RUNOFF AND EROSION IN DIFFERENT (AGRO) CLIMATOLOGICAL ZONES OF LATIN AMERICA AND PROPOSALS FOR SOIL AND WATER CONSERVATION SCENARIOS

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ABSTRACT

Steeplands, when cleared from forests, are susceptible to erosion by rainfall and are prone to land degradation and desertification processes.

The dominant factors affecting those erosion processes and hence the resulting runoff and soil losses are the aggressiveness of the rainfall during the successive plant growth stages, the soil cover-management, but also the topography (slope length and slope steepness). Depending on the type of (agro) climatological zone, the runoff water should either be limited and controlled (excess of water) or should be enhanced and collected from the slope on the downslope cropping area if water is short (negative soil water balance).

Examples are given of practical applications in Ecuador where alternative soil conservation scenarios are proposed in maize cultivation in small fields on steep slopes. Adding peas and barley in the rotation of maize and beans resulted only in a slight decrease of the soil losses. Subdividing the fields into smaller parcels proved to give the best reduction in soil loss. Because the average slope steepness is high, erosion control measures such as contour ploughing and strip cropping have only small effects.

Erosion and its effect on productivity of a sorghum -livestock farming system are assessed on four different areas in Venezuela with different levels of erosion. A Productivity Index (PI) and an Erosion Risk Index (ERI) were used to classify the lands for soil conservation priorities and for alternative land uses. Intensive agriculture can be applied on slightly eroded soil, whereas severely eroded soil can be used with special crops or agro-forestry. Semi-intensive agriculture is possible on moderately eroded soil.
Reforestation of drylands in Chili requires understanding of the infiltration/runoff process in order to determine dimensions of water harvesting systems. Infiltration processes in semi-arid regions of Chile were evaluated, using rainfall experiments and constant-head infiltration measurements. Correlations between infiltration parameters and locally variable characteristics as soil structure, field slope and stoniness were investigated for six different sites, aiming at improving the design and positioning of runoff collecting systems.

INTRODUCTION

Land degradation is the loss of productivity capacity of the land. The removal of the protective vegetative cover, excessive ploughing of the soil, heavy grazing and deforestation, all leave the soil highly vulnerable to wind and water erosion and to desertification processes.
The dominant factors affecting water erosion processes and hence the resulting runoff and soil losses are the aggressiveness of the rainfall during the successive plant growth stages, the soil cover-management , but also the topography (slope length and slope steepness).
The runoff water should either be limited and controlled in areas with excess of water, or should be enhanced and collected from the slope on the downslope cropping area or in collecting systems if water is short (negative soil water balance).
Examples are given of erosion control scenarios for alternative soil conservation in agricultural systems in Ecuador and Venezuela.
A methodology is worked out for assessing the dimensions of runoff collecting systems in semi-arid regions of Chili in view of reforestation programs.

Water erosion in small watersheds of the Paute River basin (San Cristobal, Ecuador) and erosion control scenarios

Introduction

San Cristóbal is situated near Cuenca in the watershed of the Paute River in the Austro Ecuatoriano, the southern part of the Andes, at 2800 m above sea level and with an average annual rainfall of 750 mm.(Figure 1).

The purpose of this study was to assess the effect of different soil control measures on the soil loss rate at the field scale level in order to examine the possibility of erosion control by simple modifications of traditional cultivation techniques. Agriculture is done on small fields with very steep slopes and shallow, erodible soils with vertic properties. Inappropriate cultivation techniques with tillage traditionally done up- and downwards the slopes, using animal as well as mechanical power, result in severe soil losses up to 100 ton/(ha yr) and to 300 ton/(ha yr) in some micro-subwatersheds (Cisneros,1998).

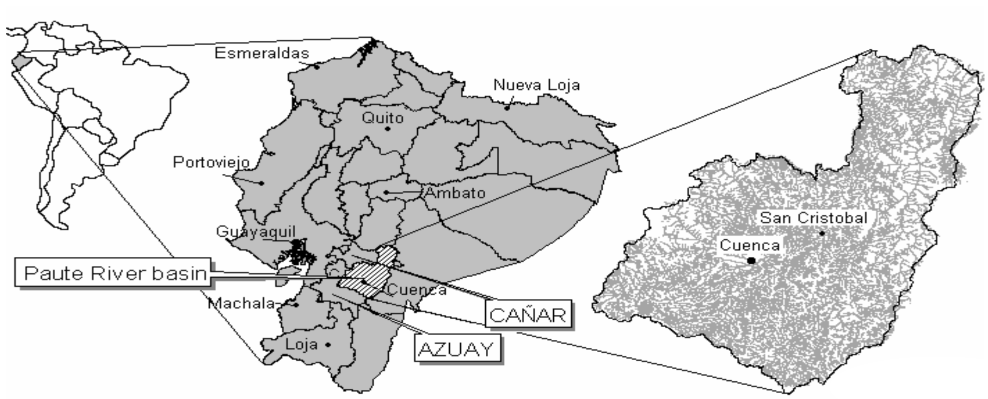

Figure 1. Location of the study area

Assessment of soil erosion

To quantify the actual soil erosion rate in 87 selected individual fields (total area: 16.3 ha) in the region of San Cristobal, the Revised Universal Soil Loss Equation (RUSLE) was used, which calculates the average annual soil loss rate based on five parameters: R, K, LS, C and P.

The rain erosivity factor R

This factor is calculated with limited rainfall intensity data from two stations near San Cristobal namely *La Esmeralda (1998-2001)* and *Ucubamba (1998-2000).*The average R value for La Esmeralda is 788.7 MJ mm/(ha hr yr) and for Ucubamba the R-value is 1140.3 MJ mm/(ha hr yr). To obtain the R-value in San Cristobal, a weighted average was calculated resulting in a value of 1006.5 MJ mm/(ha hr yr) for the average annual rainfall erosivity in the area with a maximum of 1231.4 MJ mm/(ha hr yr) for the 'worst case' scenario using the maximum R values for each station.

The soil erodibility factor K

To assess the soil erodibility in the study area, 44 samples were taken from the upper 0 – 10 cm soil layer. The soil erodibility factor K is the one derived algebraically from the nomograph developed by Wischmeier and Smith (1978).

Cisneros (1999) calculated a K factor for every soil type in the Tabacay region. He found values ranging from 0.0118 ton ha h /(ha MJ mm) for a Vertic Cambisol to 0.0520 ton ha h/(ha MJ mm) for a Drystic Leptosol. . These values comprise the values calculated in this study.

The topography factor LS

The LS factor expresses the combined effect of the factors S and L, which take into account respectively the slope gradient and slope length. The LS factor is determined using the flow lines in the field parcels. A flow line starts at a point which receives no input from adjacent pixels and ends at the lower field edge. For every pixel or elementary cell of the grid the drainage direction is determined and used to construct flow lines in the fields.

The crop-management factor

The C factor is based on the soil loss ratio (SLR) of a crop rotation, weighed by the annual distribution of the erosivity factor R. The value of SLR depends on the prior land use, the canopy cover, the surface cover, the surface roughness and the soil moisture. In the region of

San Cristobal the majority of the fields have a monoculture of maize (*Zea Mays L.)* in association with bean *(Phaseolus sativum)* from October until May. During the months June until September, on some parcels peas *(Pisum sativum L.)* are grown in association with oat *(Avena sativa)* or barley *(Hordeum vulgare L.).* The other parcels are left bare.

The annual C factors for the maize rotation and maize-peas rotation are 0.59 and 0.51 respectively. The difference between both rotation systems is rather small, because the highest rainfall erosivity occurs in March and April, i.e. during the months with a fully developed maize canopy cover. The erosivity during the period June – October is low, resulting in a limited effect of the peas cover compared to the bare soil. Some fields in the study area have permanent grassland. For these fields a C factor of 0.02 is chosen, based on data of Cisneros (1999).

The support practice factor P

The P factor takes into account the effect of contouring, strip cropping, terracing and subsurface drainage. Because no soil conservation measures are currently applied, the P factor is set equal to 1.

Actual and potential soil loss

Using RUSLE, the estimated annual potential soil loss of the 87 fields (total area: 16.3 ha) equals 296 ton/yr. Taking into account the actual crop rotation on every field, the actual soil loss is obtained, which equals 155 ton/yr. The potential and actual soil loss values of the fields are given in figure 2.

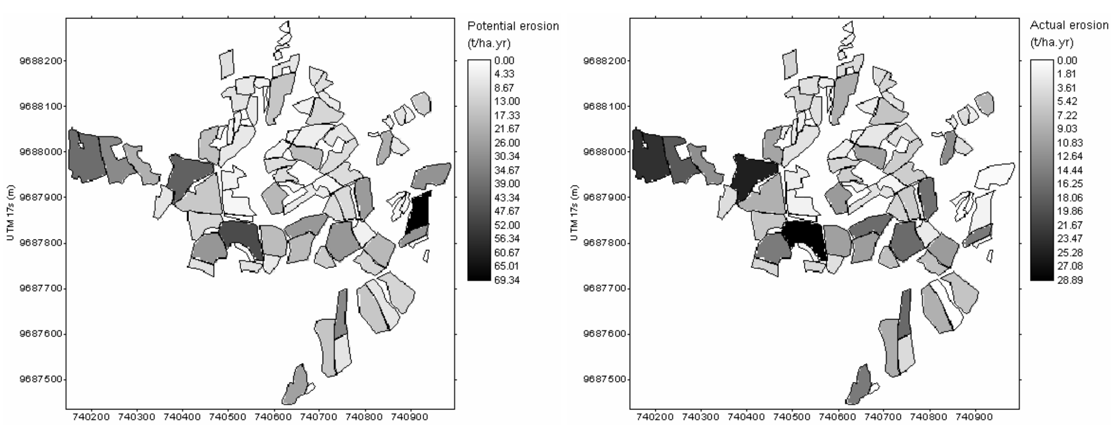

Figure 2: Potential (left) and actual soil loss (right) of the fields in the San Cristóbal study area

Soil conservation measures.

The effect of several soil conservation measures in reducing the actual soil erosion rate was assessed using the RUSLE. The conservation measures were chosen based on their possible implementation, both from a practical and financial point of view.

Maize-peas rotation

In this scenario, the maize rotation is changed into a maize-peas rotation on all fields. This results in an additional soil cover on all fields during the months June until September.

Contour ploughing

Ploughing along the contours instead of up and down the slope decreases the runoff velocity and increases the water retention capacity. However, its applicability may be more difficult for farmers using mechanical power instead of animal power.

Subdividing fields into smaller units

By using (vegetative) barriers, a large field can be split into smaller units. This reduces the slope length, resulting in a lower runoff velocity and sediment transport rate. The use of smaller fields may hamper tillage operations, especially when machinery is used. Possible barriers to subdivide the fields are: small earthen walls, strips with perennial, dense grass or hedges of Maguey americano (*Agave americana L.*). Splitting of the field was only considered if the soil loss rate exceeded 4.5 ton/(ha yr). The soil loss tolerance value of 4.5 t/(ha yr) was chosen, based on the values proposed by the Soil Conservation Service (Logan, 1982) for a shallow soil (25 to 50 cm) overlying a solid rock.

Strip cropping

In this case, strips of maize are alternated with strips of dense growing grasses. Although there is a loss of cropping area, the grass can also be used as fodder. Instead of grass, also oat (*Avena sativa*), barley (*Hordeum vulgare L.*), quinoa (*Chenopodium quinoa Willd.*) or lupin (*Lupinus mutabilis*) are possible alternatives. In this study, only the effect of grass in strip cropping is assessed. The strips are situated at a relative distance of 0.45-0.5 and 0.95-1.0 (Figure 3). Two strip lengths were considered: 5 % and 10 % of the total field length, with a maximum of 5 m and 10 m respectively. Strip cropping was only considered if the soil loss rate exceeded 4.5 t/(ha yr).

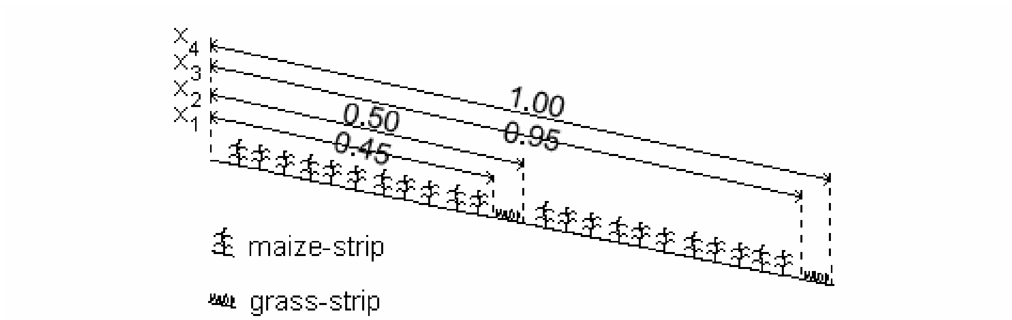

Figure 3: Position of the grass strips and relative distances to the top of the field

Comparison of the different soil conservation measures

To evaluate and compare the effect of the conservation measures, the soil loss values for the different scenarios are summarized in Table 1. The highest reduction in soil loss was obtained by dividing the fields into smaller units. This resulted in smaller LS factors and consequently in lower soil erosion rates. Buffer strips with a length equal to 10 % of the total field length (with a maximum of 10 m) are also efficient in reducing soil loss. The efficiency of contouring is rather limited, due to the steep slopes. In this case, a combination of different practices is needed, e.g. contour ploughing followed by a maize-peas rotation.

Table 1. Comparison of the total soil loss rates for different soil conservation measures

Soil conservation measure	**Soil loss rate (t/yr)**	**Number of fields with soil loss < 4.5 t/(ha yr)**
actual situation (P factor = 1)	155	48 (55.2 %)
maize-peas rotation instead of maize rotation	137	51 (58.6 %)
contour ploughing	142	50 (57.2 %)
contour ploughing + maize-peas rotation	126	54 (62.1 %)
strip cropping (grass strip length = 5 % of field length; max 5 m)	135	51 (58.6 %)
strip cropping (grass strip length = 10 % of field length; max 10 m)	109	55 (63.2 %)
subdivision of fields (87 → 125 fields)	68	95 (76.0 %)
subdivision of fields + contour ploughing	60	99 (79.2 %)

The soil loss rates predicted by the RUSLE could not be validated due to absence of erosion measurements in the area. Therefore, the modelling results should not be interpreted as exact values, but they indicate that the total soil losses can be strongly reduced through rather simple modifications of the traditional cultivation techniques.

Water erosion risk assessment and impact on soil productivity in the Central Plains of Venezuela

Introduction

The study was carried out on a Typic Haplustalf soil located in Chaguaramas in the Central Plains of Venezuela. Rainfall characteristics are reported in table 2 for two meteorological stations: Valle de la Pascua and Los Arbolitos

Table 2: Rain characteristics in the Central Plains of Venezuela

Station	**Mean annual rainfall (mm)**	**Modified Fournier Index (mm)**	**EI_{30} $MJ.mm.ha^{-1}.h^{-1}.yr^{-1}$**
Valle de la Pascua	896	151	6762
Los Arbolitos	820	144	5922

The production system was a sorghum (*Sorghum bicolor Moench.*) – livestock farming system introduced 30 years ago. Secondary tillage with a disc harrow (without mulch on the topsoil) was applied for seedbed preparation. A uniform application of fertilizers and pesticides was done over the entire fields

Four different areas with the same soil type, with slopes ranging from 3 to 6 % and with different levels of erosion were selected for the study: Chaguaramas I (slightly eroded: no loss of topsoil), Chaguaramas II, (moderately eroded: 5 cm loss of topsoil), Chaguaramas III (moderately eroded: 8 cm loss of topsoil), and Chaguaramas IV (severely eroded: 10 cm loss of topsoil).

A Productivity Index (PI) and an Erosion Risk Index (ERI) were used to classify the lands for soil conservation priorities and for alternative land uses. The relative values of soil productivity, estimated with the *Soil Productivity Index* (PI) and relative values for the water erosion risk of a land unit, estimated by means of the *Erosion Risk Index* (ERI), can be classified as indicated in Table 3

Table 3. Ranking the Soil *Productivity Index* (PI) and the *Erosion Risk Index* (ERI)

PI or ERI	Soil productivity or Erosion Risk
≤ 0.10	Low
0.11- 0.30	Moderate
0.31-0.50	High
> 0.50	Very high

Soil productivity

The objective was to evaluate the water erosion impact on soil productivity, using the Soil Productivity Index (PI) developed by Pierce *et al* (1983) and adapted by Delgado (2003) for Venezuelan soil conditions

The Productivity Index (PI) model has served as a useful tool for estimating the relative productive potential of different soils, log-term erosion-productivity impacts, and permissible soil losses for conservation planning. (El Swaify and Fownes, 1989)

Delgado (2003) proposed the productivity index (PI) as a function of the most relevant factors for Venezuelan soil conditions.

$$PI = \sum_{i=1}^{n} (A_i \cdot B_i \cdot C_i \cdot K_i) \qquad \text{with } A_i \text{ to } K_i \textit{ as factors} \qquad (1)$$

Each factor of the Productivity Index (PI) was evaluated in terms of the respective most relevant sub-factors, taking into consideration the local climate conditions.

In the case of Chaguaramas the sub-factors selected were:

Factor **A**: conditions that regulate the *air-water relations* of horizon *i*

In humid climate (P/ETP > 2.00): the soil aeration capacity is limited and determined by the % clay and the weak soil structure degree (sub-factor A_2)

Factor **B**: conditions that determine *mechanical resistances* (impedances) to the crop root exploration in horizon *i* selecting the bulk density in function of soil texture, and because the volume of coarse fragments in the soil is less than 30%, sub-factor B_1 (Soil Compaction) is selected,

Factor **C**: conditions that regulate the *potential fertility* of horizon *i*

In humid climate (P/ETP > 2.00): the pH as the most limiting sub-factor C1 (Soil reaction)

Factor **K**: evaluates the relative importance of horizon *i in* the soil profile, where K*i* = Kcum *(i)* – Kcum *(i-1)*

Hence $PI = \sum_{i=1}^{n} (A_2 \cdot B_1 \cdot C_1 \cdot K_i)$ (2)

Table 4 contains the soil properties and the corresponding sub-factors and PI index

Table 4: Soil Properties and Soil Productivity Index.

Erosion level	Depth (cm)	Clay (%)	Sub-factor A	Bulk Density Mg m^{-3}	Sub-factor B	pH	Sub-factor C	Sub-factor K	PI*
I	0 – 20	12.0	0.95	1.55	0.85	5.9	1.00	0.30	0.24
	20 – 38	17.0	0.90	1.63	0.60	6.2	1.00	0.18	0.10
	38 – 70	25.0	0.85	1.60	0.82	6.0	1.00	0.30	0.21
								Very high	0.55
II	0 – 15	12.0	0.95	1.62	0.80	5.4	0.95	0.23	0.17
	15 – 35	19.5	0.85	1.68	0.50	5.9	1.00	0.22	0.09
	35 – 60	27.0	0.82	1.61	0.82	5.7	1.00	0.35	0.24
								High	0.50
III	0 – 12	14.0	0.95	1.57	0.85	5.4	0.95	0.18	0.15
	12 – 32	20.5	0.85	1.70	0.45	5.0	0.85	0.22	0.08
	32 – 42	23.0	0.82	1.70	0.45	4.2	0.60	0.10	0.04
	42 – 70	37.0	0.75	1.60	0.82	4.8	0.80	0.30	0.18
								High	0.37
IV	0 – 10	10.0	0.9	1.58	0.82	5.3	0.90	0.15	0.09
	10 – 18	14.0	0.87	1.63	0.64	5.1	0.88	0.10	0.05
	18 – 35	17.0	0.85	1.63	0.64	5.2	0.92	0.20	0.10
	35 – 45	24.0	0.75	1.75	0.20	5.8	1.00	0.10	0.015
	45 - 70	20.0	0.80	1.83	0.10	5.0	0.85	0.25	0.017
								Moderate	0.27

PI*: Productivity Index

Soil erosion risk

A soil erosion risk was assessed by the Erosion Risk Index (ERI) taking into account the soil hydrological characteristics (infiltration / runoff ratio), rainfall aggressiveness and topography (slope). The Erosion Risk Index (ERI) was calculated by the following equation:

$$ERI = \frac{\eta}{10(1-\alpha)} \quad (4)$$

Factor α evaluates the soil runoff potential in function of soil structure, soil particle sizes, and coarse fragments.

Factor η evaluates the impact of the terrain slope (modal slope) on erosion risk under different rainfall aggressiveness determined by the Fournier Index (Fournier, 1960, quoted by FAO-PNUMA, 1980), determined by the following equation:

$$F = p_m^2 / P \qquad (5)$$

where F is the Fournier Index, p_m is the maximum monthly precipitation (mm), and P is annual precipitation (mm)

The Erosion Risk Index (ERI) has a value between 0 and 1, with 1 corresponding to a land unit that presents the highest potential conditions for inducing water erosion processes.

Table 5 shows the Erosion Risk Index (ERI) for the four erosion levels.

Table 5: Erosion Risk Index (ERI)

Level	Texture	Coarse fragments (%)	Soil Structure degree	Factor α	Factor η	Modal Slope Gradient	Fournier Index	Erosion Risk Index (ERI)	Erosion Risk
I	Sandy Loam	14.0	Weak	0.93	0.69	4.7	36.86	0.98	Very high
II	Sandy Loam	15.5	Weak	0.90	0.70	4.5	36.86	0.77	Very high
III	Sandy Loam	14.2	Weak	0.92	0.69	4.8	36.86	0.86	Very high
IV	Sandy Loam	15.0	Weak	0.91	0.69	4.8	36.86	0.76	Very high

Soil conservation priorities

The Productivity Index (PI) and the Erosion Risk Index (ERI) were used to classify the lands for soil conservation priorities, for conservation requirements and for alternative land uses (Table 5) They are assessed using a system similar to those developed by Sheng (1972) and Larson et al. (1988) The properties of the Venezuelan soil are the result of different erosion levels caused by different number of years under a sorghum – livestock farming system. The results indicate that the Productivity Index (PI) is higher in the slightly eroded soil, whereas the severely eroded soil shows the lowest value of Productivity Index.

The Productivity Index (PI) was mainly affected by changes in available water storage capacity, bulk density and pH. A strong relationship between depth of removed topsoil and Productivity Index

The erosion risk was strongly influenced by slope gradient and especially by rainfall aggressiveness.

Finally, the Soil Productivity Index (PI) and the Erosion Risk Index (ERI) enabled to establish a land classification for soil conservation using the system proposed by Delgado (2003) (Table 6)

The areas were classified as critical lands and super-critical lands, with very high soil conservation requirements, depending on the level of soil erosion. In the Central Plains of Venezuela, on slightly eroded soil, intensive agriculture is possible, whereas on severely eroded soil only special crops or Agroforestry can be applied. Moderately eroded soil can be used with semi-intensive agriculture.

Table 6. Land classification for soil conservation

Soil	Productivity Index (PI)	Erosion Risk Index (ERI)	Soil Conservation Requirements	Land Classification	General Land Use
I	0.56	0.98	Very High	Super-critical land (P) (1st priority conservation treatment)	Intensive Agriculture
II	0.50	0.77	Very High	Super-critical land (S) (1st priority conservation treatment)	Semi intensive agriculture
III	0.37	0.86	Very High	Super-critical land (P) (1st priority conservation treatment)	Semi intensive agriculture
IV	0.27	0.76	Very High	Critical land (C) (2nd priority conservation treatment)	Special crops/ Agroforestry

Assessing the dimensions of runoff collection systems in semi-arid zones of Chile

Introduction

Arid and semi-arid zones are found to be more sensitive to soil degradation and desertification compared to other climate zones. This is due to the smaller resilience of arid zones to adverse climate conditions. Since abundant soil cover is absent in these regions, the resistance against degradation processes is minimal.

Therefore, these zones are prone to an increased soil erosion hazard, especially when the limited rainfall supply is concentrated in high intensity rain storms during a short period of the year. Actions as reforestation need to be undertaken to actively reduce the negative spiral of desertification processes in these sensitive areas.

Assessment of infiltration/runoff and sediment transport

In Chile, work has been done on incorporating water harvesting systems and soil stabilization measures in affected areas (Pizarro et al., 2003). Little efforts were done, however, to estimate the efficiency of these measures. Within the framework of an adequate soil conservation and land use policy this can be very useful in designing erosion control structures and dimensioning water harvesting techniques, two very important factors in soil conservation and rehabilitation.

Reforestation of drylands in Chile requires understanding of the infiltration/runoff process in order to determine dimensions of water harvesting systems.

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Study sites and methodology

Field sites were selected on hillslopes under extensive grazing in soil-degraded areas in the vicinity of La Serena, Illapel and Ovalle, all in the Fourth Region of Coquimbo, in the semi-arid zone south of the Atacama desert. In the northern part the annual rainfall is not exceeding 20; more central in the Elqui valley the annual rainfall can reach 95 mm, and more southwards 80 to 90% of the annual precipitation (200 to 350 mm) falls between May and August in 12 to 20 rainfall events a year. Hence the water balance is negative almost the year around. And runoff water needs to be collected if trees are planted in a reforestation programme. On the already existing water harvesting structures (such as infiltration ditches) data on dimensions, sediment deposits and infiltration rates were collected. The study will propose a methodology to evaluate the dimensions and field arrangement of those infiltration zones.

Infiltration processes in semi-arid regions of Chile were evaluated, using rainfall experiments (Figure 4). Experiments were executed on six different locations, with textures ranging from loamy and sandy loam to loam and clay loam.

Figure 4: General view of the experimental design during a rainfall simulation

A set of measurements was performed at every location: rainfall intensity, runoff, soil loss and determination of infiltration in the collecting system, using the Guelph permeameter. Additionally, various samples of the upper layer were taken to determine soil characteristics such as the soil texture, the soil water retention curve and the initial soil moisture content. At every location, the experiments were performed on three different slope gradients, 10%, 20% and 30%, to allow evaluation of the slope gradient effects on runoff production. This information, together with rainfall data and a digital elevation model of the area, can serve in a 'sediment transport model' to predict the amount of sediment loss by single storm rain events in that area.

The sediment transport model is based on the *stream power* ω *concept* used by Nearing et al (1996) for rill and interrill erosion. The stream power ω can be calculated with

$$\omega = \rho .\ g .\ S .\ q$$

with ρ the density of water, g the gravitational constant, S the slope of the field, and q the discharge per unit width.

The discharge was measured straightforward from the rainfall simulation tests, where the runoff (per unit time or pluviophase) depends on the rainfall intensity during the pluviophase.

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A sediment transport equation can be derived by plotting the sediment discharge against the stream power. This regression equation can also depend on texture and (stone) cover.

This procedure will enable to determine the amount of runoff water to be collected in the infiltration zones of the water harvesting system, the dimensions of which are to be determined taking into account the amount of sediment entering the system together with the runoff water.

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