Effects of Soil Conservation Practices on Sediment Yield from Forest Road Ditches in Northern Iran

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Abstract

The fine-textured soil in forest road ditches is very susceptible to water erosion especially in rainy seasons in Hyrcanian forest. This study examined the yield of ditch segment-scale sediment after releasing two flow rates of 5 l s^{-1} and 10 l s^{-1} in segments treated by riprap (RR), grass cover by Festuca arundinacea L. (GC), compacted cotton geotextile (CG) and wooden wattle by local slash (WW). Sediment sampling from the runoff was carried out at the end of each segment every minute. Runoff flow velocity in different treatments was measured using an electromagnetic flow meter. Sediment concentration and runoff velocity in treatments of RR, GC, CG, WW was significantly lower than that of the control plot (Ctl). Increasing flow rate from 5 l s^{-1} to 10 l s^{-1} caused no significant change in sediment concentration (except for Ctl and RR) and runoff velocity (except for Ctl and CG), which means that some water might have penetrated into treated soil by RR, GC and WW and this is not acceptable in forest road maintenance practices. Sediment yield from RR (0.36 g l^{-1}) and Ctl (0.50 g l^{-1}) under the flow rate of 10 l s^{-1} was significantly higher than that of 5 l s^{-1} with values of 0.21 g l^{-1} and 0.38 g l^{-1}, respectively. Minimum amount of sediment concentration was observed for CG (0.20 g l^{-1}) with compacted ditch bed. Moreover, runoff velocity in CG and Ctl under the flow rate of 10 l s^{-1} was significantly higher than that of 5 l s^{-1}. For a forest road with dimension 30×50 cm, slope of 5%, and clay soil with porosity of 57%, treatments of compacted CG can be used in ditch with low flow rates (5 l s^{-1}) and high flow rate (10 l s^{-1}) because of their high efficiency in reducing sediment yield.

Keywords: conservation treatments, cotton geotextile, flow simulation, sediment concentration, water erosion

1. Introduction

Forest roads provide easy and quick access to forest regions in order to harvest wood and non-wood products, provide forest protection, recreation, forestry and education (Demir and Hasdemir 2005, Galia et al. 2017). On the one hand, due to the high cost of construction and maintenance, these roads are considered as one of the most important investments in forest management and at the same time they are viewed as the largest human intervention in the wild and dynamic forest ecosystems (Foltz et al. 2009, Stenberg et al. 2015). By causing natural deformation of the slope, cutting down the surface and subsurface flow, reducing the vegetation cover, and finally, increasing soil compaction, especially on the road surface, forest roads lead to the increase in the velocity of runoff, cause exacerbation in erosion and sediment production in the adjacent ditch (Tague and Band 2001, Forsyth et al. 2006, Efta and Chung 2014, Lang 2016, Streeter et al. 2019). The rate of ditch sediment is influenced by factors such as soil type (Daly et al. 2017), velocity and shear stress of runoff (Falbo et al. 2013, Haahti et al. 2014), geometric shape of ditch (Kumwimba et al. 2016), slope gradient (Broda et al. 2016, Matthew et al. 2019). Materials detached from the ditch contain nutrients (macro and microelements), solids and organics, which are suspended as sediment load (Vymazal and Březinová 2018, Schilling et al. 2018).

The temporary and/or permanent stabilization of ditch using environmentally friendly techniques and/or mechanical operations can be regarded as a useful measure in the reduction of sediment yield from roads to canals and rivers (Jia et al. 2019). In temporary stabilization techniques through the deployment of vegetation cover, geotextile installation, etc., straw and wood mulch can be found that is usually deteriorated after several years (Appelboom et al. 2002). In permanent stabilization techniques, ditch stabilization is performed by deployment of hard covers such as concrete and riprap and flexible covers such as seasonal grasslands (Cerdá 2001, Flora and Kröger 2014, Dollinger et al. 2017). Broda et al. (2016) used woolen, woolen-cotton and recycled fiber geotextile for the stabilization of forest road ditches with thicknesses of 5.8, 3 and 3 mm, and masses of 406, 512 and 265 g m^{-2}, respectively. The results showed that water absorption capacity of woolen geotextile was higher than that of woolen-cotton and recycled fibers. Javadi et al. (2005) investigated the effect of using riprap on sediment concentration under rainfall simulation experiments in soil erosion laboratory of Forest and Rangeland Research Institute. The results showed that, by increasing the percentage of riprap, sediment yield reduced significantly compared to the bare soil as control. Afzalimehr and Dey (2009) reported that two factors of using riprap and vegetation cover led to the reduction of runoff velocity and, as a result, the erosive power reduced. Wang et al. (2012) covered 40% of ditch bed by riprap, then they evaluated the effect of this treatment on the characteristics including runoff velocity, infiltration rate and sediment yield under three simulated rainfall intensities (57, 91, and 122 mm h^{-1}) and they compared the results with those obtained from the control (bare soil). The results showed that runoff velocity, sediment concentration and soil erosion rate were significantly reduced when using riprap treatment. Soil erosion rate was less than 12 g m^{-2} min^{-1} for riprap treatment at 122 mm h^{-1} of rainfall intensity, whereas for control with rainfall intensity of 57 mm h^{-1} was estimated to be more than 15 g m^{-2} min^{-1}.

Different methods have been used to estimate the sediment concentration of forest road ditches, including the use of sediment fence and ditch sampling under natural and simulated runoff using motor pump (Nearing et al. 1991, Robichaud and Brown 2002, Hamed et al. 2002). Considering the cost of measuring sediment yield under natural rainfall conditions and since it is not possible to control the performance of operation under natural rainfall in terms of time, the use of a runoff simulator pump is a suitable method estimate the sediment concentration of forest road ditches (Boulange et al. 2019). Since 1965, several experiments have been performed to study the effect of runoff on soil erosion (Sheridan et al. 2008). Lyle and Smerdon (1965) found a significant relationship between sediment yield and shear stress of runoff in a steady slope. Other experiments were performed by creating simulated runoff using a water pump on different slopes to evaluate the relationship between sediment yield rate and variables such as slope gradient, shear stress and flow velocity. Logarithmic relationship was found between sediment yield and the studied variables. Cao et al. (2009) conducted a study at Chinaś Research Center of Soil and Water Conservation, and they studied the sediment yield of earthy roads influenced by runoff. Runoff simulation experiments were performed on the road surface using a pump with a discharge capacity of 1 to 5 l s^{-1}. The results showed that sediment yield of the roads was significantly influenced by factors such as flow depth and road slope and other hydraulic variables such as shear stress and flow power. The ditch is designed to drain runoff from the road surface and prevent the flow from reaching to the pavement surface, thereby protecting the road structure and ensuring the safety of the drivers and pedestrians (Luce and Black 1999, Lin et al. 2011). A good water management plan regarding the ditch includes conservation by the use of natural products, which can be cost effective and useful. Therefore, the use of environmentally friendly techniques is essential for protecting the ditch.

1.1 Research Objectives

The main objective is to design and implement soil erosion control treatments in forest road ditches to measure and record sediment yield and identify best conservation practices.

Another objective is to produce two flow intensity in the ditch to investigate changes in the sediment concentration in different conservation treatments.

2. Material and Methods

2.1 Description of Study Area

District 1 in Shast Kalateh forests with an area of 1713 hectares is located in Golestan province, northern Iran (36°43′27″ to 36°48′6″ N and 54°21′26″ to 54°24′57″ E). The bedrock of this forest is lime and sand stone with altitude ranging from 100 to 1000 m above sea level. This is a mixed broadleaf deciduous forest, established on brown forest soil with mostly clay-loam-silty texture

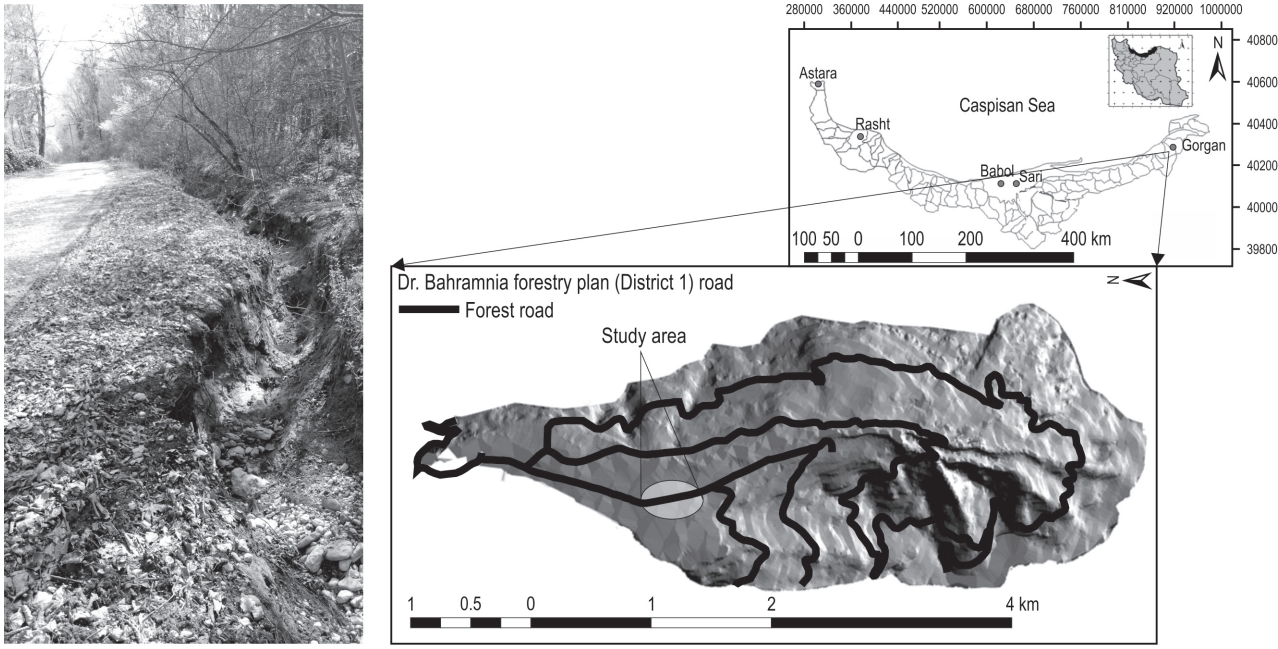

Fig. 1 Study area

and natural worn stones. The mean forest stock growth in the study area was 247 m^3 ha^{-1}. The climate of the region is Mediterranean warm and moist with mean annual precipitation of 686 mm. The minimum mean monthly rainfall is in August (31 mm) and the maximum in March (79 mm). In Shast Kalateh forests, 30.3 km of forest roads were constructed in 1989. The width and general slope of roads were 5.5 meter and 5%, respectively. Road template was crown and the mean distance of culverts was 500 m. The ditches of these roads are very susceptible to erosion, and in rainy seasons gully erosion occurrs (Fig. 1). The curve of the particle size distribution and soil texture for each treated ditch in the study area are shown in Fig. 2.

2.2 Treatment Establishments

The case study is based on five ditch segments, each with a length of 10 m, which are located in Shast Kalateh forest road network. A 2-meter buffer zone was considered between segments to exit runoff flow, collect sediment data and prevent the influence of one treatment to another (Lang 2016). The mean longitudinal slope gradient of segments was 5%. In the present study, except for shear stress and velocity of runoff, other factors are constant for all treatments. The ditches of road sections were treated by conservation practices. Ditch bed was compacted before the implementation of some treatments (CG, RR and GC) to prevent water penetration into road subbase. The soil particle size distribution of ditch bed was determined using dry sieving method. The saturated moisture content was measured using corrected soil porosity method (Williams et al. 1992). The treatments included the use of riprap (RR), grass cover by *Festuca arundinacea* L. (GC), cotton geotextile (CG), wooden wattle by local slash (WW) and control (Ctl)

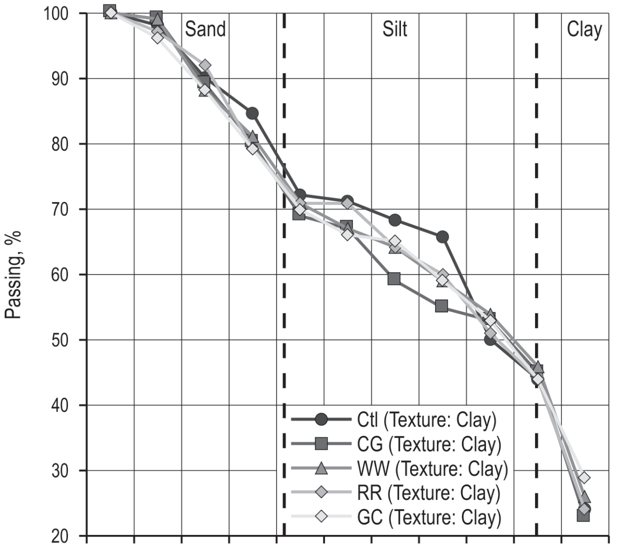

Fig. 2 Soil grain curve and classification for each treatment based on USDA soil taxonomy

Fig. 3 Conservation treatments of ditch

(Fig. 3). Local stream materials were used with an average volume of 220 cm^{-3} (Fragment volumes were calculated using Archimedes' principle) and mass value of 600 g (Fragment masses were calculated using digital balance) for each fragment in order to perform the riprap establishment (Wang et al. 2012). Cotton geotextile with a thickness of two mm and mass per square meter of 220 g was installed on ditch bed by wooden nails (Lotfalian et al. 2019). Local slash, with average diameter of 3 cm and length of 50 cm, was scraped and then used for wooden wattle construction on the ditch. Grass cover was established using *Festuca arundinacea* L. on the ditch with seed density of 70 g m^{-2} (Shixiong Cao et al. 2006). A bare soil with a length of 10 meter was selected as the control treatment for the ditch.

2.3 Runoff Simulation and Data Collection

Flow simulation was done for ten minutes at two flow rates of 5 and 10 l s^{-1} using a tank with the capacity

Fig. 4 Runoff simulation and sediment sampling at the end of each road section

of 6000 liters equipped with a motor-pump (Nearing et al. 1991, Cao et al. 2009). In order to decrease the initial flow intensity and simulate the local natural flow, a steel tube similar to the dimensions of the ditch, with a length of one meter, was provided (Fig. 4). Sediment sampling from the runoff was carried out at the end of each section every minute. Samples were transported to the laboratory and their sediment was calculated in g l^{-1}. The pure water was separated from deposited sediment. The sediment was air-dried for a week at the temperature of 30°C. Besides, it was oven-dried at 105°C for at least 24 hours and then weighted using a digital balance (Coker et al. 1993). Eq. 1 was used to calculate sediment concentration (Burroughs et al. 1991):

$$SC = SY / RV \qquad (1)$$

Where:

SC sediment concentration, g l^{-1}

SY sediment mass (g) and RV is the runoff volume, l.

Runoff flow velocity in different treatments was measured with three replications using an electromagnetic flow meter (Fig. 4).

2.4 Statistical Analysis

Factorial design was used to analyze quantitative factors of sediment concentration and runoff velocity. Conservation treatments and flow rate had 5 and 2 levels, respectively. Totally, 100 samples were collected for sediment analysis and 60 samples for runoff velocity. Data were statistically analyzed using GLM procedure in SAS program. LSD test was used to compare means among treatments and diagram designed by Excel software.

3. Results and Discussion

3.1 Effect of Conservation and Flow Treatments on Sediment Concentration

Comparison of some soil characteristics including sand, silt, clay and moisture content showed no significant differences among treatments (Table 1). The results of analysis of variance showed that conservation treatments and flow rates had a significant effect on sediment concentration. Soil surface roughness has a significant influence on water erosion, related to runoff velocity and concentration sediments. In this study, the roughness of CG, RR, GC and WW treatments increases surface tortuosity and, therefore, decreases runoff velocity and its ability to detach the soil as compared with Ctl. It was detected that CG performed well under certain circumstances due to the compaction practice prior to implementation of the treatment (Table 2). Indeed, soil cover with CG is more effective than other treatments in reducing runoff velocity, with acceptable range and sediment yield. A superior result of CG was also observed by Lotfalian et al. (2019) in the stabilization of forest road cutslopes. They found that, in this treatment, soil loss was reduced by 12.5 and 6 times compared to the Ctl plot on the new and old cutslopes, respectively, due to through cover of the surface. Broda et al. (2016) introduced the high absorption capacity and CG as the main contributors to the reduction of sediment concentration, and their results are in agreement with the results of the present study. WW provided numerous obstacles against stress force of runoff and suspended sediment. So wooden obstacles provided the necessary time for water infiltration in soil and deposition of sediment, and consequently the sediment concentration was reduced, but water penetration into the sub base of the forest road is not acceptable in road conservation practices.

The results of the current study are not consistent with the results of the study by Javadi et al. (2005), Wang et al. (2012) and Lang (2016). They implemented five treatments including Ctl (bare soil), GC, GC on

Table 1 Soil characteristics of ditches containing different conservation treatments

Variables		Treatment				
		Control	Cotton geotextile	Wooden wattle	Riprap	Grass cover
Sand, %	Mean	28.11^{a}	31.12^{a}	29.31^{a}	29.21^{a}	30.00^{a}
	Standard deviation	3.32	4.12	3.13	4.21	2.12
Silt, %	Mean	28.22^{a}	24.12^{a}	25.21^{a}	27.18^{a}	26.14^{a}
	Standard deviation	3.01	4.02	4.32	5.21	3.00
Clay, %	Mean	44.21^{a}	45.01^{a}	46.03^{a}	44.14^{a}	44.10^{a}
	Standard deviation	5.12	4.01	5.01	6.14	6.00
Bulk density, g cm^{-3}	Mean	1.11^{c}	1.31^{a}	1.12^{c}	1.23^{b}	1.20^{b}
	Standard deviation	0.21	0.12	0.22	0.31	0.23
Soil moisture, %	Mean	53.22^{a}	46.12^{a}	53.12^{a}	49.03^{a}	50.04^{a}
	Standard deviation	5.12	4.21	3.33	4.01	4.12

Different superscripts in a row show significant difference at probability level of 5%

Table 2 Comparison of different treatments in terms of sediment concentration

Variables	Flow rates		Treatment					ANOVA, *p*
			Control	Cotton geotextile	Wooden wattle	Riprap	Grass cover	
Sediment concentration, g l^{-1}	5 l s^{-1}	Mean	0.38^{a}	0.19^{b}	0.25^{b}	0.21^{b}	0.22^{b}	0.009
		Standard deviation	0.04	0.01	0.02	0.01	0.01	
	10 l s^{-1}	Mean	0.50^{a}	0.21^{c}	0.21^{c}	0.36^{b}	0.30^{b}	0.007
		Standard deviation	0.04	0.02	0.02	0.03	0.03	

Different superscripts in a row show significant difference at probability level of 5%

CG, stone bars and RR, in order to protect the forest road ditches. The results showed that the lowest sediment yield was related to RR, GC and GC on CG. The main cause for this result is due to the difference in the aggregate size of RR used in two studies. The presence of fine and unwashed particles in stream materials used for the present study has led to more sediment yield, so that, among the conservation treatments, the use of RR led to a significant increase in the sediment yield rate at a flow intensity of 10 l s^{-1}. In the study by Lang (2016), the materials used had no fine particles. The smooth surface and the presence of cracks in RR increased runoff velocity and canalization in the cracks, which increased sediment concentration at flow intensity of 10 l s^{-1}. Sediment concentration of GC at 10 l s^{-1} flow intensity was higher than CG and WW due to soil disturbance of plantation. The plantation operations also increased the cost of grass establishment (Shixiong Cao et al. 2006, Zhou and Shangguan 2007).

In the Ctl and RR, sediment concentration at flow intensity of 10 l s^{-1} was significantly higher than at the flow intensity of 5 l s^{-1} (Table 2). The reason for this is the higher runoff velocity in the Ctl and RR compared to other treatments. This is consistent with the study results of Lyle and Smerdon (1965) and Cao et al. (2009). They reported that an increase in shear stress of runoff due to increased flow velocity was the main factor in increasing sediment concentration. At both flow rate of 5 l s^{-1} and 10 l s^{-1}, the sediment concentration generally increased quickly during the 0–5 min period, especially on Ctl. It then decreased slowly and in some cases remained steady until the end of the runoff simulation because of soil saturation with water (Fig. 5).

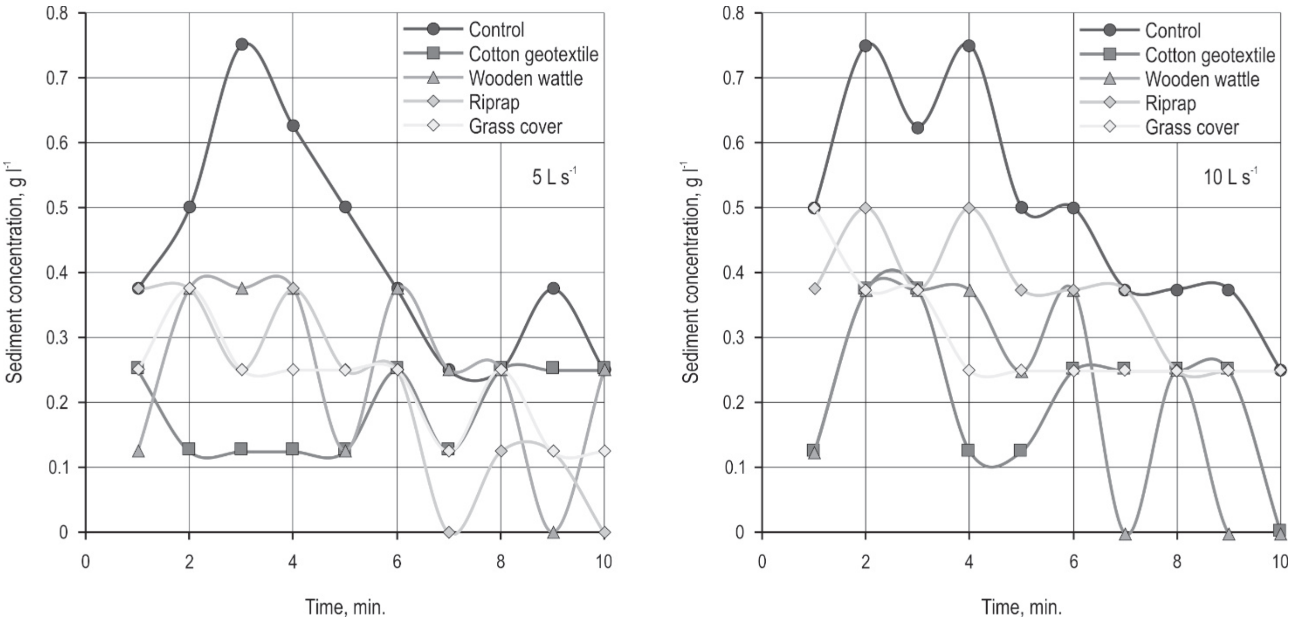

Fig. 5 Behavior of sediment concentration at flow rate of 5 and 10 l s^{-1} as function of time

3.2 Effect of Conservation and Flow Treatments on Runoff Velocity

In this study, the lowest runoff velocity was obtained for GC and WW and the highest for RR and CG (Table 3). Grass biomass with long and narrow leaves and stems can increase surface tortuosity and, therefore, decreases the runoff velocity. WW acts as check dam to reduce the velocity of concentrated water flow, and reduces erosion and sediment. Check dams are found to modify water and sediment transport by impounding runoff flow, reducing its velocity and peak rate, decreasing channel slope and allowing more time for infiltration and sediment deposition (Yuan et al. 2019), but as noted above, infiltration and consequently water penetration into the sub base of the forest road is not acceptable in road conservation practices. Except for the Ctl and CG, the flow rate conversion from 5 l s^{-1} to 10 l s^{-1} did not significantly change the runoff velocity. In the Ctl and CG, the runoff velocity at a flow intensity of 10 l s^{-1} was significantly higher than at the flow intensity of 5 l s^{-1} (Table 3). High bulk density in CG and consequently, lower porosity, contributed to accelerate the runoff velocity. In these conditions, the runoff initiated quickly in the ditch segment. Other authors have observed low sediment transport in plots with relatively high bulk density (Rodrigo Comino et al. 2016).

4. Conclusion

Hydrological behavior and sedimentation responses of the road ditches may be strongly influenced by the type of conservation treatments. Ditches collect surface runoff from the surrounding areas and roads.

Table 3 Comparison of different treatments in terms of runoff velocity (Ctl: control, CG: cotton geotextile, WW: wooden wattle, RR: riprap, GC: grass cover)

Variables	Flow rates		Treatment					ANOVA, *p*
			Control	Cotton geotextile	Wooden wattle	Riprap	Grass cover	
Runoff velocity, m s^{-1}	5 l s^{-1}	Mean	0.62^{a}	0.12^{c}	0.10^{c}	0.25^{b}	0.13^{c}	0.002
		Standard deviation	0.07	0.01	0.01	0.03	0.01	
	10 l s^{-1}	Mean	0.96^{a}	0.32^{b}	0.18^{c}	0.38^{b}	0.17^{c}	0.004
		Standard deviation	0.08	0.03	0.01	0.04	0.01	

Different superscripts in a row show significant difference at probability level of 5%

The amount of runoff collected by ditches depends on the type of treatments for soil erosion control. Some treatments, such as grass cover, decrease the ditch storage capacity. In addition, uncompacted bed, soil disturbance and unwashed materials are major threats to ditch, especially with grass cover and riprap treatments. Compacted bed and dense cover of geotextile in ditch maintain soil particles in place and consequently decrease the sediment yield. In case of wooden wattle, the amount of sediment yield from the treated segment was low like that of cotton geotextile, but in this treatment the runoff velocity decreased to 0.18 m s^{-1} and this means that water has enough time to penetrate the uncompacted soil and road base, and this issue is not acceptable. The treatments that cause water infiltration are only recommended when the shape of the slopes and ditches prevent water from penetrating the sub base of the road. Adequate conservation treatments and road construction policies should be considered for the selection of ditch erosion control materials, especially in sensible road ditches. Different geotextiles filled by cotton and/or straw can be useful materials to be used in filtering and capturing the suspended sediments in runoff.

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