequency distribution for x and y data.

R = range of the relative values, R = (max y – min y) /max y, n = number of independent validations (n must be > 3) and r^2 is the coefficient of determination from these validations.

Cross validation (Eward, 1989) was also used as a technique that allowed comparison of estimated and observed values. The cross validation results most commonly used to compare the distribution of the estimation error or residuals from the different estimation procedures. The cross validation residuals report the important spatial information with a final objective of estimation that provides insights into where an estimation procedure may run into trouble.

2.9 Extra production cost estimation

The accelerated erosion increases both on-site and off-site cost. In the erosion studies, on-site costs mostly calculated while off-site costs are often ignored. Soil erosion leads to the increasing costs of the agricultural production because of the additional fertilizer and other costs such as costs for erosion control measures.

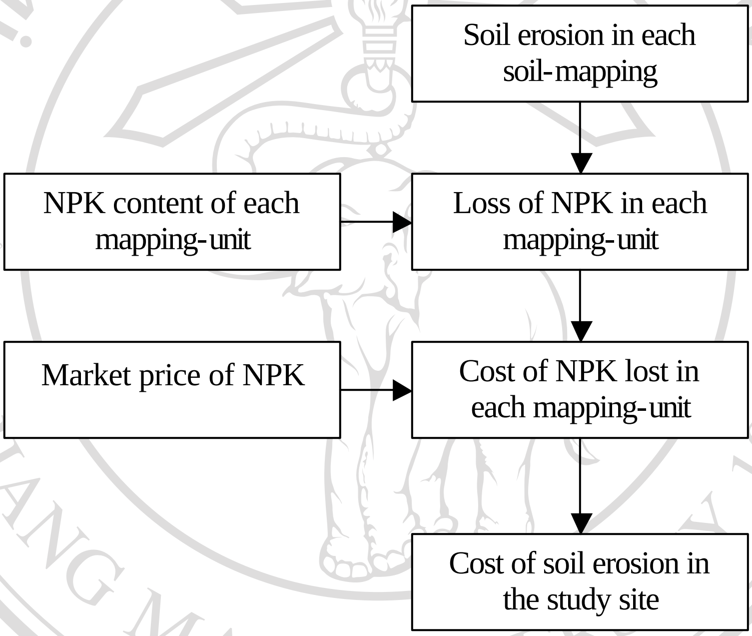

Figure 2-1 The estimation of cost of soil erosion

Several available nutrients in the soil are eroded away during the erosion process such as nitrogen, phosphorus and potassium. Stocking (1986) reported that, in Zimbabwe, there was nearly 1.6, 0.24 and 15.6 millions ton of nitrogen, phosphorus and organic carbon annually lost, respectively. Total losses of nitrogen and phosphorus approximated to US$ 1.5 billions.

Several methods can be used to estimate these losses. The replacement cost was widely practiced due to its simplicity. The replacement cost technique (Figure 2-1) was used to estimate a quantity of fertilizer applying into the soil to maintain an equivalent amount of nutrients prior to soil erosion. The replacement cost (Hazarika, 1997) was calculated according to each soil-mapping unit (SMU). The loss of the estimated nutrient was then converted to cost of nutrient in that SMU with the reference to the market price for each kind of fertilizer.

Salzer (1993) used the replacement cost technique to estimate nutrient loss of the nitrogen, the phosphorus and the potassium in the northern part of Thailand. He calculated the annual soil loss in three areas of Mae Hong Son province and the converting these losses into the economic loss.

Besides replacement cost technique, Sharpley *et al*. (1990) used EPIC as an effective tool to evaluate changes in the crop productivity for several decades even for a century due to the soil erosion. EPIC was integrated within a GIS package to model the spatial distribution of the soil erosion and the spatial variation in the crop productivity at large scales in India (Priya *et al*. 2001).

Moreover, the Productivity Index Model (PI) was also widely practiced for estimating the crop productivity (Pierce *et al*. 1983). The equation is.

$$PI = \sum_{i=1}^{n} (A_i.C_i.D_i.E_i.RI_i) \qquad [2\text{-}47]$$

Where

PI = productivity Index

A_i = sufficiency of soil water holding capacity in the i th layer

C_i = sufficiency of bulk density in the i th layer

D_i = sufficiency of soil pH in the i th layer

E_i = sufficiency of soil electrical conductivity in the i th layer

RI_i = sufficiency of rooting weighting factor of the i th layer

n = number of soil layer in the root zone depth

The EPIC and PI models require a huge dataset, so they are less applicable than other simple methods. A simple regression method (Pierre *et al*. 1985) was used for estimating the effects of erosion and a small number of other variables on the growth of corn, soybeans and wheat yields in United States. The dependent variables in this model were referred as annual trend of county yield of corn, soybean and wheat from 1950 to1980. The independent variable was defined as annual soil loss estimated by USLE model. Two dummy variables also included in this model, one of which represented the service or no service and the other represented the irrigation or no irrigation. The effect of erosion on the growth of crop yield was probably accumulative, thus soil loss was accumulated over the entire period instead of amount of soil loss in a single year.

Mahdi (2001) was used a simpler empirical equation to quantify the impact of the soil loss on the crop productivity. He found that there was a strong relationship between reductions in the soil depth and the crop productivity.

Briefly, several methods developed to estimate spatial onsite costs of soil erosion. Cost replacement technique is simpler than EPIC and PI models; however, it is more applicable in developing countries or under limited data input than the modeling technique such as EPIC model.