Sheet erosion from arable lands in Zimbabwe: prediction and control

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ABSTRACT Rill and gully erosion on arable lands in Zimbabwe have been effectively controlled by mechanical conservation measures. However, rates of soil loss by sheet erosion of between 50 and 80 t ha\(^{-1}\) year\(^{-1}\) have been estimated. Forward projections indicate that this rate of soil loss will destroy the productive potential of large tracts of cropland within the next 30-50 years. The locally developed soil loss estimator SLEMSA and a soil life-span model are described and their role in devising acceptable conservation strategies is discussed.

Erosion en nappe sur les terres arables du Zimbabwe
RESUME Sur les terres arables, l'érosion par ravinement a été efficacement contrôlée en utilisant des moyens mécaniques de conservation: cependant, on a estimé le taux de pertes de terre, provoquées par l'érosion en nappes à 50-80 t ha\(^{-1}\) an\(^{-1}\). Les évaluations prévues montrent que ce taux de perte va détruire, dans les 30 à 50 années à venir, le potentiel productif de grandes étendues de terres cultivées. Le système localement mis au point pour calculer la perte de terre (SLEMSA) et le modèle de la couche de terre arable sont décrits ci-après, ainsi que leur rôle pour la mise au point de stratégies de conservation appropriées.

INTRODUCTION

In spite of a successful programme of mechanical protection by contour ridges, storm drains and waterways, sheet erosion - the process by which thin layers of soil are washed away during thunderstorms - remains a major threat to the soil and water resources of Zimbabwe.

In 1974 it was estimated that after only a relatively short period of intense cultivation of 30-50 years, the crop productive potential of 12% of arable land in the commercial sector had suffered moderate to serious damage, principally from sheet erosion (Elwell, 1974) (Fig.1).

Since then, development of the local soil loss estimator (Elwell, 1978a) and a soil life-span model (Elwell & Stocking, 1984), has enabled current erosion rates to be assessed and a time limit to be set on the eventual destruction of the soil. Applied to general situations in the communal peasant farming sector, the models yield losses of 50-80 t ha\(^{-1}\) and predict that the soil will not be of sufficient depth to sustain even subsistence yields in 30 years' time.
Soil loss rates of this magnitude represent a potential silt load of 125-200 million tonnes annually from communal areas alone. To this must be added the yield from rills and gullies within the destabilized areas. Although not all the predicted loss contributes to dam siltation, even a small proportion of this enormous yearly load can do incalculable damage to our natural water resources (Fig.2).

Excessive sheet erosion is a symptom of a severe hydrological imbalance in the catchment area. The volume of annual runoff can range from 4 to 30% of the annual rainfall on sandveld and from 2.5 to 33% on clay soils, depending on the agricultural practice (Elwell, 1972). Naturally this must make a considerable impression on the distribution of rainfall between surface and groundwater sources, on the baseflow of rivers and streams, and on flood peaks. In badly eroded catchments, lowlying wet areas quickly dry out, baseflows become non-existent, rivers take on flash-flood characteristics, wells dry up and borehole supplies become less reliable.

It is quite obvious that if current rates of soil loss are allowed to continue unabated, man-induced droughts and crop failure will become the norm with dire consequences for the people, agriculture, the water resources and the national economy.

In this paper, the model-building framework (SLEMSA*) and a soil life-span model are described and their role in devising acceptable conservation strategies is discussed.

*Soil Loss Estimator for Southern Africa.
MODEL-BUILDING FRAMEWORK (SLEMSA)

Soil loss prediction is complex, particularly on arable lands where man's many and varied activities have a great impact on the physical environment. Ideally the raw data for estimation equations should be collected from field-size plots on which agricultural conditions are reproduced in sufficient numbers and with adequate replication. Often this requires an exorbitant number of plots. For instance, in Zimbabwe about 50,000 plots at a current capital cost of $2000 each would be required to cope with even the most common field conditions, whereas the budget is sufficient to install only two or three plots a year.

Clearly, alternative less expensive methods have to be found which, in view of the urgency of the problem, will provide an immediate basis for land protection.

SLEMSA (Fig.3), is a framework for building models to predict sheet erosion losses from arable lands in areas of high intensity rainfall. It was developed to enable soil losses for a wide range of cropping conditions to be interpreted from relatively few field plots. Initially, the soil erosion environment is divided up into its four physical systems: crop, climate, soil and topography. Within each system there are many possible factors contributing to soil loss, but, for simplicity, only the major overriding factors (control variables) have been selected for modelling purposes.

Ideally the control variables should be rational and easy to measure or their values obtainable from existing data banks. Five controls have been identified in Zimbabwe: seasonal rainfall energy $E \ (\text{J} \ \text{m}^{-2})$, proportion of the rainfall energy intercepted by the crop...
Identification of the variates at this level has important advantages: the range of values of a variate, \( i \) for instance, provides a rating of all cropping practices in order of erosion hazard, furnishes a quantitative basis for the development of prediction equations from relatively few well-chosen field plots and, once the equation has been developed, allows soil losses to be interpolated for other conditions provided only that the value of the variate is known. Under this system it does not matter if a practice on one of the field plots becomes obsolete as its contribution to the formulation of the equation is unchanged.

The control variables are related to soil loss at the submodel level. The principal submodel \( K \) combines the influences of mean seasonal rainfall energy and soil erodibility to give the estimated mean annual soil loss from conventionally tilled bare soil on 4.5% slopes, 30 m long. \( C \) is a ratio to correct the soil loss from bare fallow to that for cropped land and \( X \) is a ratio to account for different slope steepnesses and length.

The submodels combine as simple products in the main model to give a best estimate of the mean annual soil loss from sheet erosion under a specific cropping practice, climate, soil type, slope steepness and slope length.

In the construction of models, established theory, expert opinion, laboratory test data and results of field-plot measurements are all valid data sources. Elwell & Stocking (1982) have described the development of a model from a qualitative beginning through to a final quantitative stage, based on the SLEMSA framework.

At the present time, one model is in operation in Zimbabwe. Field officers are trained in the use of a handbook (Elwell, 1978b) in which an estimate of soil loss is arrived at via a series of easily read graphs and tables. Although the model was developed for the highveld, for want of more specific regional data it is applied

\[
\begin{align*}
\text{Energy interception} & \\
\text{Crop ratio} & \\
\text{Soil loss from bare soil} & \\
\text{Topographic ratio} & \\
\text{Soil loss from the cropland} & \\
\end{align*}
\]

\[
\text{FIG. 3 Model building (SLEMSA).}
\]
throughout the country. For this reason the difference between the framework and the prediction models derived from it is not always appreciated.

Since the models predict sheet erosion losses, the lands are assumed to be adequately protected from rill and gully erosion by the system of contour ridges, storm drains and waterways described by Hudson (1971).

The designer of the protection system calculates the soil loss for each crop in sequence and determines the mean soil loss for the rotation. This loss rate is compared to predetermined "acceptable" target levels of 3-5 t ha⁻¹ year⁻¹ depending on soil type. In the event of the estimated loss from the existing practices being in excess of the acceptable level, the designer seeks to lower the soil loss rate to below the target figure by adjusting the crop types in the rotation, planting dates, yield levels, tillage and ridging practices, or the effective slope length and steepness. By this means several suitable alternative farming systems can be devised and the most acceptable one selected in consultation with the farmer or communal land authorities.

Predictive models can be applied to broad scale planning problems as well as to individual farm fields. Locally, the Highveld model has been used in land use planning to draw up generally acceptable crop rotational practices, (Farm Management Handbook, 1982); and to assess the average rate of soil erosion from large areas (Meikle, 1982). Other countries, for want of local information, have employed the Highveld model in a comparative role. Schulze (1979) modified the model to identify areas of high and low eroding potential contributing silt to the Tugela basin in South Africa, while Stocking (1982) applied it to Brazilian conditions with some success.

LIFE-SPAN MODEL

The purpose of the life-span model is to provide a readily understandable measure of the consequences of a prevailing soil loss rate and to set time limits within which appropriate action should be taken. An appeal for adequate resources to protect land is more likely to be forthcoming if it can be shown that the high soil loss rate will destroy the agricultural productivity of the area within a few years.

Again, the modeller is faced with a large number of variables interacting in a complex manner and simplifying assumptions are necessary. The following assumptions have been made to develop a very straightforward mathematical model as a starting point: the soil depth is renewed at a rate equivalent to the rate of soil formation, the depth of available productive soil can be identified in the field, and the yield of a crop is directly related to soil depth.

\[ L_f = \frac{(D_e - D_o)M}{Z - Z_f} \]

\( L_f \) is the soil life-span in years; \( D_e \) is the depth (m) of available productive soil; \( D_o \) is the minimum soil depth (m) to produce a given
yield; M is the bulk mass of the soil (t ha$^{-1}$ m$^{-1}$); $Z_f$ is the estimated rate of soil formation (t ha$^{-1}$ year$^{-1}$); and K is the predicted rate of soil loss (t ha$^{-1}$ year$^{-1}$).

Locally applicable tables are provided giving values of M and $D_0$, while $D_e$ is measured on site. The value of Z is obtained from the Highveld model and $Z_f$ is assumed to be 1. For further details see Elwell & Stocking (1984).

APPLICATION

The following example illustrates the value of the soil loss and soil life models for identifying critical problems and selecting acceptable conservation strategies.

It has long been recognized that soil erosion losses are dangerously high in the communal areas but, prior to the development of the models, it was not possible to estimate how high and what effect this would have on sustained agricultural productivity; neither was there any quantitative basis for selecting suitable alternative practices.

A typical communal area situation has been taken as an example. Soils are shallow granitic sands varying from 300 mm deep on recently settled lands to 250 mm on eroded areas. Slopes are on average 4.5% and the existing contour layout divides the land up into strips 30 m long. Maize is by far the most popular crop but low yields are obtained (750 kg ha$^{-1}$) because of uncertain annual rainfall (700 mm), shallow ploughing and poor soil fertility (Fig.4).

Soil loss and soil life predictions for this situation are shown in Table 1. In section 1 the land is prepared by ploughing and/or

FIG.4 Low yielding maize in communal lands.
Sheet erosion from arable lands in Zimbabwe

Discing to leave a relatively smooth surface, whereas in section 2 the crop is grown on raised ridges (usually 0.9 or 1.0 m apart) running on true contour or at a very slight gradient.

In each case (column 1) three management levels have been chosen, represented by average yields: current communal land conditions (750 kg ha\(^{-1}\)); the lower ladder of commercial farming (1500 kg ha\(^{-1}\)); and average yields attained by top commercial farmers (4500 kg ha\(^{-1}\)).

**TABLE 1 Influence of yield and ridging practices on soil loss and soil life**

<table>
<thead>
<tr>
<th>Maize yield (kg ha(^{-1}))</th>
<th>Predicted soil loss (t ha(^{-1})year(^{-1}))</th>
<th>Minimum soil depths (mm)</th>
<th>Estimated soil life (years) for which stated yield levels (kg ha(^{-1})) can be sustained: 4500 1500 750</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. NORMAL PLOUGHING</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>49</td>
<td>150</td>
<td>16 (0) 35 (20) 47 (31)</td>
</tr>
<tr>
<td>1500</td>
<td>27</td>
<td>187</td>
<td>29 (0) 65 (36) -</td>
</tr>
<tr>
<td>4500</td>
<td>11</td>
<td>250</td>
<td>75 (0) -</td>
</tr>
<tr>
<td>1. CROP RIDGES ON CONTOUR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>9</td>
<td>150</td>
<td>94 (0) 212 (118) 281 (181)</td>
</tr>
<tr>
<td>1500</td>
<td>5</td>
<td>187</td>
<td>188 (0) 424 (236) -</td>
</tr>
<tr>
<td>4500</td>
<td>2</td>
<td>250</td>
<td>750 (0) -</td>
</tr>
</tbody>
</table>

ACCEPTABLE SOIL LOSS LEVEL = 5 t ha\(^{-1}\)year\(^{-1}\)

The rate of soil loss predicted for each management level is shown in column 2, and the minimum soil depth required to sustain the average yield levels are shown in column 3. The minimum soil depth (187 mm) required to sustain a yield of 1500 kg ha\(^{-1}\) has been assessed by fitting an experimental curve of the form \(y = ae^{bx}\) to give a yield \((y)\) to depth \((x)\) relationship.

The number of years to reduce the soil depth to the minimum required for the three chosen levels is shown in columns 4, 5, and 6. Unbracketed figures are for the area where the initial soil depth is 300 mm and the bracketed figures are for the eroded land which has a current soil depth of 250 mm.

Under existing traditional practices (row 1) at a yield of 750 kg ha\(^{-1}\) (column 1) and a predicted soil loss rate of 49 t ha\(^{-1}\)year\(^{-1}\) (column 2), the top yielding potential of the newly settled land (4500, column 4) will be destroyed in 16 years time; in 35 years the same land will not be able to sustain a yield potential of 1500 kg ha\(^{-1}\); and in 47 years time the subsistence level of 750 kg ha\(^{-1}\) will not be possible. In the eroded areas, the soil depth is already the minimum (250 mm) for top yields hence soil life is zero; and the yield potentials of 1500 and 750 kg ha\(^{-1}\) will be destroyed in 20 and 31 years respectively.

Increased production is often promoted as the sole solution to conservation problems in the communal areas on the basis that an increase in yield will feed an undernourished population and at the
same time control sheet erosion through increased protective cover. Unfortunately the argument overlooks the important consideration that it will take a long time to achieve a significant increase in crop production under the conditions described by Stubbs (1977), of too few resources, farming in an inhospitable environment.

The figure in Table 1, section 1, show that should yields be doubled from 750 to 1500 kg ha$^{-1}$, the full productive potential of the newly settled areas would still be destroyed in 29 years; and in 75 years time if the impossible could be attained and crop yields increased immediately to 4500 kg ha$^{-1}$. These are short time periods indeed considering the social, economic and political constraints hindering successful application of the total development package (Hudson, 1981).

On the eroded land, where there is no leeway at all, the "production policy" would be even more disastrous as the yield potential of the land is deteriorating annually and time limits are extremely narrow. Also, it is difficult to see how crop yields can be improved on lands where unchecked sheet erosion continues to further impoverish the soil, to wash away seeds and fertilizer and to reduce the moisture available for plant growth.

FIG.5 Crop ridges on contoured land.

The conservation merits of an alternative strategy to the direct production approach is shown in Table 1, section 2. The method of ridging crops on contour has been chosen (Fig.5), because the effectiveness of the technique is not dependent upon the vagaries of climate, pests and disease. Also, the success of the contour layout
programme has shown that a simple mechanical solution is easier to implement than a complex production package. The cost of the necessary equipment (i.e., a ridger body to the standard single furrow plough) is currently about $25, a mere fraction of that required to fertilize a 5 ha land each year ($500-$700) for top yields.

As soon as a land has been ridged, soil losses drop to 20% of their original value and soil life is increased by 6 to 10 times, thereby providing a stable base from which to promote increased crop production and a more realistic time scale in which to achieve high yield levels. Furthermore, whereas increasing yield alone (Table 1, section 1) cannot reduce soil losses to below the acceptable level of 5 t ha$^{-1}$year$^{-1}$, the target level is reached at relatively low yields (1500 kg ha$^{-1}$) on ridged lands.

CONCLUSIONS

Soil loss estimates provide a quantitative basis for judging the impact of man's agricultural activities on the welfare of the soil; while soil life predictions define the time scale for various levels of destruction to take place. Together, soil loss and soil life models yield information essential for selecting the most appropriate conservation strategies for protecting the soil and water resources.

The two models described in this paper are in an early stage of development. Considerably more information is required to improve their accuracy and scope. Although the SLEMSA approach has significantly reduced costs of data collection programmes, financial needs remain well in excess of the funds available. Thus, an immediate challenge facing researchers is to find even less costly ways of collecting model-building data.

Looking further into the future, another problem to be solved is the glaring gap between the levels of soil loss which can be achieved in the field under practical conditions and the extremely low rates of soil formation. Current target levels are about 6 to 10 times higher than the rate of soil formation recorded locally by Owens (1974). Unless new techniques are found, either to reduce soil loss rates to negligible levels and/or to increase rates of soil formation possibly by the addition of chemicals to the soil, eventual destruction of the soil appears inevitable.

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