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Transmission losses in rills on dryland hillslopes

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Abstract:

Transmission losses through the beds of hillslope rills were studied at two sites in the semi-arid south-western United States. At one site the rills were sand-bedded and at the other they were gravel-bedded. Transmission losses in the sand-bedded rills are about 66% higher than those in the gravel-bedded rills. The former show evidence of increasing transmission loss with increasing depth of flow, whereas the latter do not. In both cases, transmission losses in the rills are about an order of magnitude greater than infiltration losses in adjacent interrill areas. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS dryland hillslopes; rills; transmission loss

INTRODUCTION

Much of the water that flows in ephemeral river channels in drylands is absorbed through the alluvial material of the channel bed and banks during its transmission through the channel. Consequently, measured outflow from dryland catchments is less than measured runoff. Renard (1970), for example, found that in the 150 km^2 catchment area of Walnut Gulch in south-eastern Arizona, precipitation excess (runoff) was *c.* 50 mm per annum, but that only *c.* 6 mm per annum of surface runoff emerged from the basin outlet. Transmission losses are an important element of the hydrology of drylands since they cause reductions in stream flow and locally recharge groundwater. An understanding of transmission losses is therefore essential for hydrological modelling of dryland catchments.

Several attempts have been made to estimate the transmission loss in river channels by using routing techniques (e.g. Cornish, 1961) or by deriving equations from loss rates observed from comparisons in input and output data over a channel reach (e.g. Jordan, 1977; Lane, 1982; Sharma and Murthy, 1994a,b; Sharma *et al.*, 1994). Although such comparisons of input and output discharges define a transmission loss over a channel reach, it has been recognized that this loss is not independent of the discharge so that the rate of loss is not uniform over the reach. Jordan (1977) found that losses were proportional to the flow at the upper (input) station. Consequently, it has been necessary to attempt some standardization in the equations for transmission losses by calculating the loss for the first kilometre of the channel reach (Jordan, 1977).

Hillslope runoff that provides the flow for ephemeral river channels in dryland catchments frequently passes through rills, particularly on the lower portions of hillslopes, and these rills can also be expected to exhibit transmission losses. For a more complete understanding of both hillslope hydrology and erosion and the delivery of water and sediment from hillslopes to rivers in dryland catchments it is necessary to have information on transmission losses through these rills. Because of differences in channel bed and bank

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materials between rills and rivers, it is unlikely that the results of transmission loss studies of river channels can be directly applied to hillslope rills. However, no study has hitherto been undertaken of transmission losses in rills. The aim of this paper, therefore, is to provide the first quantitative information on transmission losses in rills on dryland hillslopes.

STUDY AREAS AND METHODS

Two sets of rills were selected for study. The first set was sited within the Jornada Long-Term Ecological Research Site (32°31′N, 106°47′W), 40 km NNE of Las Cruces, New Mexico, and the second within the USDA–ARS Walnut Gulch Experimental Watershed, Tombstone, Arizona (31°43′N, 110°41′W). Both sites experience a semi-arid climate with the majority of the rain falling during summer and early autumn from high intensity, short duration, convective thunderstorms. This rainfall accounts for almost all the hillslope runoff at the two sites.

At the Jornada site, the rills were located on the bajada surface fringing the north-eastern side of Mt. Summerford, the northernmost peak of the Donã Ana mountain range. The sediment that derives from Mt. Summerford and forms the bajada consists of granitic grus, mostly medium to coarse sand and gravel. The rills that are developed on this surface exhibit alternating reaches of well and poorly defined channels. In their well-defined reaches the rills are typically less than 2 m wide, incised up to 80 cm into the bajada surface, have a sandy bed and are fairly straight. The reaches of poorly defined channels either consist of numerous anastomosing threads occupying an area 10 or more metres wide or exhibit no clear evidence of channelized flow at all. These reaches are invariably sandy. Downstream of them one or more threads of flow becomes progressively more evident and eventually form a new, well-defined reach of the rill. All the rill sites selected for this study were located within the well-defined reaches. At these sites, the bajada vegetation is dominated by *Larrea tridentata* and has a canopy cover of about 38%. The local gradient is about 2 degrees.

At Walnut Gulch, the rills were located along a hillslope within a dissected piedmont underlain by well-cemented Quaternary alluvium (Gelderman, 1970). Such rills have developed on the lower parts of many of the hillslopes of the dissected piedmont in response to a change in vegetation from grassland to shrubland that has taken place since the 1880s (Parsons *et al*., 1996). These rills have formed within gravel-mantled swales between shrubs and, with the exceptions of locations where they divide into two channels around a shrub or clump of shrubs, they are single thread, continuous channels. They are typically 50–100 cm wide and sinuous. Their beds are coarser in texture than the rills of Jornada and typically have a gravel cover of 60–70%, not dissimilar to the surface cover of the adjacent intershrub area. At the locality of the rills selected for study, the shrub community is dominated by *Larrea tridentata*, *Dasylirion wheeleri*, *Acacia constricta*, *Rhus microphylla* and *Yucca baccata* and has a canopy cover of about 44%. The local hillslope gradient is about 6 degrees.

For the experiments reported in this study, 10 reasonably straight rill reaches of about 5 m in length and relatively uniform cross-sectional characteristics were sought at each site. In practice, the rills selected at Jornada were straighter, longer and more uniform in cross-section than those chosen at Walnut Gulch. Water simulating rill flow was introduced at the upper end of each reach from a perforated PVC pipe for which a calibration between discharge and water pressure had previously been established. By varying the pressure in the pipe the inflow to the rill could be controlled. The pipe was placed within a hollow excavated into the rill bed, lined with an impermeable sheeting and levelled across the downslope edge slightly higher than the rill bed. Discharge from the hollow overflowed across a metal ramp into the rill. Sediment was added to this discharge as it crossed the metal ramp at a rate sufficient to prevent rill scour or fill by the flow.

The downstream end of each rill reach was excavated and a flume installed at which timed volumetric samples were obtained to determine the outflow from the reach. Within each reach, cross-sections were established (four at Jornada and three at Walnut Gulch) at approximately equal spacings between the inflow ramp and the outflow flume. The short rill section between the most downstream cross-section and the outflow flume was sealed by sprinkling on it a mixture of one part Elmer's wood glue and two parts water.

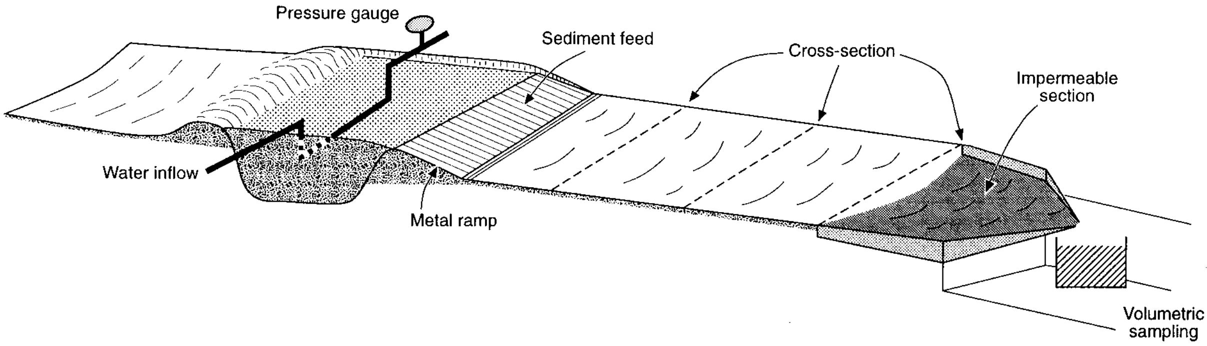

Figure 1. Experimental set-up for measurements of transmission loss at Jornada and Walnut Gulch

This mixture infiltrated to a depth of several millimetres, rendering the surface impermeable without appreciably altering its roughness. At each of the cross-sections the depth of flow was measured at 5 cm intervals on the wider rills and 2·5 cm intervals on the narrower ones to obtain cross-sectional area of flow. Because the discharge at the lowermost cross-section is the same as that at the reach outlet, an area–discharge rating curve could be established for this cross-section. Assuming no down-rill change in flow velocity (because of the uniform cross-section), this rating curve can then be used to determine discharge from the readings obtained at the other cross-sections. This experimental method is summarized in Figure 1.

EXPERIMENTS AND RESULTS

Jornada site

Using the general methodology described above, two experiments were performed on the rills at the Jornada site. The first of these sought to identify the changing transmission loss in the rise to equilibrium flow in the rill by taking timed volumetric samples from the outflow flume. The second experiment sought to identify the relationship between down-rill distance (discharge) and transmission loss by analysing the relationships of equilibrium discharges at the inflow (determined from the pipe calibration) and the four rill cross-sections (calculated from the rating curves) to the distance down-rill. These two experiments were performed on dry rill beds with an inflow discharge of 1720 $cm^3 s^{-1}$.

The results from the first experiment demonstrated that equilibrium flow through the rill reach was achieved within 1–2 minutes of the start of the flow. Unfortunately, our sampling rate was too slow to provide sufficient samples to characterize the rising limb of the rill hydrograph.

The analysis of equilibrium discharges, however, yielded a consistent set of results. The rill reaches exhibit significant transmission losses (varying from 22·5 to 50·7%) and this loss appears not to be a linear function of distance down-rill (Figure 2). Taking into account the uncertainty associated with estimating discharges at the cross-sections from rating equations, the results show a remarkably consistent pattern in which the transmission loss is an exponential function of distance, and hence discharge, down-rill.

To test further the possibility that transmission loss is a function of discharge, we have examined the relationship of transmission loss to unit discharge in the rills. Because the inflow rate was the same for all rills studied, unit discharge (and hence depth of flow) must be inversely proportional to the width of the rills. If it is the case that transmission loss is a function of flow depth then it may be expected that there should be greater transmission loss in the narrower rills than in the wider ones. Figure 3 shows unit discharge for each rill (calculated by estimating average rill width from the measurements at the four cross-sections) plotted against distance down-rill. Spearman's rank correlation of unit discharge loss per unit length of the rill reach (to take account of the differences in reach length) against unit discharge at the head of the reach yields a value of $r_s = 0{\cdot}46$. Although this value fails a test of statistical significance at 5% ($p = 0{\cdot}089$), it does

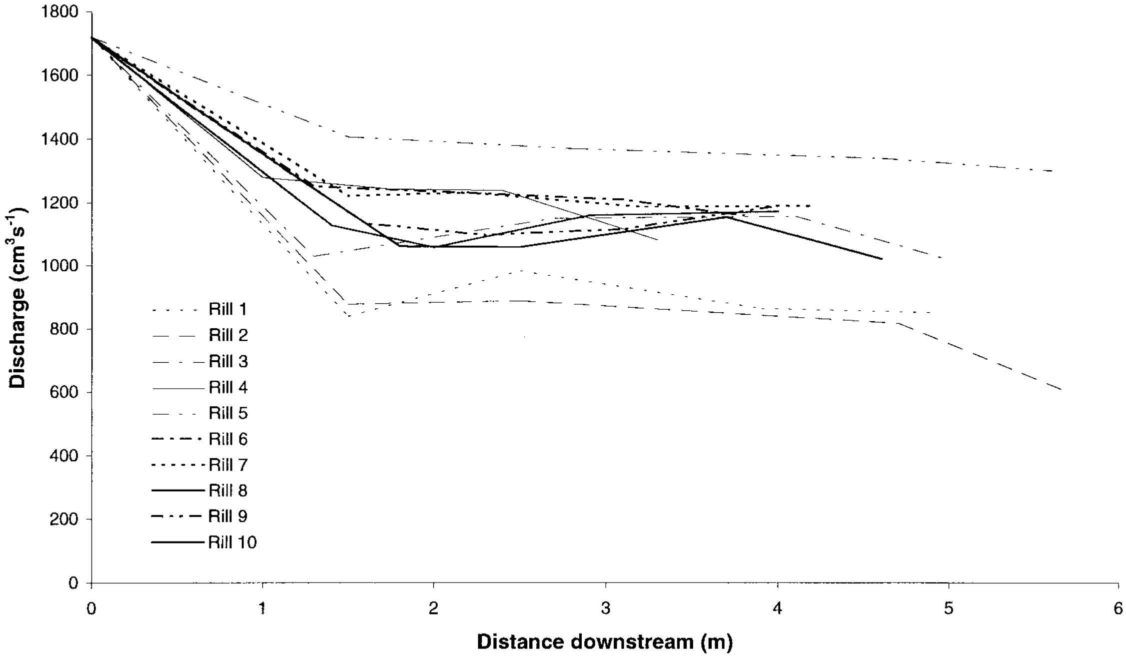

Figure 2. Rill discharge as a function of distance down the experiemental reach for the 10 rills studied at Jornada. Differences in plot length result from differences in lengths of experimental reach

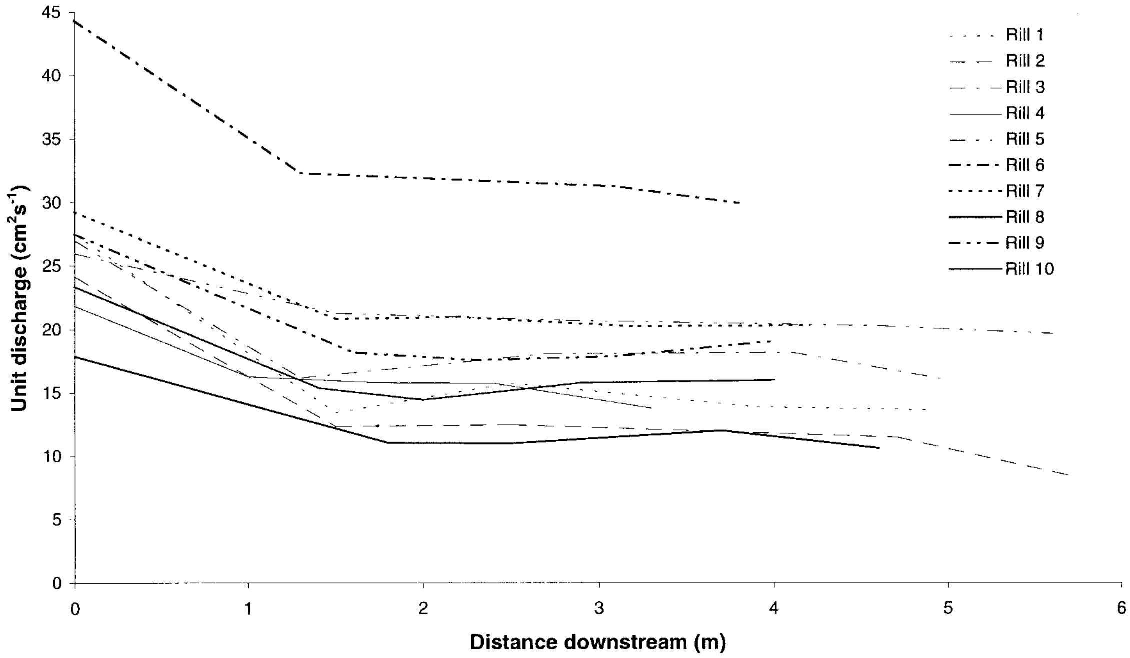

Figure 3. Unit rill discharge as a function of distance down the experimental reach for the 10 rills studied at Jornada

provide some support for the argument that transmission loss varies with discharge, particularly when this value is compared with that for the Walnut Gulch rills (see below).

Walnut Gulch site

The methodology used at the Jornada site was repeated at the Walnut Gulch site except for two modifications. First, in order to obtain a better representation of the rising limb of the hydrograph more rapid sampling of the outflow during the rising limb was undertaken. Secondly, to examine further the effect of discharge on the transmission loss a third experiment was undertaken immediately following the second. In this experiment the outflow from the perforated pipe was raised from that of the first two experiments (1578 $cm^3 s^{-1}$) in four stages (1980, 2377, 2946 and 3366 $cm^3 s^{-1}$). Once equilibrium outflow from the rill was attained at each discharge, the width and depth of flow were measured at the three cross-sections. Discharges for these cross-sections were then calculated using the rating curve method described above.

As at Jornada, equilibrium discharge through the reach is attained within 1–2 minutes. Equilibrium transmission losses, however, are lower than those at the Jornada site and range from 9·7 to 32·0%. The more frequent sampling during the rise to equilibrium permitted a much better representation of the rising limb of the hydrograph (Figure 4). Experiment two was less successful. The rating curve method failed to give any consistent pattern in the down-rill transmission loss. In all probability, this result reflects the less uniform cross-sectional form of the rills at Walnut Gulch which introduces significant errors in the rating curve method of estimating discharge. The effects of discharge on transmission loss have therefore been assessed on the basis of differences between inflow and outflow at the five discharges put through the rill reach (Figure 5). It can be argued that if transmission loss increases with discharge then the discrepancy between input and output discharge should become greater as discharge increases. Conversely, if discharge does not affect transmission loss then the difference between the input and output discharge should remain

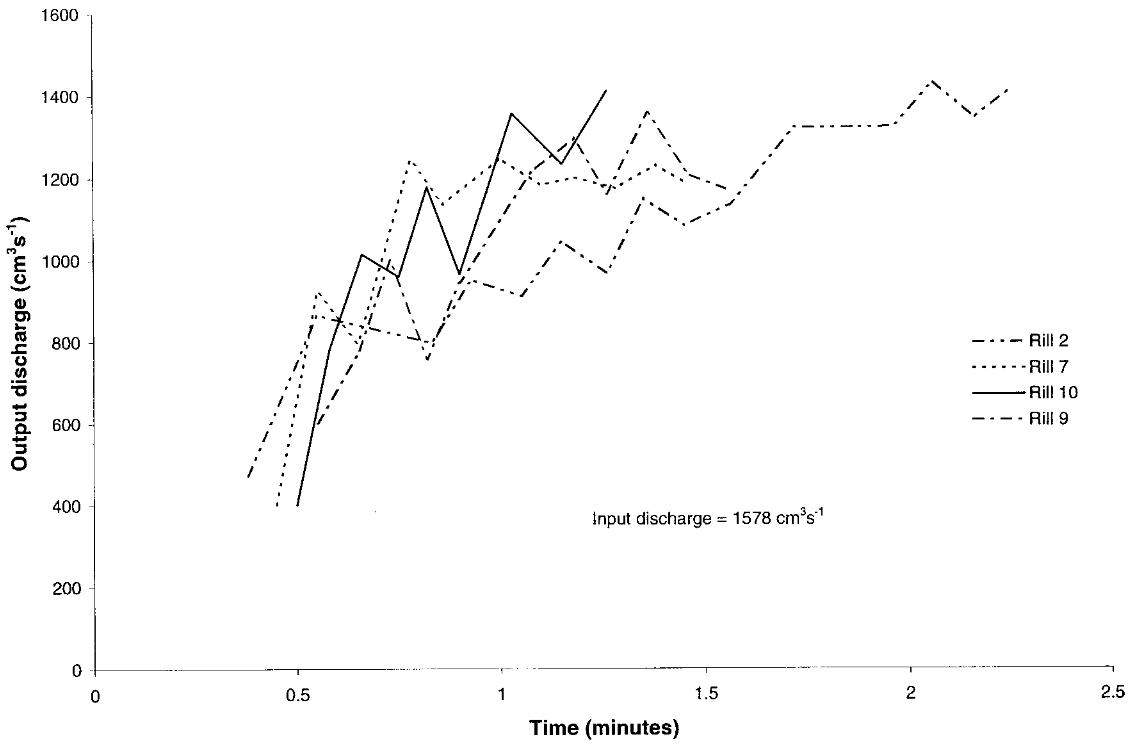

Figure 4. Plots of output discharge against time for the first five minutes of experiments on four of the rills at Walnut Gulch

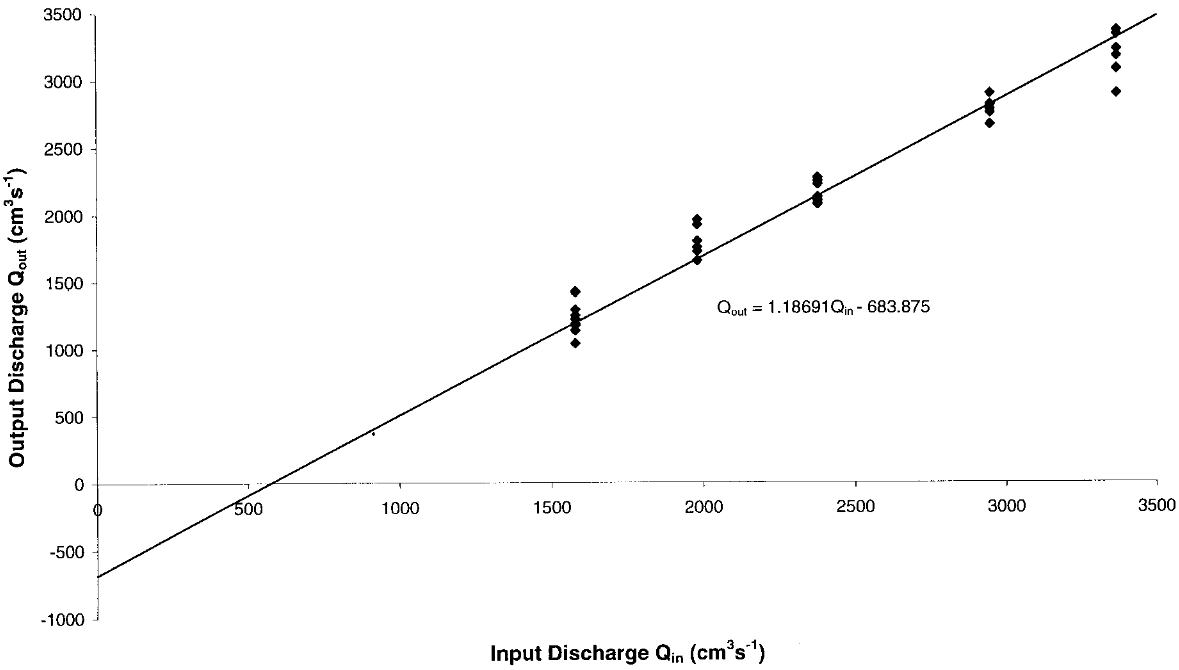

Figure 5. Comparison between input and output discharges at equilibrium for the rills at Walnut Gulch for the five values of input discharge

constant. In the former case, the best-fit line through a graph of output discharge against input discharge should have a positive value for input discharge when the output discharge is zero (the difference being the input discharge lost through the bed over rill the reach) and a slope of less than 1 (indicating that as input discharge rises so there is an increase in transmission loss). In the latter case, the best-fit line will also have a positive value for the input discharge when the output discharge is zero but the slope of the line will be 1 (indicating that the same amount of water is lost through the rill reach, irrespective of the discharge). A plot of the output discharge against the input discharge for the 10 rill reaches is shown in Figure 5. Inasmuch as the best-fit line through these points has a slope slightly greater than 1 ($b = 1{\cdot}1869$, SE $= 0{\cdot}0402$), it is evident that the difference between input and output discharge does not increase with discharge. Thus, unlike the rills at Jornada, those at Walnut Gulch exhibit no evidence of transmission loss increasing with discharge. That the slope of the best-fit line is slightly greater than 1 is probably attributable to a slight decrease in equilibrium transmission loss over time. Although it is usual to regard runoff as reaching equilibrium after some finite time, in reality a plot of runoff against time is an asymptote, and the so-called period of equilibrium runoff is more correctly regarded as a period in which runoff increases only very slowly with time.

As with the rills of Jornada, we have also tested the relationship of unit discharge loss per unit length of rill reach to unit discharge at the head of the reach. The result shows that $r_s = 0{\cdot}042$ ($p = 0{\cdot}367$) which lends support to the argument that these rills differ from thosse at Jornada in showing in evidence of transmission loss increasing with discharge.

DISCUSSION

Transmission loss is, in essence, infiltration. It is useful, therefore, to compare the transmission losses observed at the two sites with data on infiltration from the adjacent interrill areas. For the Jornada site, because of the poor representation of the rising limb of the rill hydrograph, this comparison can be only with

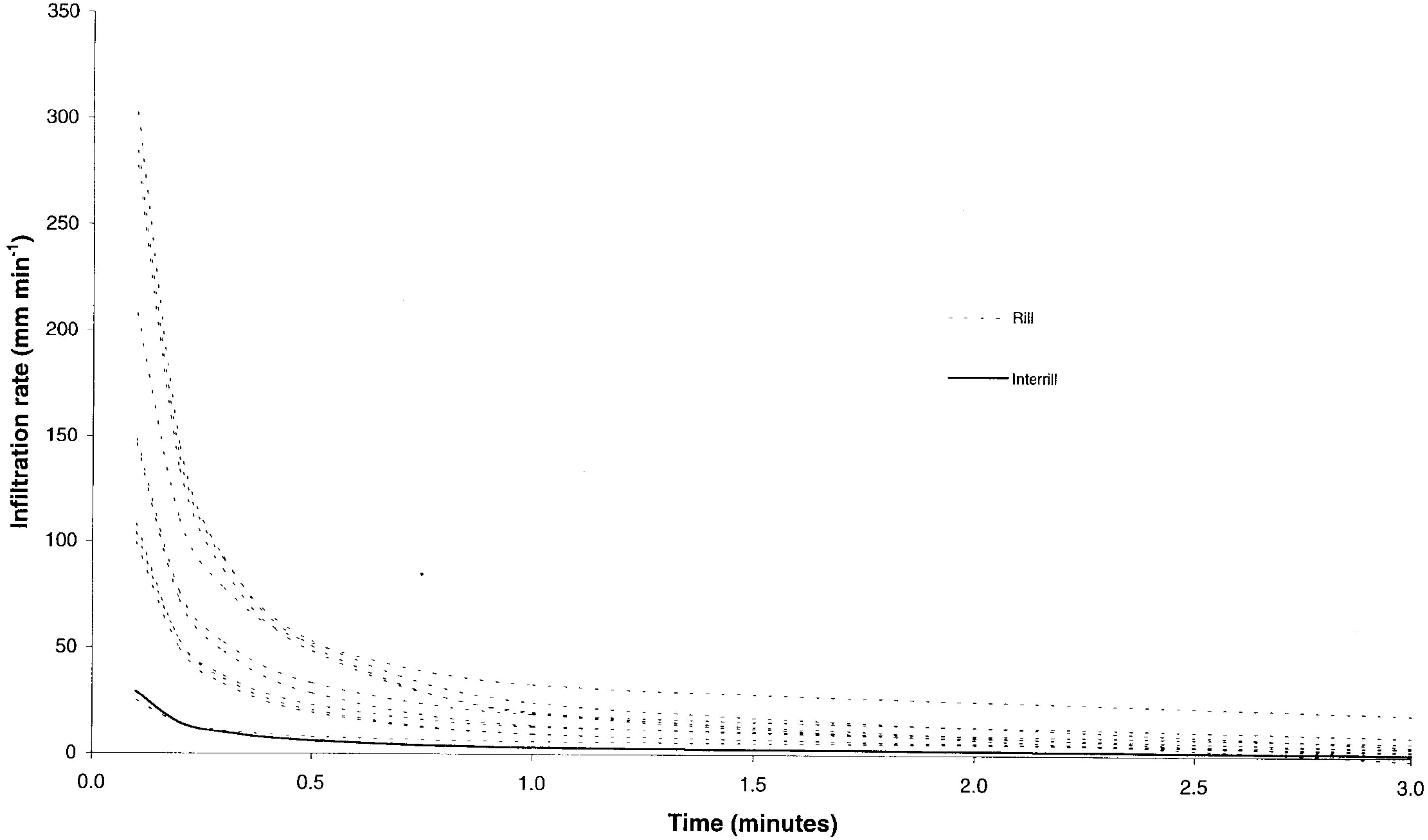

Figure 6. Comparison of transmission losses in rills with infiltration on adjacent interrill desert pavement at Walnut Gulch

the saturated hydraulic conductivity of the interrill area. Experiments performed on 1 m^2 areas under simulated rainfall at intensities ranging from 1·93 to 2·32 mm min^{-1} give an average saturated hydraulic conductivity of 0·50 mm min^{-1}, compared with an average transmission loss of 9·24 mm min^{-1} in the rills. Given the difference between the sandy rill-bed sediments and the finer textured interrill soils, it is not surprising that the infiltration through the rill beds is greater than that observed in the interrill areas. However, a further consideration in explaining the observed difference in saturated hydraulic conductivity is the method used in its determination. For the interrill areas it was determined as the difference between the rainfall rate and the runoff rate. Its value is, therefore, limited by the rainfall rate (Hawkins, 1982) and is probably further reduced by surface sealing due to rainfall impact. For the rills, the values are more akin to data obtained from ponded-infiltration experiments. Indeed, the disparity between the two values is not much greater than the difference reported elsewhere for experiments on ponded and rainfall infiltration (e.g. Watts, 1989; Wainwright, 1996).

For Walnut Gulch the better representation of the rising limb of the hydrograph means that it is possible to compare transmission loss as a function of time to infiltration curves obtained, like those at Jornada, from 1 m^2 plots under simulated rainfall. A comparison of the average transmission loss for the 10 rills to infiltration measured within the intershrub swales (Scoging *et al.*, 1992) is shown in Figure 6. In this case, notwithstanding the difference in method, the average infiltration curve for the intershrub swales lies close to the bottom end of the range of transmission loss curves for the rills. Such similarity reflects the similarity of the rill beds to the intershrub swales. In both cases a layer of coarse particles covers the surface. However, the average equilibrium transmission loss through the rill beds is 5·10 mm min^{-1}, compared with a saturated hydraulic conductivity of the interrill area of 0·52 mm min^{-1}. Thus, just as at Jornada, there is an order of magnitude difference between transmission loss in the rills and infiltration in the adjacent interrill area.

The implications of these results for modelling runoff and erosion on dryland hillslopes are as follows. Even though the observed transmission losses in rills are not greater than might be anticipated from ponded-infiltration experiments on nearby interrill areas, the fact remains that surface runoff passing through the rills is being lost at a rate an order of magnitude greater than the infiltration rate on nearby interrill areas. Thus, runoff from rills and interrill areas needs to be modelled separately both in terms of infiltration losses and in terms of runoff hydraulics (see Parsons *et al.*, 1990; Abrahams *et al.*, 1996). Furthermore, the greater rate of loss of runoff in the rills has implications for the ability of rill flow to transport sediment supplied to the rills by interrill flow.

CONCLUSIONS

This study has provided the first evaluations of transmission losses through rills on dryland hillslopes. The results show that transmission losses in the sand-bedded rills at Jornada were about 66% higher than those in the gravel-bedded rills at Walnut Gulch. In the sand-bedded rills there is evidence that transmission loss increases with discharge, whereas in the gravel-bedded rills it appears to be independent of discharge. In both cases, transmission losses are about an order of magnitude greater than infiltration rates on adjacent interrill areas. The transmission losses reported here probably encompass most of the range of such losses in rills and can be used in modelling runoff and erosion on dryland hillslopes.

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REFERENCES

Abrahams, A. D., Li, G., and Parsons, A. J. 1996. 'Rill hydraulics on a semi-arid hillslope, southern Arizona', *Earth Surf. Process. Landf.*, **21**, 35–47.

Cornish, J. H. 1961. 'Flow losses in dry sandy channels', *J. Geophys. Res.*, **66**, 1845–1853.

Gelderman, F. W. 1970. *Soil Survey of Walnut Gulch Experimental Watershed: A Special Report*. US Department of Agriculture, Soil Conservation Service and Agricultural Research Service, Portland, Oregon, 54 pp.

Hawkins, R. H. 1982. 'Interpretations of source area variability in rainfall–runoff relations', In *Rainfall–Runoff Relationships*. Water Resources Publications, Fort Collins, pp. 303–324.

Jordan, P. R. 1977. 'Streamflow transmission losses in Western Kansas', *J. Hydraul. Div. ASCE*, **103**, 905–919.

Lane, L. J. 1982. 'Distributed model for small semiarid watersheds', *J. Hydraul. Div. ASCE*, **108**, 1114–1131.

Parsons, A. J., Abrahams, A. D., and Luk, S.-H. 1990. 'Hydraulics of interrill overland flow on a semi-arid hillslope, southern Arizona', *J. Hydrol.*, **117**, 255–273.

Parsons, A. J., Abrahams, A. D., and Wainwright, J. 1996. 'Responses of interrill runoff and erosion rates to vegetation change in southern Arizona', *Geomorphology*, **14**, 311–317.

Renard, K. G. 1970. The hydrology of semi-arid rangeland watersheds. *ARS 41-162*. USDA Agricultural Research Service, Washington D.C., 26 pp.

Scoging, H., Parsons, A. J., and Abrahams, A. D. 1992. 'Application of a dynamic overland-flow hydraulic model to a semi-arid hillslope, Walnut Gulch, Arizona', in Parsons, A. J. and Abrahams, A. D. (Eds), *Overland Flow Hydraulics and Erosion Mechanics*. UCL Press, London, pp. 105–145.

Sharma, K. D. and Murthy, J. S. R. 1994a. 'Estimating transmission losses in an arid region', *J. Arid Environ.*, **26**, 209–219.

Sharma, K. D. and Murthy, J. S. R. 1994b. 'Estimating transmission losses in an arid region — a realistic approach', *J. Arid Environ.*, **27**, 107–112.

Sharma, K. D., Murthy, J. S. R., and Dhir, R. P. 1994. 'Streamflow routing in the Indian arid zone', *Hydrol. Process.*, **8**, 27–43.

Watts, G. P. 1989. Modelling the subsurface hydrology of semi-arid agricultural terraces. *Unpubl. PhD Thesis*, Bristol University, Bristol.

Wainwright, J. 1996. 'A comparison of the interrill infiltration, runoff and erosion characteristics of two contrasting 'badland' areas in southern France', *Z. Geomorphol.*, **106**, 183–198.

