Geophysical Research Abstracts, Vol. 7, 09585, 2005
SRef-ID: 1607-7962/gra/EGU05-A-09585

Ecohydrology of rilled slopes derived from opencast mining reclamation in a semiarid area.

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1 Introduction

Artificial slopes derived from reclaimed mining areas show some hydrological differences with respect to natural ones (Willgoose and Riley, 1994; Loch and Orange, 1997)

Different trajectories have been identified in relation to the hydrological response of artificial slopes in Mediterranean-continental areas (Nicola & Asensio, 2000). One of them is characterised by the prevalence of physico-chemical control on hydrological response. Soil compaction, crusting, texture, chemical composition, mainly control the hydrological processes, usually leading to rill system formation or intensive sheet erosion (Nicolau, 2002). Under such conditions soil moisture content, that is, water availability for plants is reduced and, on the other hand, soil removal by rill and sheet erosion is very intense. As a consequence, plant colonisation and growth results very difficult.

Hydric stress due to climate and soil properties can be accelerated by soil erosion processes. Several mechanisms have been described in order to explain the effects of soil erosion diminishing soil moisture content. These are as follows: crust development on soil surface by rainfall splash which reduces infiltration; soil roughness reduction by intensive sheet erosion, which diminishes the opportunities for runoff infiltration in inter-rill areas; decrease in soil depth that reduces water storage capacity (Pimentel & Harvey, 1999). In artificial slopes, rill erosion becomes an additional mechanism. Rill systems drain efficiently the runoff from the slope, diminishing the opportunities for runoff infiltration at the rill network scale (Nicolau, 2002). Additional soil water reduction due to erosion processes can be critical for native plant colonization and/ or introduced plants development, risking the reclamation process.

Artificial slopes derived from roads construction, mining and other earth moving works are becoming more and more frequents. Reclamation and revegetation efforts are failing in many cases, so it is needed a better basic knowledge about ecohydrology in order to face up successfully the water deficit problem.

This study shows a synthesis of the hydrology and plant colonization interaction in rilled-constructed slopes derived from opencast mining reclamation in Utrillas Field Site, Central Spain. Our hypothesis states that hydric stress due to climate and soil properties is accelerated by rill network dynamics. We analyze the effects of this additional soil water reduction on plant colonisation and development with regard to soil seed bank dynamics; annual herbaceous plant emergency, survival and fruit production; and planted shrubs growth.

1.1 Experimental area description

Study area

Utrillas Field Site is located in central-eastern Spain (Figure 1). The area is located in the *Sistema Ibérico* range at 1,100 m altitude. The mean annual air temperature is 11˚C (6.8˚C in December and 23.5˚C in July). The air frost period runs from October to May. The climate is semiarid, mess-thermal and without water excess according to Thornthwaite terminology. Mean annual rainfall is 466 mm, 28% falling in June and May and 20% falling in September. The hydrologic deficit is 292 mm from June to October. A wider description of the environment is available at Nicolau (2002).

2 Hillslope reclamation and characteristics

The El Moral mine was reclaimed between 1986 and 1989. The general slope is 15˚, divided into 8 steps, each 18-20˚ and 25-100 m long. The spoil bank body is made up by limestone, clay, sandstone and marls. The substratum covering the slopes –overburden- consists of 100 cm of a geological layer composed of grey clays, sandstones and silt-sands. Revegetation was undertaken by seeding with perennial grasses and leguminous (*Festuca rubra, Festuca arundinacea, Poa pratensis, Lolium perenne* and *Medicago sativa*). A dense rill network is developing. The sediment yield in the first year after seeding was around 14-16 Kg/m^2 and between 5 and 11 Kg/m^2 the second year.

Experimental layout

Three rilled slopes have been monitored in last fifteen years. They represent a gradient of rill density. The most rilled slope (Plot 1) has a density of 4,4 m/m^2; 2,7 m/m^2 the intermediate (Plot 2) and 0 m/m^2 the lowest one (Plot 3). Topography, soil properties and reclamation treatments are very similar (tables 1 and 2). Differences deal with the runon coming from the upper part of the slopes in some periods. External sources of runoff are a berm (terrace) in Plot 1 and a very deep head in Plot 2. There has not been external sources of runoff in Plot 3.

Table 1. General characteristics of slopes (mean and standard deviation)

	Length (m)	Slope angle (º)	Plant cover (%)	Aerial biomass (g/m^2)	Species richness	Rill nur
Slope 1	40.0	20	8.54 9.46	30.16 0.21	5	16.00 6.93
Slope 2	78.5	20	26.59 13.44	140.76 4.20	14	7.66 3.21
slope 3	80.2	20	35.48 12.88	323.60 0.12	20	0.00

Table 2. Soil properties of slopes (mean and standard deviation)

	pH	Conduct. (μs/cm)	Stones (%)	Sand (%)	Silt (%)	Clay (%)
Slope 1	7.62 0.45	758.83 233.27	15.72 2.00	32.71 6.82	28.51 6.41	38.77 2.61
Slope 2	8.44 0.07	116.66 12.32	27.71 5.43	36.44 0.92	28.41 0.92	35.15 1.84
slope 3	8.48 0.04	120.27 10.71	24.47 4.45	42.2 1.91	27.49 1.38	30.41 0.57

Hydrological regime has been studied in Plot 1 by means of runoff collectors at the rill network / slope scale and by means of *Gerlach* boxes and rainfall simulator at the interrill scale (Nicolau, 2002). Soil moisture content is registered monthly with TDR. Plant biomass and richness has been measured in 50 x 50 cm plots. Soil seed bank in 30x30 cm plots.

2.0.1 Soil properties strongly condition rainfall infiltration and so, water availability for plants

Hydrological response in overburden soil with low vegetation cover is determined by soil properties. The high proportion of loam and fine sands and the lack of any biological control favour soil surface changes during the year in a sequence as follows: sealing from late spring to early autumn, swelling in autumn and winter, disaggregation after the frost period and then compaction again as spring advances.

When soil surface remains sealed, runoff can be explained by the infiltration excess model. The rainfall thresholds for runoff are very low (1.8-4.0 mm) as well as infiltration rates are very low too (6.6-9.0 mm/h^{-1}), so most of the rainfall input is converted into runoff regardless of its intensity. In such a case, runoff volume depends more on rainfall volume than on rainfall intensity. Soil moisture content from surface to 20 cm depth reaches the lowest values of the year. Such hydric stress impedes grasses and annual plants survival. In late autumn and winter when soil swells, raising soil moisture content to 13-15%, rainfall threshold for runoff can be as low as 2.7 mm, runoff being also more dependent on rainfall volume than on intensity. In such conditions seeds are able to born and annual plants start their biological cycle. A third type of response was observed in early spring, when the soil is loosened by the late winter frosts and crust is not formed. In this period rainfall threshold for runoff rose up to 10 mm. Water flow runs along cracks and macropores, leading to pipe and rill generation in late spring. Infiltration curve from rainfall simulator experiment in spring shows longer time to runoff (5 minutes), higher final infiltration rate (9.0 mm h^{-1}) and lower runoff rate (52.9%) compared to autumn. In that period soil conditions for rainfall infiltration are optimum, so, if rainfall events occurs along the season, the water recharge of the soil is produced. Of course plants demanding surficial water –like annual plants- are able to grow. Late spring is a critical period for annual plants because they start the reproduction; it is the time for producing flowers. In May and June soil crust is formed again, so, soil moisture decreases. When there is not enough water most of the annual plants die when flowering.

2.0.2 Rill system dynamics strongly condition runoff routing along the slope and so, water availability for plants

2.0.3 Effects of rill erosion on moisture content

Soil moisture content at the upper part of the soil profile is negatively correlated to the rill network density. A single measurement after a storm event of 17,9 mm in two slopes confirmed the hypothesis (Table 3).

Table 3. Mean and standard deviation of soil moisture content after a storm.

	Moisture content at 3 cm depth (% weight)	Moisture content at 10 cm (% weight)
Slope A (0 cm^2 of rills)	16.81 11.66	11.83 7.79
Slope B (881.83 cm^2 of rills)	5.49 1.89	5.41 1.70

Monthly moisture measures taken in Plots 1, 2 and 3 show higher values in plot 3 –no rilled- with respect to the rilled slopes; and lower in the more rilled (1R) than in the less one (2R). On the other hand, moisture content in rills bed (2R, 1R) is higher than in interrill areas (2IR, 2R).

Figure 1. Monthly soil moisture values.

Effects of rill network development on annual plants colonization.

Tables 4 and 5 show a qualitative difference between non rilled slopes (Plot 3) and rilled slopes (Plot 1 and 2). Slope colonization by annuals is almost impossible in rilled slopes. Seeds emergency in autumn is very low, and on the other hand, most of them do not survive to the late spring drought, so are not able to produce nor flowers nor fruits. As a consequence, seed banks richness is very poor. Both indicators, autumnal seed emergency and seed bank richness, show figures of about one order de magnitude lesser in rilled than in no-rilled slopes.

Table 4. Autumnal seed emergency in 2003. (Number of germinations / m^2. Mean and standard deviation).

	Upper slope area		Down slope area	
	Inter-rill	Rill bed	Inter-rill	Rill
Slope 1	20.00 41.04	32.50 42.22	8.75 14.67	36.2 122
Slope 2	88.33 67.39	101.67 85.80	210.00 183.91	240 193
slope 3	1927.50 666.92		1305.00 493.68	

Table 5. Seed richness in soil seed bank (seeds / m^2). (mean and standard deviation)

	Upper slope area		Down slope area	
	Inter-rill	Rill bed	Inter-rill	Rill bed
Slope 1	106.90 133.67	485.20 648.02	49.34 120.51	213.82 385.17
Slope 2	230.26 216.10	444.08 936.66	263.16 263.59	756.57 1138.76
slope 3	2286.18 1788.95		1759.87 2360.70	

Effects of rill network development on shrubs colonization and growth Shrubs presence in studied slopes is a consequence of both, revegetation works and natural colonization. *Medicago sativa* is the only shrub introduced by active revegetation. It is a deep-rooted plant exploiting deep water resources into the soil profile that grows during the summer. It is present in the three slopes. Natural shrubs, like *Thymus sp.* or *Genista scorpius* are only abundant in the non-rilled slope (plot 3). They are scarce in plot 2 and absent in the most rilled slope (plot 1). Table 6 displays differences in plant cover, aerial biomass and species richness.

Table 6. Vegetation response at the community level (mean and standard deviation)

The growth of *Medicago sativa* during the summer even in the most rilled slope deserves an explanation. Of course it is exploiting deep water. Where does it come from?

	Plant cover (%)	Aerial biomass (g/m^2)	Species richness
Slope 1	8.54 9.46	30.16 0.21	5
Slope 2	26.59 13.44	140.76 4.20	14
Slope 3	35.48 12.88	323.60 0.12	20

It comes from infiltration from inter-rill areas, that occurs in winter and in some wet springs. And it also comes from bed rills infiltration. In fact, infiltration inside bed rills is a second source of water to plants, which goes into the soil directly at 40-50 cm depth. This could be considered like a by-pass way because runoff drained from inter-rill surface re-infiltrates into the soil at 40-50 cm depth, without flowing through the whole soil profile. According to the runoff data at the rill network and the inter-rill scale, infiltration in rills bed is between 25% and 43% of the total annual overland flow, depending on rill network density (Nicolau, 2002). A possible paradoxical negative feedback between erosion and plant growth could be produced: As rill erosion increases and rills become deeper and deeper, more deep moisture would be available for shrubs, so these could develop a higher growth.

2.1 Conclusions

Physic-chemical properties of overburden substratum lead to crust formation, which strongly limits rainfall infiltration and soil moisture content.

Rill networks by draining efficiently overland flow at the slope scale, contribute, in an additional way, to the water deficit at the upper soil level.

Runoff re-infiltration in bed rills is a deep source of water that plants can exploit in summer.

Plant colonization by seeds is not possible in the rilled slopes because of the late spring drought at the soil surface, which inhibits flowering. Failure in developing the whole biological cycle leads to soil seed bank impoverishment.

Only deep-rooted shrubs introduced by means of the revegetation works can resist and growth exploiting deep water resources. Introduced grasses species also disappear in the most rilled slopes because of the lack of moisture at the top levels of the soil.

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Acknowledgements

This research has been supported by the *Minas y Ferrocarril de Utrillas* SA company; the project UAH PI2004/024 of the Alcalá de Henares university and the CYCIT project from the Spanish government *Restauración ecológica de áreas degradadas en ambientes mediterráneos continentales. Optimización del uso del agua*