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SOIL EROSION ASSESSMENT WITH INVEST MODEL: CASE STUDY IN WEE-OYA WATERSHED IN SRI LANKA

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Abstract– Human-induced soil erosion is one of the most significant types of land degradation in the Wee Oya watershed in Sri Lanka. The high intensity of rainfall, steep slopes, and inappropriate land use practices are strongly associated with soil erosion in the area. The prime aim of the study was to estimate soil erosion in the watershed and its seven sub-watersheds using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), Sediment Delivery Ratio (SDR) model. Furthermore, a comprehensive household (HH) questionnaire survey (n=30) was conducted to ascertain key socio-economic information such as the farmer's age, gender, education level, the extent of land for cultivation, and the degree of practicing soil and water conservation (SWC) measures. Then, the multiple regression analysis was applied to determine the significant socio-economic determinants of erosion in the watershed. The results of the assessment disclosed that the present average annual rate of human-induced soil erosion of the watershed is 167 t/ha/yr. Moreover, the most significant ($p<0.05$) socio-economic determinants of the soil erosion of the study area are the farmer's age and family size. Furthermore, the study revealed that more than 50% of the farmers do have not a substantial perception of existing government policies' implications concerning human-induced soil erosion. Finally, the outcome of the assessment has highlighted the necessity of human intervention for effective SWC measures in the study area.

INTRODUCTION

Soil erosion is one of the major global environmental problems which have resulted in both on-site and off-site consequences. It is a complex dynamic process that facilitates the detachment of soil structure, transport, and soil accumulation in distant places, resulting in subsurface soil exposure and sedimentation in reservoirs. Water is the most considerable agent of soil erosion, responsible for 56 percent of the global land areas in Asia and Africa (Anamika Shalini Tirkey, 2013). Soil erosion induces soil reduction, soil quality, soil surface layer, and soil organic matter content and ultimately leads to crop yield loss. Severe soil erosion not only affects cultivated land and the livelihood of the local people but also causes the long-term consequences of desertification for all biological species. The main factors of this natural process are population growth, deforestation, agriculture on marginal lands, poor land practices, construction activities, urbanization, climate change, and overgrazing (Sisay, 2014).

Soil erosion has become the most concerned environmental problem In Sri Lanka, since the 1990s and has generally been identified as the most serious environmental issue, especially in the upper basin areas of the country (Stocking, 1992). Previous studies of Sri Lanka have shown that the degree of land degradation varies with the agroecological regions of the country (Chisholm, 1999). For example, the soil profile analysis has shown that tea plantation areas in the interior of the country have completely lost ground horizons. It is also suggested that an upland soil surface of 30cm has been lost during the last century and supposed it equivalent to an average loss of 40 t /ha/yr. According to the study of the effect of land degradation on the country's rubber production, (Samarappulli *et al.*, 1999), found the rate of land degradation is significantly high in rubber plantations as it is a closed canopy crops. On the other hand, land degradation is more severe in unmanaged agroecosystems than in crop plantations (Stocking, 1992). According to Somaratne (1998), the estimated average annual cost of soil erosion in Sri Lanka in terms of nutrient replenishment cost is US $ 86.3 million per year, which highlights the severity of soil erosion in the region country.

Soil erosion is one of the serious environmental problems in Sri Lankan river basins. It is serious in the areas located in the middle and high country where steep slopes are due to the high intensity of the precipitation. watershed erosion induces a variety of deleterious external consequences due to the siltation of reservoirs (Manipura, 1971). Subsequently, siltation affected hydroelectric production, expansion of flood plains, soil fertility, and downstream water quality. On the other hand, the silting of the reservoirs leads to becoming less quantity of water downstream for irrigation due to the clogging of the water pipes by the sediments. Thus, sedimentation is the greatest source of non-point pollution and it becomes to cause negative consequences for the productivity of any country due to the leaching of soil nutrients (Manipura, 1971). Soil erosion is the main factor of deterioration in the quality of surface water. Low levels of oxygen, eutrophication, and high concentrations of nutrients and organic matter in water bodies are associated with the pollution of sediment-associated water (Noor *et al.,* 2013). Water turbidity occurred by sedimentation becomes a barrier to the penetration of light into the water and prevents the productivity of aquatic ecosystems. Sediment accumulation also disrupts ecological processes and degrades fish spawning habitats and habitats in aquatic environments (Noor *et al.,* 2013).

Vegetation helps to hold soil and capture the sediments coming from the highlands. Therefore, land use land cover is an important and considerable factor that directly affects soil erosion and sedimentation. Otherwise, it is the most considerable factor responsible for the sediment retention capacity of a certain area. The Sediment retention capacity of an area can vary not just only with land use land cover type but also with the changing of the land use practice (Ricketts, 2003). These variations mainly occurred due to development projects and agricultural activities.

Soil erosion estimation of catchment areas is important as the rapid changes in the land cover type and land use practices are common in these areas. InVEST is a GIS-based tool for modeling ecosystem services that allow for the assessment of the interaction between various environmental and economic components. The InVEST model in the ArcGIS is also facilitated to estimate the annual average soil loss (Wilson JP, 2000). The SDR model is one of the InVEST models. The outputs from this model include the sediment load delivered to the stream at an annual time scale, as well as the amount of sediment eroded in the catchment and retained by vegetation and topographic features (Adinarayana *et al.,* 1999).

Quantitative estimation of soil erosion is important for land management. But the estimation is often difficult due to the complex interaction of many factors such as climate, soil cover, soil, topography, and human activities. In addition to biophysical components, social, economic, and political components also affect soil erosion (Ananda *et al.,* 2003). Erosion models are generally a useful tool for estimating soil erosion. These erosion models can be categorized into two groups, empirical models and physical models. Most erosion models are based on the well-known empirical Equation Universal Soil Loss (USLE) model (Angima *et al.,* 2003). It was developed to estimate the annual average soil loss using sheet and rill erosion and is valid only in a study area of approximately 1 ha. It was used worldwide although it was developed in the United States because it seemed to meet the needs of researchers better than other tools available (Boggs *et al.,* 2001). This concept has been modified and adapted during the past 45 years.

RUSLE is a derivative of the universal soil loss equation (USLE). It is commonly used worldwide to calculate the average annual soil loss. The USLE model was originally developed for situations of gently sloping land (Samarappulli *et al.,* 1999). However, the RUSLE model applies to the estimation of soil erosion in rangelands, forests, disturbed sites, and slopes It is mentioned in the literature that the GIS (Rabia, 2012) is an appropriate tool in the fields of research such as forestry, agriculture, hydrogeology, and soil sciences. In addition, the joint use of GIS and USLE / RUSLE has been accepted as a successful approach for estimating the quantitative and spatial distribution of soil erosion risks.

This approach consists of a simple procedure. It requires a conservative calculation because the spatial extent of the attributes of the slope class and the length of the slope is specific to the polygon. Thus, the estimation of soil erosion is limited to polygons of slope and slope length. If land parcels are not selected correctly, recovery can result in an average of erosion levels on the affected polygons (Wijesekera and Samarakoon, 2001). The raster approach makes it easy to minimize the above overestimation of erosion means.

However, even though substantial land use change has occurred in the Wee-Oya watershed (situated in the Kelani river basin) as in many others, no soil erosion-related recent study has been carried out. The lack of recent data limits the application of some empirical and process-based models. Another limitation is that most soil erosion studies do not take into account the socio-economic factors of soil erosion. Hence, the study mainly focused to assess soil erosion of the Wee-Oya watershed in the Kelani river basin while considering the socioeconomic determinants of soil erosion.

METHODOLOGY

Study area

The study area, the Wee-Oya watershed, is located in the upper watershed of the Kelani river basin (Figure 1). (Thuraisingham and Weerasinghe, 2013). Further, the Kelani river is very famous for tourism activities *viz.* swimming, white water rafting, boating, etc. Occurrences of heavy rains annually and existing steep slopes in the area are the main reasons for soil erosion by water. Thus, this results in the leaching of essential nutrients and low productivity of crops. It has reported that there are 31 mini-hydroelectric power stations are located along the Kelani river. Hence, soil erosion in the upper watersheds may affect on power generation of those power plants due to the reduction of reservoir capacity.

Assessment of soil erosion

In this study, InVEST, SDR model was employed to map and assess soil erosion. InVEST was developed as part of the Natural Capital Project (www.naturalcapitalproject.org), a partnership between Stanford University, the Nature Conservancy (TNC), and the World Wildlife Fund (WWF) working with many other institutions. This model was developed to align economic forces with

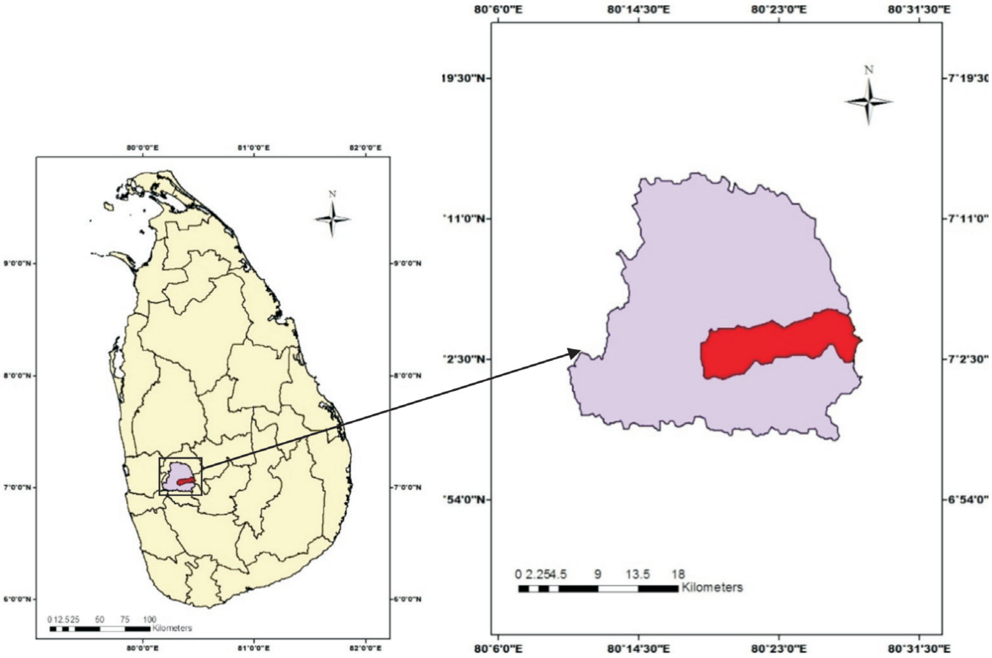

Fig. 1. Location of the study area

conservation objectives (Nelson *et al.*, 2009, Udayakumara and Gunawardena, 2016).

The SDR model is a spatially-explicit model working at the spatial resolution of the input digital elevation model (DEM) raster. For each pixel, the model first computes the amount of annual soil loss from that pixel, then computes the sediment delivery ratio, which is the proportion of soil loss reaching the stream. Once sediment reaches the stream, we assume that it ends up at the catchment outlet, thus the numbers in-stream processes are modeled. This approach was proposed by Borselli *et al.* (2008) and has received increasing interest in recent years (Cavalli *et al.*, 2013); (López-Vicente *et al.*, 2013); (Sougnez *et al.*, 2011). Further, we could see the User Guide section differences between the InVEST SDR model and the original approach developed by Borselli *et al.* (2008). The main data used for the model are given below.

Digital elevation model (DEM)

A Raster dataset with an elevation value for each cell was used to make sure that the DEM was corrected by filling in sinks and comparing the output stream maps with hydrographic maps of the area. To ensure proper flow routing, the DEM was extended beyond the watersheds of interest, rather than being clipped to the watershed edge. [units: meters], (Figure 2).

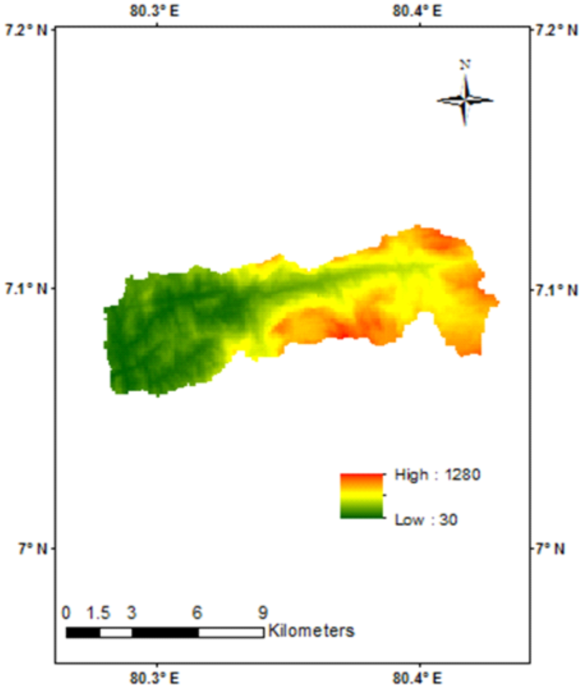

Fig. 2. Digital elevation model

Rainfall erosivity index (R)

A Raster dataset, with an erosivity index value for each cell, was used. This variable depends on the intensity and duration of rainfall in the area of interest. The greater the intensity and duration of the rain storm, the higher the erosion potential. [units: *MJ · mm · (ha · h · yr)–1*], (Figure 3)

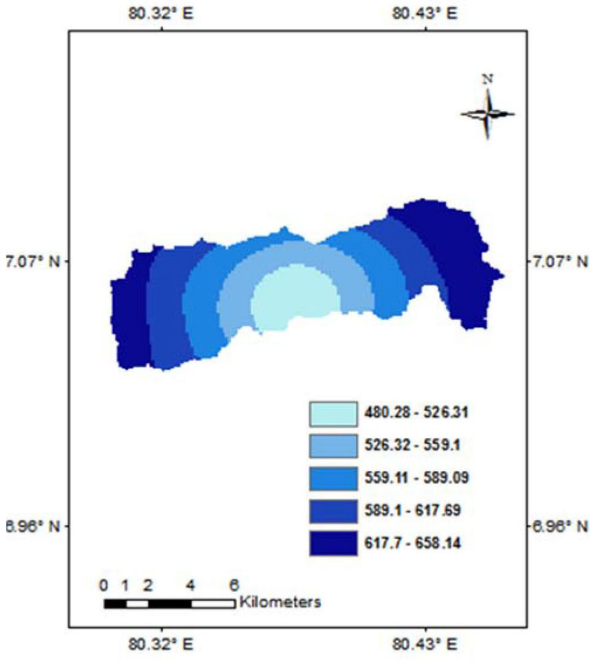

Fig. 3. Rainfall erosivity index

Soil erodibility (K)

A raaster dataset, with a soil erodibility value for each cell, was used. Soil erodibility, K, is a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff. [units: *tons · ha· h · (ha · MJ · mm)–1*], (Figure 4).

Land use/land cover (LULC)

A raster dataset, with an integer LULC code for each cell, was used. All values in this raster were corresponding entries in the Biophysical table (Figure 5).

Watersheds

This was a layer of watersheds such that each watershed contributes to a point of interest where water quality was analyzed (Figure 6).

Biophysical table

A .csv (Comma Separated Value) table containing model information corresponding to each of the land use classes in the LULC raster.

Threshold flow accumulation

The number of upstream cells that must flow into a cell before it is considered part of a stream, which was used to classify streams from the DEM. This threshold directly affects the expression of hydrologic connectivity and the sediment export result: when a flow path reaches the stream, sediment deposition stops and the sediment exported is assumed to reach the catchment outlet. It is important to choose this value carefully, so modeled streams come as close to reality as possible.

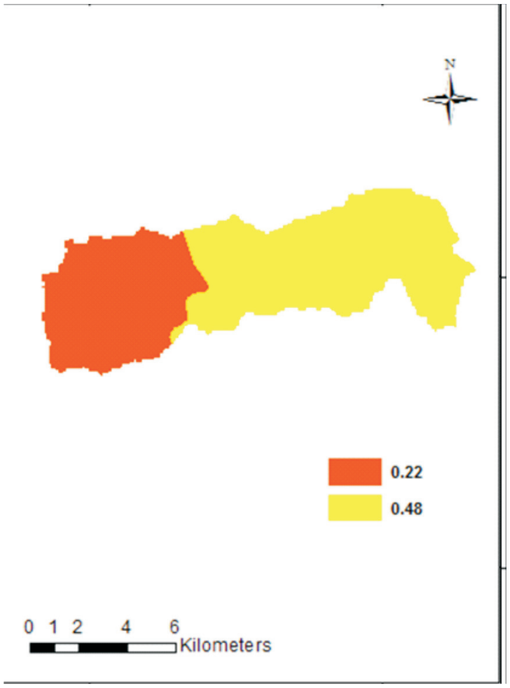

Fig. 4. Soil erodibility

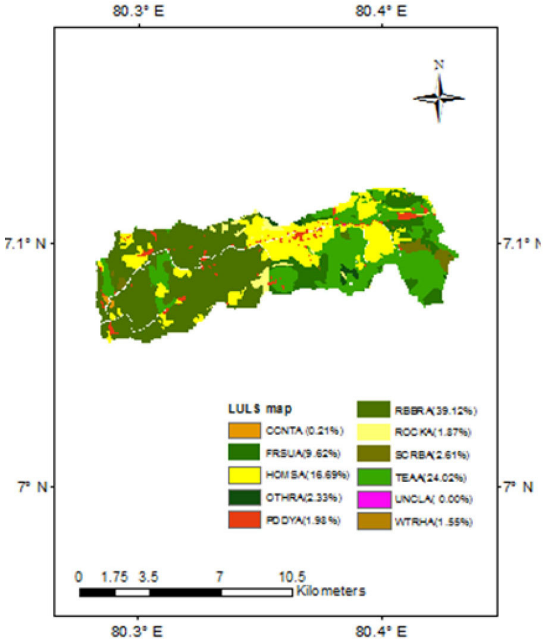

Fig. 5. Land use/land cover

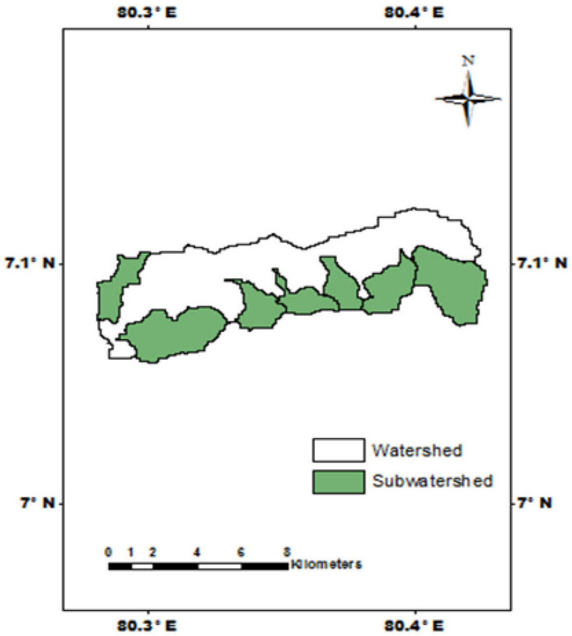

Fig. 6. Sub-watersheds within the watershed

SDRmax

The maximum SDR that a pixel can reach, is a function of the soil texture. More specifically, it is defined as the fraction of topsoil particles finer than coarse sand. For this study, the default value of 0.8 was used.

Socio-economic determinants of soil erosion

Socio-economic variables are important determinants of soil erosion (Wahid *et al.*, 2008; Udayakumara *et al.*, 2010; Udayakumara and Shrestha, 2011). Decisions on SWC measures should therefore be made based on socio-economic considerations and assessments. To understand the major socio-economic factors contributing to soil erosion in the study area, multiple regression analysis was employed. Multiple regression analysis is one of the multivariate statistical analysis techniques, which can predict changes in the dependent variable in response to several independent variables (Hair *et al.*, 1992). The average rate of soil erosion was identified at each sampling locality from the generated soil erosion map with support of average GPS readings taken at each surveyed location. The reading was considered as the dependent variable (Y). Socio-economic covariates variables, which were collected from a HH survey (n=30) were used in this study to present the full spectrum of conditions for soil erosion in the watershed. The selected variables used in the multiple regression analysis were the age of the HH head, family size, the extent of cultivation, level of education of the HH head, and the adoptability of SWC measures for their farmlands.

RESULTS AND DISCUSSION

It has been found that the average annual rate of soil erosion in the Wee-Oya watershed is 167 t/ha/yr. However, the soil erosion is varied from 0-2500 t $ha^{-1}yr^{-1}$ within the watershed mainly due to the different land uses (Figure 7). Moreover, the current rate of erosion is also 33 times higher than the permissible soil rate of 5t/ha/yr of the region (Jha *et al.*, 2009, Udayakumara *et al.*, 2010).

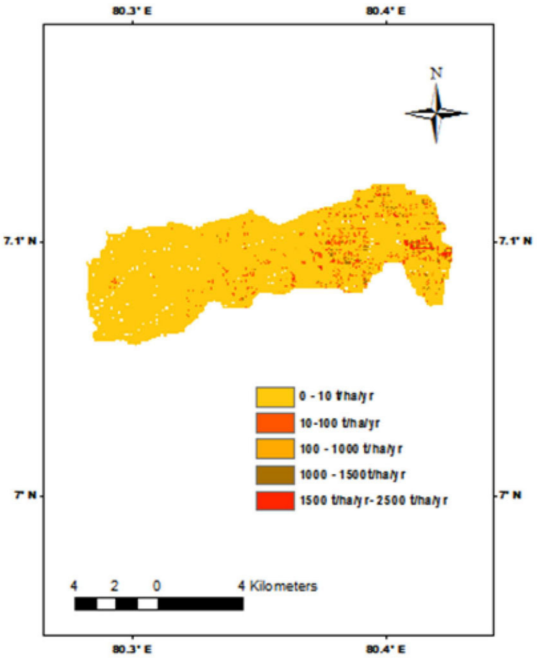

Fig. 7. Pixel-based soil erosion

Table 1 shows the watershed (WO) and seven sub-watersheds (WO1-WO7) level sediment export, sediment retention, and soil loss rates. However, sub-watersheds level average soil erosion is varied from 13-606 t $ha^{-1}yr^{-1}$. The highest average soil erosion rate (606 t $ha^{-1}yr^{-1}$) was recorded in the WO7 sub-watershed while the least average value (13 t $ha^{-1}yr^{-1}$) was recorded in the WO1 sub-watershed.

Table 1. Summary of soil erosion estimation

Ws_Id	Sediment export (t $ha^{-1}yr^{-1}$)	Sediment retention (t $ha^{-1}yr^{-1}$)	Soil loss (t $ha^{-1}yr^{-1}$)
WO	13.8	698.3	167.8
WO1	0.5	25.5	13.1
WO2	1.4	164.2	25.9
WO3	8.9	1158.4	103.8
WO4	9.9	710.9	125.1
WO5	11.7	2240.0	147.7
WO6	22.8	1024.8	276.6
WO7	73.3	629.8	606.4

Wee-Oya watershed is situated in the Kelani river basin *i.e.* one of the most important river basins of Sri Lanka. Our study disclosed that the average annual soil loss of the Wee Oya watershed is 167.9 t $ha^{-1}y^{-1}$ *i.e.* 15 times faster than that of the Kelani river basins (10.9/t $ha^{-1}yr^{-1}$) (Sandamali, 2017). Numerous reasons can be attributed to the high rate of soil loss in the Wee-Oya watershed. However, the main reasons are due to the prevalence of steep slopes in the watershed, rapid conversion of forested lands to agriculture, new settlements at unsuited lands, and the dearth of proper practicing of SWC measures at different croplands.

When we compare to the Wee-Oya watershed, the highest (606 t $ha^{-1}yr^{-1}$) soil loss is recorded at the WO7 sub-watershed followed by WO4, WO5, and WO6 sub-watersheds due to the dominant land use type being tea. In the past, soil erosion was not a frequent issue in the tea and rubber estates located on the hill slopes due to the effective adaptation of SWC measures (Manipura, 1971). The sub-watersheds (WO1, WO2, and WO3) are dominated by rubber and coconut. Hence, those lands have moderately low soil erosion values. According to the comprehensive report of the Committee on Soil Erosion (1931), the estates were the most responsible sectors for the greater part of soil erosion, particularly tea estates and to a lesser extent rubber and coconut estates (Herath, 2001).

At present, most soil erosion studies are carried out aside from socio-economic considerations, even though it is one of the main decisive factors that affect soil erosion in any farmland. Hence, in this study we tried to find out major socio-economic determinants for soil erosion using multiple regression analysis with five input variables that are important for the considered watershed. However, the model yielded that only two variables such as the age of the HH head and the extent of cultivation significant ($p<0.05$) for soil erosion in the watershed. Age of HH head: the farmer's age can be considered as a composite of the effect of farming experience and planning horizon. While longer experience has a positive effect, young farmers on the other hand may have a longer planning horizon and hence may be more likely to invest in conservation activities (Asrat *et al.,* 2004, Udayakumara *et al.,* 2010, Udayakumara *et al.,* 2011). Featherstone and Goodwin (1993) disclosed that an older farmer who is looking at a shorter time horizon, might not be able to get back all of the benefits from any conservation investment. Therefore, in this study, it was hypothesized that age has a negative influence on the adoption of SWC measures. The extent of the land under crop, which denotes the total area of cropland (ha) owned by sample respondents at the time of the survey. Farm size is often correlated with the wealth that could help ease the needed liquidity constraints (Asrat *et al.,* 2004). Some studies have disclosed that large farms are more likely to use conservation measures than small farms (Norris and Batie, 1987, Bekele and Drake, 2003). Thus, the size of cropland was considered to be positively related to the adoption of the SWC measures.

CONCLUSION

This study revealed that the present rate of human-induced soil erosion in this watershed ranges from 13 to 606 t ha^{-1} yr^{-1} with an annual average value of 167 t/ha/yr. However, the majority of the land areas have exceeded the natural rate of soil generation (~5 t/ha/yr) in Sri Lanka. Further, it has disclosed that the tea smallholders' lands without proper SWC measures result in a high rate of human-induced soil erosion when compared to that of large tea estates with proper SWC measures presently. Furthermore, the study revealed the importance of consideration of socioeconomic factors for soil erosion assessment. The regression model shows that two socio-economic factors *viz.* age of HH head and extent of cultivation area are significant ($p<0.05$) for soil erosion in this watershed. Thus, a successful soil conservation policy in Sri Lanka will require careful planning and coordination of SWC measures with inputs of physical and financial resources. There is an urgent need for strong public and private partnerships to combat soil erosion in the Wee-Oya watershed of Sri Lanka. Hence, these results should be carefully considered when designing and implementing soil conservation policies and programs in the future.

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