

Design of Soil and Water Conservation Structures for Smallholder Agriculture

Training Notes by Prof. Bancy M. Mati

1. INTRODUCTION

1.1 What is soil and water conservation?

Soil and Water Conservation (SWC) are activities that maintain or enhance the productive capacity of land in areas affected by or prone to soil erosion. **Soil erosion**, on the other hand, is the movement of soil from one part of the land to another through the action of wind or water (Figure 1.1). Thus, soil erosion by water is caused by raindrop impact surface sealing, and crust formation leading to high runoff rate and amount, high runoff velocity on long and undulating slopes, and low soil strength of structurally weak soils with high moisture content due to frequent rains. Soil erosion by wind is caused by lack of vegetation cover, dry pulverized soils, strong wind speeds, and poor land management practices such as continuous tillage and over-grazing.



Figure 1.1 (a) These long, steep slopes require soil conservation structures *(photos by B. Mati)* **(b) Badly gullied semi-arid land requires multi-faceted rehabilitation measures.**

Therefore, SWC includes the prevention, reduction and control of soil erosion alongside proper management of the land and water resources. Effective erosion management involves:

- Reduction of the amounts and velocity of surface runoff,
- Maintaining good soil cover through mulching and canopy cover
- Conservation and retention of soil moisture,
- Prevention or minimizing the effects of raindrop impact on the soil
- Maintaining favourable soil structure for reducing crusting
- Re-shaping the slope to reduce its steepness and slope length so as to minimize runoff flows
- Maintenance or improvement of soil fertility, and
- Removal of unwanted excessive runoff safely.

Based on these principles, erosion control measures are grouped into two broad categories:

- (i) Preventive techniques, and
- (ii) Control measures.

The erosion preventative measures mainly comprise the **agronomic soil and water conservation** practices that improve land productivity without construction of structures (see Training Manual 4 in these series). The erosion control measures involve the **construction of various structures** for the control, diversion or conservation of runoff, which is the focus of this Training Manual (Figure 1.2). For improved agricultural productivity, both the agronomic and structural measures of soil and conservation are necessary, especially on steeply sloping lands, where water conservation or drainage of excessive water are required.

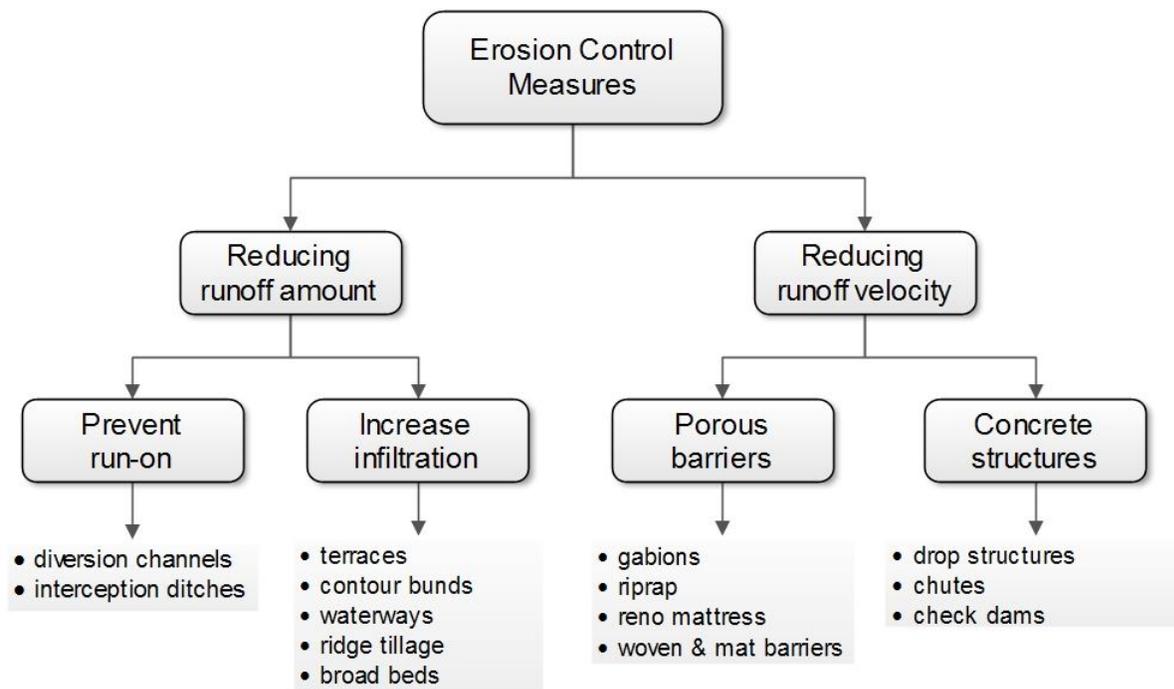


Figure 1.2 Flow chart depicting various methods of erosion control measures

1.2 What are soil and water conservation structures?

Soil and water conservation structures include all mechanical or structural measures that control the velocity of surface runoff and thus minimize soil erosion and retain water where it is needed. They usually consist of engineering works involving physical structures, made of earth, stones, masonry, brushwood or other material for the construction of earthworks such as terraces, check dams, and water diversions, which reduce the effects of slope length and angle. SWC structures can be designed to either conserve water or to safely discharge it away. They supplement agronomic or vegetative measures but do not substitute for them. Suitability of SWC structure depends on:

- Climate and the need to retain or discharge the runoff.
- Farm sizes.
- Soil characteristics (texture, drainage, and depth).

- Availability of an outlet or waterway.
- Labor availability and cost.
- The adequacy of existing agronomic or vegetative conservation measures.

1.3 Determining amounts of runoff for design of SWC structures

1.3.1 Characteristics of surface runoff

Surface runoff (or simply runoff) is the portion of precipitation that makes its way towards the stream channels, lakes or oceans as surface or subsurface flows. Runoff occurs when precipitation rate exceeds infiltration rate, and is the most destructive component of rainfall. In the design of SWC structures, the most important factors used are (i) peak runoff rates, (ii) runoff volume, and (iii) temporal distribution of runoff rates and volumes.

Factors affecting runoff

These include both catchment factors and rainfall factors.

1.3.2 Catchment factors

Runoff is influenced by catchment factors such as topography, vegetation, infiltration rates, soil storage capacity and drainage pattern. In addition the size of the catchment, its shape, orientation, geology and surface culture also affect runoff. The larger a catchment, the more runoff it will generate. Slope steepness is particularly important as soil erosion is more prone on steeper slopes. Surface culture includes the soil tilth, whether there is vegetative cover or not, and other land management activities, e.g. cultivation that would increase erosion.

1.3.3 Rainfall factors

Rainfall factors associated with surface runoff and erosion include; rainfall amounts, storm duration, intensity and distribution, as well as seasonal patterns, e.g. Dry areas are more prone to erosion than wet areas because prolonged dry spells destroy vegetation cover, and rain storms tend to be high intensity and thus erosive. The most significant component of rainfall is its intensity, which is a function of the energy the raindrops impact on the soil. The intensity-duration relationship of rainfall gives an indication of expected runoff. For example:

$$I = a/(t+b)$$

Where: I = Rainfall intensity

T = Duration of rainfall (min)

a & b are constants

For any given duration, the graph or equation will indicate the highest average intensity which is probable for a storm of that duration. This is calculated as:

$$I = kT^x/t^n$$

Where,

T = is the return period in years

T = is the duration in minutes

k, **x**, and **n** are all constants

Calculations involving rainfall probability must relate to a chosen return period, e.g. for conservation works on small farms, about 10 years.

Time of Concentration (T_c)

The storm duration which corresponds with the maximum rate of runoff is known as the time of concentration (T_c). It is assumed that during the time of concentration, all parts of the watershed are contributing simultaneously to the discharge at the outlet. T_c is also described as the longest time for water to travel by overland flow from any point in the catchment to the outlet. It is equivalent to the time it takes water to flow from the furthest corner of the catchment to the outlet.

Design storm

A design storm, is a storm of known return period. It is used as a basis for designing structures. For example, a 10-year, 1-hour rainfall is the maximum rainfall amount expected in a 1-hour period with a 10-year return period.

Design runoff rates

The capacity to be provided in a structure that must carry runoff may be termed as the design runoff rate. Structures and channels are designed to carry runoff that occurs within a specified return period (T_R). e.g. 10 years for vegetative waterways, and 100 years for permanent channels.

1.3.4 Estimation of surface runoff

It is important to know the quantities of water to be handled. If the objective is to impound water e.g. dams, peak volumes are used, if the purpose is to convey water e.g. channels/waterways, peak runoff rates are used. It is necessary to estimate runoff or design of conservation and also conveyance structures, to avoid failure due to overtopping. Estimates of the rates of surface runoff therefore depend on two processes: (i) estimating the rate of rainfall, and (ii) estimating how much of the rainfall becomes runoff. The runoff rate is more crucial and is determined using various methods or equations as described here below:

a) The Runoff Coefficient

The simplest method is to use a single coefficient which represents the ratio of rainfall loss. If half of the rainfall is “lost” by infiltration, the other half appears as runoff, then the coefficient, C is 0.5.

Examples of runoff coefficients:

Woodland on flat sandy loam, $C=0.10$

Woodland, flat tight clay $C = 0.40$

Cultivated, hilly clay soil, $C = 0.60$

Urban, rolling, 50% built up, $C = 0.65$.

b) Catchment Characteristics or Cook's method

The method consists of summing numbers each of which represents the extent to which runoff from the catchment will influence a particular characteristic. The effect of four features is considered in Cook's method, which are (i) the relief, (ii) soil infiltration, (iii) vegetal cover, and (iv) soil surface storage.

Each of these is considered in turn and the condition of the watershed compared with four descriptions, i.e. extreme, high, normal, and low. Each description/feature has a number. For example, an arithmetic total (e.g. $30+10+15+10=65$) is the watershed characteristic and will lie between the extreme values of 100 and 25. The main problem of this method which estimates by addition is that the errors are propagated.

c) Runoff Curve Numbers

This is an extension of Cook's method, which allows for variations in the physical conditions of a catchment and also the land use. Like in Cook's method, four variables are considered and in each case, a selection has to be made from a list of options. Ten categories of land use or cover are offered (row crops, pasture, woods, fallow, farmstead etc) with a choice of soil conservation practices such as contouring and terracing. The hydrologic condition of the catchment is graded good, fair or poor and a subjective assessment of this factor is designated one of four major hydrologic soil groups described earlier. The method relies on subjective non-measurable assessment.

e) The Rational Formula

The Rational method predicts runoff through this equation:

$$Q = 0.0028CIA$$

Where:

Q = The design peak runoff rate in m^3/s

C = Runoff coefficient (a function of catchment vegetation, slope, surface culture)

A = Area of the watershed in hectares

I = Rainfall intensity in mm/hr for the design return period and for a duration equal to the time of concentration of the watershed.

The Rational method is developed on the assumption that (i) rainfall occurs at uniform intensity for a duration equivalent to the time of concentration, and (ii) rainfall occurs at a uniform intensity over the entire area of the catchment.

1.4 General principles for the design of SWC structures

The design of SWC structures considers severity and extent of erosion damage or risks, the factors causing erosion, as well as the suitability of land to the identified intervention. SWC control measures are directed at protecting the soil from raindrop impact and hydraulic forces of runoff. The process involves three areas of attention: (i) Reduction of raindrop impacts on soil; (ii) Reduction of overland flows; (iii) Increase infiltration rate, and (iv) Slowing runoff velocities.

1.4.1 Factors considered

Soil and water conservation structures are usually made by hand labour or machinery although some terraces develop naturally from vegetative barriers. They are particularly important on steep slopes where annual crops are grown and in marginal rainfall areas where there is a need to conserve rainfall in situ. The selection and design of structure depend on many factors such as:

- Climate and the need to retain or discharge runoff.
- Farm size and system (large or small-scale, mechanized or non-mechanized).
- Cropping pattern (perennial or annual, with or without rotations).slope steepness.
- Soil characteristics (erodibility, texture, drainage, depth, stoniness and risk of mass movement).
- The availability of an outlet or waterway for safely discharging runoff away from cropland.
- Labour availability and cost
- The availability of material e.g. stone
- The adequacy of existing agronomic or vegetative conservation measures.

1.4.2 Structures for retention or discharge of runoff

Structure can be designed either to retain or discharge runoff. They can also be designed so that part of the runoff is retained but the excess, during heavy storms, is discharged. In the higher rainfall areas(e.g. over 1,250 mm per annum), where crops are rarely short of water, or where there is a risk of water logging at certain times, it is usually to design structures to discharge runoff if there is no suitable outlet such as a natural waterway, artificial waterway or grassed slope. Discharging water onto a footpath, road or existing gully would aggravate soil erosion. On large-scale farms it is usually possible to set land for waterways. In densely settled area this is much more difficult.

In the drier areas (e.g. less than 750 mm per annum) it is usually desirable to keep rainwater in situ and to prevent runoff. Other factors that must be considered in reaching a decision, besides the availability of a discharge area or waterway, include the soil type, soil depth land slope and the risk, if any, of retaining water in situ. Soils in higher rainfall areas that are prone to water logging because they are shallow or because of the clay content, such as the grey soil (planosols) or black cotton soils (vertisols) in other areas, normally require structures that will drain water. Some soil on steep slopes, such as the areas with Andosols, it is better to drain water. Also, areas prone to landslides become unstable if they very wet, and conservation structures should be designed to drain the water away.

When there is a need to discharge water but no suitable space for a waterway, there are two options. One is to change the land use to a permanent crop or fodder grass that does not require conservation structure. The other is to use contour barriers designed to conserve all the runoff.

1.4.3 Size of conservation structure

The design of any structure to retain or discharge runoff should be based on a reasonable estimate of the volume of runoff (m^3) to be retained or the peak rate of runoff (m^3/s) to be discharged. A

retention structure can rarely be made big enough to capture all runoff during exceptionally wet period, unless the catchment area is very small. One alternative with retention structures is to incorporate a spillway to take the overflow.

Similarly the design of a structure to discharge runoff can rarely be based on the heaviest storm possible. Usually it is based on the heaviest storm that can be expected in a given period (e.g. 10 years) with the knowledge that a heavier storm, of a magnitude that occurs once in twenty, fifty or a hundred years, could take place (the frequency in years with which a storm of a given amount is likely to occur is known as the return period).

1.4.4 Risks

The risk of damage due to an exceptional storm should be considered when designing structures. If the risk cannot be eliminated, it must be minimized by ensuring that the structures are stable when they are made and carefully maintained afterwards. Failure to pay attention to this point can lead to damage during heavy storms and greater erosion than if the structures had not been installed in the first place. Where there are a series of structures on a hills slope there is a risk if a structure is breached near the top, then those downhill would also get damaged.

1.5 Types of conservation structures

The main SWC structural measures used on croplands comprise diversion ditches (cut-off) drains), retention (infiltration) ditches, terraces and waterways. Supportive cultural measures such as grass or vegetative material for stabilizing the structures are also required for selection of proper species. The identification of appropriate types of SWC structures should take into account the need to retain runoff in areas where water is short or discharge runoff where it is in excess. The design of structures to discharge runoff, such as diversion ditches and waterways, should be based on an estimate of the peak rate of runoff. Structures which are intended to discharge runoff should not be installed unless there is safe place for disposal of water e.g. a natural or artificial waterway or permanent vegetation.

In higher rainfall areas e.g. areas receiving more than 1000mm of rain per annum, and where crops rarely lack water, or where there is a risk of water it is usually necessary to design structures to discharge runoff. However, it would be a mistake to design a structure to discharge runoff if there is no suitable outlet such as a natural waterway, artificial waterway or grassed slope. Discharging water onto a footpath, road or existing gully will aggravate the problem of erosion. In the drier area (less than 750 mm per annum) it is usually desirable to keep rainwater in situ and prevent runoff.

1.6 Benefits of conservation structures

Soil and water conservation bears benefits over a longer time span after construction. However, some benefits such as increased crop yields can be attained within the first year. In general, the benefits of SWC can be summarized as follows:-

- Increased agricultural productivity (higher yields, fodder for livestock)
- Conservation of potentially productive land i.e. SWC supports sustainable agriculture

- Reduced nutrient loss from the soil, and thus less fertilizer requirements
- Environmental conservation, by storing more water within the soil profile and thus improved catchment hydrology
- Soil drainage benefit in areas prone to floods or waterlogging,
- SWC benefits irrigation and drinking water supplies, by protecting reservoirs from sedimentation
- SWC protects infrastructure such as roads from erosion damage, e.g. gullies.

1.7 Limitations

The planning and construction of SWC structures on smallholder farms can be complicated by the small sizes of plots on given slope. This is because farm boundaries are not necessarily aligned to the contour or following a natural feature such as a crest line or drainage line. Thus, it is difficult to get appropriate site and space for an artificial waterway. Sometimes, the best site for a waterway may already be occupied by a footpath or a gully. Attempting to plan one farm in isolation from the others is likely to cause failure. A catchment plan is needed but there are social implications which must first be resolved.

SWC structures can be expensive to install. In particular, gully control structures can be very expensive. There is also a lot of labour needed to excavate terraces, especially bench terraces. SWC requires some level of engineering design, and thus technical know-hoe can be a limitation. SWC structures function by retaining water in-situ, thus denying runoff to downstream areas. This can be a potential source of conflict which should be addressed.

1.8 Management and maintenance

SWC structures require regular maintenance and repairs if they get damaged. Grazing in cultivated lands treated with SWC structures should not be allowed as the animals can damage the structures. Instead, fodder should be cut and taken to animals preferably under cut and carry systems. Replanting vegetative materials and lining out of construction and channels should be done at least every season.