Abstract: Soil erosion remains an environmental concern in the Laguna Lake watershed where land use changes have caused increased sediment delivery into the lake causing continued shallowing of the lake, underscoring the importance of an integrated watershed-lake management. However, soil erosion in the watershed has not been comprehensively assessed and approaches to doing this have not been explored fully. There is also a need to develop an assessment system which local government units within the watershed can use in dealing with erosion problems. In this study, three spatially distributed-type models - Universal Soil Loss Equation (USLE), Unit Stream Power Erosion/Deposition (USPED), and CASC2D - implemented in GIS were used to assess changes in the relative magnitude and pattern of soil erosion as a result of land use/land cover changes determined from Landsat images (1993-2002) and to examine their utility in identifying “hot spots”, where soil conservation measures are most needed. USPED results for 1993 and 2002 indicate that around 65% of the watershed is experiencing net erosion. Total estimated soil loss for the entire watershed is overestimated by as much as 50% if USLE is also applied for net depositional areas, a common mistake by users. Marikina, Tanay and Angono subwatersheds have the highest mean soil loss rate with Marikina and Tanay experiencing rate reduction of 16% and 22%, respectively, compared to 10% for the watershed. GIS analysis is used to discover relationship between watershed characteristics, erosion estimates and lake sedimentation pattern. The spatial pattern of erosion generated by USLE and USPED are compared to CASC2D results to determine whether the models are applicable for tropical environments. This will also provide insights on how to develop a soil erosion index system more appropriate to local area characteristics.

Keywords: Soil erosion, GIS, USLE, CASC2D, USPED, Laguna Lake, remote sensing

1. INTRODUCTION

Laguna de Bay (or Laguna Lake), the largest lake in the Philippines (approximate total surface area of 900 km²; average depth of 2.5 meters) is a multi-use lake – aquaculture, irrigation, transportation route, industrial cooling, among others. Aquaculture in the lake is intensive and extensive aquaculture, providing an estimated 85,000 metric tons of fish
and accounting for approximately 40% of the total fish production through aquaculture in the Philippines (UNEP, 1999). In addition, with the declining quantity and quality of water supply in Metro Manila, the lake may be tapped in the future to provide water for domestic use, including drinking. Considering these, it is imperative to maintain the lake’s storage capacity and protect it from further degradation.

The Laguna Lake watershed, with an area of approximately 3820 km², has undergone significant changes resulting from population increase, urbanization, industrialization and land use conversion (Nauta et al., 2003). Guerrero III (1996) noted that forest cover in the watershed has been reduced from 93,000 ha. (1963) to less than 18,000 ha. (1988) and that sediment loading has been estimated by SOGREAH (1991) to be at around 1.5 million m³/yr. The watershed is characterized by a long term average rainfall of around 2,000 mm/year. The dry months (December to March) have an average of 30 mm of rainfall per month while during the rainy season (June-September), rainfall amount can exceed 400mm in a month. Lee (1997) noted that this peaky rainfall pattern leads to periods of heavy runoff and soil erosion. The early monsoon rains, coming after a relatively long dry period, can cause excessive erosion considering that at this time the land is most vulnerable to erosion due to minimal vegetative cover. This underscores the importance of using satellite images taken at similar time periods to enable valid comparison of changes in erosion potential.

Soil erosion causes environmental degradation through increased sedimentation in water bodies and transport of sediment-attached nutrients and chemicals. It can also result to direct economic loss as fertility of the land decreases due to removal of fertile topsoil. Soil erosion remains an environmental concern in the Laguna Lake watershed. Land use changes in the watershed have cause increased nutrient discharge resulting to increased eutrophication in the lake and increased sediment delivery into the lake causes continued shallowing of the lake, underscoring the importance of an integrated watershed-lake management. However, soil erosion in the watershed has not been comprehensively assessed and approaches to doing this have not been explored fully. Simple empirical models and GIS-based erosion indices have been preferred for watershed-wide erosion assessment owing to simplicity and minimal data requirement. On the other hand, application of more complicated models has been hindered by the lack of appropriate data. However, empirical models may not be applicable to local conditions and sometimes can be misused if limitations are not recognized. GIS-based index or scoring approach may be too simple to capture erosion characteristics and can lead to erroneous interpretation of erosion potential in the watershed if the index is not based on field observations or simulation results. Thus, there is a need to develop a watershed-scale soil erosion...
assessment index system that is easy to use but has appropriate physical basis. Furthermore, for watershed planning, a different approach involving the modeling of patterns of soil erosion and deposition instead of the computation of absolute magnitudes of mass sediment fluxes has been increasingly pursued. Understanding of these patterns provides a rationale for ranking of intervention measures and maintains the possibility of comparing different management scenarios (Pistocchi et al., 2002). In this paper, three spatially distributed models of varying complexity are utilized to assess changes in erosion potential in the Laguna Lake watershed. The erosion rates and patterns generated by the models are analyzed and compared to identify important factors affecting erosion and how these factors interact with or affect each other. This study serves as an initial step towards development of a new erosion index system.

2. EROSION MODELS AND DATA USED

2.1 Models

Three soil erosion models of increasing complexity – USLE, USPED, and CASC2D – were used in this study. These models were to investigate the erosional (and also depositional in the case of the latter two models) patterns generated by the models.

2.1.1 Universal Soil Loss Equation (USLE)

The USLE is an empirical soil erosion model used to predict longtime average soil loss for specific cropping and management conditions (Wischmeier and Smith, 1978). It is based on more than 10,000 plot-years of runoff and soil loss data. The USLE only predicts soil loss due to sheet and rill erosion. The universal soil loss equation is:

\[ A = R K L S C P \]  

Where:
- \( A \): Soil loss per unit area (t/ha)
- \( R \): Rainfall and runoff factor (MJ mm ha\(^{-1}\) hr\(^{-1}\) yr\(^{-1}\))
- \( K \): Soil erodibility factor (t ha hr MJ\(^{-1}\) mm\(^{-1}\) ha\(^{-1}\))
- \( LS \): Slope-length factor (L) and slope-steepness factor (S), collectively called the topographic factor (LS) (dimensionless)
- \( C \): Cover and management factor (dimensionless)
- \( P \): Support practice factor (dimensionless)

The estimation of LS factor has proved to be more problematic than any other USLE factors, particularly if the model is to be applied at a catchment scale (Wilson and Lorang, 2000; Renard et al., 1991). The LS factor has undergone improvement with the consideration of the influence of profile convexity/concavity by segmenting of irregular slopes and improving the equation (Foster and Wischmeier 1974, Renard et al. 1991). One of the revisions is the development of improved empirical equations (in SI) for the LS factor:

\[ LS = \left( \frac{\lambda}{22.13} \right)^{m} (10.8 \sin \beta + 0.03) \quad \text{when } \sin \beta < 0.0896 \]  

(2a)
\[ LS = \left( \frac{\lambda}{22.13} \right)^m \left( 16.8 \sin \beta - 0.5 \right) \quad \text{when } \sin \beta \geq 0.0896 \]  

(2b)

where \( \lambda \) is the slope length in meters, \( \beta \) is the slope in degrees, \( m \) is the slope length exponent which is computed as \( m = \frac{F}{1+F} \), where \( F = \frac{(\sin \beta/0.0986)/[(3 \sin \beta)^{0.6} + 0.56]}{22.13} \) when there is erosion or \( F=0 \) when there is deposition (Renard et al., 1994).

A number of algorithms have been developed to estimate the LS factor for complex terrain. Desmet and Govers (1996) developed the following equation which uses the unit contributing areas (UCA), which is the defined as the contributing area per unit width of contour, in place of the slope length:

\[ LS_{i,j} = \frac{S_{i,j} \left( As_{i,j-out}^{m+1} - As_{i,j-in}^{m+1} \right)}{\left( As_{i,j-out} - As_{i,j-in} \right) 22.13^m} \]  

(3)

where \( LS_{i,j} \) is the slope length factor for a grid cell with coordinates \( i,j \), \( As_{i,j-out} \) is the unit contributing area at the outlet of grid cell with coordinates \( i,j \) in \( m^2/m \), \( As_{i,j-in} \) is the unit contributing area at the inlet of grid cell with coordinates \( i,j \) in \( m^2/m \), and \( m \) is the slope length exponent. Moore and Wilson also developed an LS equation (Equation 4) based on the unit contributing area. If \( n \) equals 0.4 and \( m \) equals 1.3, this equation gives LS values close to the Revised USLE LS for slope less than 14% and slope length less than 100 meters.

\[ LS = (n+1) \left[ \frac{A_s}{22.13} \right]^m \left( \frac{\sin \beta}{0.0896} \right)^m \]  

(4)

where \( n = \) constant, 0.4, \( \beta = \) slope (degrees), \( m = \) constant, 1.3, \( A_s = \) unit contributing area.

Equations 3 and 4 were developed on the assumption that erosion is transport-limited and consider convergent and divergent hillslopes. This is contrary to USLE or RUSLE equations, which were developed for the detachment-limited case and for planar hillslopes. Thus, using Equations in place of the USLE/RUSLE equations for LS is not appropriate for they violate the basis on which the models were developed. These equations may however be used as starting point from which new erosion models that considers the effects of flow convergence and divergence can be developed (Wilson and Lorang, 2000). Since USLE neglects the influence of flow convergence/divergence and the equation must only be applied to areas experiencing net erosion, making direct application to complex terrain limited (Mitasova et al., 1996). Areas experiencing net deposition must be identified prior to the application of the model. Despite its limitations, USLE is the simplest soil erosion model that is usually considered sufficient for assessment purposes considering the availability of data. The USLE has been used for on-farm conservation planning. It can be applied to determining alternative land use and management practice to reduce soil loss if the computed value exceeds the soil loss tolerance set. The USLE has also been used in estimating watershed sediment yields due to sheet and rill erosion upstream. The result of USLE may be used for pinpointing areas of high soil erosion rates and as input to the non-point source pollution modelling provided that its limitations are recognized.
2.1.2 Unit Stream Power based Erosion/Deposition Model

The Unit Stream Power based Erosion/Deposition model (USPED) is a simple model which predicts the spatial distribution of erosion and deposition rates for a steady state overland flow with uniform rainfall excess conditions for transport capacity limited case of erosion process (Mitas and Mitasova, 1998). USLE or Revised USLE (RUSLE) parameters are used to incorporate the impact of soil and cover and obtain at least a relative estimate of net erosion and deposition since no experimental work was performed to develop parameters needed for USPED. In the work of Mitasova et al. (2001), USLE factors were used to include relative impact of soil and cover on sediment transport capacity and model coefficients to obtain erosion rates comparable to those estimated by USLE. Sediment flow at sediment transport capacity is estimated using the following equation

\[ T = R \cdot K \cdot C \cdot P \cdot A^m \cdot (\sin b)^n \]  

where \( R \) approximates the uniform rainfall intensity, \( K \) approximates the transportability coefficient \( K_t \) and \( LS = A^m \cdot \sin b^n \), \( A \) is the upslope contributing area per unit contour width, \( b \) is the slope and \( m = 1.6, n = 1.3 \) for prevailing rill erosion while \( m = n = 1 \) for prevailing sheet erosion. Then the net erosion/deposition is estimated as

\[ ED = \frac{d(T \cos a)}{dx} + \frac{d(T \sin a)}{dy} \]  

where \( a \) (in degrees) is aspect of the terrain surface. Foster (1990) emphasized that caution should be used when interpreting the results because the USLE parameters were developed for simple plane fields and detachment limited erosion therefore to obtain accurate quantitative predictions for complex terrain conditions they need to be re-calibrated. Nevertheless, this model has been used in various studies (e.g. Mitas and Mitasova 1998; Pistocchi et al. 2002; Zalusi et al. 2003) which found out that USPED-predicted erosion-deposition patterns correspond well with actual field observations.

2.1.3 CASC2D

CASC2D is a two-dimensional physically based distributed watershed model utilizing grid cells to provide a spatially distributed representation of the watershed, simulating spatially-varied surface runoff while fully utilizing raster GIS (Julien et al., 1995). The model considers processes such as infiltration, overland and channel routing, upland erosion and sedimentation. The model uses Green and Ampt infiltration method, and the diffusive wave formulation for overland and channel flow routing. Elevation, surface roughness, soil parameters, channel network and precipitation are some of the basic input requirements of the model. The model has been calibrated and independently verified to provide accurate simulations of catchment response to moving rainstorms on watersheds with spatially-varied infiltration.

2.2 Data

The following data were used in this study:
- Landsat images: 02 April 1993, 17 May 1997, 03 April 2002
- Topographic maps (1:50,000): Contours were digitized and then digital elevation model (DEM) was generated. The DEM was “conditioned” by using mapped rivers and streams in the watershed.
- Soil classification layer: The attribute table was updated to include estimated values of K factor and other parameters required by CASC2D.
- Rainfall (annual average) distribution map

3. METHODOLOGY

The overall methodology used in this study is shown in Figure 2. In general, the procedures can be grouped into three: preparation of input layers and attribute tables, model application, and analysis of results.

Figure 2. GIS-based methodology used in comparative soil erosion assessment

3.1 Preparation of input data

The Landsat images were classified using K-means clustering, an unsupervised classification method, to give 100 spectral classes. The spectral classes are examined to obtain corresponding land cover classes. Contextual editing is employed to correct obvious classification errors. Normalized difference vegetation index (NDVI) is used to refine the classification. C factor layers are then generated from the land cover layers. The land cover layer generated through image analysis represents the land cover existing at the time the
images were taken. As such, the cover classification may only be valid for up to a few months only. The images were taken during summer, after which monsoon season starts causing soil erosion. It can be assumed that at the start of the monsoon period, soil loss makes up a significant portion of the annual soil loss. Image-derived land cover layers can be interpreted and generalized to produce general land use layers for use also in erosion potential estimation. LS factor layers were generated from the corrected DEM using three algorithms (described above) considered applicable for complex terrain and enabling the application of USLE on watersheds. The P factor is assumed to be equal to 1 (assuming no soil conservation practice is employed). R factor layer is generated from average annual rainfall P distribution layer using the formula $R = 38.5 + 0.35P$, which give acceptable result for tropical conditions.

3.2 Model application

All the models have been implemented in ESRI ArcGIS using the Visual Basic for Applications (VBA) scripting language. Application of the model thus becomes an easy task of specifying the input layers, text files and simulation parameters in the case of CASC2D. The USLE model is run three times for each year since three LS algorithms are utilized for comparison purposes. Both the USLE and USPED models are rerun, this time considering a uniform R factor for the entire watershed. The results of this second batch of model runs will be compared with CASC2D results. The CASC2D model is run two times for each land cover considering two spatially uniform rainfall patterns: temporally-varying rainfall and temporally constant. Simulation is for a period of one day at 10-minute time step.

3.3 Analysis of results

USLE estimates calculated using three algorithms of LS factor computation are compared to each to assess differences in relative magnitudes and in the distribution of areas of low and high erosion potential. The erosion rates calculated using USLE and USPED on net erosional areas are compared. The estimated rates can only be considered relative magnitudes since the factors are relative estimates and have not been calibrated for local conditions. Overestimation caused by USLE being applied all areas regardless of whether an area is experiencing net deposition or net erosion prediction is quantified. The USPED-generated patterns of erosion and deposition are compared with the result of CASC2D model with the assumption that the result of CASC2D being considered as closer to actual erosion-deposition patterns. GIS spatial analysis is used to calculate relevant summary statistics for each subwatershed and to determine relationship between known factors influencing the intensity of soil erosion. The relationship of the generated patterns of erosion and deposition and subwatershed characteristics (e.g. topography, cover, soil) is also examined. In the absence of soil erosion measurements, erosion distribution in the watershed is compared with the sedimentation patterns in the lake.

4. RESULTS AND DISCUSSION

4.1 Land use and land cover change

The minimal closed forest cover in the watershed remains almost unchanged but tree cover increased particularly in Marikina and Tanay subbasins, which may be a result of various
reforestation efforts in the two subbasins. It is evident from the original and classified images that the area of bare land during summer season is quite extensive but this was reduced in 2002. Built-up areas have spread in the southeast part of the watershed and in portions of Rizal province, as a result of conversion from agricultural use. The effect of these changes can be seen in Figure 4 where there is decrease in soil loss rate in some subwatersheds (e.g. Marikina, Tanay, Siniloan, Sta. Maria) and increase in others (e.g. Pila, Calauan, Pagsanjan, Muntinlupa).

![Figure 3. Land cover distribution in Laguna Lake watershed](image)

**4.2 Ranking of subwatersheds**

Based on USLE estimation, Marikina, Tanay and Angono subwatersheds have the highest annual average soil loss rates primarily due to steep slopes combined with minimal vegetation on some areas. On the other hand, the lowest rates can be found in Muntinlupa, Taguig and Pila subwatersheds, which are characterized by relatively flat topography. In terms of total soil loss, Marikina, Sta. Maria, Pagsanjan have the highest values. Angono and Tanay also have relatively high soil loss.

**4.3 Patterns of erosion and deposition**

USPED provides a slightly different picture with Cabuyao subwatershed having the highest average soil loss rate, followed by San Critoabal, Tanay, Morong and Marikina subwatersheds. In terms of total soil loss, the subwatersheds with highest values are Marikina, Sta. Maria, Pagsanjan, Jala-jala and Cabuyao in agreement with USLE results.

USPED correctly identified 74% of the net erosional area based on CASC2D results. The erosional patterns generated by USPED and CASC2D are similar. Higher erosion potential can be seen in areas at the base of hillslopes.
Figure 4. USLE-estimated annual soil loss rate (using 3 LS factor methods) for years 1993, 1997, 2002 averaged for each subwatershed.

Figure 5: USPED-estimated annual soil-erosion deposition rates for each subwatershed.

Figure 6: Net erosional areas: (a) DEM, (b) USPED-predicted, (c) by CASC2D
4.5 Erosion in watershed and lake sedimentation patterns

The distribution of high erosion areas in the watershed correspond well with the long-term patterns of sedimentation determined by Duyanen et al. (1999) through bathymetric change analysis using 1983 and 1997 bathymetric maps of Laguna Lake. Shoaling in West Bay can be attributed to Marikina watershed, which due to high erosion rates and its huge area contributes the largest amount of sediments also to Cabuyao subwatershed. In Central Bay, it is mainly due to erosion in Tanay and Morong subwatersheds. Shoaling in South Bay is mainly due to San Cristobal subwatershed, which has the highest total erosion rate in southeastern part of Laguna Lake watershed and due to areas around Mt. Makiling.

4.6 On USLE application

As can be seen in Figure 3, the choice of which LS factor computation algorithm to use greatly affects the absolute magnitude of soil loss estimates. LS method 2 (Equation 3) provides the lowest estimates while LS method 3 (Equation 4) estimates have the highest magnitudes and variation of values. Possibly the most serious misuse of the USLE is applying the model on all areas regardless whether an area is experiencing net erosion or net deposition. The model does not consider the effects of flow divergence and convergence and hence the model should only be applied on net erosional areas. Doing otherwise will result to over-estimation of soil loss in the watershed. Based on USPED model result, 65% of the watershed is experiencing net erosion. USLE can overestimate soil loss by as much as 66%, 50% and 33% using LS method 1, LS method 2 and LS method 3, respectively, if applied on all areas including net depositional ones.

4.8 Implications for developing new soil erosion index system

The USLE has a rigid structure preventing modifications to fit fundamental data and sufficient representation of experimental trends that may be observed. The equation also lacks an explicit term to take into consideration runoff effects, decreasing the effectiveness of the equation when runoff-reducing practices are involved (Foster, 1991). Runoff effect is incorporated in most of the USLE factors and not in just a single factor. To take into account the effect of runoff, all the factors will have to be considered and reevaluated (Renard et al., 1991). Furthermore, effect of factors on each other is not modeled. Factors are just combined multiplicatively. Previous research has focused on the LS factor in order to overcome some of the limitations of the USLE. Even so, they may be a need to determine areas where a certain LS algorithm, either based on slope length or unit contributing area, would perform better. For flat areas, UCA-based LS method can greatly underestimate soil loss since UCA would be very small. Furthermore, an alternative to R factor may be needed to account for episodic and high-intensity rainfall pattern characteristic of tropical areas. USPED models steady state water flow as a function of upslope contributing area per unit contour width. Approximation by upslope area neglects the change in flow velocity due to cover. Thus, a potential improvement is to include cover effects by analyzing the spatial of land cover within the unit contributing area to improve predictions of areas of erosion and deposition. The physically based CASC2D model integrated in GIS can be used for studying erosion dynamics in the watershed by running
simulations with variations in parameter values. This is to investigate factor interactions under different conditions.

5. CONCLUSION

Direct use of the USLE model can result in overestimation of soil loss. To avoid misuse, the USLE should be applied to net erosional areas only. USLE and USPED can be used in an integrative manner to avoid such misuse. Physically based models like CASC2D can be used in the development of new erosion assessment indices starting from simple models. Integration of models with GIS allows investigations and analysis to be made in this direction.

ACKNOWLEDGEMENTS

The authors are grateful to the JSPS Core University Program, under which this study was carried out and to the Department of Agriculture-Bureau of Agricultural Research (DA-BAR), LLDA-Integrated Water Resources Management Division (LLDA-IWRM) and DA-Bureau of Soil and Water Management (DA-BSWM) for providing some of data used in this study.

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