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A PROCEDURE FOR THE ANALYSIS OF SOIL EROSION AND RELATED PROBLEMS IN WATER AND LAND RESOURCES MANAGEMENT STUDIES

Research Report

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Preface

This report is the result of a 6 week stay, from Januari the 25th till the 8th of March 1987, at the Cisadane-Cimanuk Integrated Water Development Project (BTA-155) in Bandung, Indonesia. The project is a Water and Land Resources Management study and is carried out by the Directorate General of Water Resources Development (DGWRD) of the Indonesian Ministry of Public Works (DPU) on the one hand, and Delft Hydraulics, Rijkswaterstaat, and Euroconsult, on the other hand.

The objective of the BTA-155 study is to support decisions which aim at an optimized water and land resources development. The study comprises all relevant aspects of WLRM, including all users and uses of water, natural phenomena like flooding, erosion, and groundwater, and the related social and institutional aspects of water, water utilization and proposed management actions. Given the fact that all these aspects are interrelated and influence each other, a systems analysis approach will be used to deal with this complexity.

Soil erosion is one of the major problems affecting the water resources in the area of study and despite the attempts to implement soil conservation programmes, it is to be expected that the growing population density and pressure on the land will further increase soil erosion and related problems in the future.

In other projects carried out by Delft Hydraulics, in Kenya and Taiwan, it was also recognized that a study of soil erosion and related problems is of crucial importance for a successful analysis in Water and Land Resources Management planning projects.

It was therefore decided to put DH research effort in developing a methodology for the analysis of soil erosion, that will easily fit into the existing framework for analysis and computation, as used in WLRM studies, and that is applicable on a regional scale. In a preparatory study, carried out in Delft, a number of soil erosion models have been evaluated on their suitability in WLRM studies and two models were selected for further evaluation. The BTA-155 project provided the data and working environment to to carry out such an evaluation in a realistic way. The results of the evaluation proved to be useful in the BTA-155 context.

This report aims at giving an overview of the "state of art" of soil erosion research and at providing a general procedure for the analysis of soil erosion and related problems in Water and Land Resources Management studies. Although a general procedure is aimed for, part of the work is especially relevant within the Indonesian context.

After a general introduction to soil erosion processes in catchment areas (chapter 1), the objectives of an analysis of erosion and erosion related problems in WLRM studies are discussed in chapter 2. In chapter 3 a methodology for the estimation of the soil loss on the catchment slopes, based on the Universal Soil Loss Equation, is outlined. The effects of soil erosion and soil conservation measures on catchment sediment yield and the hydrological responses of the rivers draining the catchments, are discussed in chapter 4. Chapter 5 deals with the damages caused by soil erosion and the effectiveness of soil conservation measures.

Chapter 1. Soil erosion processes in catchment areas

1.1 Introduction

Soil erosion, the removal of soil material by wind and water, is causing serious problems in many developing countries. It is a symptom of ecological imbalance, often brought about by the ever increasing need for food and fiber of the growing populations of these countries. Over-exploitation of the soils, not seldom rendering them degraded and unproductive is the result.

Soil erosion has many ecological and economical consequences. The productive top-soil is removed and the soil productivity deteriorates, landslides and gullies reduce the area of productive land and may damage roads and buildings, the hydrologic regimes of the rivers change and increased sediment loads result in eutrofication and the silting up of reservoirs and irrigation structures. Once the environmental degradation has started it can only be stopped with great effort and at considerable costs.

Under natural conditions the rate of soil erosion, the so-called geologic norm of erosion, is in equilibrium with the rate of weathering and soil formation. To prevent accelerated erosion on agricultural lands, in other words to keep the erosion rate at more or less the geologic norm, appropriate soil conservation techniques have to be selected. This requires a good understanding of the soil erosion process. However, erosion is a very complicated phenomenon; it is the result of many processes, whose controls and mechanisms are not yet fully understood, or as Lal (1985) stated, "erosion research is more an art than a science".

The most important factors controlling soil erosion are: rainfall, surface runoff, wind, soil, slope, plant cover and absence or presence of conservation measures. Morgan (1979) grouped these and other related factors under three headings: energy, resistance and protection (fig 1). The factors grouped under the heading energy include the potential abilities of the rainfall, the surface runoff and the wind to cause erosion. This ability is generally referred to as erosivity. Incorporated in this group are also the factors that directly affect the erosivity such as the reduction of slope lengths by the construction of terraces. In the resistance group the erodibility of the soil is of major importance. It depends on physical and chemical properties of the soil. Infiltration capacity and management of the soil are other factors in this group. Good soil management practices result in well aggregated soils that do not crust, and thus have high infiltration rates. High infiltration rates on their turn decrease the erodibility by reducing the surface runoff. The protection group includes factors related to plant cover. The vegetation intercepts part of the rainfall and reduces the erosivity of the falling raindrops and the velocity of the surface runoff and the wind. The protection offered to the soil depends on the nature of the plant cover, and by changing the land use man is able to change the degree of protection given to the soil. Land use changes and crop management therefore are important tools for soil conservation purposes, the other factors given in the table are much less easily manipulated by man.

LOW___Rainfall erosivity___HIGH
LOW___Run off volume______HIGH
LOW___Wind strength_______HIGH
LOW___Relief______________HIGH
GENTLE_Slope angle__________STEEP
SHORT_Slope length_________LONG
SHORT_Slope shortening_____LONG
(terraces, ridges)___LONG
SHORT_Length of wind fetch_LONG
SHORT_Shortening of fetch__LONG
(shelterbelts)

LOW___Soil erodibility______HIGH
HIGH__Infiltration capacity_LOW
GOOG__Soil management_______POOR
(use of fertilizers;
tillage practices)

LOW____Population density____HIGH
(pressure on land)
DENSE__Plant cover__________NONE
(crops, improved &
natural pasture, forest
LOW____Amenity value_________HIGH
(pressure of use)
GOOD___Land management_______POOR

PROTECTION
GOOD --- --- POOR
FACTOR

ENERGY
LOW --- --- HIGH
FACTOR

RESISTANCE
GOOD --- --- POOR
FACTOR

UNLIKELY -- SOIL EROSION -- LIKELY

Figure 1. Factors controlling the intensity of soil erosion processes (After Morgan, 1979)

1.2 Processes and mechanisms of erosion

Soil erosion is a two-phase process, consisting of detachment of individual particles from the soil mass and their consequent transport by the erosive agents, such as wind and running water. Actually a third proces should be distinguished, the deposition or sedimentation that occurs when the available energy is insufficient for further transport of the detached particles.

The impact of falling raindrops is an important detaching agent. Soil particles are thrown into the air and travel over considerable distances. Other processes such as physical and chemical weathering, tillage operations by man and trampling by cattle also contribute to the detachment of soil particles, as do running water and wind. Once the soil is loosened, the detached soil particles can be easily removed by the transporting agents.

Two groups of transporting agents can be recognized, the first group comprises those who act area wide and result in the removal of a soil layer of relatively homogeneous thickness. Examples are rainsplash (splash-erosion), overland flow (sheet-erosion) and wind (wind-erosion). The second group of agents are those that concentrate their actions in defined channels: water flow in channels that are so small that they can be filled in by ploughing (rill-erosion) or in larger, more permanent, features (gully-erosion and channel-erosion). Transport of soil material by mass-movements (mudflows, landslides, creep, etc.) is another form of erosion that is more or less restricted to a limited area.

The quantity of material supplied by detachment processes and the capacity of the transporting agents to remove this material determine the severity of the soil erosion. Conservation measures can be aimed at either reducing the detachment, e.g. by maintenance of a protective vegetation cover that reduces the rainfall impact, or decreasing the transport capability of the eroding agent, e.g. by terracing to reduce the velocity of the overland flow. To be able to make an optimal choice between possible conservation techniques, it is important to know whether detachment or transport is the limiting factor in the soil erosion process.

In Indonesia wind-erosion is of limited importance. Of the water related soil erosion processes sheet- and rill-erosion are dominant over gully-erosion. A systematic survey of mass-movement frequency has not been carried out, but the contribution of landslides and mudflows to the sediment yield of the rivers may be considerable. On the contrary, gully-erosion is an important feature in many parts of (semi-arid) Africa. In the mountaneous parts of Latin America mass-movements are relatively more important than sheet- and rill-erosion.

1.3 Soil erosion estimation and prediction

Traditionally soil erosion has always been measured on a field or slope scale for conservation purposes. Since a number of years soil erosion is also considered as a source of sediments, causing damage in rivers, reservoirs and irrigation schemes, and non-point pollution, e.g. pesticides and fertilisers washing off agricultural fields. As such soil loss estimation procedures have become incorporated in a number of extensive hydrological models.

The terminology used in studies dealing with soil erosion is somewhat confusing, soil erosion, soil loss, soil degradation and sediment yield are terms often referred to. According to Morgan (1979) these terms should be defined as follows:

- soil erosion is the gross amount of soil moving as a result of raindrop impact, overland flow or wind;
- soil loss is the amount of soil removed from a field or slope;
- soil degradation, a more comprehensive term that includes both the soil erosion process (the loss of soil) and the resulting physical and chemical degradation of the soil (the loss of productivity); and
- sediment yield is the soil loss delivered to a certain point under evaluation, usually the outlet of a basin or a catchment.

On most slopes both erosion and sedimentation occur, soil particles eroded at one point may be deposited in topographic irregularities at another part of the slope. As a result, the soil erosion at a certain point of a slope normally differs from the soil loss at the base of that slope. Deposition of sediment at field borders, along water courses and in the river channel further reduces the total amount of sediment leaving the catchment as sediment yield of the river.

Soil erosion rates can be estimated in three different ways. These different methods do not stand alone, usually they are applied in combination with each other. Methods used in soil erosion research are:

- mapping and direct field observations;
- measurements in the field, using erosion plots or by means of discharge recording and sediment sampling; and
- calculation of soil erosion rates from known erosion explaining factors, using deterministic equations or computer models.

Mapping of erosion features, often with the aid of arial photographs, only provides information on the state of erosion. Areas affected by sheet- rill- and gully-erosion can be recognized on arial photographs and the growth of the erosion affected areas or the effects of conservation measures can be determined from time series of maps or photographs. Additional information is collected in the field, using a simple scoring system to rate the severity of the erosion from e.g. the exposure of tree roots, the surface crusting, the thickness of the A horizon etc.

Maps produced in erosion surveys can be used to establish the nature and rate of erosion and to make a distition between natural (geologic) erosion and accelerated erosion. The spatial variation in erosion can be evaluated in relation with topography, land use, climate, etc., so providing information on research and conservation priorities.

For most countries in the world special maps displaying the state of erosion have been produced on different scales. Maps produced as a result of detailed reconnaissance land resources surveys generally also contain information on the erosion hazard and on evidence of past erosion. In Indonesia the 1:50,000 maps of AGRARIA contain information on the state of erosion of the soils.

Field measurements with erosion plots provide information on the soil loss and enable the evaluation of conservation measures and the effect of different crops and management practices. This information can be used to establish parameters for predictive equations and models. Sediment yields of rivers are calculated from discharge and sediment load observations. Empirical equations to predict sediment yields from a number of catchment characteristics are generally established using multiple regression techniques.

Erosion plot measurements with standard Wischmeier plots are nowadays carried out in most parts of the world, and often aim at obtaining values for the K factor of the Universal Soil Loss Equation. In tropical Africa the efforts are concentrated in Nigeria (the International Institute for Tropical Agriculture), in Zimbabwe (Hudson and co-workers) and in West Africa (the french OSTROM, Roose and co-workers). In Indonesia plot experiments were conducted by the Soil Research Institute in Bogor, the Gajah Mada University in Yogjakarta, PU in Bandung and at present the Kali Konto project in Eastern Java.

The most important empirical equations and models to estimate and predict soil erosion have been described in an earlier memo. Most widely used in tropical areas is the Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1978), an equation used to predict average annual soil loss and to evaluate the effect of conservation measures and different crop and management practices. The distributed models described in the memo have mostly been used in small basins and for research purposes. The input data needed to obtain good predictions with these models are generally not available in third world countries, except for some experimental basins, where detailed soil research and water and sediment output monitoring has been carried out. The ITC (Meyering et al.) tried to use the ANSWERS model on a more regional scale in Indonesia (Sumatra). This attempt failed as a result of lack in reliable data and the fact that the infiltration processes of the tropical soils were not very well represented in the model. This resulted in an overestimation of the throughflow component of the runoff.

In Delft two models were selected for use in Indonesia: the USLE and the distributed ANSWERS model. It was also hoped that a working version of the Land Evaluation Computer System Methodology (LECS) model could be obtained at the Soil Research Institute in Bogor. Attempts to lay hands on the latter model failed. The present status of the LECS model is very uncertain but it seems that no working versions, certainly not for a PC, are available.

The USLE is widely used in Indonesia and is commonly accepted as a good method to establish soil erosion rates and evaluate conservation measures, but the necessary input data are not always readily available. Information is scattered over a large number of institutes, presented at different scales and with different detail and collected for different areas. Information on a regional scale for the whole province West-Java certainly is not easy to collect.

The USLE can only be used to calculate long-term averages of sheet- and rill-erosion; gully- and channel-erosion processes are not taken into account. This means that the formula can only be applied to limited areas of a field or slope scale. On this scale estimations of the erosion rate in tonnes/ha are given for a certain soil, with a certain slope angle, and a given land use and land management, including conservation measures. This erosion rate on the slope can not directly be translated to an amount of sediment entering the river channel and certainly not to amounts of sediment leaving the drainage basin. To connect erosion rates on the slopes with sediment outputs of the rivers other techniques have to be used (see chapter 4).

Input data needed for the ANSWERS model, with which soil erosion and surface runoff processes in small watersheds can be simulated, are related to detailed (continuous) information on rainfall, soil physical and chemical properties and land use. Inventory of the data sources revealed that the necessary information is not available on Java, and test runs with the model can only be done after a time consuming fieldwork to collect the additional information. This falls outside the scope of both the Delft Hydraulics Research and the BTA-155 study and is therefore omitted.

It is to be expected that the situation in respect to availability of data in other third world countries will not differ that much from the situation in Indonesia. In other words, it will be very difficult to use distributed soil erosion models in Water and Land Resources Management (WLRM) studies, the more so because these studies are generally carried out on a regional scale. It seems therefore logical to concentrate the efforts on developing a methodology for the analysis of soil erosion problems for WLRM studies, that is based on the USLE.

1.4 Soil erosion rates and tolerable soil loss

The soil erosion rate is generally expressed in units of mass or volume of eroded soil per unit area per unit of time. According to Young

(1969), erosion rates under natural conditions (the so-called geologic norm of erosion) range between 0.045 to 0.450 tonnes/ha per year, for areas with moderate, respectively steep relief. For agricultural land erosion rates from 45 to 450 tonnes/ha per year are classified as accelerated erosion.

Whether or not a certain erosion rate causes problems with respect to soil productivity depends on the rate of weathering and soil formation. If soil properties such as nutrient status, texture and thickness of the soil remain unchanged through time, the rate of soil erosion is thought to be in equilibrium with the rate of soil formation. The rate and depth of soil formation depend on climate, parent material, vegetation and relief, because these factors determine the rate of organic matter influx and decomposition, the soil water reaction, and the rate and depth of leaching. Weathering and soil formation rates observed in the tropics indicate that soil formation in volcanic material, covering large parts of Java, is faster than is soils derived from residual- and igneous parent material (table 1, after Lal, 1983).

Table 1. Weathering and soil formation rates of tropical soils (After Lal, 1983)

Country	Region	Rate (mm, year^{-1})	Soil
SOILS OF VOLCANIC ORIGIN			
Indonesia	Humid tropics	0.73	Andisol
Trinidad	Humid tropics	0.460-0.508	Andisol
Papua New Guinea	Humid tropics	0.058	Andisol
RESIDUAL SOILS			
Ivory Coast	Humid tropics	0.013-0.045	Ultisol
Zimbabwe	Subtropic	0.011	Ultisol
Zimbabwe	Subtropic	0.41	Alfisol
Cameroon	Humid tropics	0.07	Alfisol
	tropics	0.0017	

The objective of soil conservation measures should be to keep the soil erosion at such a rate that the economical productivity and the stability of the ecosystem are maintained, without costly high inputs of fertilisers, even at the long run, and without deteriorating the soils to such a bad state that they have to be taken out of production permanently. On the other hand siltation of reservoirs, rivers, and canals, reducing their capacity, increasing the flood hazard and decreasing the water quality, should be prevented as well. Although these two objectives can be met accepting different tolerable soil erosion rates, the general rule is that erosion rates should not exeed the rate of soil formation. For the soils of temporate regions the acceptable rate of erosion ranges from 5 to 15 tonnes/ha per year.

This figure is also more or less valid for the Indonesian soils. Wood and Dent (1983) used an average rate of soil formation for Indonesian soils of 0.55 mm/year (6 tonnes/ha per year) to calculate tolerable soil losses. In their study they introduced the concept of "soil resource life", the period in years over which a certain soil profile is allowed to degrade to a minimum acceptable level. This minimum acceptable level depends on the minimum soil depth required for the growth of a certain crop. For a deep soil, 120 cm, a minimum acceptable soil depth of 30 cm and a resource life of 100 years, this results in a tolerable soil loss of 1.16 mm or 14 tonnes/ha per year. It will be clear that the tolerable soil loss decreases when soil formation rates are smaller, when the soils are less deep, and when longer resource lifes are aimed for.

For African soils the soil loss tolerance is much lower than for the Indonesian soils. The soil formation rates on this continent are lower (see table 1), and the soils are generally much shallower. Smith and Stamey (1967) and Skidmore (1979) calculated that the acceptable rates of soil erosion for shallow soils with a low inheritant fertility in Nigeria ranged from only 0.5 to 2.0 tonnes/ha per year.

Erosion rates observed in Indonesia surpass the tolerable erosion rates many times and range from 0.8 to 8.0 mm (10-100 tonnes)/ha per year for major river basins (Puslitbang Pengairan, 1984). In minor river basins the measured erosion rates are even higher, up to 12 mm (150 tonnes/ha) per year (Arif, 1986). In the latter publication, figures of on site erosion rates, on a plot or field scale, are given as well. These figures are extremely high and range between 50 and 520 tonnes/ha or 4 to 40 mm per year. Soil erosion rates for a number of catchments on Java are given in table 2.

Erosion rates reported for African soils are not as high as those reported for Indonesia. An erosion rate of 2.5-9 tonnes/ha per year was measured in Ghana (Adu, 1972), 27 ton/ha per year in Lesotho (Chakela, 1981), 4.8 ton/ha per year in Nigeria (Oyebande, 1981) and 18 tonnes/ha per year in Malawi (Balek, 1977). The erosion rates reportad above are calculated from sediment yields of major rivers and are equivalent to 0.2 to 2.5 mm soil loss per year. On a plot or field scale the erosion rates vary between 0.5 and 220 tonnes/ha per year, depending on the dominant land use (various sources, reported by Jansson, 1982).

Table 2. Soil erosion rates observed in a number of catchments on Java.

P. T. Pancasona Jaya Sakti, 1984

Basin (location)	area (km^2)	erosion rate (mm/y)	observ. period
Sisanggarung (Hulu)	130	2.5	Nov 83-jan84
Cipedak	72	26.7	"
Citaal	83.5	7.6	"
Cisrigading	45.6	16.8	"
Cijangkelok	147.0	10.7	"
Cisanggarung (Meneungteung)	650.0	4.0	"

West Java Provincial Board of Planning and Cimanuk Basin Development project

Basin (location)	area (km^2)	erosion rate (mm/y)	observ. period
Cilutung 0.9 1911			
Citulung		1.9	1934
(Dam Kamun)	631	8.0	1978
(Dam Kamun)	631	2.7	1981
Cimanuk		3.7	1978
Cimanuk		2.5	1981
Cipeles		4.3	1978
Cipeles		1.3	1981

SMEC-NEDECO, 1973

Basin (location)	area (km^2)	erosion rate (mm/y)	observ. period
Cimanuk (Balubur Limbangan)	840	3.8	1971-1972
Cimanuk (Parakankondang)	1450	3.7	"
Cilutung (Dam Kamun)	646	8.0	"
Cipeles (Warung Peti)	440	4.3	"
Cimanuk (Rentang)	2950	5.0	"
Cimanuk (sea)	3600	5.3	"

Roedjito D. M. and Soenarno, 1986

Basin (location)	area (km^2)	erosion rate (mm/y)	observ. period
Citanduy	3500	3.1	?
Cimanuk	1461	2.8	?

Chapter 2. Objectives of an analysis of soil erosion and related problems in Water and Land Resources Management studies.

A analysis of erosion and sedimentation as part of a Water and Land Resources Management (WLRM) study should focus on the relationship between soil erosion and its impacts on the water resources in the catchments under study. Hydrological (frequency and magnitude of floods and low flows) and morphological impacts (sedimentation) should receive most attention. However, it has to be stressed that decreasing soil productivity, as a result of soil erosion, is a serious socio-economic problem as well, the more so because severe degradation of the soils in a particular area will further increase the pressure on the remaining productive land.

For the purpose of WLRM studies it seems most important that a regional picture of the magnitude of the erosion problem, its impacts, its future developments, the measures that can be applied to control these developments and their corresponding effects, is provided. Of importance is also that only readily available data can be used, that the method applied has to be consistent throughout the project area and that the implementation of measures has to be socially and politically feasible.

The final objective of an soil erosion analysis in a WLRM study is threefold:

- Indicate where soil and water conservation practices are most effective from the point of view of water (and land) resources conservation.

- Provide information that will enable a cost-effectiveness analysis of soil conservation practices.

- Provide information for the construction of a number of strategies of the implementation of soil conservation measures and their hydrological and morphological impacts.

Van der Most (memo87/55) made some remarks concerning these objectives, that are of relevance in the Indonesian context:

- The Ministry of Public Works (PU) in Indonesia, the authority in charge of water resources management planning, is not responsible for soil conservation measures. This implies that a cost-benefit analysis of these measures is not the direct task of PU and that the analysis of the benefits for water resources management is only of importance to indicate to other ministries, more directly involved with soil conservation, where and to what extent the conservation measures will also benefit the water resources.

- Analysis of the benefits of soil conservation also includes evaluation of the changes in soil productivity, both for agricultural areas and forests, that result from these measures. This topic also lies outside the direct interest of PU, although prediction of the probability and magnitude of conservation measures that may be taken in the future and that will result in changes in land use (e.g. reforestation) and therefore in hydrological response of the catchments, are certainly important for PU.

- Finally it was quite rightly remarked that other considerations than economic may influence the decision making process in respect with conservation measures and that those who have the benefits, are not always those who make the investments. Furthermore, investments made now will only start to pay off over a number of years or may not result in direct benefits at all but only avoid more serious problems in the future.

The general objectives of an erosion study for WLRM purposes can only be met by analysing the erosion problems according to the more specific objectives of erosion studies as given by SMEC (1979):

1- delineate the areas of accelerated erosion;
2- describe the erosion processes active in the area;
3- attempt to quantify the magnitude of the soil erosion;
4- seek the cause of the severity of the problem;
5- propose technical remedial measures;
6- analyse the relationships between soil erosion on the slopes and sediment output of the catchments; and.
7- analyse the relationships between conservation measures/ land use changes and the hydrologic response of the basins under study.

Other specific objectives to be added to this list are:

8- quantify the costs of the proposed technical measures;
9- analyse the benefits of the proposed measures, both in terms of increased (or not reduced) soil productivity and reduced damages (floods, sedimentation of irrigation infrastructure and reservoirs); and
10- recommend how these measures might be achieved within the socio-economic environment of the area.

Once the first seven objectives, summarized in this list and dealing with the physical soil erosion processes are fulfilled, the results of the analysis can be used to reach the more economic objectives 8,9 and 10.

Chapter 3: A methodology for the estimation of soil erosion in WLRM studies

3.1 Introduction

As stated in chapter 1 the methodology outlined in this chapter is based on the Universal Soil Loss Equation. Some background information on this equation will be given in this section.

The USLE is a mathematical model, used to predict soil losses due to areal erosion. The equation was developed at the National Runoff and Soil Loss Data Centre of the Science and Education Administration, in co-operation with the Prudue University (USA). Field measurements with standard runoff plots, 22.1 m long and 1.83 m wide, at 49 locations throughout the USA, provided more than 10,000 plotyears of basic information on surface runoff and soil loss to this centre for summarizing and statistical analysis. Since 1960 rainfall simulator experiments on field plots were used to fill in the gaps in information needed for the factor evaluation.

The equation has been successfully used on agricultural land in the USA from 1953 onwards. Since 1972 modifications exist, that permit the use for range and forest lands. Outside the USA caution is needed because some of the relationships used do not always apply under conditions different from those prevailing in the United States. For instance the rainfall factor R has a high correlation with soil loss on Java (Abujamin et al,, 1985), but is not very well correlated with soil loss in Benin (Arnoldus, 1977). Adaptions to local circumstances may thus be needed; especially the rainfall-, slope- and cropping/management factors need to be checked. Although the USLE is a fairly simple steady state model, a rather sophisticated data set is needed, with respect to rainfall, vegetation/land use and soil conditions. The use of unreliable data may lead to erroneous estimations and predictions.

As pointed out by Wischmeier and Smith (1978) the USLE can be used for the following purposes:

- predict average annual soil loss from a field slope with specific land use conditions;
- guide the selection of cropping and management systems, and conservation practices for specific soils and slopes;
- predict the change in soil loss that would result from a change in cropping and conservation practices on a specific field;
- determine how conservation practices may be applied or altered to allow more intensive cultivation;
- estimate soil losses from land use areas other than agricultural; and
- provide soil loss estimates for conservationists, to be used for determination of conservation needs.

Although the equation was originally designed for conservation planning

purposes, it is also aplicable to calculate soil loss rates for correlation with other parameters. Use of the equation on a yearly or storm basis is not recommended, only long-term estimates of erosion are reliable.
The basic equation of the USLE reads as follows:

$$A = R * K * L * S * C * P, \text{ in which:} \quad (1)$$

- A = computed soil loss per unit area (tonnes/ha, when metric units are used)

- R = the rainfall factor, the number of erosion index units (EI units) in the period of consideration. The erosivity index is a measure of the erosive force of a specific rain

- K = the soil erodibility factor, the erosion rate per unit of erosion index for a specific soil, in a cultivated, continuous fallow plot, 22.1 m long, on a 9% slope

- L = the slope length factor, the ratio of soil loss from the field slope length to that from a 22.1 m slope length on the same soil type with the same gradient and the same crop and management

- S = the slope gradient factor, the ratio of soil loss from the field gradient to that from a 9% slope, on the same soil type, slope length, crop and management

- C = cropping/management factor, the ratio of soil loss from a field with a specific crop and specific management to that from a fallow slope with the same soil, slope length and slope gradient

- P = the erosion-control practice factor, the ratio of soil loss from a field slope with conservation practices to that with straight row farming up and down slope, on the same soil type and with the same slope length

Hamer (1981) concluded that, for the Indonesian circumstances, a number of these parameters (the so-called USLE factors) are quite different from those prevailing in the USA:

- the rainfall factor is bigger than 950, the maximum value observed in the USA;
- the soils are of primarily volcanic- instead of loess- and sedimentary origin; and
- slopes steeper than 18% are frequently cropped.

Nevertheless he also concluded that, although care has to be taken, the USLE can be succesfully applied in Indonesia.

3.2 Procedure to be followed

To be able to use the USLE to estimate the actual magnitude and distribution of the soil erosion in WRM project areas, it will be necessary to obtain information on the areal distribution of the explanatory variables on a regional scale. Two different approaches exist to get a picture of this areal distribution:

- compilation of overlay maps, based on a set of maps on which the explanatory variables are separately displayed
- compilation of a grid system, information on the USLE factors can be derived from other maps and assigned to the grid elements

On an overlay map distinctive landscape units can be recognized that are internally homogeneous in their (erosional) response to rainfall. Map overlays may be compiled manually, but the use of a graphical tablet to digitize the maps could decrease the required working time significantly. Further advantages of using digitized information are that maps of different scales can be easily enlarged and reduced to match each other and that they can be easily transformed to a database, what may speed up the eventual calculations. Using the USLE, the actual magnitude of the soil erosion on every unit can be calculated, as well as the effect of conservation measures and changes in the vegetation or land-use. The latter is simulated by changing the C and P factors in the formula.

To compile a reasonable reliable landscape unit map, maps displaying the erosion determining factors on a 1:50,000 to 1:100,000 scale should be used. The scale of the final overlay map should be in the order of 1:250,000. Given the area of the project (ca 30,000 km^2) an average size of the mapped units of 1 cm^2, would result in 4,500 sampling points.

In comparison with a grid cel approach, compilation of a landscape unit map is generally more efficient to represent geographical data. Homogeneous landscape units may be variable in area, their size depending on the spacial variability of the erosion determining rainfall- and land characteristics. This implies that on a landscape unit map, as compared to a map based on grid cel information, more detail is available where required, while large homogeneous areas can be treated as one unit.

A grid cel approach is preferable in situations where digitized information is not available and where maps at different scales have to be used. The contents of each grid element have to be entered in a database to enable calculation of the erosion rates and evaluation of changes in the individual parameters.

In Indonesia the Badan Koordinasi Survey dan Pemtaan Nasional (Bakosurtanal) has experience with digitizing land surface properties and processing large data bases with a Geographical Information System (GIS). For example, a land suitability map of the Citarum river basin has been prepared by overlaying digitized slope-, vegetation-, soil-, agro-climatic- and physiographic maps. However, a visit to this institute learned that this was a one time exercise and that no digitized information on other parts of Java is available. Manually constructed overlay maps were made for 16 "critical watersheds" in Indonesia, on behalf of the Ministry of Forestry. For West-Java the Citarik, Cikapundung, Cisadane, Cipeles and Cibaliung catchments were mapped on a 1:50,000 scale. For each watershed the USLE factors have been mapped and the erosion rates calculated.

The grid cel approach has more or less been followed by Ir. Arif of the Department of Hydrology of PU Bandung, who calculated mean soil erosion rates for the Upper-Citarum river basin using a grid system with 10 km^2 grid elements. For each element the average values of the R, K, L, S, C and P factor were established and the erosion rate within each grid element was calculated with the USLE. To calculate the average erosion rate on a (sub) basin level, it was assumed that the average erosion rate of the grid elements within the basin represented the average erosion rate for that (sub) basin as a whole. In the study the average erosion rate of a number of basins on Java were compared with sediment outputs of the basins. The sediment yield of the rivers was established with the aid of continuous discharge registrations and sediment rating curves.

For the BTA-155 project purposes the grid cel approach should be adopted. Most of the information needed is presented on maps of different scales and digitizing equipment and computer programs to process digitized information are not available.

For each grid element the average value of the USLE factors has to be established and entered in a database. Average erosion rates for waterdistricts or watersheds can than be calculated, and the effects of soil conservation measures or land use changes can be evaluated by changing the C and P factors for the grid elements concerned and recalculation of the erosion rates can be made. The results can be compared with the results of the more detailed studies by Ir. Arif and Bakosurtanal. The information of Ir. Arif is available, but the Bakosurtanal maps are not yet officially published.

3.3 Data requirements and availability

In this section will be described which data are needed for the use of the USLE, how these data have to be processed to derive the erosion determining factors, and which approximative methods can be used. Again, special emphasis will be given to the Indonesian situation. The information presented in this section has been mainly derived from the USDA Agricultural Handbook No 537 (Wischmeier and Smith, 1978) and from Arnoldus (1977).

3.3.1 The rainfall erosivity factor R

Storm soil losses from agricultural fields are, holding other factors constant, related to the product of the total kinetic energy of the rainstorm (E) and its maximum intensity over 30 minutes (I_{30}). The R factor is defined as the EI_{30} index divided by 100. To calculate the kinetic energy the rainfall event is divided in periods of more or less constant rainfall intensity, using the charts of an automatic rainfall recorder. For each period with constant intensity the kinetic energy is calculaterd with the formula:

$$E = 210.2 + 89 * \log I, \text{ in which:} \qquad (2)$$

E = the kinetic energy in ton meters/ha per cm of rain
I = the average rainfall intensity over the period considered, in cm/hour

Tables exist in which the relationship between rainfall intensity and the kinetic energy are given. However, these relationships are only valid for non-orographic rain and have not been tested for tropical areas.

The total kinetic energy of a storm equals the sum of the kinetic energy for each period, multiplied with the centimeters of rainfall in that period. The R value is calculated by multiplying the kinetic energy with twice the maximum average 30 minute intensity (I_{30}, in cm/h)and dividing this product by 100.

To arrive at the long-term average rainfall factor R, the EI_{30} indices of the individual storms have to be summarized and devided by the number of years of observation. Average annual values of the R factor are displayed on iso-erodent maps. Such maps exist for large parts of the world.

Hudson (1971) stated that the EI_{30} value is not usefull for regions which receive a large part of their total rainfall in high intensity rainstorms. Based on research in tropical Africa, he proposed the use of a KE>25 index. To calculate this index, the total energy of the rain falling with intensities >25mm/h is only summarized but not multiplied with the I_{30} index to represent the R factor.

In many tropical countries, automatic rainfall recorders are widely scattered or observation periods are either to short or frequently interrupted. For these reasons a number of methods to approximate the EI_{30} values or R factors have been developed:

- Wischmeier (1962) reported a high correlation between the average annual EI_{30} index and the product of the average annual rainfall, the 2 year 1 hour rainfall amount and the 2 year 24 hour rainfall amount, in formula:

$$EI_{30} = f\,(P * I_{1}^{2yr} * I_{24}^{2yr}), \text{ in which:} \qquad (3)$$

I_1^{2yr} = the 1 hour rainfall amount with a return period of 2 years

I_{24}^{2yr} = the 24 hour rainfall amount with a return period of 2 years

For each region the regression equation has to be calculated separately.

- Lal (1976) proposed the use of the AI_m index, based on findings in Nigeria. The AI_m index is computed by multiplying the total rainfall amount for a storm with the maximum 7.5 minute intensity. However, to establish this maximum 7.5 mm intensity, data of pluviographs are needed as well.

- A modified Fournier index (Fournier, 1960) was used by Arnoldus (1980) to estimate the rainfall factor R for West Africa. The overall formula, based on observations in 176 climate stations throughout the USA and West Africa, has the following form:

  $$\text{Log } R = 1.93 \log \sum_{1}^{12} p^2/P - 1.52, \quad (4)$$

  for stations in West Africa the equation reads:

  $$R = 5.44 \sum_{1}^{12} p^2/P - 416, \quad (5)$$

  in which:

  p = the average monthly rainfall in mm
  P = the average annual rainfall in mm

  The results for the USA and West Africa were very promising, but the equation is not directly applicable in other climatic regions. For 3 stations on Java the R factor has been calculated using the overall formula. The results, shown in table 3, are not very comparable with R factor values derived with other methods.

- Roose (1977) found a simple empirical relationship between the average yearly erosivity index (Ram) and the average annual rainfall amount (Ham):

  $$Ram/Ham = 0.50 \pm 0.05$$

  The equation has been verified for 20 stations in West Africa (Ivory Coast, Niger, Senegal and Tchad). Stations in mountaneous areas and along the coast were not included.

  A direct linear relationship between the R factor and the average annual rainfall amount has also been established in Belgium (Bolline et al, 1980) and was tentatively indicated for Indonesia by van Lavieren (1985), based on SMEC, 1984 (see table 3).

In Indonesia the number of automatic rainfall recorders is limited and the erodibility index has to be approximated. A generally accepted and widely used approximation of the R factor is the Bols index (Bols, 1978). The index was developed with limited pluviometer data and covers a range of R values generally between 1900 and 4000 but peaking to 8000. This is beyond the maximum values observed in the USA (R<950)and obviously also beyond known reliability of the linear relationship between soil loss and the R factor. However, scattered research results indicate that this relationship is linear upto R values as high as 11,000. This linearity is also assumed to exist on Java (Hamer, 1981). Another condition of the R factor concept is that the EI_{30} values of the individual rainstorms are additive, according to the above mentioned author there neither is reason to doubt the validity of this condition for the circumstances on Java.

The formula developed by Bols has the following form:

$$R = 6.12 * (P_m)^{1.21} * (N)^{-0.47} * (P_{max})^{0.53}, \qquad (6)$$

in which:

P_m = the average monthly rainfall amount (in cm)
N = the average number of raindays per month
P_{max} = the average maximum 24 hour precipitation per month (in cm)

The average annual R factor equals the sum of the average monthly values.

Table 3. Average yearly rainfall amounts and calculated R factors for 3 stations on Java.

Station	Average yearly rainfall (mm)	Bols R (tm/ha)	Arnoldus R (tm/ha)
Ciwara	3510	3492	3350
Kuningang	2723	2357	1963
Losari	1699	1536	1019

For the erosion study in the BTA-155 project the use of the Bols formula is recommended. Data for a more detailed assessment of the rainfall erosivity are not available and for the Indonesian circumstances the formula proved to give a good estimation of the R factor as calculated from the registration charts of automatic rainfall recorders.

According to memo 87/050 by Herman van der Most, dated 870102, the database entry of monthly rainfall figures for West Java has been completed for the time span 1947-1980. The years 1980-1986 will soon follow, daily amounts of rainfall have not yet been entered. In the memo it is proposed to enter these values for only a limited number of rainfall stations. The database presently in preparation will therefore not be very useful for the R factor calculations according to Bols.

Three options exist: expanding the existing data base using additional information available at BMG, Puslitbang, and IMDEC or construct a new data base, using the data published by Berlage (1970) in his "Verhandelingen no. 37" of the department "Verkeer, Energie en Mijnwezen". In this publication average monthly rainfall amounts, average number of rainy days per month and the average maximum 24 hour precipitation per month are given for 4339 stations in Indonesia for the period 1911-1941. A more recent publication, covering the period 1941-1971 also exists but is not yet available at BTA-155. The third option is to use the original Bols data. However, the scale on which this map has been published, 1:250,000, provides insufficient detail. The preferable option therefore is the construction of a new iso-erodent map, based on the data of Berlage.

R factors for Java range between 1900 and 8000 tm/ha (PRC/ECI, cited by Van Lavieren, 1986). Plotting of isolines on 1:100,000 maps for the individual major river basins with an interval of 100 tm/ha seems appropriate.

3.3.2 The soil erodibility factor K

The soil erodibility factor K gives a quantitive description of the inherent susceptibility of a given soil to detachment and transport, and thus to erosion. The factor represents the amount of soil that erodes from a bare standard plot per unit of rainfall erosivity. In other words differences in K factor are reflected in differences in erosion rates under otherwise equal conditions. The soil erodibility factor can be evaluated on experimental plots by solving the equation:

$$K = \frac{A}{R * L * S * C * P} \text{, under non standard conditions or,} \qquad (7)$$

$$K = \frac{A}{R} \text{, on standard plots, 22.1 m long.} \qquad (8)$$

K is expressed in tonnes/ha per unit rainfall erosivity.

Maintenance and monitoring of erosion plots should be carried out very carefully, otherwise large errors of estimate will result. The main sources of error are:

- inhomogenity of the erosion determining factors within the plot, mainly of the erodibility-, slope- and crop factor;

- silting up of channels and pipes that conduct the overland flow water and sediment to the collectors;
- inadequate covering of the collector throughs, leading to an over-estimation of the surface runoff amounts;
- inadequate connections between the collector throughs and the soil surface;
- concentration of surface runoff along the plot boundaries, resulting in the formation of rills, that otherwise not would have developed;
- insufficient capacity of the collector tanks, leading to overflow and loss of sediment in suspension; and
- unreliable measurements of the amounts of sediments due to wrong assumptions concerning the sediment settling velocity and sediment densities.

Erosion plot results must always be evaluated in the light of these possible sources of error.

Experimentally determined erodibility factors for all soils range between 0 and 0.89 (in metric units), for tropical soils the variation is also considerable, from 0 to 0.71 (El Swaify, 1977). The variation is not only observed between the 10 orders of the USDA Soil Taxonomy, but also at a suborder and great group level. Measured values of K factors of tropical soils have been summarized by El Swaify and Dangler (1982). The only general trend observed was that more weathered soils (Oxisols and Ultisols) are less erodible and the less weathered soils (Alfisols, Aridisols, Mollisols and Vertisols) more erodible.

The great variation in K values observed for the same soil type may be partly due to the fact that the K factor value is directly depending on the measured R factor, a factor that is not always established with great care, and the fact that erosion plot experiments are very costly and time consuming, and therefore not always continued for a long enough period to obtain reliable long-term averages of the K value. It should also be kept in mind that quite often different units are used, metric and psf, without clearly stating which system was adopted.

Soil plot experiments in third world countries are of limited number, but K factors can also be estimated with the aid of a nomograph, devised by Wischmeier, Johnson and Cross (1971). For the use of the nomograph information is needed on 5 easily established soil parameters. The nomograph has been transformed to a formula that reads:

$$K = [2.713M^{1.14}(10^{-4})(12-a)+3.25(b-2)+2.5(c-3)]/100, \quad (9)$$

in which:

K = the soil erodibility in tonnes/ha
M = a particle size parameter
a = the percentage organic matter
b = the soil structure code
c = the profile permeability code

The particle size parameter has the following form:

$$M = (\underset{(0.002\text{-}0.05mm)}{\text{percentage silt}} + \underset{(0.05\text{-}0.1mm)}{\text{very fine sand}})(100 - \underset{(<0.002mm)(10)}{\text{percentage clay}})$$

To be able to calculate the parameter M a detailed particle size analysis has to be carried out. In the absence of such analyses data an approximation of the M parameter may be used, see table 5, after Hamer, 1981.

The weight percentage organic matter has to be obtained from laboratory analyses and equals 1.724 * (the organic carbon content). Soils having more than 6% organic matter in their surface horizon have a default value 6 for a.

The soil structure is coded as follows, based on the USDA pedon codes for soil structure:

1 very fine granular and very fine crumb (<1 mm)
2 fine granular and fine crumb (1-2 mm)
3 medium granular and medium crumb (2-5 mm) and coarse granular (5-10 mm)
4 platy, prismatic, columnar, blocky and very coarse granular

For the permeability the following classification is used, based on the USDA permeability classes:

1 rapid to very rapid	>50	(in cm/hour)
2 moderately rapid	16.1-50	
3 moderate	5.1-16	
4 moderately slow	1.6-5.0	
5 slow	0.2-1.5	
6 very slow	<0.2	

The USDA Soil Survey Manual gives general permeability data, laboratory measurements are not necessary.

Wischmeier et al. (1971) give rules of tumb for the use of codes 4, 5 and 6:

- soils with fragipans should be coded as 6;
- permeable surface soils, underlain by massive clay or silty clay are coded as 5;
- moderately permeable soils underlain by silty clay or silty clay loam, having a weak sub angular or angular blocky structure, are coded as 4; and
- if the subsoil structure grade remains moderate or strong or the texture remains coarser than silty clay loam, the code is 3.

The grain size distribution, organic carbon content and the structure code have to be determined for the upper 15 to 20 cm of the soil profile. The permeability has to be established for the profile as a whole.

Table. 4 Particle size parameter (M) approximation (After Hamer, 1981)

Standard USDA texture classes	Approximation to M
heavy clay	210
medium clay	750
sandy clay	1215
light clay	1685
sandy clay loam	2160
silty clay	2510
clay loam	2830
sand	3035
loamy sand	3245
silty clay loam	3770
sandy loam	4005
loam	4390
silt loam	6330
silt	8245
(estimate)	4000

Research in the USA proved that 65% of the nomograph estimations of the K factor differed less than 0.02 and 95% less than 0.04 from measured values. For general purposes the following K value classes, as proposed by Arnoldus (1977), can be used: <0.13, 0.13-0.19, 0.19-0.22, 0.22-0.26, 0.26-0.31, 0.31-0.36, 0.36-0.41, 0.41-0.48, 0.48-0.56, 0.56-0.63, 0.63-0.71, 0.71-0.83 and >0.83. A number of Indonesian soils have very low erodibilities, it is therefore proposed to subdivide the first class in <0.05, 0.05-0.09 and 0.09-0.13.

Plot experiments carried out in different parts of the world generally aim at measuring soil erosion rates under certain fixed conditions, but quite often the results have also been used to evaluate the validity of the nomograph. Ambar and Wiersum (1980) and Kurnia et al. (1986) reported that measured and estimated K factors for a number of Indonesian soils, representing 5 soil orders, Oxisols, Vertisols, Alfisols, Ultisols and Entisols, were very well comparable (table 5). On the other hand Wahyu (personal communication) concluded that K factors measured with plot experiments in the Citanduy watershed (West Java) were twice as high as those established with the nomograph.

Roose (1977) concluded that measured erodibilities are reasonable comparable with values obtained using the nomograph for 9 different soil types in West Africa. However, El Swaify and Dangler (1982) state that the ranges of the nomograph parameter values encountered for tropical soils are so different from those found for the soils of temporate regions, for which the nomograph was designed, that the estimates are not always reliable. In their publication an extended summary of K factor values of tropical soils within different taxonomic orders is also given. Lal (1985) gives a summary of the erodibility of soils in tropical Africa.

In Indonesia plot experiments have been carried out by a number of research institutes and consultants. A summary of the collected data is given in table 5. This table is not complete, additional information is available at PU Bandung, the Padjadjaran University in Bandung, the Gajah Mada University in Yogjakarta, the Citanduy Project Authority and the Kali Konto project on East Java. Comparison of the different sources is difficult, different soil classification systems have been used and it is not always clearly stated whether metric or pfs units are used.

The number of plot experiments carried out on Java is insufficient to give a complete picture of the ranges of K factors of the soils of the project area. Therefore additional nomograph estimations will be necessary.

The grain size distribution and organic matter parameter of the soils have to be derived from laboratory data. These data are often not available. However, this information can also be derived from detailed soil maps and accompanying descriptions. For the Cimanuk river basin on West Java a detailed Reconnaissance Land Resources Survey has been carried out. The the legend of the produced 1:100,000 soil maps contains information on the texture, organic carbon content, structure and profile permeability of the 150 different soils distinguished in the project area. This information can be used to (make nomograph estimations of) the K factors for most of the soil orders, suborderes and great groups, that are encountered on Java.

Table 5. Estimated and measured K factors for some soils in Indonesia.

Lenvain (1975), Bols (1979) published by Ambar and Wiersum (1980)

Soil type (location)	Measured K-value	Estimated K-value
Andosol (Lembang)	0.16	0.14
Latosol (Darmaga)	0.04	0.044
Latosol (Citaman)	0.135	0.121
Red yellow podzolic (Jonggol)	0.13	0.15
Red mediterranean (Punung)	0.18	0.15
Idem (Putat)	0.25	0.15
Grumusol (Jegur)	0.24-0.31	0.25
Lithosol (Sentolo)	0.19	0.20

Ambar and Wiersum (1980)

Soil type (location)	Estimated K-value
Regosol/Aeric tropaquept (Ubrug)	0.22 (forest)
	0.21 (non-forest)
Red latosol/Oxic dystropept (Sayang heulang)	0.10
Limestone regosol/Typic dystropept (Ciganea)	0.29 (forest)
	0.23 (non-forest)
Colluvium regosol/Lithic tropothent (Pasir	0.45 (forest)
Jatiluhur)	0.39 (non-forest)
Regosol/Aeric tropaquept	0.22 (irr.rice)
	0.20 (dryl.agr.)
	0.21 (grazing)
	0.17 (bamboo)

Kurnia and Suwardjo (1984)

Soil type (locality)	Measured K-value
Latosol/Haplortox (Darmaga, Bogor)	0.02-0.03 (0.03)
Latosol/Haplorthox (Citayam, Bogor)	0.08-0.09 (0.09)
Regosol/Troporthent (Tanjungharjo, Kulon Progo)	0.11-0.16 (0.14)
Grumusol/Chromudert (Jegu, Blitar)	0.24-0.30 (0.27)
Podsolic/Tropudult (Jonggol, Bandung)	0.12-0.19 (0.16)
Mediterranean/Tropohumult (Citaman, Bandung)	0.09-0.11 (0.10)
Mediterranean/Tropudalf (Putat, Gunung Kidul)	0.16-0.29 (0.23)
Mediterranean/Tropaqualf (Punung, Pacitan)	0.18-0.25 (0.22)

Kurnia et al., 1986

Soil type (location)		Estimated K-value
Tropohumults	West Sumatra	0.15-0.16
Tropudalfs	idem	0.19

Haplorthox	idem	0.16-0.21
Tropudults	idem	0.17-0.27
Tropudalfs	Northern Ceram	0.19-0.40
Tropudults	idem	0.31-0.33

3.3.3 The topographic factors L and S

The topographic factors slope length and slope steepness (respectively the factors L and S in the USLE equation) are only treated separately for research purposes. For field applications a combined LS factor is more convenient. The LS factor is an important factor in the USLE, it accounts for more variation in the gross erosion than any of the other factors, except for the crop/management factor. However, little research has been done to develop methods for determination of this factor. This is due to the fact that the USLE was originally designed for use on field size areas, where slope length and steepness are easily established.

Slope length is defined as the distance from the point where overland flows starts to the point where either the slope steepness decreases to such an extent that deposition occurs, or where surface runoff enters a well defined channel. The effect of slope length on the annual surface runoff per unit area of cropland is limited, but soil loss per unit area increases drastically with increasing slope length. On longer slopes surface runoff increases in velocity and thus in detaching and transporting capacity.

The slope length factor is defined as:

$$L = (l/22.1)^m, \text{ in which:} \qquad (11)$$

L = the slope length factor
l = the slope length in m
m = a coefficient, that ranges from 0.3 for very long slopes with a gradient of less than 0.5% to 0.6 for slopes over 10%. In most cases a value of 0.5 can be applied.

Surface runoff from agricultural lands increases with slope steepness, but other factors, such as type of crop, surface roughness and profile saturation are of importance as well. Soil loss increases faster with slope gradient than surface runoff. This is due to the increased soil detachment by raindrop impact and the higher surface runoff velocities.

The formula for the slope steepness factor S reads as follows:

$$S = 65.41 \sin^2 a + 4.56 \sin a + 0.065, \text{ in which:} \qquad (12)$$

a = the slope gradient in %

The topographic factor LS can then be expressed as:

$$LS = (l/22.1)^m (65.41 \sin^2 a + 4.56 \sin a + 0.065) \quad (13)$$

Nomograph representations of the formula are given by Wischmeier and Smith (1978) and Kirkby and Morgan (1980).

Although the LS factor is used without major modifications in most tropical countries, Hudson and Jackson reported, as long ago as 1959, that the effect of slope steepness on soil loss is stronger under tropical climatological conditions, with more high intensity rainfall events, than in the USA. Furthermore, the experiments in the USA were conducted on slopes of maximal 22%, in tropical areas slopes much steeper are frequently cropped. For example, dryland agriculture on slopes of 35-40% is very common in Indonesia. Wood and Dent (1983) therefore used the following formula (after Gregory, et.al, 1977) for the calculation of the slope factor for the LECS model:

$$LS = (l/22.1)^m \, c \, (\cos a)^{1.503} \, [0.5 \, (\sin a)^{1.249} + (\sin a)^{2.249}] \quad (14)$$

in which: l = slope length in m
m = 0.5 for slopes >5%
= 0.4 for slopes of 3.5 to 4.9%
= 0.3 for slopes <3%
c = 34.7046
a = slope angle in degrees

They assumed a relationship between slope steepness and average slope length and used the above given formula to calculate a number of characteristic LS factors (see table 6).

Table 6. LS factors for characteristic slopes in Indonesia

slope gradient class (%)	assumed slope length (m)	mean LS rating
0-5	45	0.35
6-15	35	1.60
16-35	25	4.60
36-50	20	7.90
>50	20	9.00

The LS factor is particularly sensitive to errors in the average slope steepness, because these errors are magnified in the calculation of LS for slopes above 3%. Errors in the slope length determination are less critical because they are reduced by half or more in the calculation.

Information on slope gradients can be derived from slope maps, that are available in most third world countries, even at a regional scale. If slope maps are not present, the average drainage basin slope gradient can be measured quickly and accurately from topographic maps, using one of the following methods (Williams and Berndt, 1977):

- the contour lenght method, using the following formula:

  $$S = 0.25\ z\ (LC_{25} + LC_{50} + LC_{75})/DA, \text{ in which:} \tag{15}$$

  S = average slope gradient (%)
  LC_{25}, LC_{50} and LC_{75} are the contour lengths at 25, 50 and 75% of z (km)
  z = total watershed height (km)
  DA = the drainage basin area. (km^2)

- the grid contour method. The length of each grid line within the watershed is measured and the contours crossing or tangent to that line are counted. The land slope in any direction is than computed by the equation:

  $$S_d = N_d * H/D_d, \text{ in which:} \tag{16}$$

  S_d = the average slope in direction d
  N_d = the total number of contour crossings in direction d
  H = the difference in elevation between the contours
  D_d = the total length of grid lines in that direction

  The average watershed slope is determined by computing the slope in both grid directions with the formula and calculation of the resultant according to:

  $$S = (S_1)^2 + (S_w)^2, \text{ in which:} \tag{17}$$

  S = the average watershed slope
  S_1 = average slope length along the watershed length
  S_w = average slope length along the watershed width

  The grid has to be placed over the watershed in such a way that one direction is parallel to the line connecting the basin outlet with the highest point in the basin. The maximum watershed width is divided by four to determine the grid spacing.

Accurate and fast methods to determine the average slope length are also given by Williams and Brendt (1977) and by Chinnamani et.al (1982)

- the drainage density method. The drainage density of a catchment, the total length of the channels divided by the catchment area, is equivalent to the average slope length. In formula:

  $$L = 0.5\ DA/LCH, \text{ in which:} \tag{18}$$

  L = the average slope length
  DA = the drainage area

LCH = the total channel length

Actually average slope length is underestimated with this formula, because the channel slope is not taken into account. Methods to compensate for the channel slope are existing but their application is very time consuming.

- the contour extreme method. The average watershed slope length is computed from the contour length and the number of extreme points (upslope inflexions) on the contours. In formula:

  $$L = LC/2EP, \text{ in which:} \qquad (19)$$

  LC = the total length of all contours
  EP = the total number of extreme points

  This formula can only be applied for slopes about 1.4 times as great as channel slopes. For all other cases the following modified formula should be used:

  $$L = \frac{(LC * LB)}{(2EP\sqrt{LC^2 - LB^2}}, \text{ in which:} \qquad (20)$$

  LB = the length around the base of the contour, i.e. the length that the contour would have, provided there were no inflexions

- the first order channel method. The average basin slope length is calculated with the following formula:

  $$L = (1/22.1)^{0.3}, \text{ in which:} \qquad (21)$$

  1 = the average length of the first order channels in the basin

  This method has been used by Chinnamani et al. (1982) in India. No further information is available.

Besides slope steepness and slope length, the slope form, e.g. convex, concave, straight, also influences the soil loss. Gradient, length and form of the slope are all three heavily depending on the landform. If more than one major landform are present in a basin, the basin should be subdivided according to these landforms for the determination of the LS factor.

In Indonesia, information on slope gradients is available on the 1:50,000 maps of AGRARIA. Information on slope lengths is not available. Slopes in Indonesia are never continuous, but always very interupted by vegetated field borders etc. Using overall slope lengths would give an exaggeration of the influence of the L factor. It is therefore more logical to adopt the LECS approach and use the established slope steepness-slope length combinations and their respective LS factors, as given in formula 14 and table 6.

3.3.4 The cropping/management factor C

This factor describes the total effect of vegetation, crop residues and soil management on the soil loss. The factor is defined as the ratio of soil loss from a field with a particular cropping and management to that of a field with a bare, tilled soil. The factor ranges from 0 to 1, a value of 0 indicating a 100% protection of the soil against erosion. Crop cover and management effects are combined in one factor, because they have many interrelationships. Crop residues can be removed, left on the surface or incorporated in the soil, while the effect of the residue management depends on the amount of residue present, which, on its turn, is depending on the type of crop, the soil fertility, the management decisions (e.g. fertiliser input) etc. The canopy protection of a certain crop or vegetation not only depends on the crop type but also on the quality and stage of growth. The C factor therefore is not constant throughout the year.

For crops the C factor has to be established for all stages of the cultivation/crop growth period and for all crops in the rotation. The following periods are distinguished:

- rough fallow, from ploughing to seeding;
- seeding, seedbed preparation till one month after planting;
- establishment, 1 to 2 months after seeding;
- growing and maturing, till crop harvest; and
- residue or stubble.

The other factors of the USLE, mainly the rainfall erosivity, influence the C factor as well. To calculate the proper value of the factor, the distribution of the R values over the year has to be taken into account. This distribution of the erosivity in respect to the annual cropping pattern is a critical variable in predicting soil loss. A high percentage of uncropped lands at the beginning of the rainy season will give high erosion rates. In Indonesia the most erosive rains fall in the period November to March (SMEC, 1984).

Cropping/management factors are generally established on experimental plots or estimated with a procedure outlined by Wischmeier and Smith (1978). Taking planting and harvesting dates, rates of canopy development and crop and residue management practices into account, tables can be used for this estimation. However, these tables have been developed for the USA and are not valid in other geographical areas. Furthermore, only persons with exprience in the procedure will arrive at the right conclusions. For these reasons tables have been made that give average annual values of the C factor for a particular combination of crop system, management practices and rainfall pattern for the different parts of the USA. Use of these tables outside the USA is not possible and similar information is not available for tropical crops.

The rapid decomposition of organic material in tropical regions has as a result that protective crop residues are difficult to maintain and that the same residue management practices as applied in temporate regions may give different C factors.

General values for the C factor are available for Africa where much experimental work has been done at the Institute for Tropical Agriculture in Ibadan (Lal and co-workers) and in West Africa (OSTROM, Roose, 1977). In Indonesia research has been concentrated at the Soil Research Centre in Bogor. Estimated cropping/ management factors for different crops and vegetation types are given by Hamer (1979) and Van Lavieren (1986). Wood and Dent (1983) also give a table with C factors for 50 crops and crop combinations grown on Java (see table 7). Additional information, not yet collected, is available at Puslitbang in Bandung, Bakosurtanal, and the Gajah Mada and Padjadjaran University.

3.3.5 The erosion-control practice factor P

The erosion-control practice factor P is the ratio of soil loss using a specific practice compared with the soil loss occurring under up and down hill cultivation. This factor also ranges from 0 to 1. The conservation measures usually included in this factor are contouring, contour stripcropping, terracing and surface mulching. Conservation measures like conservation tillage, crop rotations, residue management etc. are incorporated in the C factor. The effectiveness of conservation practices and thus the value of the P factor, generally depends on the slope steepness.

Again, tables exist displaying the values of the P factors, as established in the USA. Although these tables are often used in tropical areas their applicability has not really been tested (El Swaify and Dangler, 1982). Only Roose (1977) provides limited data on P factors for West Africa.

For Indonesia, estimates of the erosion-control practice factors for the most commonly used conservation measures are given by Hamer (1979). These figures are based on research data of the Soil Research Institute.

In Indonesia another approach was used in the LECS exercise (Wood and Dent, 1983). The C and P factor were redefined as a land use factor and a management factor. The land use factor is only based on the type of crop grown, management practices like residue management are not incorporated. On the other hand the management factor not only includes mechanical conservation practices like ridge- and bench terracing, but also cultural practices like crop rotation and fertiliser application. The management factors have been established for different slope classes. The method provides usefull information but requires detailed input data on mainly the cultural practices. This information is not easily retrieved from maps or other data sources and can only be gathered in the field. However the tables are of use for determining the influence of slope steepness on the control- practice effectiveness.

The latter information is not given in the tables of Hamer.

For the erosion study of the BTA-155 project the lecs approach is not very suitable and the erosion control practice factor tables of Hamer (1979) have to be used.

3.4 Evaluation of the USLE procedure in the light of the general objectives of an erosion study for WLRM projects

With the USLE approach as proposed in the foregoing sections the following general objectives of an erosion analysis, as given in chapter 2, may be fulfilled:

- the areas of accelerated erosion on the slopes are delineated; a map with the actual erosion rates on the slopes can be produced and so;
- the magnitude of the erosion problem can be quantified;
- the causes of the severity of the problem can be seeked by analysing the importance of the various erosion determining factors on the final erosion rate, e.g. whether steep slopes, certain land use or the climatic factor is of primary importance in causing high erosion rates; and
- remedial technical measures can be proposed by analysing the effect of a change in cropping pattern or introduction of certain conservation measures (changing the C and P factor) on the erosion rates

Three other general objectives of the analysis related to the physical processes of soil erosion, viz.,

- description of the erosion processes;
- to analyse the relationships between soil erosion on the slopes and the sediment output of the catchments; and
- to analyse the relationships between conservation measures/land use changes and the hydrological response of the basins under study.

will not be met with the USLE approach.

Description of the erosion processes active in the area is possible by analysing aerial photographs of the area, followed by some field trips and will not be very time consuming.

Analysis the relationships between the erosion rate on the slopes and the hydrological response and sediment yields of the river, draining the basin is possible with statistical techniques, that will be described in chapter 4. The more socio-economic related objectives of erosion studies will be discussed in chapter 5.

Table 7. C Factors for 50 crops and crop combinations grown on Java (after Hamer, 1981)

CROP	C FACTOR	CROP		C FACTOR
MONOCROP		INTERCROPS		
Maize	0.64	Rice, Sawah, ____	cassava, bordercrop	0.10
Sorghum	0.24	Rice, upland ____	maize	0.50
Rice, Sawah transplanted	0.10	Rice, upland ____	cassava	0.50
Rice, Sawah, direct seeded	0.10	Rice, upland ____	beans	0.45
Rice, upland	0.56	Rice, upland ____	groundnuts	0.45
Irish Potato	0.45	Rice, upland ____	soybeans	0.42
Sweet Potato	0.40	Maize ____	sweetpotato	0.45
Cassava	0.65	Maize ____	beans	0.45
Yams	0.70	Maize ____	groundnuts	0.35
Taro	0.70	Maize ____	soybeans	0.45
Phaseolus bean, Mung bean	0.35	Maize ____	cassava	0.55
Sugar cane	0.30	Groundnuts ____	cassava	0.20
Ground nuts	0.45	Soybeans ____	cassava	0.18
Soybean	0.40			
Cotton	0.85			
Tobacco	0.16	CRIA : Rice sawah, Rice partly irrigated ___ interplant with maize, soybean-maize, cassava, (11 months continuous cover, always one leguminous crop, all grown in sawah).		
Chilli	0.80			
Bananas	0.55			
Pineapple	0.40			
Cashew Nuts	0.50			
Coffee	0.60			
Cocoa	0.80			
Tea	0.35	ESTATE PRODUCTION		
Coconut	0.70	Sugar Cane		0.20
Oilpalm	0.55	Tobacco		0.16
Cloves	0.50	Coffee		0.60
Kapok	0.70	Cocoa		0.80
Rubber	0.85	Tea		0.35
Quinine	0.90	Oilpalm		0.55
Pasture (open grassland)	0.10	Rubber		0.60

Chapter 4. Catchment sediment yields and hydrological response

4.1 Introduction

As stated before the USLE can only be used to estimate soil loss on a slope or field scale, the sediment yield, the total sediment output of a drainage basin or a watershed during a given time, and the hydrological response of a river, expressed as e.g. the specific annual runoff, the 10% peak discharge or the 10% low flow, have to be calculated otherwise. Both the sediment yield and the hydrological response of a river established using one of the following methods:

- Continuous measurements of stream discharges and regular sediment sampling, to determine total streamflow, and for the construction of sediment rating curves. A sediment rating curve is a graphical representation of the relationship discharge-sediment load. Combining this relationship with the continuous discharge records enables the calculation of sediment yields for any chosen interval.

- Calculation of statistical relationships, that relate the sediment yield or hydrologigal response of a basin to hydrological-, geomorphological-, climatological-, soil- or land use characteristics of the catchment. Once these relationships are known, the sediment yields and hydrological responses of basins that are not continuously monitored or where basin characteristics (e.g. land use) change, can be assessed.

To be able to evaluate the effect of soil loss on the slopes on the sediment yield of the river, not only sediment yields have to be established, but sediment delivery ratios have to be calculated as well. The sediment delivery ratio is defined as the ratio between soil loss on the slopes and sediment yield of the river, somewhere downstream in the drainage basin. If the sediment delivery ratio of a basin is known, the effect of soil conservation measures or changes in land use, resulting in changes in soil loss can be translated to changes in sediment yield of the river.

4.2 Sediment yields

Not all the soil loss on the slopes is delivered to the river, generally deposition takes place at various locations in the watershed. The eroded soil that is transported to, and passes a certain point along the stream channel in a certain period, is called the sediment yield, and is expressed in tonnes or m^3 per year or tonnes or m^3/ha per year.

4.2.1 Direct measurements

The best way to obtain sediment yields of rivers is, as stated before, by direct measurement. The wash load of a river is load is fairly easy to establish, but the problem of accurate bed material measurement has not yet been solved satisfactory. Although bed material may comprise as much as 90% of the total sediment load, most sediment yield figures refer only to the wash load. Normally the bed material contribution to the total sediment yield of a river is less than 10% (Gregory and Walling, 1983). A figure of 10% bed material was also given by Wahyu (personal communication) for the Citanduy river on West Java.

Global figures for sediment yields range from less than 0.02 tonnes/ha per year for areas covered with virgin forest (Douglas, 1973) to more than 250 tonnes/ha per year (various sources, cited by Hadley et al., 1985). Figures for rivers on West Java range from 12 to 81 tonnes/ha per year (Puslitbang 1984). Sediment yield data for a large number of rivers on West Java are available at Puslitbang and in various consultant reports. In table 2 sediment yields for a number of rivers on Java are given.

However, comparing information on sediment yields from different sources is always difficult, the reliability of the data is very much depending on the sampling techniques used and the frequency of sampling. For budgetary reasons sampling frequencies are often limited and given the fact that sediment duration curves demonstrate that high sediment concentrations and discharges only occur during a very small proportion of the period of record, up to 80% of the annual suspended sediment load may be transported in less than 1% of the time, large errors of estimate may result. Gregory and Walling (1983) reported that inadequate sampling techniques and consequent inadequate rating curves may give an under-estimation of the sediment yields of more than 60%.

4.2.2 Predictive equations

Few theoretical relationships are available to describe the processes between the moment of detachment of a soil particle and its eventual sedimentation in, or transport out of the river basin. Sediment prediction equations therefore are almost always empirical. A large number of equations, having sediment yield as the dependent variable and various watershed parameters as independent variables, have been developed. It should be stressed that these equations normally only have regional applicability.

Three groups of variables can be distinguised that are commonly used to explain the spacial variation in the magnitude of sediment yields: climatic parameters, physiographic and hydrological parameters and vegetation/land use and soils parameters.

Various attempts have been made to relate sediment yields to a simple climatic index such as annual rainfall, the rainfall erosivity or the seasonallity of the rainfall. Those studies were reviewed by Wilson (1972) who concluded that these single relationships were not valid, not even within a relatively homogeneous area. He stated that land use/vegetation was a much more important single variable. Jansen and Panter (1974) , on the other hand, came to the conclusion that , next to climate, topographic factors are very important in controling sediment yields. More recent work showed the multivariate nature of the sediment yield controls and instead of a small number of key variables, complex black box relationships between sediment yields and its explanatory variables proved to be more effective prediction tools. Generally multiple regression techniques are used to establish these relationships.

Overviews of recent work done on the prediction of sediment yields have been given by Hadley et al. (1985), Jansson (1982) and Gregory and Walling (1983). The information given in this section has mainly been derived from these publications.

In these overviews a number of climatic, physiographic and hydrological and land use/vegetation and soils parameters are given that have been successfully used in attempts to establish multiple regression equations to predict sediment yields. The most important factors are listed below.

Climatic variables:

- mean annual precipitation;
- the average number of rainfall events per year or the number of rainy days per year;
- the average annual rainfall events equal to or eceeding 25mm;
- precipitation erosivity indices, such as the USLE R factor, the Fournier (1960) factor p^2/P and the modified Fournier index after Arnoldus (1977); and
- annual evapotranspiration.

Physiographic and hydrologic variables:

- catchment area;
- the length of the nain channel;
- the relief-basin length ratio;
- the catchment shape, Horton's (1952) form factor $F = A/L^2$, in which A = basin area and L = the basin length, Schumm's (1956) basin elongation factor $E = (2\sqrt{A/\pi}) / L$, in which A = the diameter of the circle with the same area as the drainage basin and L = the basin length;
- the drainage density, the total channel length devided by the area of the drainage basin;
- the bifurcation ratio, the ratio of the number of streams of order n to the number of streams of the order (n+1);
- the LS factor of the USLE;
- average annual runoff in mm or as % of the precipitation;
- average annual specific discharge or discharge;
- average annual maximum discharge;
- the discharge fluctuation, the average annual ratio of the minimum discharge to the maximum discharge;

- the maximum annual 7 day flow;
- the minimum annual 7 day flow; and
- the discharge variability index, the standard deviation of the daily flows.

Land use/vegetation and soil factors:

- the percentage area covered with forest;
- the percentage area in use for dryland agriculture;
- the percentage area in use for paddy rice;
- the impervious area;
- the population density;
- the percentage area with degraded soils;
- the weighted average C and P factors of the USLE;
- the weigthed average K factor;
- the average soil depth;
- the average soil texture; and
- the average soil profile permeability.

In section 4.2 will be discussed which of these variables are appropriate for use in Indonesia and how they have to be calculated.

As stated before, regression equations relating sediment yield to watershed variables are only of regional applicability. Therefore the equations developed for different parts of the world will not be discussed here in detail. Only some general equations developed in tropical regions, and that are thought to have a wider applicability will be treated briefly.

Fournier (1960, 1966) developed an equation that relates suspended sediment yields to three environmental parameters: mean altitude, mean slope gradient and an index of rainfall erosivity. The equation reads:

$$\log E = 2.65 \log p^2/P + 0.46 \log H * \tan s - 1.56, \quad (22)$$

in which:

E = the suspended sediment yield (tonnes/km per year)
p = the monthly rainfall in mm
P = the yearly rainfall in mm
H = the mean altitude above sealevel of the basin
s = average slope gradient of the basin

This equation has widely been used in tropical areas and served as a base for the construction of a global erosion map by Fournier (1960). Other equations for tropical Africa were developed by Solomon (1967), who used average annual rainfall, evaporation and runoff as independent variables and Jansen and Painter (1974), who correlated sediment yields with annual specific runoff, basin area and relief-length ratio and mean annual temperature. Dunne (1979) found strong correlations between the sediment yield and the mean annual runoff and relief for 61 basins in Kenia, subdivided in groups after major land use.

In Indonesia Nad Darga (1979) investigated the relationships between basin characteristics and sediment concentrations of 30 river basins on West Java, ranging in area from 20 to 2000 km^2. Five dependent variables, discharge fluctuation, mean annual discharge, mean annual specific discharge (see section 4.4), average sediment content in the dry season and average sediment content in the wet season, were connected to basin characteristics by means of multiple regression. The independent variables used were parameters expressing basin geometry, climate, land-use, topography, soil characteristics and population density.

Dry season sediment concentrations of the river water was depending on: % of the area cultivated for 60 to 80%, % of the area with very erodible soils, the basin geometry, the % of the area cultivated for more than 80% and the % of the area with slopes steeper than 40%. The wet season sediment concentrations are best explained by the basin geometry, the % area for 60 to 80% under cultivation and the % of the area, cultivated for more than 80%.

According to Nad Darga personal communication the relationships can be used to do predictions of the effect of changing landuse; a student of the Soil Research Institute used the equations succesfully in the Citarum river basin. Although the study seems to be done very well the impression exists that the used variables are not the most logical and suitable for this kind of analysis. For instance % areas in a certain class were used instaed of absolute values and it is very well possible that auto-correlations exist between the independent variables. This makes interpretation of the results difficult.

4.3 Sediment delivery ratios

The sediment delivery ratio is defined as the percentage of the gross erosion, the total erosion in the catchment, that is actually leaving the catchment as sediment load. In other words, not only sheet- and rill- erosion on the slopes have to be taken into account, but also gully- and channel-erosion processes. In Indonesia sheet- and rill-rosion are thought to be the most important erosional processes and sediment delivery ratios can be calculated from soil loss estimations based on the USLE and measured or estimated sediment yields. This is the most accurate procedure. In the case of absence of information concerning these variables, multiple regression techniques can be used to relate the sediment delivery ratio (SDR) to basin parameters. Multiple regression equations, relating the SDR to basin parameters, are often used to establish sediment yields for basins where only the soil loss on the slopes is known, or vise versa.

Although the concept of SDR is logical and simple, many of the processes involved are not yet fully understood. Sediment sources and sinks may be distributed in various ways over the catchment and large quantities of sediment may be kept in storage in the basin. The SDR depends basically on the same independend variables as the sediment yield.

Variables that are often used in the predictive equations are: basin area, relief, total stream length, the bifurcation ratio and the dominant land use. The United States Soil Conservation Service, for example, derived a direct relationship between SDR and basin area. The relationship shows that the SDR varies, approximately as the 0.2 power of the drainage area, between 58% for basins <0.05 km^2 and 5.9% for basins >1000 km^2. USLE based soil loss rates and measured sediment yields of a number of rivers, draining catchments of variable area on West Java, indicate that SDR values of these streams range between 5 and 25%. These figures have been calculated from data presented by Arif (1986). No information is at present available for other tropical areas, but at a global scale SDR's range from less than 3% to more than 90%.

4.4 Hydrological responses of drainage basins to soil erosion and soil conservation measures

The hydrological responses of drainage basins to increased or reduced soil erosion on the catchment slopes, due to land use changes or conservation measures, have untill now only been investigated to a limited extent. A commonly adapted policy in tropical countries to rehabilitate watersheds, and so to reduce erosion and sedimentation of streams and restore the hydrological regulation function of the watershed, is reforestation or afforestation. The term reforestation is defined as the natural or artificial restocking of an area with forest trees, including measures to obtain natural regeneration, as well as tree planting or seeding. In common use the term is restricted to forest seeding and planting. The term afforestation should be used for forest seeding and planting activities in areas, that were not forested previously or in recent history. Most research on the watershed impact of forests has been done by investigating the effects of deforestation However, it is generally assumed that the effects of reforestation on hydrological and soil erosion processes is the reverse of the effects of deforestation. Most of the information presented in this section is derived from the publication "Tropical Forested Watersheds, hydrologic and soils response to major uses and conversions" by Hamilton and King (1983). This publication provides an exellent overview of the recent research on this topic.

Reforestation has many consequences on the hydrological behaviour of a watershed. The processes involved are, once again, very complex and interrelated and generally both the magnitude and distribution of streamflow and sediment yield are affected. The environmental processes changing as a result of deforestation are summarized in figure 2 after Hamilton and King (1983).

The direct impact of reforestation is fourfold:

- The tree canopy, undergrowth and litter layer protect the soil against raindrop impact and reduce the area of bare soil.

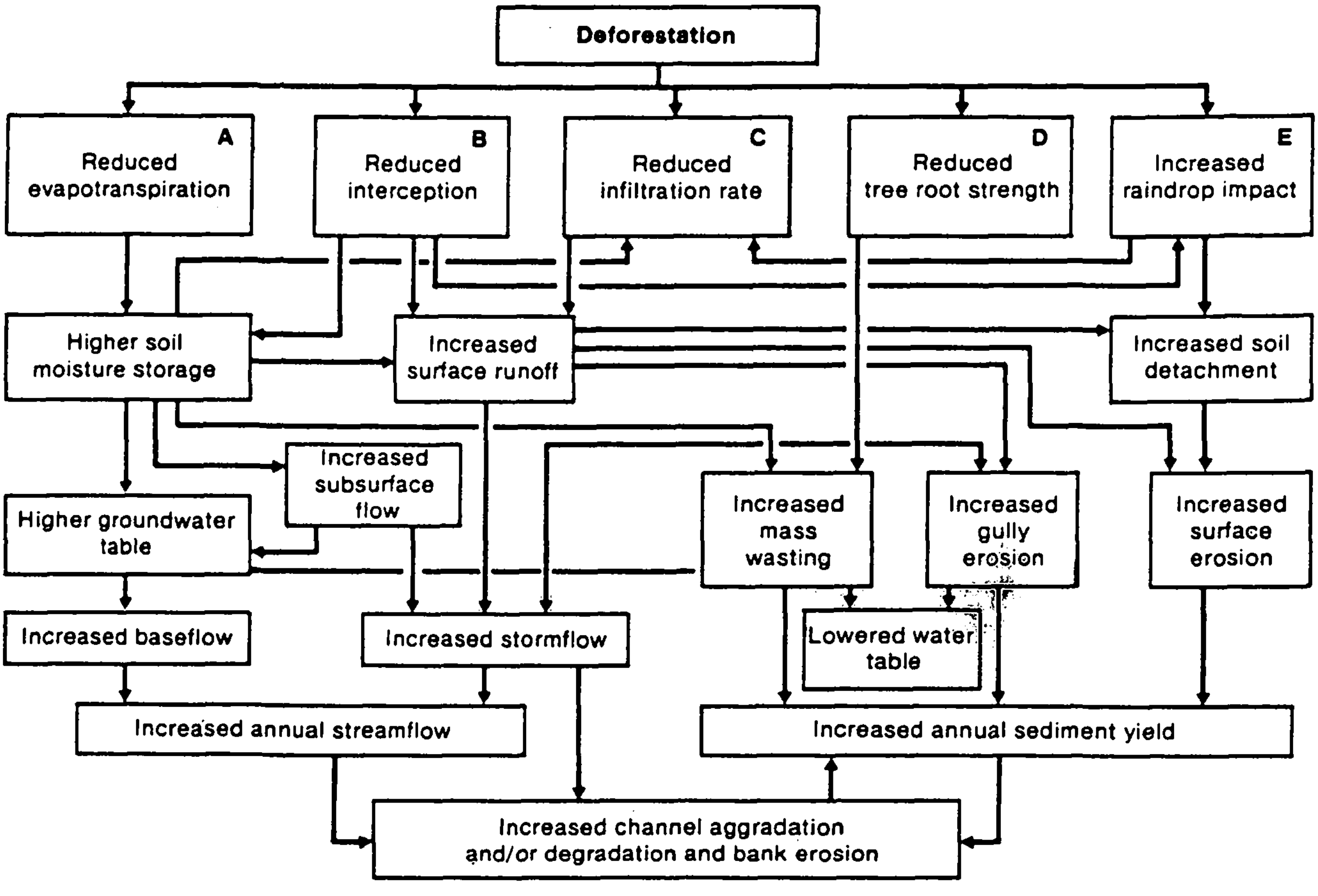


Figure 2. The impact of deforestation on the hydrological response of a river basin (After Hamilton and King, 1983).

- A number of soil properties change in such a way that the infiltration capacity of the soil increases and the soil erodibility decreases. Processes involved are bioturbation, aggregation and increase of soil organic matter content.

- Increased transpiration and interception of rainfall, evaporating directly from the leaf surfaces, increases evapotranspiration losses.

- The root mass increases, what results in a reduction of the mass-movement hazard.

The impact of reforestation on the catchment response depends strongly of the kind of conversions that take place, a change from grassland to forest will have other consequences than a change from cropland to forest.

The following hydrological parameters change as a result of reforestation:

- the discharge of springs and the level of groundwater and wells;
- the streamflow quantity;
- the timing and distribution of streamflow;
- the on site erosion rates; and
- the sediment yields of the watershed.

Groundwater levels, springs and wells:

Research evidence indicates that reforestation of open lands usually results in lower groundwater levels, most pronounced in the dry season. Increasing evapotranspiration and interception losses, 15 to 25% of the rainfall is intercepted by a tropical forest vegetation, and the extraction of water from the subsoil by deep treeroots reduce the amount of soil moisture available to recharge the groundwater. Aquifers in semi-arid areas this may result in serious spring and well level problems. A marked lowering of dry season groundwater levels was reported to follow reforestation in Thailand and Southern Australia. In the latter area 10% of the annual precipitation on a grassland reached the aquifer, in a nearby pine plantation no recharge took place.

Reduced soil compaction and better aggregation of the forest soils, as compared to degraded lands, resulting in higher infiltration rates and lower surface runoff amounts, are often thought to compensate for the increased evapotranspiration losses and to increase the reliability of springs and wells. However, this popular believe is not supported by research data.

Streamflow quantity:

It is also generally thought that reforestation increases the streamflow quantity and makes more water available for human use. Except for cloud- forest areas, where mist interception by tree canopies may increase the amount of water reaching the forest floor, research proved that total wateryield always decreases as a result of reforestation. In the Jonkershoek catchment (South Africa), streamflow started to decrease four years after reforestation with Pinus radiata, a decline that continued for 8 years before stabilizing at a level lower than the before reforestation yield.

Experiments in the South African Transvaal province, where grasslands were transformed to Eucalyptus grandis and Pinus patula plantations, showed similar trends, amounting to a streamflow reduction of more than 300 mm per year in the eucalypt plantation. The pine plantation showed smaller decreases. A 28% decline in wateryield, following planting of eucalypt was reported from India. Other considerable wateryield declines are reported from Fiji after reforestation of dry grasslands and from numerous experimental watersheds in temporate regions.

Lal (1985) states, based on various studies, that deforestation increases streamflow at a rate generally proportional to the reduction of forest cover over the catchment. It is conceivable that this rule of thumb can also be applied the other way around.

Timing and distribution of streamflow:

As stated before the yield decreases seem to be greatest in low flow periods. This was first proved by experiments in Fiji, where minimum flows over the period 1969-1978 in a reforested area decreased by 50%, while the low flow period wateryields decreased with 65%. Lal (1985) reported an increase in dry season base flow of practically zero to 3.2 mm per month in a small catchment in Nigeria after deforestation. However, research data from Indonesia (Hardjono, 1980) give another impression. The author compared a 100% agricultural watershed with a 25%- and a 100% reforested watersheds and came to the conclusion that the streamflow in the dry season was 2.5 times higher for the completely reforested watershaed than for the agricultural watershed. The results of this study are doubtful, the research was not carried out in completely comparable experimental watersheds, and other variables influencing stream flow may not have been constant.

The effects of reforestation on peak and storm flow are variable, but most studies report somewhat smaller stormflow volumes, a marked reduction in peakflow, and also a marked delay in time to peaking. The study by Hardjono (1980) showed a reduction in wet season peakflow of 28%. Experiments in temporate regions, Tennessee Valley, not only indicate reduced seasonal peaks, but also reduced total peak volumes (by some 95%). In this area the time needed to discharge 20 and 95% of the storm runoff increased with 5 and 18 times respectively. On very shallow soils the effect of reforestation on stormflow peaks and hydrograph form is often limited.

On site erosion and sediment in streams:

Reforestation often aims at decreasing erosion rates that prevail under some existing non-forest land use. This goal is generally reached, both practical and research experience show a marked reduction in erosion rates after reforestation. Although in most studies only sediment yields of rivers are measured, it can be assummed that sediment yields are indicative for erosion rates on the slopes. A forest canopy and undergrowth, in combination with a continuous litter layer decrease the effect of raindrop impact. The total amount of rainwater reaching the forest floor is reduced by interception, while higher infiltration rates decrease the amounts of surface runoff and sheet erosion. Soil loss rates under a forest canopy are therefore only a fraction of those reported for agricultural areas and are generally well below 1 ton/ha per year. Exceptions to this general rule exist. Erosion rates under a forest vegetation may be significant on steep slopes and under conditions where the understorey and litter layer are absent. In eucalypt forests, for example, undergrowth is almost absent and Van der Goot (1976) reported erosion rates of 500 tonnes/ha per year in a 6 year old eucalypt plantation in the upper Solo basin in Indonesia. Similar high erosion rates (up to 160 tonnes/ha per year) were reported for a teak plantation with no undergrowth (Brunig et al., 1975).

Other experiments in Japan showed a decrease in erosion rates from 0.71mm in the first year, to 0.5 mm in the fifth year, 0.34 mm in the tenth year and 0.05 mm in the fifteenth year after reforestation. Catchment reforestation with pine, also in Japan resulted in a decrease in erosion rates from 72 m^2 /ha per year to 0.17 m^2/ha per year. Hardjono (1980) showed that erosion rates on reforested lands are significantly lower than on agricultural lands: 8.1, 13.6 and 20.1 tonnes/ha per year for a 100% reforested, a 25% reforested and a completely cultivated area watershed in Indonesia, respectively.

From the foregoing in will be clear that the popular belief that reforestation improves groundwater recharge and increases low flow in the dry season is not always valid. Flooding hazard on a local scale may be reduced, but this does not account for major river basins, where the effect of vegetation changes is dominated by other river basin variables. Only when a major part of the catchment is in a badly degraded, gullied, soil compacted state, where almost all the precipitation is quickly channeled to the streams and rivers, the plantation of forest might slow down and reduce surface runoff to the point where there would be flood reduction. The most pronounced benefit of reforestation is without any doubt the reduction of erosion rates and sediment yields. Other benefits may be the restoration of the nutrient budgets and the fact that unproductive land is put into production again. Much of the eventual effects of reforestation depend on the previous erosional state and land use of the area under treatment.

In Indonesia, Nad Darga (1979) used regression techniques to establish the relationships between discharge fluctuation, mean annual discharge and mean annual specific discharge on the one hand, and a number of basin characteristics on the other hand

The fluctuation in dischage was best explained by: the % area that is farmed for 60 to 80%, the % area with soils less than 60 cm deep, the % of the area with 1500 to 2000 mm rain per year, the catchment area and the % dense forest.

The variation in mean annual discharge was most depending on: the catchment area, the % area with more than 3000 mm rain, the % settlement area, the population density and the % area with rainfall between 1500 and 2000 mm.

Independent variables explaining the variation in specific discharge are: the % of the area in settlement, the % area with 1500-2000 mm rain per year, the % area with 1500-2000 inhabitants per km^2 and the % area with an altitute of 100 to 500 m above sea level.

4.4.1 Procedure to be followed.

It will be clear that sediment yields, SDR's and the hydrological response of watersheds to soil erosion or soil conservation measures can best be evaluated using direct measurements of river discharges and sediment loads. Given the fact that continuous discharge measurements and sediment sampling programmes are very expensive and have to be carried out by trained personal, these direct measurements are often of a limited number and only cover short or interrupted observation periods in many developing countries.

To be able to extent the scattered information to a more complete, regional, picture the study of sediment yields, SDR's and hydrological responses in WLRM projects will have to use indirect methods. Multiple regression techniques, as outlined in the foregoing sections seem the most appropriate way to do this. It should be stressed once again that interpretation of the results of these techniques is often very difficult and may lead to erroneous conclusions, when not considered in the proper content.

The analysis will have to start with the collection of all stream flow and sediment yield data available. Streamflow data can be retrieved from existing HYMOS output. Sediment loads are not processed by HYMOS and have to be gathered at other sources. In Indonesia sediment yield measurements are carried out by Puslitbang, these data and data from a fairly large number of other institutes and project authorities are available. For the purpose of the analysis, observation periods of at least 5 to 10 years should be selected to be able to calculate average yearly figures. Yearly runoff and sediment data are too much influenced by the weather conditions in that specific year and may deviate considerable from the average annual figures.

The selected runoff measurement/sediment sampling points are than indicated on a small scale map (1:250,000) and it is evaluated whether or not the whole range of basin sizes and characteristics is covered. If not it should be tried to collect additional information. After this the measurement points are transformed to large scale maps (1:50,000 or 1:100,000) for the determination of the catchment parameters. For convenience sake the points should coincide as much as possible with the water district boundaries.

For each of the (sub) catchments the runoff characteristics, the sediment yields, the basin parameters and the average erosion rates have to be entered in a data base or SPSS system file for the multiple regression analysis. Once a SPSS system file is constructed various stepwise multiple regression analyses can be carried out on different groups of cases, e.g. basins within a certain size class or in a certain physiographic unit, and the most appropriate sets of dependent variables can be selected. Familiarity with SPSS is required.

4.4.2 Data requirements and availability

In this section emphasis will be laid on the BTA-155 project objectives and the specific Indonesian situation. The folowing variables are selected as dependent variables for the regression analysis:

- the average annual specific sediment yield, the amount of sediments leaving the catchment in tonnes/km^2. This information is available from Puslitbang and other sources;

- the sediment delivery ratio, the sediment yield as a percentage of the average catchment soil loss, as calculated with the USLE approach;

- average annual discharge in mm, available as HYMOS output or, if the selected basins do not coincide with the HYMOS water districts, at Puslitbang;

- average annual discharge as % of the yearly effective precipitation: $(D/(P-E_{st})) * 100$, in which; D = average annual discharge, P = average annual precipitation and E_{st} = the average annual standard evapotranspiration. This variable is used to get an insight in how much a certain catchment is deviating from the average catchment, and what are the factors that are responsible for this deviation;

- average annual maximum daily, maximum 7 day and maximum 30 day specific discharge (m^3/km^2), available as HYMOS output;

- average annual minimum daily, minimum 7 day and minimum 30 day specific discharge (m^3/km^2), available as HYMOS output; and

- the ratio of the average annual minimum daily, minimum 7 day and minimum 30 day specific discharge to the average annual maximum daily, maximum 7 day and maximum 30 days discharge.

It should also be tried to relate soil loss on the slopes, as calculated with the USLE approach, directly to the basin characteristics. This enables direct evaluation of changes in soil loss on the slopes as a result of changing basin parameters like land use, conservation measures applied etc. The results of this evaluation can then be compared with the USLE recalculations based on the same changes in parameters, mainly the C and P factors.

Each of the dependent variables requires its own set of independend variables, but as a first attempt, all variables can be taken together. In the calculation of the regression equation of the sediment yield and the sediment delivery ratio, the hydrological dependent variables, as specified above have to be taken into account as independent variables as well.

The independent variables can be subdivided into three groups: climatic, physiographic- and hydrological variables and land use/vegetation and soil variables.

Climatic variables:

- the average annual rainfall for the catchment, this information is available in the HYMOS data base;

- a precipitation seasonallity index, the average annual precititation in the driest month divided by the average annual precipitacion in the wettest month, to be derived from the HYMOS data file;

- the average annual rainfall erosivity index for the basin. This index is available as the R factor in the USLE data base; and

- the average annual evapotranspiration (in mm), also available in the hymos data file.

Physiographic and hydrological variables:

For the derivation of the catchment physiographic parameters topographic maps (1:50,000 or 1:100,000) have to used, unless otherwise stated.

- the catchment area (km^2), derived by planimetry or with the aid of a digitizer;

- the length of the main channel (km), idem;

- the slope of the main channel, the ratio of the difference in elevation between the origin of the main channel and the basin outlet to the length of the main channel (dimensionless);

- the relief-basin length ratio, the difference in elevation between the highest and the lowest point within the basin divided by the basin length, the distance along the longest dimension of the basin, parallel to the main drainage channel (dimensionless);

- the catchment shape, 1- the factor F, the area of the basin divided by the basin length, and 2- the basin elongation factor E, the diameter of the circle with the same area as the basin, divided by the basin length (dimentionless);

- the drainage density, the total length of the channels divided by the basin area (km);

- the bifurcation ratio, the ratio of the number of streams of order n to the number of channels of the order (n+1). This ratio is constant for different values of n. For the procedure to determine the bifurcation ratio see: Drainage basin, form and process by Gregory and Walling, 1983, page 53;

- the average catchment slope, as determined with the contour length method , desribed in chapter 3; and

- the average catchment slope (contour length method) and the average drainage basin slope length (the drainage density method) to be derived from 1;50,000 topographic maps.

Land use/vegetation and soil variables:

For the determination of these factors various sources have to be used, but the main sources are the 1:50,000 and 1:100,000 maps of AGRARIA and the USLE data file.

- the percentages area covered with forest, dryland agriculture, homestead gardens, and paddy rice as displayed on the AGRARIA maps;

- the percentage impervious area, available in the HYMOS files;

- the percentage area with severely degraded soils (AGRARIA maps);

- the weighted average values of the C, P and K factor of the USLE, available in the USLE data files;

- the weighted average soil depth, soil texture, and profile permeability as derived from the AGRARIA maps; and

- the population density; figures of average population densities may be available at the socio-economic group.

Part of the variables listed above are fairly easy extractable, other will pose more problems, mainly the average values of the soil parameters. It could turn out that these figures are only available in an aggregated form and subdivided in a small number of classes. This would reduce their usefullness for the regression analysis.

4.5 Evaluation of multiple regression techniques in the light of the general objectives of a WLRM study

At the end of chapter 3 it was concluded that two of the general objectives of an erosion study for WLRM project purposes could not be fullfilled with the USLE approach. These objectives were:

- to analyse the relationships between the soil loss on the slopes and the sediment output of the rivers; and

- to analyse the relationships between conservation measures/land use changes and the hydrological response of the basins under study.

Using multiple regression techniques as described in the foregoing sections these objectives can be met. The sediment yields of the rivers, as far as not directly available from measurements, can be derived from the soil loss rates on the slopes using the sediment delivery ratio concept or from the direct relationships between sediment yield and basin characteristics.

Relationships between land use changes or applied soil conservation measures, resulting in changes in soil erosion rates, and the hydrological response of a basin can only be evaluated using multiple regression analysis. Direct calculations are not possible. This part of the analysis is by far the most difficult and it is at the moment not to be foreseen whether or not the equations that will be derived have any explanatory value. This will depend on the nature of the independent variables that will eventually explain the bigger part in the variation in hydrologic response of the rivers.

Looking back at the final objectives of a soil erosion study in a WLRM project, as given in chapter 2, namely:

- indicate where soil- and water conservation practices are most efficient from the point of view of water and land conservation;

- provide information that will enable a cost benefit analysis of soil conservation measures; and

- provide information for the construction of a number of strategies of the implementation of soil conservation measures and their hydrological and morphological impacts.

It appears that the first and third objective can reasonably be met with the procedures outlined in this chapter and chapter 3.

With the USLE it is possible to calculate where soil loss occurs or might occur and which conservation measures are most suitable to reduce the soil losses on the slopes. Using the sediment delivery ratio approach or direct relationships, soil losses can then be translated to sediment yields. Hydrological responses of the rivers to conservation practices, like reforestation, can be predicted with multiple regression equations. Given certain predicted land use changes, as caused by a growing population and a growing demand for agricultural products, conservation measures, that are needed to keep sediment yields and hydrological responses of the rivers within certain desired ranges, can be established with direct USLE recalculations or regression equations. The base figures for the scenario's, e.g. projected population growth and land use changes will have to be provided by the activity analysis and socio-economic group.

The second objective, provide information that will enable a cost-effectiveness assessment of soil conservation measures, is not easily met. Evaluation of which conservation measures are necessary is possible, as is a calculation of their costs. To calculate the cost of soil erosion or the benefits of soil conservation is very hard. Only scarse literature, often in very general terms, is available concerning this topics. In chapter five it will be tried to give an overview of the damages caused by soil erosion, the benefits of soil conservation practices and how these can be translated to a cost effectiveness assessment. This attempt will be very tentative and only give some general insight. Much more information than is at present available will be necessary to complete the picture.

Chapter 5. Towards a cost-effectiveness assessement of soil conservation measures

5.1 Introduction

The economic damage of soil erosion, is twofold: direct or on-site, affecting the crops and resulting in damage on a farm level, and indirect or off-site, the sum of the problems that are manifest on the farm level and that result in hydrological and ecological desequilibrium in the region. Examples of direct effects are a reduction in crop yield, reduction in productive area etc. Indirect effects are related to sedimentation problems, reducing the capacity of reservoirs, increased flood damages etc. To be able to make a cost-effectiveness assessment of conservation measures, the decrease in these damages, as a result of conservation measures, has to be established. This will not be easy, not much is known of the impact of soil erosion on soil productivity and even less information is available on the economical damage caused by the indirect effects of soil erosion. The contents of this chapter will therefore merely be qualitative. Further data collection and research is necessary to complete the picture and to be able to make a, allbeit tentative, cost-effectiveness assessment. Costs of conservation measures, on the other hand, can be established fairly accurate.

5.2 Direct damages caused by soil erosion

The direct damages are the damages that affect the crop production costs and revenues at the farm level. This is generally adressed to as soil productivity decline. Soil productivity is not a very appropriate term in this respect; the productivety of a soil in not only dependent on the erosion rate, but is influenced by a number of factors. Rijsberman and Wolman (1984) state that soil productivity is an intrinsic property of the soil that is not directly measurable, because it is a function of various factors among others soil type, climate, landscape and management. Crop yield is a in mass or volume units per unit area meas able parameter that can be used to establish the actual production. Lal (1984) states that the optimum range of soil physical and soil chemical properties for grop growth is very depending on the type of crop and the type of soil and that there is little research information available concering these relationships.

Soil properties that affect crop growth have been summarized by Lal (1984) as well. They include:

- limited root growth possibilities, either due to insufficient soil depth or unfavourable subsoil conditions such as the presence of hard pans or a gravelly layer;
- soil compaction, often due to a decrease in soil organic matter as a result of erosion;
- a decline of the available water holding capacity, again as

result of declining soil organic matter contents; and

- decreasing soil organic matter contents and related chemical fertility. In tropical soils the organic matter is usually concentrated in a thin surface layer and therefore easily eroded. Organic matter plays a very important role in improving the aggregate stability and the water holding capacity of the soil and in decreasing the soil compaction. Furthermore, it is a very important nutrient reserve and prevents leaching losses.

Evidence of decreasing crop yields as a result of soil erosion or the artificial removing of the top soil is given by many authors. A summary (based on Lal, 1984) will be presented here.

A sharp decline in maize yields was reported by Huat (1974) (cited by Lal, 1984) after removal of 0.15 and 0.30 m of the top soil in an experiment in Malaysia. The decrease was attributed to decreasing nutrient availability. Experiments in Hawaii showed that the loss of 0.35m top soil of an Eutrustox affected maize yield in such a way that it could not be compensated for by any addition of fertiliser. The reason was the hindered root growth in the compacted subsoil. The results of these experiments by Yost et al. (1983) are given in table 8. In Nigeria, removal of 0.025 m top soil reduced maize yields with 23% (Lal, 1976), a similar experiment in Cameroon resulted in a 50% decline in yields (Rehm, 1978). After removal of 0.075 m of the soil the exposed subsoil turned out to be totally unproductive. Other research in Nigeria (Mbagwu et al., 1984) showed that the effects of the removal of 0.05 m topsoil on grain yields could only be compensated for by the application of 60-120 kg N and 15-30 kg P fertiliser per ha. In Upper Volta Fournier (1963) observed a decrease in millet yield from 727 to 352 kg/ha due to an increase in soil erosion from 143 to 1318 tonnes/km^2 per year. Experiments in temporate regions show similar trends as those discussed above: sharp decreases in crop yields with decreasing top soil depth. According to Lal (1983 B) the effects of natural soil erosion are even more pronounced than the effects of top soil removal, because of the preferential removal of soil colloids in the natural soil erosion proces. A number of crop-yield- soil erosion rate relationships, developed by different authors, for different crops, and for different climatic regions are presented in fig. 3.

In Indonesia no major soil loss - soil productivity research has been undertaken. According to Hamer (1982) limited research has been done at Citayam, where experiments were conducted on natural soils and soils of which 30 cm of the top soil was removed. Yield differences were minimal. In his report Hamer gave suggestions for further research in this area, to be carried out by the Soil Research Institute in Bogor. Whether or not a research project is carried out at the moment is not known. This should be checked.

For our purposes the LECS approach, once again, is usefull. Soil depth loss - soil productivity loss curves were established for 3 groups of soils: soils that are least, intermediate and most susceptible to productivity loss due to soil depth loss (fig. 4). For the major soil

Table 8. Crop responses to simulated erosion with various nutrient replenishment levels (after Yost et al., 1983).

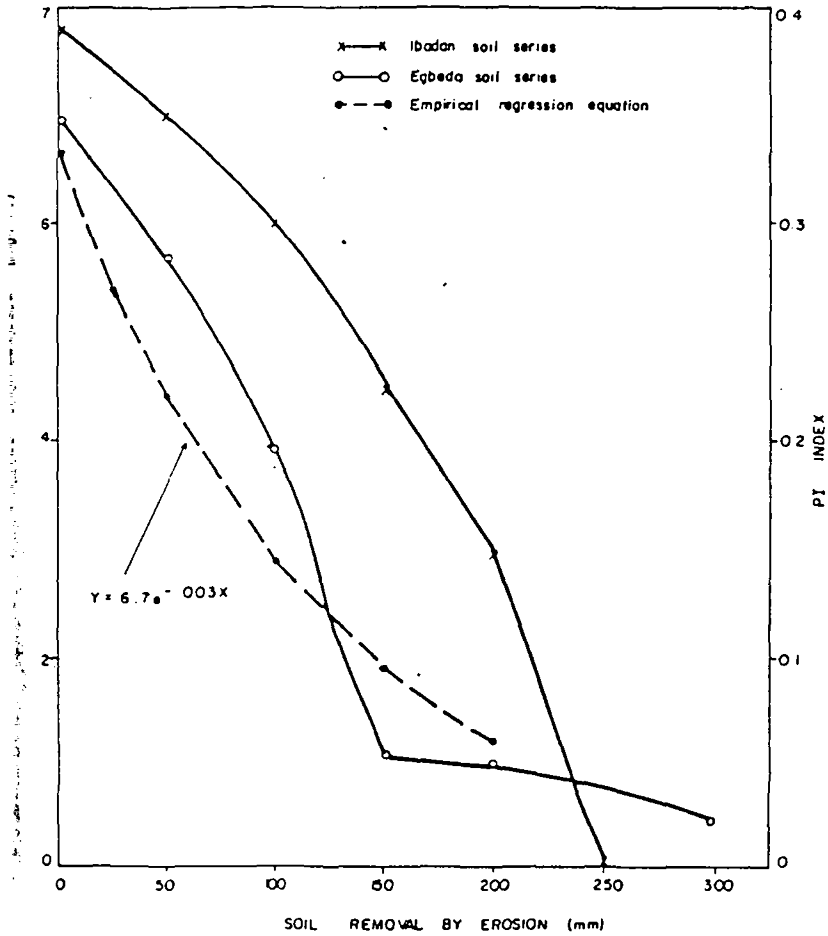
	Grain or tuber yield, tons/ha and harvest data		
Treatment*)	Corn September 16, 1981	Corn April 6, 1983	Potatoes
E_0F_0	2.59	2.65	10.6
E_0F_1	6.86	5.20	19.9
E_0F_2	10.80	8.42	28.5
E_1F_0	1.40	0.93	7.3
E_1F_1	4.79	3.85	16.8
E_1F_2	10.40	8.48	29.7
E_2F_0	0.01	0.00	2.3
E_2F_1	1.59	1.15	9.5
E_2F_2	5.48	2.84	21.3

*) E_0 = no erosion, E_1 = 10 cm eroded, E_2 = 35 cm eroded
F_0, F_1, F_2 = zero, medium, and optimum soil nutrient replenishment respectively.

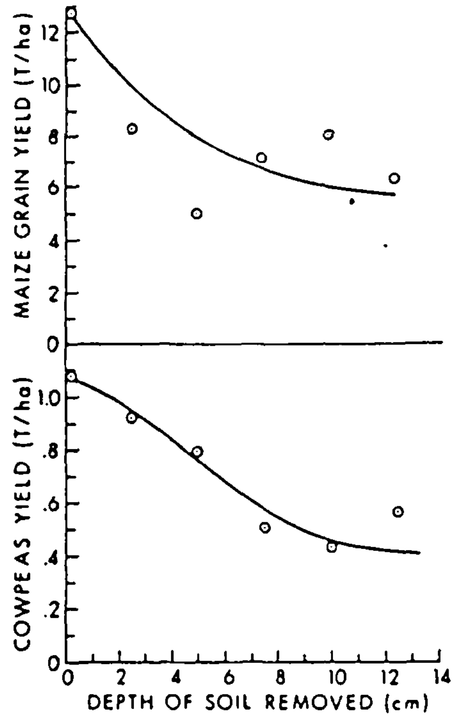
sub orders the physical and chemical degradation hazard was established, as well as the most appropriate management options to prevent degradation. With these curves and tables it is possible to indicate which soils are most prone to productivity loss, and so where the benefits of conservation measures are maximal. To be able to develop a further specified methodology more information is needed on the backgrounds of the rating system. LECS also provides figures on the minimal soil depth required to grow certain crops. This information can be used to calculate in how many years, given the present erosion rates, a soil will not longer be suitable for the cultivation of that crop. Evaluation of alternatives is also possible as is the calculation of the reduction in revenues due to a change in crop.

Other direct damages caused by soil erosion are:

- the loss of seeds that wash away shortly after sowing or become covered with sediments in downslope areas of the fields, where sedimentation occurs;
- loss of cultivation efficiency; fields may become subdivided in different parts as a result of rill and gully formation. This problem will be of minor importance in Indonesia, gully formation

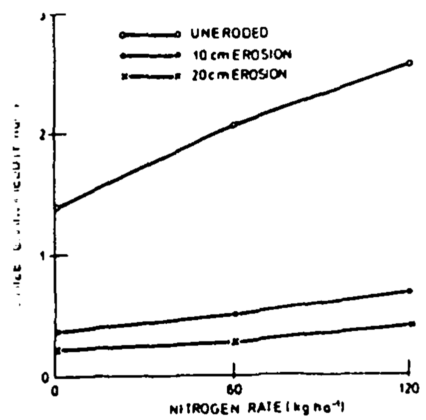


After Lal (1984)



Effects of soil removal on the yields of maize and cowpea on Alfisols.

After El Swaify and Dangler (1982)



Maize grain yield from a desurfaced Alfisol at three levels of N fertilizer application.

After Lal (1983)

Figure 3. Crop yield-soil erosion rate relationships for different crops in different climatic regions

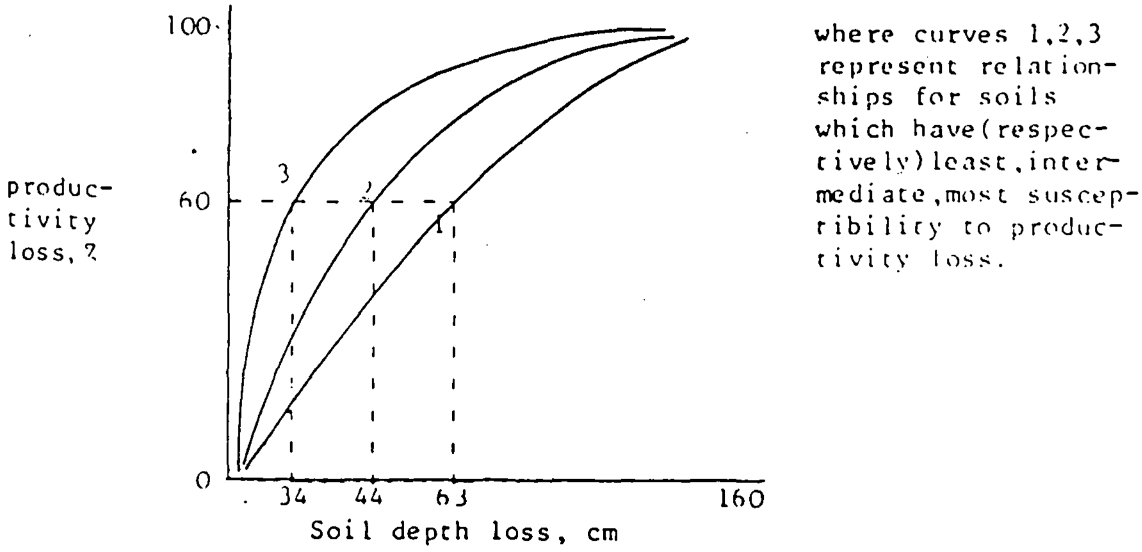


Figure 4. Soil production loss-soil erosion rate relationships for 3 groups of crops grown in Indonesia (After Hamer, 1982).

is rare and the use of machinery is limited; and

- loss of cultivated area; the formation of sterile areas and gullies and the covering of fertile soils with relatively infertile sediments reduces the total area available for cultivation.

Of the magnitude of these direct effects and their economic damage, very limited information is available.

5.3 Indirect damages caused by soil erosion

The indirect damages caused by soil erosion are related to sedimentation problems and changes in hydrological regimes of the rivers. Reservoir sedimentation is one of the major off-site effects of erosion and may result in considerable economic damage. Lal (1985) reports a decrease in reservoir capacity with 39% between 1957 and 1969 for the Ikawa reservoir in Tanzania. In this period 1.5 million m^3 sediment accumulated in the reservoir. The mean erosion rate in the catchment area was estimated at only 0.2 mm per year. Other research in Africa (Nigeria, reported by Oyebande, 1981) indicates that the annual sedimentation in 13 reservoirs, ranged from 0.05 to 20 million tonnes and resulted in an annual storage loss of 0.02 to 10.5 million m^3.

Besides storage loss of reservoirs high sediment yields also lead to the clogging of irrigation canals, so reducing the efficiency of the irrigation system and increasing the maintenance costs. High sediment concentrations in the river water also imply high purification costs of water to be used for domestic or industrial purposes, and may cause problems in the aquaculture. Sediment entering the gills of fish causes infections, which retart their growth and results in high mortality rates.

Changes in hydrological regime of the rivers due to erosion may incresse the flood hazard (see chapter 4). Once a reduction in flood hazard as a result of soil conservation is established, it seems possible to establish the reduced economic damage of floods. In Indonesia flood hazard maps are produced by Pusat Data in Jakarta and it is likely that figures on the economic damage of floods exist. Thes data have not yet been collected.

Ecological/environmental effects of erosion is another aspect that has received little attention. High sediment loads of river reduce the penetration of sunlight in the water and leads to eutrophication. Sedimentation of shelf seas changes the ecology of the coastal waters and the vegetation along the coast.

5.4 Costs of conservation measures.

To evaluate the cost of conservation measures, it should be kept in mind that the total short- and long-term costs consist of three components:

- the value of land removed from production, either permanently, e.g. for the construction of waterways or bench terraces, or at a permanently reduced level of production, e.g. land cultivated with conservation crops (e.g. grass as animal feed) may give returns that are lower than the returns of the original crop;
- construction and installation costs, consisting of labour and material costs. Materials include stones, cement and fertiliser. The life expectancy of the various constructions ranges from 5 to 300 years; and
- maintenance cost of labour and materials for keeping up the effectiveness of the measures. Material costs consist primarily of the costs of fertilisers.

Cost of soil conservation measures are varying from country to country, the following therefore refers only to the situation in Indonesia. The value of lands taken out of production is very much depending on the agricultural suitability of the lands considered and is about 15 times higher for first class irrigated sawah lands than for third class dryland agricultural lands (based on rental values). These figures are given by Hamer (1981) and are based on information of the Kantor Sensus dan Statistik. The report by Hamer also contains a very complete list of the percentage land loss and the installation and the maintenance costs, expressed both in mandays and in Rupiahs, for a number of conservation practices. His figures are based on data collected at the Watershed Development Centre in Solo. More up to data figures, provided by the Ministry of Forestry, and having the same source, are given in the report by Van Lavieren (1986).

5.5 Procedure to be followed

It will be clear that cost-effectiveness analysis of soil conservation measures is hardly possible with the information available. Additional information has to be gathered and a discussion with the members of the socio-economic group of the project team will have to give more insight in the data necessity and the procedure to be followed. However, the objectives of the erosion study that are more related to the physical soil erosion processes have to be met first. The kind and extent of the conservation measures that have to be implemented to keep the erosion and sedimentation rates within certain desired limits have to be etablished before a start can be made with an economic cost-effectiveness analysis. This leaves a bit more time to collect the missing data and to work out a more specified procedure.

Chapter 6. Summary and conclusions

In many tropical countries accelerated soil erosion is a problem of serious magnitude, and with a multitude of detrimental impacts. Not only agricultural production is threatened, but increasing soil erosion rates also affect the water resources and result in pollution and sedimentation taken of reservoirs, canals and irrigation structures. Growing population pressures and the associated pressure on the land will further aggravate the soil erosion problem in the future. An analysis of soil erosion related problems in Water and Land Resources Management (WLRM) planning projects, as presently being carried out by Delft Hydraulics in Indonesia, Kenia and Taiwan, is therefore of major importance. This report aims at providing a general procedure for the analysis of soil erosion problems in WLRM planning projects. Special emphasis is laid on the Indonesian situation.

The objectives of an analysis of soil erosion processes in WLRM projects have to be concentrated on the hydrological impacts of soil erosion and soil conservation on a regional scale, and can be summarized as follows:

- indicate where soil- and water conservation measures are most effective from the point of view of water and land resources conservation;

- provide information that will enable a cost-effectiveness analysis of soil conservation measures;

- provide information for the construction of a number of strategies of the implementation of soil conservation measures and their hydrological and morphological impacts.

To be able to meet these objectives, information has to be gathered on the magnitude and intensity of the soil erosion processes, their areal distribution, and on possible remedial measures that can be taken to reduce the impact of these processes on the water and land resources. Furthermore the damages caused by soil erosion and the effectiveness of conservation measures have to be established.

To evaluate the beneficial effects of soil conservation measures, the actual magnitude and distribution of the soil erosion have to be established, as well as the changes in soil loss rates that will result from applied conservation measures. In developing countries, and on a regional scale, this is only possible with the Universal Soil Loss Equation (USLE). More sophisticated, distributed models, that have been developed for research purposes, are not applicable because the required input data are generally not available.

The USLE has been developed for use in the United States, but has recently successfully been applied in various tropical countries. Research in Indonesia proved the validity of the method for this country, although some adaptions are necessary.

The data required for the application of the USLE comprise of 5 factors: the rainfall erosivity factor, the soil erodibility factor, the topographic factor, the crop factor and the soil conservation practice factor. Establishing the rainfall erosivity factor is time-comsuming and requires detailed rainfall data. For Indonesia an approximative formula has been developed, that can be used in the analysis for the BTA-155 project. Other approximative formulas for other tropical regions exist as well. The most appropriate way to calculate the soil erodibility factor is with the aid of standard soil erosion plots. This is also time-comsuming and costly, but again an approximative formula exists, that enables calculation of this factor from a number of soil parameters. This formula has been tested in Indonesia and the results were satisfactory. In a number of other tropical countries, the formula proved to be less reliable. The topographic factor has to be derived from existing slope gradient- and slope length maps, or from topographic maps with the aid of one of the procedures that have been developed to approximate the factor. In Indonesia a specific methodology has been adopted; slopes with a certain gradient are thought to have a certain slope length and so a certain topographic factor. For the evaluation of the crop and conservation practice factors tables are available in most countries, this is also the case in Indonesia.

However, the USLE has some serious limitations, actually only the soil loss on a slope or field scale can be established, and only sheet- and rill-erosion processes are dealt with. The effects of gully formation, mass-movements and channel- and bank-erosion are not incorporated in the calculations and neither is it possible to calculate total amounts of sediment delivered to the river channel, nor to evaluate the hydrological response of the river to soil erosion and soil conservation measures. Gully-erosion and mass-movements are relatively unimportant in Indonesia and the contribution of river channel- and bank-erosion can be compensated for.

Two procedures can be followed to establish average soil loss on a scale larger than a field or slope, i.e. a river basin, with the aid of the USLE: using a grid cel appraoch, or by establishing landscape units, that are internally homogeneous in their erosional response to rainfall. The first procedure has to be adapted if the information on the USLE factors is only available on maps of different scale. The second procedure is preferable when map information has been, or can be, digitised and processed with a geographical information system. The average soil loss in the basin is assumed to be represented by the average soil loss as calculated for the grid cels or by the weighted average soil loss for the different landscape units. Future developments can be simulated by changing the factor values and recalculation of the soil loss.

To translate the soil loss rates on the slopes to sediment transport of the rivers, sediment delivery ratios have to be calculated. The sediment delivery ratio is the ratio of the amount of soil loss on the slopes to the amount of sediment leaving the catchment at a certain point along the river channel. To be able to calculate sediment delivery ratios, data on sediment loads and discharge are needed. In most countries these variables are monitored quite extensively. In Indonesia data of a large number of river basins are available. Sediment delivery ratios are variable, ranging from less than 5% to more than 90%, and depend on a number of climatic, hydrological and basin characteristics. Multiple regression techniques can be used to evaluate which factors are most important in explaining the observed variation in sediment yields. Once these multiple regression equations have been established, the effects of predicted changes in basin characteristics on the sediment delivery ratio of a certain river, can be established, and predicted soil loss rates on the slopes can be translated to associated sediment yields. Next to this indirect method to determine changes in sediment yields, via changes in soil loss on the slopes, the changes can also be estimated directly. This is possible by establishing direct regression equations between the basin characteristics and the sediment yield. Independent variables, that are commonly most successful in explaining the observed variation in sediment yields are fairly well known from the literature and can be derived from existing maps and HYMOS output files.

Hydrological responses of rivers to soil erosion and soil conservation measures are not very well established and research data are often contradictive. Reforestation is generally accepted as a good method to rehabilitate eroded lands, reduce flood hazards and increase dry season river flows. That reforestation reduces erosion rates is without any doubt, however, the validity of the other two statements is less certain. Flood hazards in relatively small catchments may decrease after reforestation, in large catchments other factors, climatological or hydrological, exert much more influence on the hydrological regime of the river than land use factors, and only in very badly eroded catchments, that become reforestated for a high percentage of their area, a marked reduction in high flows may be observed. Recent research also proved that the influence of reforestation on low flows is often the reverse of the general accepted idea: not only the total amount of runoff decreases as a result of reforestation, as a rule of tumb with a percentage equal to the percentage of area reforestated, but this reduction is most pronounced in the dry season. Few general rules exist to describe the hydrological response of a river to soil erosion and soil conservation measures, and the only possibility to get some insight in the responses is, again, the calculation of regression equations. Hydrological variables like mean annual specific runoff, discharge fluctuation, 7 days or 30 days low flows etc. have to be used as dependent variables and climatological and basin characteristics are used as independent variables in the analysis. With the obtained regression equations the effect of changes in the explanatory variables on the hydrological behaviour of the river can be determined.

With the techniques described above, the impacts of soil erosion and soil conservation on the sediment yields and hydrological responses of the rivers can be reasonably well established and prediction of the effects of future developements, in other words the construction of a number of strategies, is, within certain limits, possible. However, translation of these effect to economical costs and benefits is less easy. Hardly any information is available on the effects of erosion on soil productivity, and the few methods established to make an estimation require detailed information on soil physical and chemical properties. In Indonesia a method has been developed that enables a crude assessment of the decline in productivity. Soil productivity-soil loss relationships were established for 3 groups of soils: soils most, intermediate and least sensible to productivity decline due to loss in soil depth. For each soil type the most appropriate soil conservation method to prevent soil productivity loss was established as well. This provides a means to evaluate where soil erosion conservation measures are most effective, as far as soil productivity loss is concerned. To evaluate the benefits of conservation measures in respect to flood reduction and reduced sediment yields of the rivers, additional data are needed. The costs of conservation measures can be reasonably well established, tables exist that give information on the costs in terms of loss of productive land, construction costs and maintanace costs.

The first part of the analysis, calculation of the actual erosion rates and prediction of the effects of future land use changes and conservation measures can be carried out relatively independent of the rest of the activities in a WLRM project. Only the availability of HYMOS output data is essential. Integration of the results, i.e. the construcion of strategies and the associated cost-effectiveness analysis requires close cooperation with the other project team members.

An analysis of soil erosion related problems in respect to the general WLRM project objectives seems possible with the procedure outlined in this paper. However, a study of these problems has not been included in a WLRM project before and, in contrast to the other parts of the analysis carried out in such projects, no well established and well tested framework for setting up- and carrying out of the analysis exists. This means that part of the procedure may turn out to be ineffective and may have to be adapted by trial and error. This, together with the fact that quite a lot of data are needed that are usually not readily available, implies that an erosion analysis as part of a WLRM project may be very time comsuming and only give satisfactory results at the cost of great effort.

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