https://doi.org/10.5552/crojfe.2022.1563

Effectiveness of Water Diversion Structure to Mitigate Runoff, Sediment Yield, Nitrate and Phosphate Concentrations in Skid Trail of Mountainous Forest Ecosystem

Meghdad Jourgholami, Maryam Etehadi Abari, Rachele Venanzi, Farzam Tavankar, Rodolfo Picchio

Abstract

It is well-known that soil and water conservation actions (e.g., installing water diversion structures) are necessary to restore skid trails after logging operations. However, there are some points that have yet to be determined concerning the efficacy of rehabilitation on sediment yield and nutrient export to the aquatic environment. The objectives of this study were to determine the optimal distance among the water diversion structures (WDSs) to suppress runoff, sediment yield, and measure nitrate and phosphate concentrations on the skid trails of a mountainous ecosystem. The study was conducted on a total of 18 bounded runoff plots, each with a width of 4 m and a length of 120 m, divided into six treatment compartments done in triplicate. Beech logs were placed at a distance of 5, 10, 20, 30, and 40 meters. An untreated area (U) was set up during the recording period from 18 September 2015 to 17 September 2016. In all the WDS treatments and untreated trails (U), the observed peaks of runoff, sediment yield, as well as nitrate and phosphate concentrations was found to be significantly correlated with the amount of rainfall events. Results show that there was a decrease in surface runoff and runoff coefficient, sediment yield, and nitrate and phosphate concentrations by installing of WDS at different distances. The runoff and runoff coefficients (2.67 mm and 0.101, respectively) were at the lowest level in the WDS20 (WDS at a distance of 20 m). The sediment yield was significantly higher on the U, 13.52 g m^{-2} followed by WDS40, whereas the lowest values were detected at the WDS10. Significantly higher values of nitrate were found in the U (3.63 mg l^{-1}), while the lowest amounts of nitrate were determined at WDS5 followed by the WDS20 treatment. The highest values of phosphate were found on the U treatment (0.278 mg l^{-1}) followed by the WDS40 treatment, whereas the lowest phosphate values were measured in the WDS20 treated area. Therefore, it can be deduced that the recommended water diversion structure should be placed at a distance of 20 m to mitigate runoff, sediment yield, nitrate and phosphate exports on the skid trails.

Keywords: logging operation, rainfall intensity, contour-felled logs, soil loss, nutrient loss

1. Introduction

Nitrate as an inorganic form of N is one of the main nutrients in forest soil which is naturally present in the environment. It contributes to the nitrogen cycle, which is easily exported from the soil through leaching (Kreutzweiser et al. 2008a, Kaila et al. 2014). Phosphorus (P) is another important nutrient in forest soil, and it also exported into receiving waters (Shah and Nisbet 2019). Nitrate and phosphate are the major components in the soil nutrient web that are essential to the growth of plants in forest ecosystems (Kreutzweiser et al. 2008a). Soil enhancement after harvesting raised the amounts of N and P in the soil, thus increasing the levels of N and P exported to water bodies. The leaching rates of N were especially high, thus leading to N losses from forested catchment (Löfgren et al. 2009).

Soil disturbances caused by machinery traffic after logging operations cause to increase soil bulk density, remove organic layers, destroy pore structures, decrease ground roughness, and reduce infiltration rate, which lead to increase overland flow (Sohrabi et al. 2019, 2020, Jourgholami and Labelle 2020, Picchio et al. 2020). The litter layer plays a key role in protecting soil by intercepting raindrops, enhancing infiltration, mitigating runoff generation, as well as nutrient cycle equilibrium (Picchio et al. 2012, Cambi et al. 2016, Jourgholami et al. 2019a, b, Zhao et al. 2019). In situations where there is no litter layer raindrops hit the bare mineral soil, causing the detachment of soil particles which are then transported as eroded materials, and eventually deposited in the downstream and aquatic environments. This leads to export of dissolved organic C, dissolved organic N, and P (Jourgholami et al. 2018a, Kreutzweiser et al. 2008a).

The extent of surface flow and sediment yield can be attributed to several factors including slope length, gradient, aspect, shape, rainfall intensity and duration, condition of soil surface, and soil texture (Parsons et al. 2006, Han et al. 2019, Jourgholami and Labelle 2020). However, slope length is an important factor that has a crucial effect on overland flow and sediment yield, although this issue is still a topic of discussion (Nadal-Romero et al. 2011, Kinnell 2016, Zhang et al. 2018). Numerous studies have elucidated the effectiveness of slope length on overland flow and sediment yield (Parsons et al. 2006, Leys et al. 2010, Han et al. 2019). Accordingly, Kinnell (2009) reported that the duration, intensity, and infiltration of precipitation events, as well as slope length had an influence on overland flow and on the discharge of sediment. Furthermore, Han et al. (2019) indicated that the minimum amount of soil erosion was observed in the plot length of 30–40 m on the moderate slope. Parsons et al. (2006) found that sediment yield increased by increasing the slope length to reach a peak at the particular length and then decreased by further increasing the slope length. Jourgholami et al. (2020b) found that contour-felled logs at a distance of 10, 20, and 30 m reduced sediment yield by 90.6, 94.7, and 88.3%, respectively, compared to the untreated trails.

Previous studies have demonstrated that the installation of water diversion structures (*WDS*) (also called water bars) as contour-felled log erosion barriers can help reclaim the ecological surroundings by reducing sediment yield, enhancing the physico-chemical and biological environments, and augmenting the nutrient cycling (Robichaud et al. 2008, Masumian et al. 2017). Applying *WDS* on skid trails can also accelerate the restoration processes of soil quality (Jourgholami et al. 2018b, 2020a). Furthermore, the water diversion structures (i.e., installing small diameter logs on the skid trails in a shallow trench placed in a parallel or diagonal direction to contour lines) is an effective method which provides a physical barrier, and provides better protection for the soil surface. Moreover, water diversion structures (i.e., contour-felled logs) can slow down the surface flow, cut down slope length, improve water infiltration rate, enhance ground roughness, and trap and store eroded materials thus reinforcing and stabilizing hillslopes (Wagenbrenner et al. 2006, Kim et al. 2008, Robichaud et al. 2008).

Rainfall intensity plays a major role in regulating the detachment and transport of eroded materials (Fu et al. 2016, Han et al. 2019, Jourgholami and Labelle 2020). For example, Fu et al. (2016) reported that the rainfall intensity had a greater impact than the slope length on sediment yield. Likewise, Jourgholami and Labelle (2020) demonstrated that the runoff and sediment yield were strongly correlated to rainfall intensity.

The intensification of microbial activities within the forest floor and the upper soil layers causes some alteration to the nutrient mobility forms, thus increasing the delivery of dissolved nutrients from the hillslope areas to receiving waters (Buttle et al. 2005, Feller 2005, Palviainen et al. 2014, Nieminen et al. 2017). Accordingly, Shah and Nisbet (2019) found that nitrate concentrations increased after clearfelling. Moreover, Palviainen et al. (2015) showed that total nitrogen, nitrate, ammonium, and phosphate concentrations increased significantly during the 2 to 6 year period after clearcutting. In the boreal forest, Walley et al. (1996) reported that concentrations of soil NO_3- increased due to a reduction in plant uptake. Similarly, Palviainen et al. (2014) observed an increase in NO_3-N by 270% and PO_4-P by 12% after clearcutting on an annual basis over a 14-year period.

Related to these aspects, some interesting results have been observed using *WDS*s. These seem to be a particularly beneficial instrument for erosion control on retired skid trails (Akbarimehr and Naghdi 2012a, b). However, there are different suggestions and approaches on the recommended distances of *WDS*s among various best management practices (BMPs) (Akbarimehr and Naghdi 2012b, Copstead et al. 2003, Masumian et al. 2017). In particular, the numerous studies have mainly addressed two important issues affected by *WDS* as follows:

⇒ these features may decrease surface flow and sediment yield after wildfires and logging operations (Wagenbrenner et al. 2006, Robichaud et al. 2007, 2008, Masumian et al. 2017, Jourgholami and Labelle 2020, Jourgholami et al. 2020b)

⇒ these features favor the rehabilitation of the soil physical and chemical properties after impacts or disturbance actions (Jourgholami et al. 2018b, 2020a).

However, the effectiveness of *WDS* to mitigate nitrogen and phosphorus concentrations in overland flow remains unclear. Hence, the current study was developed to obtain data on the impact of logging operations on overland water quality.

The hilly mountainous areas of the Hyrcanian forest located in the southern area of the Caspian Sea are susceptible to overland flow and soil erosion caused by machinery traffic in logging operations. They present a considerable challenge in reaching sustainable forest management. The objectives of this study were to:

⇒ elucidate the short-term effects of logging operations on runoff and sediment yield

⇒ characterize the variations in surface flow quality (i.e., nitrogen and phosphorus concentrations) on the machine-induced compacted soil

⇒ determine the optimal distance among water diversion structures (*WDS*s) to suppress sediment yield.

We hypothesized that the distance among water diversion structures may have a notable influence on surface runoff, sediment yield, as well as nitrogen and phosphorus concentrations in overland flow.

2. Materials and Methods

2.1 Site Description

The forest area located in compartment no. 314 of the Gorazbon district in the Kheyrud forest research station of the Hyrcanian forests, northern Iran (Fig. 1a) was chosen for the study. The coordinates are 51°33′12″ E and 51°39′56″ E and 36°32′08″ N and 36°36′45 5″ N. The study area has a mixed beech-hornbeam stand, humid cold climate with a mean annual temperature of 7.8 °C (SD±0.8 °C). The area is on hilly mountainous terrain ranging 5–40% with a southern aspect, while the elevation of the forest area ranges between 1160 and 1300 m a.s.l. According to meteorological records from 1977 to 2016, the mean annual precipitation is 1380 mm (SD±191.0 mm), with the most occurring between September and October. According to the USDA Soil Taxonomy, the study area soils are classified as loam inceptisols, developing on dolomite limestones relating to the upper Jurassic and lower Cretaceous periods. This study site is dominated by natural forests including native tree species such as beech (*Fagus orientalis* Lipsky), hornbeam (*Carpinus betulus* L.), chestnut-leaved oak (*Quercus castaneifolia* C.A.M.), velvet maple (*Acer velutinum* Boiss.), and Caucasian alder (*Alnus subcordata* C.A.M.).

The volume of trees that were uprooted and/or wind damaged totaled as follows: 450.6 m^3, total number: 76 stems, number of extracted: 124 logs, BDH: 76 cm, height 32.7 cm, and species type: beech, hornbeam, and Caucasian alder. Wind damaged and uprooted trees were delimbed and bucked with a chainsaw in August 2015. To extract logs from the stump area to roadside landings, a Timberjack 450C wheeled skidder was used in August and in the beginning of September 2015. The Timberjack 450C skidder is characterized by an empty weight of 10.3 metric tons, tire inflation of 220 kPa, the average load volume of 2.48 cubic meters, and the skid trail width of 4 m.

2.2 Experimental Design and Measurements

In this study, five skid trails without any vegetation cover or similar aspects were selected to install the runoff plot with the same slope gradient of 20% and level of machine traffic intensity of 18 cycles (i.e., both empty and loaded drive of the machine on the skid trails) immediately after logging operations with the skidder. 18 runoff plots with a width of 4 m and length of 120 m were randomly installed on the skid trails, where the upper and lower limits were restricted with wooden boards covered with plastic to prevent water from entering into or going out of each plot. In this study, six treatments were done in triplicate by installing the beech logs with diameters ranging 25–30 cm and a length of 4 m in a diagonal direction (interior angle of 10 °) to the longitudinal axis of the skid trails with different distances, plus a trail without *WDS* or untreated area (*U*) (Fig. 1 b–d). Hence, treatments were presented in Table 1. Runoff was surveyed with 54 rainfall events during the first year from 18 September 2015 to 17 September 2016. Rainfall that occurred for a continuous amount of time, ceasing for at least six hours, was considered a rainfall event. To keep water from coming into or going out of the plot surface, the wooden boards were inserted to a depth of 20 cm inside the soil and extended 20 cm above the surface. To collect the surface runoff, storage tanks were installed at the lower end of the plot in each treatment (Table 1). The surface runoff was routed through a plastic pipe to the storage.

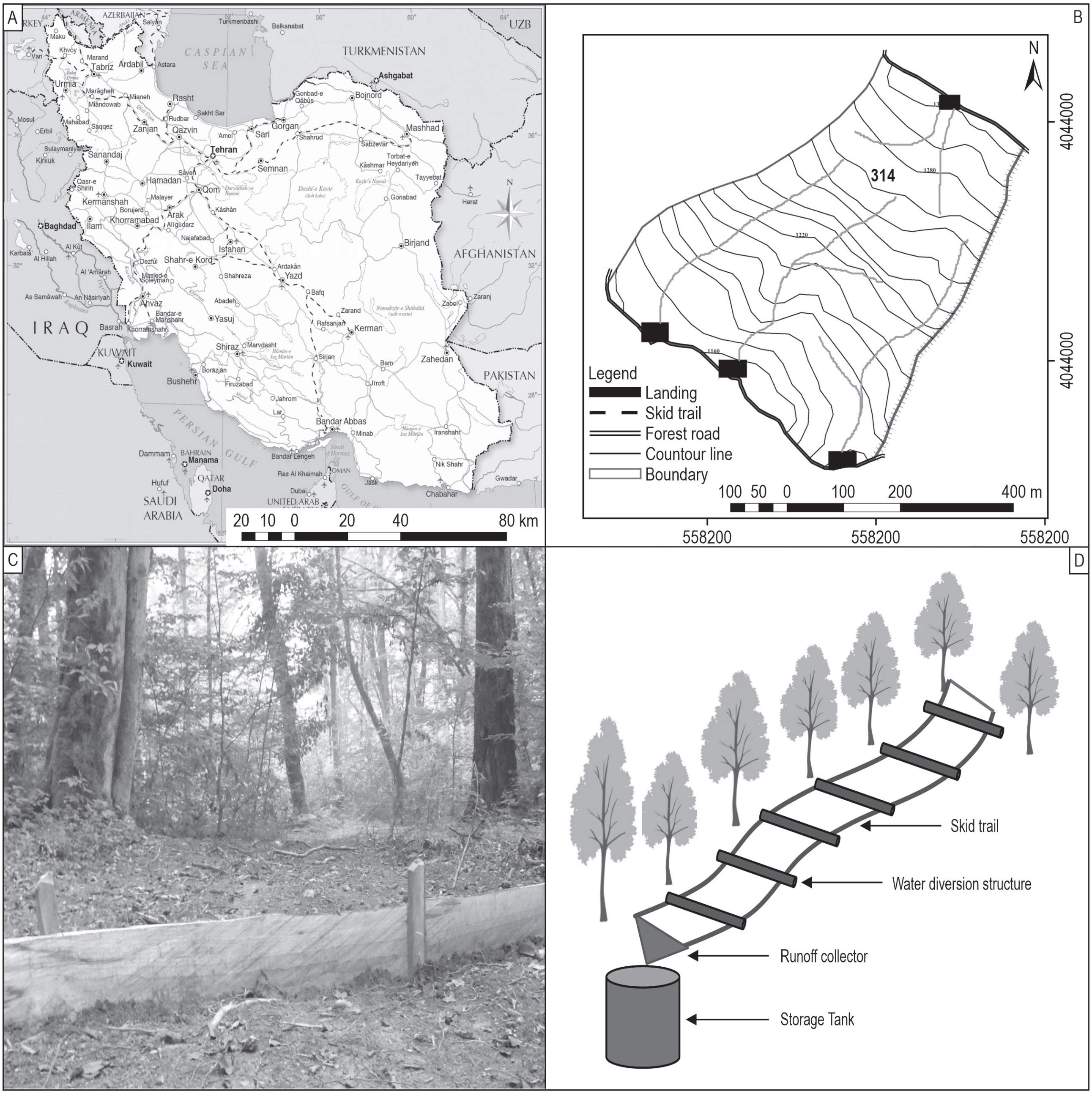

Fig. 1 Location of the study area in the Hyrcanian forest, Northern Iran (a) in the compartment no. 314 of the Gorazbon district (b); A schematic diagram of the experimental design on the skid trails (c); wooden boards surrounding the perimeter of the plot (d)

Determination of the runoff was done in mm by collecting runoff in the storage tank. It was measured by gauge and was then divided by the area of each plot. The collected runoff in the storage tank was adequately mixed, and a 1-L sample was immediately collected in a plastic bottle previously rinsed with hydrochloric acid (pH<2.0), and distilled water, then transported to the laboratory in cool boxes. The storage tank was thoroughly washed, drained, and installed for collecting the next event. To determine sediment weight, all sub-samples of 1 liter for each runoff plot were filtered through Whatman 42 filter paper, oven-dried at 105 °C for 24 h. The filtered runoff samples were reserved at 4 °C in a refrigerator. The filters and sediment remaining were weighed and then the weight of the filter was subtracted. The sediments at dry weight (in 1 liter runoff sample) were multiplied by the total amount of runoff collected in

Table 1 Treatments applied in the skid trails

Treatment	Distance among contour-felled logs, m	Storage tank, m^3
U	–	–
*WDS*5	5	0.06
*WDS*10	10	0.06
*WDS*20	20	0.25
*WDS*30	30	0.25
*WDS*40	40	0.25

the storage tank to determine the sediment concentration (g l^{-1}). To calculate the sediment yield (g m^{-2}), the sediment concentration was multiplied by runoff volume (L), then was divided by the square-meters of the plot area. The filtered runoff sample that was stored in a refrigerator were additionally filtered with a 0.45-μm membrane for determination of nitrate (NO_3-N) and phosphate (PO_4-P) concentrations in overland flow (mg l^{-1}) using the method as shown in Table 2. Runoff volume (mm) was divided by total rainfall (mm) to calculate the runoff coefficient for each event. A rainfall gauge was set up in an area without canopy cover to measure gross rainfall. A manual rain collector with a diameter of 9 cm and a height of 20 cm was set up beside the runoff plot to measure the amount of throughfall above each runoff plot.

Some soil parameters such as soil bulk density, total porosity, organic matter content, and soil particle-size distribution, as well as canopy cover were analyzed and calculated in every runoff plot. The soil was sampled in two parts; one part from the surface soil with depth of 0–10 cm using a steel cylinder (with a length of 40 mm and a diameter of 56 mm) to measure soil bulk density, and the other part was measured from an area (50×50×10 cm), placed in plastic bags, labeled, transported, air-dried, and analyzed for soil properties by analysis methods shown in Table 2. To estimate the canopy cover at the top of each plot, ocular observation was applied in three points. In order to assess the effect of different distances between *WDS* and the amount of rainfall on nitrate (NO_3-N) and phosphate (PO_4-P) concentrations, the full cubic polynomial regression model was used to determine runoff, runoff coefficient, and sediment yield.

2.3 Statistical Analyses

The treatments plots and the untreated plot (*U*) were randomly established on the skid trails to elucidate the effects of various treatments on runoff, runoff coefficient, sediment yield, and nitrate (NO_3-N) as well as phosphate (PO_4-P) concentrations. The Kolmogorov-Smirnov test (α=0.05) was employed to check the normality of variables. The homogeneity of variance (α=0.05) was examined by the Levene's test. One-way analysis of variance (ANOVA) was conducted to compare the effects of topsoil conditions and canopy cover in different treatments. One-way analysis of variance (ANOVA) was applied to characterize the effects of different treatments on runoff, runoff coefficient, sediment yield, and nitrate (NO_3-N) as well as phosphate (PO_4-P) concentrations. The post hoc test was conducted to examine the significant differences among the different treatments (*WDS*5, *WDS*10, *WDS*20, *WDS*30, *WDS*40, and *U*) by the Duncan test at $P\leq0.05$. The Pearson correlation was applied to examine the relationship among treatments, topsoil parameters, canopy cover, and overland flow characteristics, which can be considered as a significant correlation when $P\leq0.05$. The SPSS software package (release 20; SPSS, Chicago, IL, USA) was applied to accomplish all statistical tests. The Curve Expert Professional 1.6 software was used to fit the polynomial

Table 2 Methods of analyzing soil and runoff properties and calculations

Soil and runoff properties		Unit	Method	Reference for method
Soil	Soil bulk density	g cm^{-3}	Clod method	Kemper and Rosenau 1986
	Water content	%	By drying soil samples at 105 °C for 24 h	Thien and Graveel 2008
	Soil particle size distribution	%	Hydrometer method	Gee and Bauder 1986
	Soil particle density	g cm^{-3}	ASTM D854-00 2000 standard	Thien and Graveel 2008
	Soil organic C	%	Walkley-Black technique	Walkley and Black 1934
Runoff	Nitrate (NO_3-N) concentrations	mg l^{-1}	By spectroscopy method using ultraviolet (UV) spectrophotometer (UV-1200)	Palviainen et al. 2015
	Phosphate (PO_4-P) concentrations	mg l^{-1}	By spectroscopy method using ultraviolet (UV) spectrophotometer (UV-1200)	Palviainen et al. 2015

Table 3 Mean values (±Std. Error) of different soil physical properties before the experiment started in 2015 in the runoff plots at the skid trails with the different treatments and the untreated area (*U*). *WDS*5 contour-felled logs at a distance of 5 m, *WDS*10 = contour-felled logs at a distance of 10 m, *WDS*20 = contour-felled logs at a distance of 20 m, *WDS*30 = contour-felled logs at a distance of 30 m, *WDS*40 = contour-felled logs at a distance of 40 m

Treatment	Bulk density, Mg m^{-3}	Total porosity, %	Organic matter content, %	Canopy cover, %	Sand, %	Clay, %	Silt, %
U	1.35±0.02	47.30±0.69	2.89±0.45	73±2.1	37.0±6.2	20.7±4.2	42.3±5.5
*WDS*5	1.34±0.03	46.67±1.00	2.98±0.20	74±3.5	35.3±3.2	21.0±0.2	43.7±3.2
*WDS*10	1.33±0.03	47.53±0.96	2.83±0.22	73±1.2	35.0±1.0	24.3±1.5	40.7±2.5
*WDS*20	1.36±0.04	47.87±1.39	2.97±0.14	75±1.0	37. 3±5.5	22.0±2.7	40.7±3.1
*WDS*30	1.35±0.03	47.33±1.10	2.94±0.21	73±2.3	31.7±5.7	21.0±5.3	47.3±0.6
*WDS*40	1.35±0.01	47.30±0.40	2.93±0.31	73±2.7	40.0±1.0	19.3±2.5	40.7±2.1

regression model as a function of rainfall and different treatments to estimate the runoff, runoff coefficient, sediment yield, and nitrate (NO_3-N) as well as phosphate (PO_4-P) concentrations in overland flow.

3. Results

3.1 Rainfall and Plot Characteristics

The amount of rainfall measured from 54 rainfall events was 980.1 mm during the recorded period from 18 September 2015 to 17 September 2016 in the study site. However, 21.9 mm of the total recorded rainfall was from events that were not measured, due to the fact that the events that were <2 mm did not pass through the canopy cover. As a result, a total of 39 precipitation events with a rainfall amount of 958.2 mm were considered for the basis of measuring runoff. The rainfall events varied from 2.6 to 91.5 mm with an average of 24.57 mm.

According to the results of Duncan's test, there were no significant differences among topsoil properties and canopy cover in different treatments (Table 3).

Table 4 Pearson correlations among treatments, topsoil parameters, canopy cover, and overland flow characteristics

Variable	Runoff mm	Runoff coefficient	Sediment g m^{-2}	NO_3-N mg l^{-1}	PO_4-P mg l^{-1}	Bulk density Mg m^{-3}	Total porosity %	Organic C %	Canopy cover %	Sand %	Clay %	Silt %
Treatment	0.79**	0.84**	0.95**	–0.01	–0.19	0.11	–0.10	0.05	–0.07	0.10	–0.21	0.06
Runoff, mm	1	0.94**	0.80**	–0.39	–0.54*	0.09	–0.08	0.08	–0.09	0.03	–0.16	0.11
Runoff coefficient	–	1	0.85**	–0.33	–0.48*	–0.01	0.02	0.09	–0.08	–0.06	–0.08	0.15
Sediment yield, g m^{-2}	–	–	1	–0.0	–0.32	0.23	–0.22	0.06	–0.05	0.03	–0.19	0.13
NO_3-N, mg l^{-1}	–	–	–	1	0.92**	–0.02	0.03	–0.22	–0.08	0.15	0.00	–0.18
PO_4-P, mg l^{-1}	–	–	–	–	1	–0.13	0.13	–0.26	–0.09	0.19	0.08	–0.30
Bulk density, Mg m^{-3}	–	–	–	–	–	1	–0.99**	–0.14	0.04	–0.15	0.24	–0.02
Total porosity, %	–	–	–	–	–	–	1	0.14	–0.07	0.15	–0.26	0.03
Organic C, %	–	–	–	–	–	–	–	1	0.22	0.08	–0.43	0.26
Canopy cover, %	–	–	–	–	–	–	–	–	1	–0.01	0.08	–0.06
Sand, %	–	–	–	–	–	–	–	–	–	1	–0.59**	–0.73**
Clay, %	–	–	–	–	–	–	–	–	–	–	1	–0.12
Silt, %	–	–	–	–	–	–	–	–	–	–	–	–

Note: *P<0.05; **P<0.01

Pearson correlation analysis showed that treatment (different distance among *WDS* and *U*) was significantly correlated with the runoff (r=0.79, P<0.01), runoff coefficient (r=0.84, P<0.01), and sediment yield (r=0.95, P<0.01). In addition, runoff was positively and significantly correlated with the runoff coefficient (r=0.94, P<0.01) and sediment yield (r=0.80, P<0.01), whereas negatively correlated with the phosphate (PO_4-P) concentrations (r=-0.54, P<0.05). Also, nitrate (NO_3-N) was not significantly correlated with runoff, whilst were positively and significantly correlated with phosphate (PO_4-P) concentrations (r=0.92, P<0.01) (Table 4).

3.2 Runoff and Sediment Yield

Results demonstrated that runoff, runoff coefficient, and sediment yield were significantly influenced by the placement at different distances of water diversion structures (*WDS*) (P<0.001) (Table 5).

The highest runoff and runoff coefficient volume was detected in the untreated plot (*U*) by 8.64 mm and 0.311, respectively. The installing of *WDS* at a different distance resulted in a decrease in surface runoff and runoff coefficient. Hence the untreated plot (*U*) had significantly greater runoff and runoff coefficient than the values of the *WDS* treatments. However, different trends for runoff and runoff coefficient were observed after applying the *WDS* on the skid trails. First, there was an increase when the distance among the *WDS* increased from 5 to 10 m; there was a decrease when the distance among the *WDS* increased from 10 to 20 m. Then these increased by increasing the distance of the *WDS* from 20 to 40 m. The lowest runoff and runoff coefficient (2.67 mm and 0.101) were found in the *WDS*20 (Table 6).

Table 5 ANOVA for the effect of the different distance of water diversion structures (*WDS*) on runoff, runoff coefficient, sediment yield, and concentrations of nitrate (NO_3-N) and phosphate (PO_4-P) in overland flow

Source	Sum of squares	df	Mean square	F	*P* value
Runoff	2684.79	5	536.96	13.38	≤0.001**
Runoff coefficient	3.55	5	0.71	51.68	≤0.001**
Sediment	5301.59	5	1060.32	8.81	≤0.001**
Nitrate, NO_3-N	467.01	5	93.40	15.28	≤0.001**
Phosphate, PO_4-P	2.30	5	0.46	11.93	≤0.001**

Note: $^{*}P<0.05$; $^{**}P<0.01$

The variation patterns of runoff in relation to the amount of rainfall as a time sequence following the installation of *WDS* and untreated trails (*U*) are presented in Fig. 2. In all treatments, the observed peaks of runoff were attributed to the amount of rainfall events. In each rainfall event, the highest runoff were detected in the untreated trails (*U*), whereas the lowest amount of runoff were found in the *WDS*20. The variation pattern of runoff showed that the runoff peaked in the first 2 months after operation, although the peaks observed in the last months of this study occurring independent to the time-since-logging operation (Fig. 2).

The sediment yield was significantly higher on the *U* (13.52 g m^{-2}) followed by *WDS*40>*WDS*30>*WDS*5≈ *WDS*20, whereas the lowest values were detected at the *WDS*10. However, two distinct trends for sediment yield were detected in response to install the *WDS* on the skid trails; first decreased as the distance among

Table 6 Mean (±Std. Error) of runoff, runoff coefficient, sediment yield, and nitrate (NO_3-N) and phosphate (PO_4-P) concentrations on the skid trails with the different treatments and the untreated area (*U*). *WDS*5 = contour-felled logs at a distance of 5 m, *WDS*10 = contour-felled logs at a distance of 10 m, *WDS*20 = contour-felled logs at a distance of 20 m, *WDS*30 = contour-felled logs at a distance of 30 m, *WDS*40 = contour-felled logs at a distance of 40 m

Treatment	Runoff, mm	Runoff coefficient	Sediment, g m^{-2}	NO_3-N, mg l^{-1}	PO_4-P, mg l^{-1}
U	8.64±0.90a	0.311±0.018a	13.52±1.56a	3.63±0.36a	0.278±0.029a
*WDS*5	3.84±0.39de	0.141±0.006d	7.57±0.64cd	1.13±0.09d	0.138±0.013cd
*WDS*10	5.06±0.51cd	0.192±0.009c	5.46±0.61d	1.89±0.18c	0.186±0.016bc
*WDS*20	2.67±0.28e	0.101±0.005e	6.33±0.66cd	1.56±0.15cd	0.114±0.010d
*WDS*30	5.74±0.56bc	0.234±0.009b	9.05±0.94c	2.05±0.21c	0.133±0.013cd
*WDS*40	6.94±0.67b	0.262±0.012b	10.85±1.16b	2.73±0.27b	0.221±0.020b

Note: Different letters after means within the same column indicate significant differences by Duncan's test ($P<0.05$)

WDS increased from 5 to 10 m, then increased by increasing the distance among *WDS* ranging 10–40 m (Table 6).

The variation patterns of sediment yield relating to the amount of rainfall as a time sequence following installing the *WDS* and the untreated trails (*U*) are presented in Fig. 2. In all the *WDS* treatments and the untreated trails (*U*), the observed peaks of runoff were attributed to the amount of sediment events. The sediment yield peaked during the study period in the

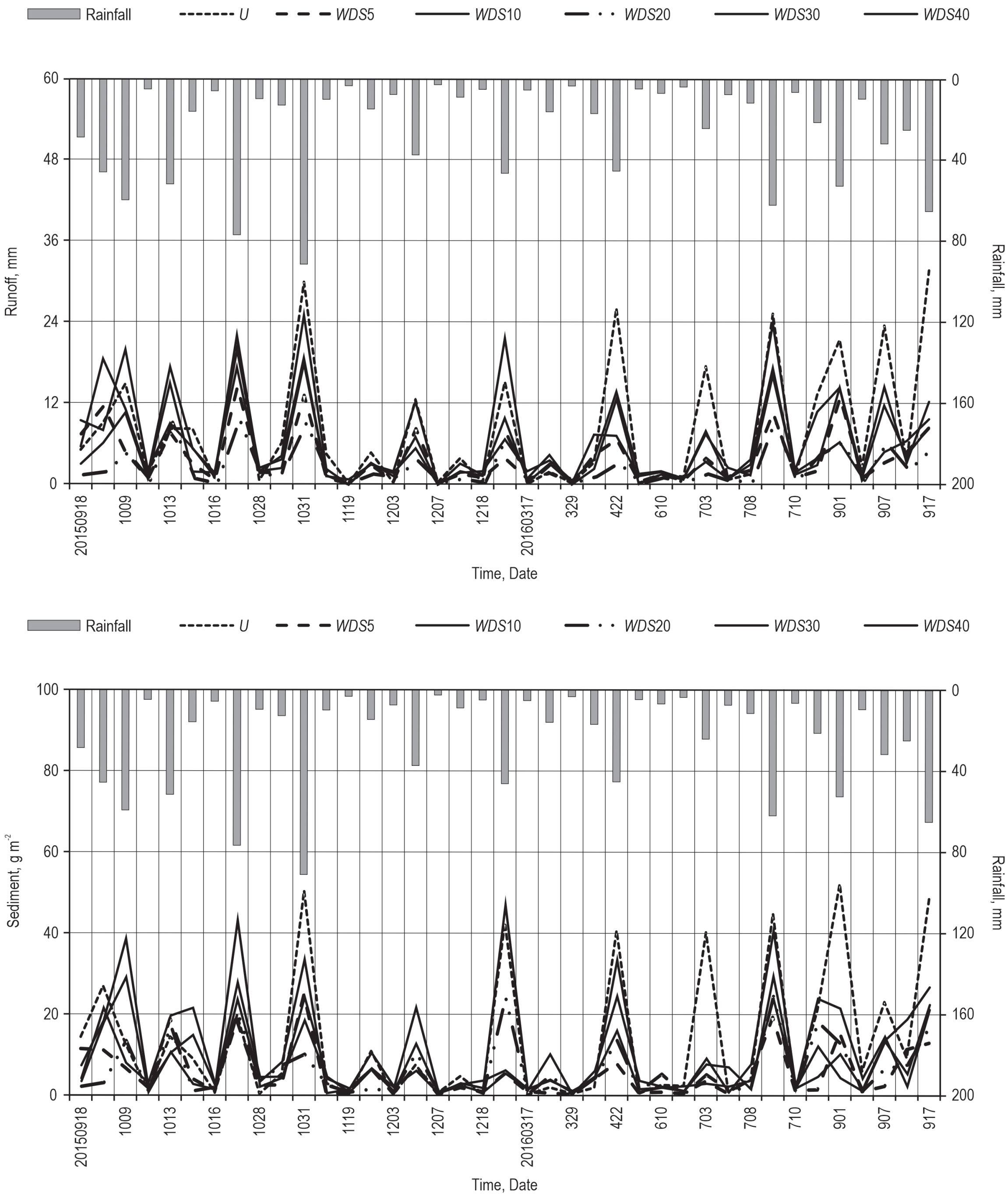

Fig. 2 Rainfall (mm), and average runoff (mm) and sediment yield (g m^{-2}) at the skid trails with the different treatments and the untreated area (*U*) during the first year after skidding operations. *WDS*5 = contour-felled logs at a distance of 5 m, *WDS*10 = contour-felled logs at a distance of 10 m, *WDS*20 = contour-felled logs at a distance of 20 m, *WDS*30 = contour-felled logs at a distance of 30 m, *WDS*40 = contour-felled logs at a distance of 40 m

untreated trail (*U*), which seems to be dependent on rainfall and runoff in each treatment. The variation pattern of peaks in sediment is irregularly observed at most times of the year, which is associated to the runoff generation after rainfall (Fig. 2).

3.3 Nitrate (NO_3-N) and Phosphate (PO_4-P) Concentrations

Results revealed that concentrations of nitrate (NO_3-N) and phosphate (PO_4-P) were significantly affected by the different distances of water diversion structures

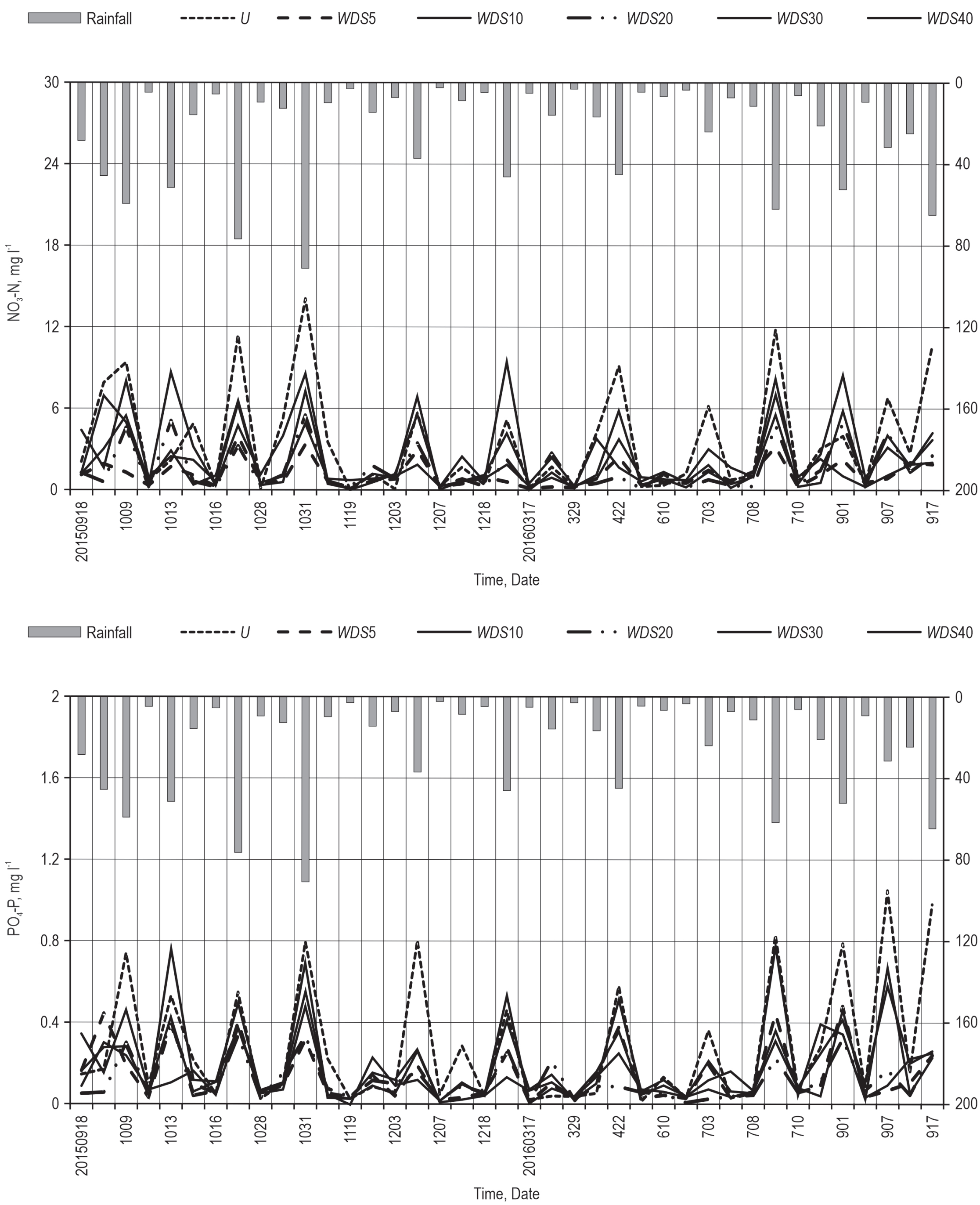

Fig. 3 Rainfall (mm), and average nitrate (NO_3-N) and phosphate (PO_4-P) concentrations (mg l^{-1}) on the skid trails with the different treatments during the first year after skidding operations. *WDS*5 = contour-felled logs at a distance of 5 m, *WDS*10 = contour-felled logs at a distance of 10 m, *WDS*20 = contour-felled logs at a distance of 20 m, *WDS*30 = contour-felled logs at a distance of 30 m, *WDS*40 = contour-felled logs at a distance of 40 m

(*WDS*) (P<0.001) (Table 5). When comparing to the untreated trails (*U*), the application of the *WDS* on the skid trail caused a significant reduction in nitrate and phosphate (Table 6). Significantly higher values of nitrate were found in the *U* (3.63 mg l^{-1}), while the amounts of nitrate were at the lowest level in *WDS*5 followed by the *WDS*20 treatment. The highest phosphate levels were found on the *U* treatment (0.278 mg l^{-1}) followed by the *WDS*40 treatment, whereas the phosphate values were at the lowest level in the *WDS*20 treated area (Table 6). Also, concentrations of nitrate (NO_3-N) and phosphate (PO_4-P) showed a similar trend by increasing the distance among the *WDS* on the skid trails as follows: increased (by increasing the *WDS* distance ranging 5–10 m), decreased, and then increased (by increasing the distance of *WDS* from 20 to 40 m) (Table 6).

The variation patterns of nitrate (NO_3-N) and phosphate (PO_4-P) concentrations in runoff following treatments are presented in Fig. 3. In each rainfall event, the concentrations of nitrate (NO_3-N) and phosphate (PO_4-P) were at the highest levels in the untreated trails (*U*), whereas the lowest nitrate (NO_3-N) and phosphate (PO_4-P) concentrations were found in the *WDS*20. In the *U* treatment, the highest concentrations of nitrate and phosphate by 14.11 and 1.045 mg l^{-1} occurred at the corresponding rainfall of 91.5 and 31.7 mm on 31 October 2015 and on 7 September 2016, respectively. Most of the observed peaks in nitrate (NO_3-N) and phosphate (PO_4-P) concentrations were associated with peaks in rainfall events and runoff volumes. However, the variation in values of nitrate and phosphate concentrations in different *WDS* treatments and the untreated trails (*U*) could be significantly attributed to the scale-dependency of runoff and effectiveness of the *WDS* treatments (Fig. 3).

3.4 Runoff, Sediment Yield, Nitrate and Phosphate Concentrations Model

Table 7 shows the results of the full cubic polynomial regression model for the relationship between dependent variables of runoff, runoff coefficient, sediment yield, and nitrate (NO_3-N) as well as phosphate (PO_4-P) concentrations and independent variables of different distance among *WDS* (*WDS*) and amount of rainfall (*R*). Results indicated all correlation coefficients (R^2) were statistically significant (P<0.01).

The oscillation pattern for runoff, runoff coefficient, and sediment yield as well as concentrations of nitrate and phosphate in response to the different distance among *WDS* and rainfall intensity according to the cubic polynomial regression model are shown in Figs. 4 and 5. Compared to the *U* treatment, the values of runoff, runoff coefficient, and sediment yield were at the lowest level in the *WDS*20 (Fig. 4). By increasing the distance among the *WDS*, the peak in concentrations of nitrate (NO_3-N) and phosphate (PO_4-P) were associated with the peaks in rainfall intensity (Fig. 5). In each *WDS* treatments, the values of runoff and sediment as well as nitrate and phosphate yield were greater in the high rainfall intensity than in the low rainfall intensity (Figs. 4 and 5).

4. Discussion

4.1 Runoff and Sediment Yield

Logging operations lead to an increase in soil bulk density, destruction of soil aggregates, and reduction of water infiltration (Picchio et al. 2012). These are the results of raindrops which strike bare soil, increase

Table 7 Full cubic polynomial regression model for the relationship between runoff, runoff coefficient, sediment yield, and nitrate as well as phosphate concentrations, different distance among *WDS* (*WDS*) and amount of rainfall (*R*). The coefficients of determination are given for each model

Dependent variables	Full cubic polynomial regression model	R^2, %
Runoff	$= 0.17 - 0.38WDS + 0.37R + 0.025WDS^2 - 0.0011R^2 - 0.0004WDS^3 + 0.000004R^3 - 0.017WDS \times R + 0.0004WDS^2 \times R + 0.000001WDS \times R^2$	74.6
Runoff coefficient	$= 0.19 - 0.024WDS + 0.011R + 0.0013WDS^2 - 0.0002R^2 - 0.00002WDS^3 + 0.000001R^3 - 0.0002WDS \times R + 0.000003WDS^2 \times R + 0.0000007WDS \times R^2$	26.4
Sediment yield	$= 0.84 - 0.75WDS + 0.45R + 0.052WDS^2 + 0.0032R^2 - 0.0009WDS^3 - 0.00003R^3 - 0.022WDS \times R + 0.0006WDS^2 \times R + 0.000066WDS \times R^2$	66.8
Nitrate	$= 0.52 - 0.19WDS + 0.11R + 0.01WDS^2 - 0.0002R^2 - 0.0002WDS^3 + 0.000002R^3 - 0.0048WDS \times R + 0.00016WDS^2 \times R - 0.00002WDS \times R^2$	65.6
Phosphate	$= -0.015 - 0.0018WDS + 0.013R + 0.00017WDS^2 - 0.00002R^2 - 0.000002WDS^3 + 0.0000003R^3 - 0.00059WDS \times R + 0.000012WDS^2 \times R - 0.0000008WDS \times R^2$	65.1

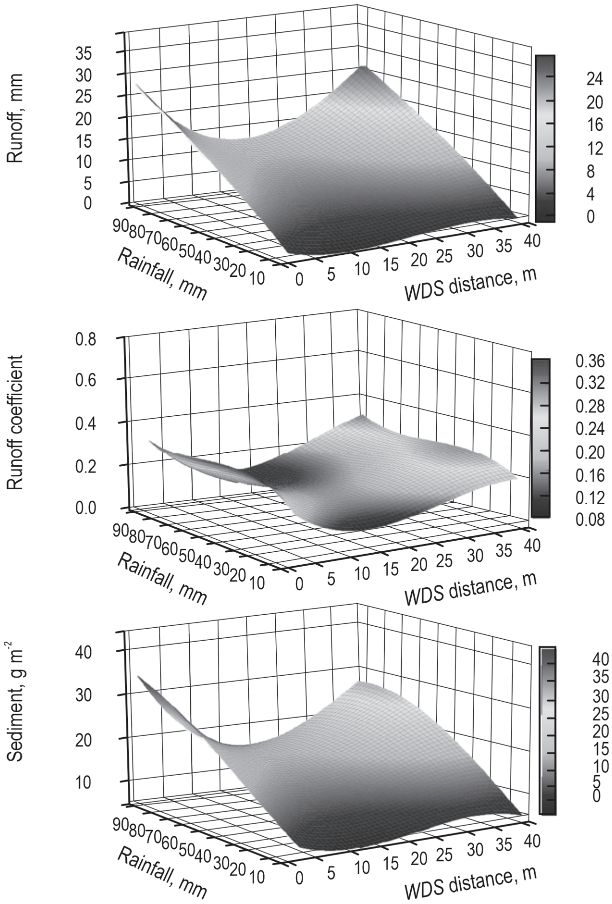

Fig. 4 Predicted runoff, runoff coefficient, and sediment yield at treatments with different distance of water diversion structure (*WDS*) along skid trail under various amount of rainfall based on polynomial regression analysis ($n=702$)

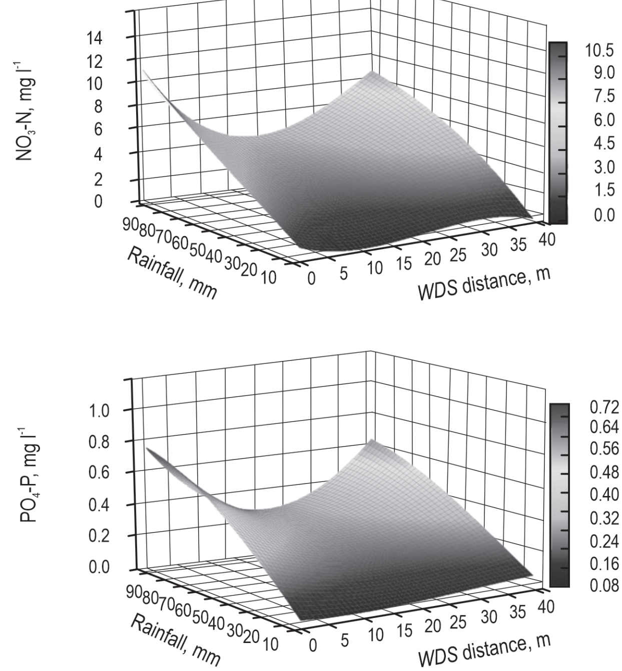

Fig. 5 Predicted nitrate (NO_3-N) and phosphate (PO_4-P) concentrations (mg l^{-1}) at treatments with different distance of water diversion structure (*WDS*) along skid trail under various amount of rainfall based on polynomial regression analysis ($n=702$)

hillslope flow, detach and transport eroded materials (Picchio et al. 2020), and ultimately cause more runoff depth, sediment yield, and nutrient export to the aquatic environments (Kreutzweiser et al. 2008a, Palviainen et al. 2014, 2015, Lindroos et al. 2016, Nieminen et al. 2017, Shah and Nisbet 2019).

Our findings demonstrate that the installation of water diversion structures led to a decrease in runoff and runoff coefficient in all the treatments, as compared to the untreated trails. In line with the current study, previous studies have indicated that forest harvesting caused a decrease in canopy interception, a subsequent decrease in evapotranspiration, and soil compaction, all leading to increased surface runoff flow (Kreutzweiser et al. 2008a, Palviainen et al. 2014, Etehadi Abari et al. 2017, Jourgholami and Etehadi Abari 2017). Likewise, Palviainen et al. (2014) found that runoff increased by 16% after clearcutting. The installation of the *WDS* on the skid trails suppresses the continuity of surface runoff in the hillslope areas, since the *WDS* forms a mini dam that holds the surface water behind the logs, slows down the surface runoff, and disperses the surface runoff away from the trails into the intact soil layer, increasing infiltration rate (Wagenbrenner et al. 2006, Robichaud et al. 2008, Jourgholami and Etehadi Abari 2017, Jourgholami et al. 2020b).

Results of the present study showed different trends in runoff by increasing the distance among the *WDS* as: increase (from 5 to 10 m), decrease (from 10 to 20 m), and increase (from 20 to 40 m). Consistently with our study, several studies have observed the controversial results regarding the plot length effect (i.e., the distance among the *WDS* in the current study) on runoff and sediment yield (Poesen et al. 1994, Moreno-de las Heras et al. 2010, Ghahramani et al. 2011, Prats et al. 2016, Xing et al. 2016, Zhang et al. 2018, Han et al. 2019, Jourgholami et al. 2020b). In line with the current study, Jourgholami et al. (2020b) observed the decreasing-increasing trends in runoff and sediment yield as the distance between contour-felled logs from 10 to 30 m increased. Similarly, Han et al. (2019) concluded that the runoff rate decreased as the slope length increased in the range of 30–40 m, and then continued to increase with the further increase of slope length. He stressed that the slope length of 30 or 40 m could be considered as a threshold, as the continuity of runoff may be affected by the increasing slope length. As was reported by Boix-Fayos et al. (2007) and Han et al. (2019), the walls on both sides of the rills broke down following surface flow causing an obstruction of water flow, and an increase in the infiltration rate, which then led to a decrease in runoff.

Results of the current study revealed that the installation of the *WDS* on the skid trails led to hinder the sediment yield with the highest decrease in the *WDS*10 and *WDS*20 by 59.6% and 53.2%, compared to the *U* treatment. Our findings demonstrated that the oscillation of sediment yield in response to the increase in the distance among the *WDS* showed two trends:

⇒ a decrease from 5 to 10 m

⇒ an increase from 10 to 40 m.

Consistent with the current results, previous studies have concluded that slope length had some negative effects on sediment yield (Bagarello and Ferro 2010, Nadal-Romero et al. 2011, Sadeghi et al. 2013, Xing et al. 2016, Zhang et al. 2018, Jourgholami et al. 2020b). Meanwhile, Sadeghi et al. (2013) concluded that the plot length ranging 15–20 m could be effective to mitigate sediment yield as reported in the current study. Under natural rainfall conditions, Han et al. (2019) revealed that sediment yield was at the lowest level in a slope length of 30 or 40 m. By increasing the slope length, the detached soil particles were transported to the downhill slope generating overland flow (Bagarello and Ferro 2010). The energy needed to move eroded materials were produced by the slope (Parsons et al. 2006, Han et al. 2019), leading to block the energy of runoff for the further movement of eroded loads. Further increasing the slope length caused a decline in the kinetic energy of runoff, and therefore, erodibility is inadequate to transport sediment (Jourgholami and Labelle 2020). In contrast, Ghahramani et al. (2011) reported that sediment increased in the plot length from 5 m to 10 m, and decreased with a slope longer than 10 m. Likewise, Jourgholami and Labelle (2020) found that sediment yield increased significantly with increasing plot length.

4.2 Nitrate and Phosphate Concentrations

Results of the current study demonstrated that the application of the *WDS* treatment on the skid trails significantly reduced the concentrations of nitrate and phosphate ranging 24.8–68.9% and 20.5–59%, compared to the *U* treatment. Consistent with the results of the present study, previous studies have concluded that *WDS* treatments can enhance infiltration and trap as well as store the eroded materials by reducing flow velocities, particularly during the rainstorms occurring during the early Fall, which ultimately lead to detain the nitrate and phosphate exporting them to an aquatic environment and so enhancing the quality of water (Yanosek et al. 2006, Kim et al. 2008, Robichaud et al. 2008, Fernández and Vega 2016). In the current study, concentrations of NO_3-N and PO_4-P increased in the *U* treatments, which is in accordance with the results of the other studies (Feller 2005, Kreutzweiser et al. 2008b, Palviainen et al. 2015, Lindroos et al. 2016, Nieminen et al. 2017, Shah and Nisbet 2019).

Our results indicate that the concentrations of nitrate and phosphate showed a similar trend by increasing the distance among *WDS* as: an increase–to decrease– to increasing trend. The oscillation pattern for concentrations of nitrate and phosphate in response to increasing the distance among *WDS* can be attributed to the concentration time as well as rainfall intensity and duration (Moreno-de las Heras et al. 2010, Zhang et al. 2018, Jourgholami et al. 2018b, 2020b). However, the efficacy of *WDS* treatment to retain nitrate and phosphate export to receiving waters can be associated to some important factors such as installation quality, storage capacity of sediment, rainfall intensity, and the distance among the *WDS* (Wagenbrenner et al. 2006, Kim et al. 2008, Robichaud et al. 2008, Jourgholami et al. 2020b).

According to Kreutzweiser et al. (2008a) and Palviainen et al. (2015), soil disturbances due to traffic of forestry machines led to alter topsoil conditions including soil temperature, moisture conditions, organic matter content, nutrient uptake by plants, and microbial activities. These caused an increase in nitrate and phosphate exporting from the disturbed area to receiving waters. Similarly, Schmidt et al. (1996) indicated that logging operations can lead to increased N availability, increased N export to aquatic environments, resulting in an increase of N losses for forest catchments. Furthermore, Shah and Nisbet (2019) reported that concentrations of nitrate and phosphate increased after clearcutting and returned to pre-harvest levels over a 3–5 year period. The average concentration of nitrate by 2.89 mg l^{-1} in the skid trail were higher than the NO_3-N concentrations of 0.19 mg l^{-1} at the 100% clearcut boreal catchment reported by Palviainen et al. (2014), and lower than the nitrate concentration of 3.8 mg l^{-1} in temperate streams reported by Feller (2005). In three paired-catchments in Eastern Finland, Palviainen et al. (2014) reported that clearcutting annually led to export NO_3-N and PO_4-P by 270 and 12% over a 14-year period, respectively. By clearcutting of >50% of the area of boreal watershed, Lamontagne et al. (2000) found that the export of total N (mostly dissolved organic N) to receiving waters was from 2 to 3-fold higher in the logged area than that of the unharvested stand.

Previous studies reported that the NO_3^- concentrations increased during the first years after logging operations, and then the NO_3^- concentrations reduced following the restoration of the herbaceous layer, plant regeneration, and tree regrowth (Schmidt et al. 1996, Walley et al. 1996, Kreutzweiser et al. 2008a, Palviainen et al. 2015). Similarly, Brais et al. (2002) concluded that the reduction of litter inputs and litter decomposition as well as N mineralization contributed to the lower N pools. The soil N deficit following logging due to accelerated leaching processes was reported by Schmidt et al. (1996). In the aspen stand in the Boreal Plain, Carmosini et al. (2003) reported that concentration of NO_3^- in forest floor increased within the first year after logging operations. Three years after forest harvesting, Lindo and Visser (2003) reported that PO_4^- concentrations in soil water were lower in the clearcut area than in undisturbed stands. However, Whitson et al. (2005) concluded that the lower concentrations of P in the harvested area can be attributed to increased plant uptake following regeneration and understory growth.

4.3 Rainfall Intensity and Predicted Model

Results of the present study indicated that rainfall intensity has a greater impact than the distance on surface runoff flow and sediment yield among the *WDS*. As Figs. 6 and 7 show, the fluctuation patterns for runoff and sediment yield among the different treatments of *WDS* were more remarkable in the low rainfall intensity than in the high rainfall intensity. In consistence with the current results, previous studies have reported that rainfall intensity plays a key role in regulating surface flow generation and sediment yield (Kinnell 2016, Malvar et al. 2017, Zhang et al. 2018, Han et al. 2019, Jourgholami and Labelle 2020, Jourgholami et al. 2020b). Moreover, partitioning the overland flow to infiltrate into soil or to generate runoff flow is mostly dependent on the rainfall intensity as reported by Kinnell (2016). Results of the current study showed that the peaks in rainfall intensity significantly contributed to the peaks in runoff, sediment yield, nitrogen and phosphorous concentrations during the study period. Without a litter layer to intercept the kinetic energy of raindrops, the crushed soil aggregates were easily detached by the increasing rainfall intensity, which resulted in an increase in flow velocity, enhancing the energy of upslope flow that coincided with the loads of eroded materials, thus leading to export the nutrients towards receiving waters (Kreutzweiser et al. 2008b, Palviainen et al. 2015, Lindroos et al. 2016, Nieminen et al. 2017, Zhang and Wang 2017, Shah and Nisbet 2019).

5. Conclusions

Our results indicate that the distance among the water diversion structure (*WDS*; 5, 10, 20, 30, and 40 m) had a significant influence on runoff, sediment yield, and concentrations of nitrate and phosphate. The impact of raindrops causes the detachment of soil particles from the nutrient-enriched mixed layers on the skid trails. The key findings of the current study are summarized as follows:

- ⇒ the installation of water diversion structures led to a decrease in runoff, sediment yield, nitrate, and phosphate concentrations in all the treatments including *WDS*5, *WDS*10, *WDS*20, *WDS*30, and *WDS*40, as compared to the untreated trails
- ⇒ the peaks in runoff, sediment yield, nitrate, and phosphate concentrations can be attributed to the peak in rainfall intensity as well as the distance among the *WDS*
- ⇒ regardless of the rainfall intensity, significant positive quadratic relationships were observed between runoff, runoff coefficients, sediment yield, and concentrations of nitrate and phosphate and the distance among the *WDS* on the skid trails.

Our study highlights the effects of different distances among water diversion structures (*WDS*) on nitrogen, phosphorus, and sediment yield, hence the distance of 20 m among the *WDS* can be considered as the optimal length. This length resulted in the least nitrogen and phosphorus exporting to receiving waters, runoff, and sediment yield under natural rainfall conditions. However, there are still some uncertainties about the conclusion of these findings, that will require further survey, especially regarding factors which influence runoff response, such as slope, traffic, soil type, bulk density and soil penetration resistance as well as proximity or distance to log landing.

Acknowledgments

Authors would like to acknowledge the assistance of Jafar Fathi, Ghodrat Daneshvar and Asghar Ghomi of the Kheyrud Forest Research Station, Nowshahr.

We thank to University College of Agriculture & Natural Resources, University of Tehran (Grant No. 28514) for providing the financial support and funding. Moreover, we would like to thank for the valuable and constructive suggestions provided by two anonymous reviewers.

6. References

Akbarimehr, M., Naghdi, R., 2012a: Assessing the relationship of slope and runoff volume on skid trails (Case study: Nav 3 district). J For Sci 58(8): 357–362. https://doi.org/10.17221/26/2012-JFS

Akbarimehr, M., Naghdi, R., 2012b: Determination of most appropriate distance between water diversions on skid trails in the mountainous forest, northern Iran. Catena 88(1): 68–72. https://doi.org/10.1016/j.catena.2011.08.005

Bagarello, V., Ferro, V., 2010: Analysis of soil loss data from plots of differing length for the Sparacia experimental area, Sicily, Italy. Biosyst Eng 105(3): 411–422. https://doi.org/10.1016/j.biosystemseng.2009.12.015

Boix-Fayos, C., Martínez-Mena, M., Calvo-Cases, A., Arnau-Rosalén, E., Albaladejo, J., Castillo, V., 2007: Causes and underlying processes of measurement variability infield erosion plots in Mediterranean conditions. Earth Surf. Process. Landforms 32(1): 85–101. https://doi.org/10.1002/esp.1382

Brais, S., Pare´, D., Camire´, C., Rochon, P., Vasseur, C., 2002. Nitrogen net mineralization and dynamics following whole-tree harvesting and winter windrowing on clayey sites of northwestern Quebec. For Ecol Manage 157(1–3): 119–130. https://doi.org/10.1016/S0378-1127(00)00643-5

Buttle, J.M., Creed, I.F., Moore, R.D., 2005: Advances in Canadian forest hydrology, 1999–2003. Hydrol Process 19(1): 169–200. https://doi.org/10.4296/cwrj3402113

Carmosini, N., Devito, K.J., Prepas, E.E., 2003: Net nitrogen mineralization and nitrification in trembling aspen forest soils on the Boreal Plain. Can J For Res 33(11): 2262–2268. https://doi.org/10.1139/x03-153

Cambi, M., Grigolato, S., Neri, F., Picchio, R., Marchi, E., 2016: Effects of forwarder operation on soil physical characteristics: A case study in the Italian alps. Croat J For Eng 37(2): 233–239.

Copstead, R.L., Johansen, D.K., Moll, J., 2003: Water/Road Interaction: Introduction to Surface Drains. Department of Agriculture Forest Service Technology and Development Program. 9877 1806—SDTDC, San Dimas, U.S.

Etehadi Abari, M., Majnounian, B., Malekian, A., Jourgholami, M., 2017: Effects of forest harvesting on runoff and sediment characteristics in the Hyrcanian forests, northern Iran. Eur J Forest Res 136(2): 375–386. https://doi.org/10.1007/s10342-017-1038-3

Feller, M.C., 2005: Forest harvesting and streamwater inorganic chemistry in western North America: a review. J Am Water Resour Assoc 41(4): 785–811. https://doi.org/10.1111/j.1752-1688.2005.tb03771.x

Fernández, C., Vega, J.A., 2016: Are erosion barriers and straw mulching effective for controlling soil erosion after a high severity wildfire in NW Spain? Ecol Eng 87: 132–138. https://doi.org/10.1016/j.ecoleng.2015.11.047

Fu, X.T., Zhang, L.P., Wang, X.Y., 2016: The effect of slope length on sediment yield by rainfall impact under different land use types. Water Resour 43(3): 478–485. https://doi.org/10.1134/S0097807816030052

Gee, G.W., Bauder, J.W., 1986: Particle-size analysis. In: Klute A (Ed.), Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods. Soil Science Society of America, Madison, WI, 383–411 p.

Ghahramani, A., Ishikawa, Y., Gomi, T., 2011. Slope length effect on sediment and organic litter transport on a steep forested hillslope: upscaling from plot to hillslope scale. Hydrol Res Lett 5: 16–20. https://doi.org/10.3178/hrl.5.16

Han, Z., Zhong, S., Ni, J., Shi, Z., Wei, C., 2019: Estimation of soil erosion to define the slope length of newly reconstructed gentle-slope lands in hilly mountainous regions. Sci Rep 9(1): 4676. https://doi.org/10.1038/s41598-019-41405-9

Jourgholami, M., Etehadi Abari, M., 2017: Effectiveness of sawdust and straw mulching on postharvest runoff and soil erosion of a skid trail in a mixed forest. Ecol Eng 109(Part A): 1–9. https://doi.org/10.1016/j.ecoleng.2017.09.009

Jourgholami, M., Labelle, E.R., Feghhi, J., 2017: Response of runoff and sediment on skid trails of varying gradient and traffic intensity over a two-year period. Forests 8(12): 472. https://doi.org/10.3390/f8120472

Jourgholami, M., Fathi, K., Labelle, E.R., 2018a: Effects of foliage and traffic intensity on runoff and sediment in skid trails after trafficking in a deciduous forest. Eur J Forest Res 137(2): 223–235. https://doi.org/10.1007/s10342-018-1102-7

Jourgholami, M., Khajavi, S., Labelle, E.R., 2018b: Mulching and water diversion structures on skid trails: Response of soil physical properties six years after harvesting. Ecol Eng 123: 1–9. https://doi.org/10.1016/j.ecoleng.2018.08.023

Jourgholami, M., Labelle, E.R., Feghhi, J., 2019a: Efficacy of leaf litter mulch to mitigate runoff and sediment yield following mechanized operations in the Hyrcanian mixed forests. J Soils Sediments 19(4): 2076–2088. https://doi.org/10.1007/s11368-018-2194-x

Jourgholami, M., Ghassemi, T., Labelle, E.R., 2019b: Soil physio-chemical and biological indicators to evaluate the restoration of compacted soil following reforestation. Ecol Indic 101: 102–110. https://doi.org/10.1016/j.ecolind.2019.01.009

Jourgholami, M., Khajavi, S., Labelle, E.R., 2020a: Recovery of forest soil chemical properties following soil rehabilitation treatments: an assessment six years after machine impact. Croat J For Eng 41(1): 163–175. https://doi.org/10.5552/crojfe.2020.620

Jourgholami, M., Ahmadi, M., Tavankar, F., Picchio, R., 2020b: Effectiveness of three post-harvest rehabilitation treatments for runoff and sediment reduction on skid trails in the Hyrcanian forests. Croat J For Eng 41(2): 309–324. https://doi.org/10.5552/crojfe.2020.732

Jourgholami, M., Labelle, E.R., 2020: Effects of plot length and soil texture on runoff and sediment yield occurring on machine-trafficked soils in a mixed deciduous forest. Ann For Sci 77(1): 19. https://doi.org/10.1007/s13595-020-00938-0

Kaila, A., Sarkkola, S., Laurén, A., Ukonmaanaho, L., Koivusalo, H., Xiao, L., O'Driscoll, C., Asam, Z.U.Z., Tervahauta, A., Nieminen, M., 2014: Phosphorus export from drained Scots pine mires after clear-felling and bioenergy harvesting. For Ecol Manag 325(1): 99–107. https://doi.org/10.1016/j.foreco.2014.03.025

Kemper, W.D., Rosenau, R.C., 1986: Aggregate stability and size distribution. Klute, A., (Ed.), Methods of Soil Analysis. Physical and Mineralogical Properties. Part I (2nd ed.), ASA-SSSA, Madison, WI. Agronomy 9: 425–442.

Kim, C.G., Shin, K., Joo, K.Y., Lee, K.S., Shin, S.K., Choung, Y., 2008: Effects of soil conservation measures in a partially vegetated area after forest fires. Sci Total Environ 399(1–3): 158–164. https://doi.org/10.1016/j.scitotenv.2008.03.034

Kinnell, P.I.A., 2016: A review of the design and operation of runoff and soil loss plots. Catena 145: 257–265. https://doi.org/10.1016/j.catena.2016.06.013

Kinnell, P.I.A., 2009: The impact of slope length on the discharge of sediment by rain impact induced saltation and suspension. Earth Surf Processes Landf 34(10): 1393–1407. https://doi.org/10.1002/esp.1828

Kreutzweiser, D.P., Hazlett, P.W., Gunn, J.M., 2008a: Logging impacts on the biogeochemistry of boreal forest soils and nutrient export to aquatic systems: A review. Environ Rev 16: 157–179. https://doi.org/10.1139/A08-006

Kreutzweiser, D.P., Good, K.P., Capell, S.S., Holmes, S.B., 2008b: Leaf litter decomposition and invertebrate communities in boreal forest streams linked to upland logging disturbance. J N Am Benthol Soc 27(1): 1–15. https://doi.org/10.1899/07-034R.1

Lamontagne, S., Carignan, R., D'Arcy, P., Prairie, Y.T., Pare, D., 2000: Element export in runoff from eastern Canadian Boreal Shield drainage basins following forest harvesting and wildfires. Can J Fish Aquat Sci 57(2): 118–128. https://doi.org/10.1139/f00-108

Leys, A., Govers, G., Gillijns, K., Berckmoes, E., Takken, I., 2010: Scale effects on runoff and erosion losses from arable land under conservation and conventional tillage: The role of residue cover. J Hydrol 390(3–4): 143–154. https://doi.org/10.1016/j.jhydrol.2010.06.034

Lindroos, A.J., Tamminen, P., Heikkinen, J., Ilvesniemi, H., 2016: Effect of clear-cutting and the amount of logging residue on chemical composition of percolation water in spruce stands on glaciofluvial sandy soils in southern Finland. Boreal Environ Res 21: 134–148.

Löfgren, S., Ring, E., von Brömssen, C., Sørensen, R., Högborn, L., 2009: Short-term effects of clear-cutting on the water chemistry of two boreal streams in northern Sweden: A paired catchment study. Ambio 38(7): 347–356. https://doi.org/10.1579/0044-7447-38.7.347

Malvar, M.C., Silva, F.C., Prats, S.A., Vieira, D.C.S., Coelho, C.O.A., Keizer, J.J., 2017: Short-term effects of post-fire salvage logging on runoff and soil erosion. For Ecol Manag 400: 555–567. https://doi.org/10.1016/j.foreco.2017.06.031

Masumian, A., Naghdi, R., Zenner, E.K., 2017: Effectiveness of water diversion and erosion control structures on skid trails following timber harvesting. Ecol Eng 105: 370–378. https://doi.org/10.1016/j.ecoleng.2017.05.017

Moreno-de las Heras, M., Nicolau, J.M., Merino-Martín, L., Wilcox, B.P., 2010: Plot-scale effects on runoff and erosion along a slope degradation gradient. Water Resour Res 46(4): W04503. https://doi.org/10.1029/2009WR007875

Nadal-Romero, E., Martinez-Murillo, J.F., Vanmaercke, M., Poesen, J., 2011: Scale dependency of sediment yield from badland areas in Mediterranean environments. Prog Phys Geogr 35(3): 297–332. https://doi.org/10.1177/0309133311400330

Nieminen, M., Sarkkola, S., Lauren, A., 2017: Impacts of forest harvesting on nutrient, sediment and dissolved organic carbon exports from drained peatlands: a literature review, synthesis and suggestions for the future. For Ecol Manag 392: 13–20. https://doi.org/10.1016/j.foreco.2017.02.046

Palviainen, M., Fine´r, L., Laure´n, A., Launiainen, S., Piirainen, S., Mattsson, T., Starr, M., 2014: Nitrogen, phosphorus, carbon, and suspended solids loads from forest clear-cutting and site preparation: Long-term paired catchment studies from Eastern Finland. Ambio 43(2014): 218–233. https://doi.org/10.1007/s13280-013-0439-x

Palviainen, M., Finér, L., Laurén, A., Mattsson, T., Högbom, L., 2015: A method to estimate the impact of clear-cutting on nutrient concentrations in boreal headwater streams. Ambio 44(2015): 521–531. https://doi.org/10.1007/s13280-015-0635-y

Parsons, A.J., Brazier, R.E., Wainwright, J., Powell, D.M., 2006: Scale relationships in hillslope runoff and erosion. Earth Surf Process Landf 31(11): 1381–1393. https://doi.org/10.1002/esp.1345

Picchio, R., Mederski, P.S., Tavankar, F., 2020: How and How Much, Do Harvesting Activities Affect Forest Soil, Regeneration and Stands? Curr For Rep 6(2): 115–128. https://doi.org/10.1007/s40725-020-00113-8

Picchio, R., Neri, F., Petrini, E., Verani, S., Marchi, E., Certini, G., 2012: Machinery-induced soil compaction in thinning two pine stands in central Italy. For Ecol Manage 285: 38–43. https://doi.org/10.1016/j.foreco.2012.08.008

Poesen, J.W., Torri, D., Bunte, K., 1994: Effects of rock fragments on soil erosion by water at different spatial scales: a review. Catena 23(1–2): 141–166. https://doi.org/10.1016/0341-8162(94)90058-2

Prats, S.A., Wagenbrenner, J., Malvar, M.C., Martins, M.A.S., Keizer, J.J., 2016: Mid-term and scaling effects of forest residue mulching on post-fire runoff and soil erosion. Sci Total Environ 573: 1242–1254. https://doi.org/10.1016/j.scitotenv.2016.04.064

Robichaud, P.R., Pierson, F.B., Brown, R.E., Wagenbrenner, J.W., 2007: Measuring effectiveness of three postfire hillslope erosion barrier treatments, western Montana, USA. Hydrol Process 22(2): 159–170. https://doi.org/10.1002/hyp.6558

Robichaud, P.R., Wagenbrenner, J.W., Brown, R.E., Wohlgemuth, P.M., Beyers J.L., 2008: Evaluating the effectiveness of contour-felled log erosion barriers as a post-fire runoff and erosion mitigation treatment in the western United States. Int J Wildland Fire 17(2): 255–273. https://doi.org/10.1071/WF07032

Sadeghi, S.H.R., Bashari Seghaleh, M., Rangavar, A.S., 2013: Plot sizes dependency of runoff and sediment yield estimates from a small watershed. Catena 102: 55–61. https://doi.org/10.1016/j.catena.2011.01.003

Schmidt, M.G., Macdonald, S.E., Rothwell, R.L., 1996: Impacts of harvesting and mechanical site preparation on soil chemical properties of mixed-wood boreal forest sites in Alberta. Can J Soil Sci 76(4): 531–540. https://doi.org/10.4141/cjss96-066

Shah, N.W., Nisbet T.R., 2019: The effects of forest clearance for peatland restoration on water quality. Sci Total Environ 693: 133617. https://doi.org/10.1016/j.scitotenv.2019.133617

Sohrabi, H., Jourgholami, M., Tavankar, F., Venanzi, R., Picchio, R., 2019: Post-harvest evaluation of soil physical properties and natural regeneration growth in steep-slope terrains. Forests 10(11): 1034. https://doi.org/10.3390/f10111034

Sohrabi, H., Jourgholami, M., Jafari, M., Shabanian, N., Venanzi, R., Tavankar, F., Picchio R., 2020: Soil recovery assessment after timber harvesting based on the Sustainable Forest Operation (SFO) perspective in Iranian temperate forests. Sustainability 12(7): 2874. https://doi.org/10.3390/su12072874

Thien, S.J., Graveel, J.G., 2008: Laboratory Manual for Soil Science: Agriculture & Environmental Principles. Preliminary. McGraw-Hill Companies, Inc., Boston, MA, 218 p.

Wagenbrenner, J.W., MacDonald, L.H., Roug, D., 2006: Effectiveness of three post-fire rehabilitation treatments in the Colorado Front Range. Hydrol Process 20(14): 2989–3006. https://doi.org/10.1002/hyp.6146

Walkley, A., Black, I.A., 1934: An examination of the Degtjareff method for determining soil organic matter and a proposed modification of chromic acid titration method. Soil Sci 37(1): 29–38. http://dx.doi.org/10.1097/00010694-193401000-00003

Walley, F.L., van Kessel, C., Pennock, D.J., 1996: Landscape-scale variability of N mineralization in forest soils. Soil Biol Biochem 28(3): 383–391. https://doi.org/10.1016/0038-0717(95)00153-0

Whitson, I.R., Abboud, S., Prepas, E.E., Chanasyk, D.S., 2005: Trends in dissolved phosphorus in Gray Luvisol soil profiles after forest harvest. Can J Soil Sci 85(1): 89–101. https://doi.org/10.4141/S04-030

Xing, W., Yang, P., Ren, S., Ao, C., Li, X., Gao, W., 2016: Slope length effects on processes of total nitrogen loss under simulated rainfall. Catena 139: 73–81. https://doi.org/10.1016/j.catena.2015.12.008

Yanosek, K.A., Foltz, R.B., Dooley, J.H., 2006: Performance assessment of wood strand erosion control materials among varying slopes, soil textures, and cover amounts. J Soil Water Conserv 61(2): 45–51.

Zhang, X., Hu, M., Guo, X., Yang, H., Zhang, Z., Zhang, K., 2018: Effects of topographic factors on runoff and soil loss in Southwest China. Catena 160: 394–402. https://doi.org/10.1016/j.catena.2017.10.013

Zhang, X.C., Wang, Z.L., 2017: Interrill soil erosion processes on steep slopes. J Hydrol 548: 652–664. https://doi.org/10.1016/j.jhydrol.2017.03.046

Zhao, L., Hou, R., Fang, Q., 2019: Differences in interception storage capacities of undecomposed broad-leaf and needle-leaf litter under simulated rainfall conditions. For Ecol Manage 446: 135–142. https://doi.org/10.1016/j.foreco.2019.05.043

Authors' addresses:

Prof. Meghdad Jourgholami, PhD *
e-mail: mjgholami@ut.ac.ir
Maryam Etehadi Abari, PhD
e-mail: metehadi@ut.ac.ir
University of Tehran
University College of Agriculture & Natural Resources
Faculty of Natural Resources
Department of Forestry and Forest Economics
31585–4314, Zob-e-Ahan Street, Karaj
Alborz
IRAN

Rachele Venanzi, PhD
e-mail: venanzi@unitus.it
Prof. Rodolfo Picchio, PhD
e-mail: r.picchio@unitus.it
Tuscia University
Department of Agriculture and Forest Sciences (DAFNE)
Via S. Camillo de Lellis 01100, Viterbo
ITALY

Prof. Farzam Tavankar, PhD
e-mail: tavankar@aukh.ac.ir
Islamic Azad University, Khalkhal Branch
Faculty of Natural resources
Department of Forestry
Valie Asr Street
56817-31367, Khalkhal City
Ardebil Province
IRAN

* Corresponding author

Received: March 02, 2021
Accepted: July 29, 2021