GEOGRAFICKÝ ČASOPIS / GEOGRAPHICAL JOURNAL 78 (2026) 1, 5-18
DOI: https://doi.org/10.31577/geogrcas.2026.78.1.01

INSTITUTE OF GEOGRAPHY SLOVAK ACADEMY OF SCIENCES

Geografický časopis
Geographical Journal

River flow response under different silvicultural methods in Hyrcanian forests: an indicator-based statistical assessment

Farshad Keivan Behjou[1], Raoof Mostafazadeh[2,*], Nazila Alae[3]

[1] Department of Forest Science and Engineering, Faculty of Agriculture and Natural Resources, University of Mohaghegh Ardabili, Ardabil, Iran, farshad.keivan@gmail.com
[2] Department of Natural Resources, Member of Water Management Research Center, Faculty of Agriculture and Natural Resources, University of Mohaghegh Ardabili, Ardabil, Iran, raoofmostafazadeh@uma.ac.ir
[3] Watershed Management Science and Engineering, Faculty of Natural Resources, Urmia University, Urmia, Iran, nazila.alaie96@gmail.com
* Corresponding author

Abstract

Assessing the hydrological effects of different forestry management practices is important to predict future impacts and determine suitable forest management methods. This study aimed to evaluate the effects of forestry management practices on monthly river flow and hydrological indicators in Asalem forests, Gilan province. In this study, monthly river discharge data from two hydrometric stations (Kharjegil and Khalian) over a 30-year period (1986–2016) were collected, along with forest management operation data obtained from the regional forest management company; the monthly data were selected to investigate the long-term effects of forest management and reduce short-term fluctuations. Two-way ANOVA and Generalized Linear Model tests were used to evaluate the difference in monthly flow due to different forestry management practices. Additionally, One-way ANOVA for three types of forestry operations and an independent t-test for two types of forestry operations across three consecutive 10-year periods (1986–1996, 1997–2006, and 2007–2016) were used to assess significant differences in nine hydrological indicators focusing on various aspects of river flow regimes. In Kharjegil, Selective (Femel) cutting had a higher impact on monthly flow values than Shelterwood/clear cutting ($p<0.05$), while Near nature cutting had a more significant effect ($p<0.002$). No significant difference was observed between Selective cutting and Near nature cutting methods in Kharjegil and Khalian, except for the "Minimum flow index (MinF)" indicator ($p<0.05$) in Kharjegil. The location of the study stations may explain some differences in results. The statistical analysis suggests that Selective cutting and Near nature cutting methods have similar effects on most river flow indicators. However, in the Khalian station, Selective cutting has lower values for the "coefficient of variation (CV)" indicator compared to Near nature cutting, while Shelterwood/clear cutting has a higher impact on the MinF indicator than Selective cutting and Near nature cutting. Therefore, using Selective cutting and Near nature cutting methods instead of Shelterwood/clear cutting is recommended to minimize the impact on minimum river flow.

Key words: *hydrological indicators, water yield, silviculture systems, forestry operations, flow response*

1 INTRODUCTION

Forestry operations for wood production can be a beneficial economic activity if planned and executed properly, but poor design and implementation can lead to environmental damage, reduced wood yield, decreased resource use, and lower labor productivity (Vose et al., 2011; Asbjornsen et al., 2022). The aim of forest exploitation is to implement practical and technically feasible plans with minimal environmental impact that are economically acceptable. Achieving the sustainable forest management requires continuous planning and improvement of the best possible program that incorporates ecological considerations such as following the natural sequence stages in the forest ecosystem, reducing destruction, and avoiding exploitation in vulnerable areas. Changes in vegetation cover can have a significant impact on river flow components and the hydrological cycle, as vegetation cover controls runoff and soil erosion through the canopy, root system, and litter and organic matter layer (Gyssels et al., 2005; Talebi Khiavi & Mostafazadeh, 2021). Understanding the hydrological sensitivity to forest change, defined as the intensity of hydrological response per unit change in forest cover, can help predict the potential hydrological consequences of forest disturbances such as deforestation, fire, and insect infestation (Hou et al., 2023). Wood harvesting in forests can increase sediment production through increased surface runoff and erosion, which can alter the pattern of streamflow (Swank et al., 1988; National Research Council, 2008; Du et al., 2016). In a forest watershed, logging and wood harvesting can affect the water balance by reducing evapotranspiration and interception, and changes in forest cover can have significant impacts on hydrology and soil erosion (Bosch & Hewlett, 1982; Mostafa et al., 2017a; Tague et al., 2019; Picchio et al., 2021). Land use changes in forests can significantly impact the hydrological cycle and biodiversity, which affects human communities' livelihoods. The spatial distribution and canopy cover of forest trees are critical in the hydrological cycle by absorbing precipitation, spatially and temporally distributing water, reducing the impact velocity of raindrops, increasing infiltration, and reducing runoff.

Unsustainable exploitation of forest trees can lead to continuous changes in hydrological conditions, increased destruction, and sediment production (Armstrong et al., 2014; Ning et al., 2015; Cook et al., 2020). Changes in streamflow, groundwater flow, evapotranspiration, suspended sediment transport, water quality parameters, and water balance have been reported due to land use changes, forest disturbance, especially in forested watersheds. Deforestation increases surface runoff and annual peak flow, but the percentage of forest cover has a direct relationship with base flow, reducing streamflow continuity in dry seasons (Robinson et al., 2003; Mehry et al., 2017). Therefore, deforestation and conversion of natural lands into man-made areas leads to destructive floods and soil erosion, reducing water resources. Recovery from changes in forest cover caused by afforestation, such as changes in low-flow and peak flow regimes, may take longer than expected due to reduced soil permeability capacity after deforestation (Cui et al., 2012; del Campo et al., 2022).

Lavigne et al. (2004) used the GIBSI hydrological modeling system to study the impact of deforestation on the Famine River watershed in Québec, Canada. They found that deforestation led to a 57% increase in annual runoff and significant changes in the proportion of runoff to precipitation. Moore and Wondzell (2005) reviewed the impact of forest harvesting on hydrology in the Pacific Northwest. They observed that forest harvesting raises streamflow through increased precipitation, accelerated snowmelt, and altered runoff pathways. Overall, forest harvesting typically increases annual runoff and peak flows while decreasing low flow severity in small headwater catchments, although exceptions occur. Recovery to pre-harvest conditions varies based on catchment characteristics. Eisenbies et al. (2007) reviewed the effects of forestry operations on extreme flooding events in the Appalachians and found that forest operations can have varying impacts on streamflow, particularly through poorly located and designed road networks (Mostafa et al., 2017b). Kuchment et al. (2011) developed a model to study the hydrological cycle and the impacts of forest harvesting. They found that forest harvesting increased pre-snowmelt snow water equivalent by 15%, reduced losses due to snow sublimation by half, raised snowmelt rates by 30%, and extended snowmelt duration by 10 days. Although annual runoff only increased by 10%, there were significant changes in the seasonal distribution and water balance components. Spring flood peak discharge decreased by 50%, floods started later by 5-7 days, and the flood recession was longer. Subsurface flow became the dominant contributor, accounting for 80% of runoff in the deforested basin. The study by Dung et al. (2012) on the effects of forest thinning on runoff generation in a Japanese cypress forest revealed that the impact of forest thinning (harvesting of some trees) on runoff was strongly scale dependent and emphasized on the optimizing water and forest management in forested watersheds. Coble et al. (2020) reviewed the long-term hydrological effects of forest harvest during seasonal low flow in the Pacific Northwest. They identified distinct low flow periods following forest harvest and emphasized the significance of factors like riparian buffers and reforestation requirements in lessening the impact on hydrology.

Existing studies have explored the hydrological impacts of forest management, but few have statistically compared how different silviculture methods affect runoff, streamflow, and water balance components. This research gap limits our understanding of the specific hydrological changes linked to each technique. A statistical assessment can clarify these differences and support more targeted, evidence-based forest management strategies for sustainability. Despite extensive studies on forest management impacts on hydrology, there remains a lack of systematic, statistical comparison of how different silviculture methods specifically affect hydrological processes. Most previous research focuses on general effects of deforestation or harvesting, without differentiating between methods like shelterwood, selective, or near-nature harvesting. This study aims to fill this gap by quantitatively evaluating and comparing the hydrological responses of various harvesting techniques using long-term river flow data and hydrological indices in the Hyrcanian forests.

Different methods of timber harvesting have been developed to maintain the overall health of the forest and promote natural regeneration. Shelterwood harvesting, clear cutting, Selective (Femel) cutting, and the near-nature approach are among the most commonly used methods, each with its advantages and disadvantages. Shelterwood harvesting involves removing trees in a series of stages, leaving some trees to provide shelter for new growth, which can help maintain the overall health of the forest and promote natural regeneration. However, it can be complex to implement and may not be suitable for all types of forests. Selective cutting is a selective method of timber harvesting that involves removing only the mature trees that are ready for harvest, leaving the younger trees to continue growing. This method can help maintain the overall health of the forest and promote natural regeneration, as well as reduce the ecological impact of timber harvesting. Studies have shown that Selective cutting can be an effective method of timber harvesting, particularly in mixed-species forests, due to its moderate impact on hydrological processes and its compatibility with sustainable forest management principles (Clarke et al., 2015; Nordén et al., 2019; Poudyal et al., 2019). However, it can be more time-consuming and labor-intensive than other harvesting methods. The near-nature approach is a timber harvesting method that seeks to maintain the ecological integrity of the forest while still allowing for the extraction of timber. It involves selectively harvesting trees in a way that imitates natural disturbances like windthrow or insect outbreaks. This method can help maintain the overall health of the forest and promote natural regeneration.

The Hyrcanian forests of northern Iran are one of the oldest forest ecosystems globally, boasting about 80 tree species and 50 shrub species and are generally considered part of the deciduous broad-leaved or summer green forests. These forests are environmentally and socio-economically significant, and their exploitation needs assessment for their impact on the river regime. The studied forests have at least three distinct age classes based on their age and biophysical characteristics. Among the tree species, Oriental beech (Fagus Orientalis), hornbeam (Carpinus betulus), and chestnut-leaved oak (Quercus castaneifolia) are of special importance in terms of density, ecological role, and economic exploitation. This study examines the impact of different tree harvesting methods, such as shelterwood/clear cutting, Selective cutting, and the near-nature approach, on the hydrological aspects of the river flow regime, including monthly river flow data and nine hydrological indices, over three consecutive periods in the Caspian forests of northern Iran.

2 MATERIAL AND METHODS

Study area

The Navroud catchment area is located in the western part of Gilan province in northern Iran, covering an area of 307 square kilometers in the Talish region. The Navroud River‘s primary branches originate from the eastern slopes of the Talesh and Hejab mountains, including Soltekhouni, Asbariseh, Haftekhouni, and Boughrou. After merging with other tributaries, the river flows from east to west, passing through the city of Asalem, and eventually reaches the Caspian Sea, 6 kilometers after the Kharjegil station. A section of the Navroud basin is a plain of approximately 41 km^2, while the rest, up to the Kharjegil station, is mountainous, covering approximately 266 km^2. The study area includes a portion of the Hyrcanian forests of Iran, which are moist forests, while the highlands have alpine vegetation (Fig. 1). The study area‘s minimum and maximum elevations above sea level are 118 and 3016 meters, respectively, and the total length of the main river up to the Kharjegil station is approximately 33.28 kilometers. The entire basin‘s average slope is 47 percent. The average annual precipitation in the entire basin during the 15-year statistical period is 983 mm, and the region‘s climate is classified as „humid“ and cold in the highlands and „very humid“ in the lowlands according to the modified De Marten‘s climate classification. According to the Ambergris method, the climate classification is „humid“ in the upper elevations and „very humid“ in the lower elevations.

Research Methodology

The present study collected statistical data on daily precipitation and river flow from meteorological and hydro-metric stations in the study area over a 30-year period (1986-2016) in Gilan Province, obtained from the Regional Water Company. Although daily precipitation and river flow data were available for the 30-year period, the analysis was based on monthly data. This choice was made because the hydrological effects of forest management, especially over long-term silvicultural periods, are better reflected at the monthly scale. Monthly data reduce short-term fluctuations and highlight broader trends aligned with forest changes. The selected hydrological indicators (e.g., minimum flow, average flow, variability) are also more interpretable and statistically stable at the monthly level. There were no major data gaps; the use of monthly data was a methodological decision, not a response to data limitations.

Information and documents provided by the Shafaroud Forest Company were used to obtain the different forest management and harvesting methods. The first period of harvesting used the shelterwood/clear cutting method (1986-1996), the second period used the Selective cutting method (1997-2006), and the third period used the near-nature approach (2007-2016).

Forest harvesting methods

Shelterwood/clear cutting: A staged timber harvesting method that removes most trees while leaving some for regeneration, significantly affecting surface and subsurface runoff.

Selective (Femel) cutting: A selective harvesting method that removes individual or small groups of trees, preserving forest structure. Its impact on runoff varies with cutting intensity and timing.

Near-nature cutting: A low-impact harvesting approach that supports forest health and minimizes ecological disturbance (Keivan Behjou et al., 2024).

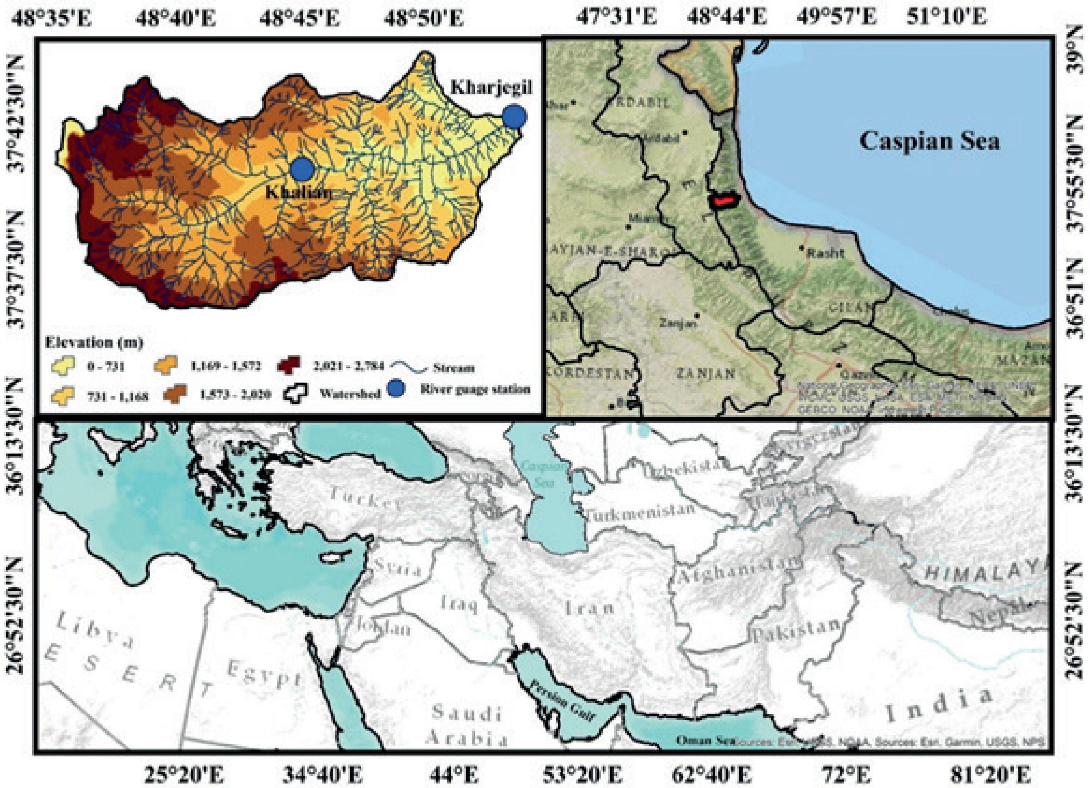

Fig. 1. Geographical location and the stream network and river gauge stations in Navroud Asalem Forested area

Hydrologic alteration indices

The following section evaluates changes in the hydrological regime and river flow characteristics based on nine indicators. These include minimum flow, maximum flow, average flow rate, minimum flow condition index, maximum flow condition index, coefficient of variation, water yield (million cubic meters), runoff height, and runoff coefficient index (Jones & Grant, 1998; Esfandyari Darabad et al., 2020; Mostafazadeh et al., 2020). One hypothesis examined in this study is that different forest management operations have varying effects on the hydrological components of flow, and the impact of these operations on flow characteristics can range from mild to severe. Therefore, changes in hydrological indicators of flow were compared and evaluated for three different forest harvesting periods: Shelterwood/clear cutting, Selective cutting, and Near nature approach. The selected indicators for hydrologic alteration analysis were divided into two categories. The first category evaluated indicators based on the components of the flow regime, while the second category used dimensionless indicators to assess the net effect of harvesting methods by removing the impact of precipitation values and fluctuations on the runoff regime.

Minimum flow index (MinF): This indicator can evaluate the effect of different forest harvesting methods on the base flow of the river.

Maximum flow (MaxF): This indicator is used to determine the effect of different forest harvesting methods on flood flows.

Average flow rate (AvgF): The average flow rate indicator represents the watershed response to the combination of surface, base, and sub-surface flows and is commonly used as a useful and measurable indicator in evaluating the impact of management practices.

Minimum flow condition index (LowF): The minimum flow condition index is obtained by dividing the minimum monthly flow data by the average flow rate.

Maximum flow condition index (HighF): The maximum flow condition index is obtained by dividing the maximum flow rate by the values of the minimum flow condition index. This indicator represents the flow rate values under high water conditions.

Coefficient of Variation of flow discharge (CV): The CV of river flow used to assess data distribution, obtained by dividing the standard deviation by the mean. In other words, the CV of river flow expresses the level of dispersion for a unit of mean. This value is defined when the mean is not zero. This value is dimensionless, which makes it suitable for comparing statistical data with different units. The flow variation coefficient is only applicable to relative scales and cannot be used to measure values that can take negative values or, in other words, cannot be used to measure distance values.

Water yield (WY): This indicator is the result of surface runoff, infiltration, and sub-surface flows that contribute to the river‘s water yield with a time lag. It is measured in the unit of time in cubic meters per second.

Runoff height (RH): This indicator is obtained by dividing the runoff by the watershed area. Runoff height is the percentage of precipitation that is converted to surface runoff. The runoff height index is used to show the effect of different management practices on infiltration and runoff production.

Runoff coefficient index (RC): Since the runoff coefficient is influenced by many variables that affect the formation and intensity of floods, it can change due to forest management operations. The amount and intensity of precipitation affect the runoff coefficient at different time scales. In the present study, the runoff coefficient index was calculated by dividing the runoff height by the mean monthly precipitation.

Statistical analysis of monthly river flow data

In this stage, the monthly discharge values of the studied stations during the available statistical periods were analyzed using the general linear model (GLM) method to test the influence of different silviculture methods. The GLM is a widely used statistical technique for analyzing relationships between variables and allows for the inclusion of multiple independent variables, such as the different silviculture methods, to assess their impact on the dependent monthly river flow variables (Gelman & Hill, 2006; Neter et al., 1996). Univariate analysis of variance (ANOVA) was used to determine the relationship between categorical silviculture variables and dependent monthly river flow variables. ANOVA is a statistical method that tests whether the means of two or more groups are significantly different from each other and allows for the comparison of the mean monthly river flow values between the different silviculture methods (Ghasemi & Zahediasl, 2012; Borcard et al., 2018).

Statistical Analysis of hydrological river flow indices

To determine the significance of different river flow indicators resulting from various forest management practices, One-Way ANOVA and independent t-tests were employed, which are common statistical methods in hydrological studies. One-Way ANOVA tests the null hypothesis that there is no difference between the means of the examined periods, while the alternative hypothesis is that there is a significant difference between the means of at least two groups (Ghasemi & Zahediasl, 2012). Rejecting the null hypothesis indicates that there is a significant difference between the indicators in different forest management practices. Additionally, the Tukey post-hoc test can be used to determine the degree of difference and the effect of different forest management practices on flow indicators (Borcard et al., 2018). The type of forest management system is considered as a treatment, and One-Way ANOVA is used to test the significance between different management practices, which is a widely used approach in hydrological studies. Subsequently, based on the normality test of the data, mean comparison tests such as the independent t-test can be used to determine which of the treatments are significantly different (Field, 2013). These statistical methods can provide valuable indications for the effects of different forest management practices on river flow indicators, assisting in the development of sustainable forest management practices.

It should be noted that in the Khalian station, where there were two periods (Selective cutting, and Near nature cutting method) for statistical analysis, an independent t-test was used to test the significance of the difference between the hydrological flow indices.

Software used

All statistical analyses and data visualizations were conducted using both R software (version 4.3.1) and IBM SPSS Statistics (version 26). R was primarily used for data preprocessing, visualization (ggplot2), and exploratory analysis, while SPSS was employed for conducting ANOVA, independent t-tests, and post-hoc analyses such as Tukey’s test.

3 RESULTS

Table 1 and Figure 2 presents the results of the Tukey HSD test in multiple comparisons of the effects of silviculture methods on monthly flow values in Kharjegil station.

According to the Table 1, the Tukey HSD results show that Shelterwood/clear cutting produced significantly higher monthly flows than selective cutting (0.79) and near nature cutting (0.84) ($p < 0.01$). No significant difference was found between selective and near nature cutting (0.05, $p = 0.97$). Overall, intensive cutting methods greatly increased monthly flows, while less intensive methods showed similar hydrological effects. The largest differences were between Shelterwood/clear cutting and the other two methods.

Figure 2 illustrates the variations in the mean monthly streamflow at the Kharjegil station under three different logging methods. As observed, the Shelterwood/clear cutting method (No. 1) exhibits the highest discharge values during most months of the year, particularly in autumn and winter. In contrast, the Selective cutting (No. 2) and Near nature cutting (No. 3) methods display very similar streamflow patterns and values throughout the year, both generally lower than those of the first method. This pattern clearly indicates the stronger impact of the Shelterwood/clear cutting method on increasing monthly discharge, likely due to the significant reduction in vegetation cover, which decreases evapotranspiration and increases surface runoff.

Table 2 and Figure 3 presents the results of the Tukey HSD test in multiple comparisons of the effects of silviculture methods on monthly flow values in Khalian station.

Table 2 presents the results of the Tukey HSD test comparing the effects of different silvicultural methods on monthly flow values at the Khalian station. The comparison was made between the Selective cutting (2) and Near nature cutting (3) methods. The mean difference in flow between these two methods is -0.154, indicating that the Near nature cutting method tends to produce slightly higher flow values than the Selective cutting method.

Although the difference in mean flow values is not statistically significant ($p = 0.085$), the numerical gap (0.154) suggests a moderate variation between the two cutting approaches. The confidence interval (-0.330 to 0.021) includes zero, confirming that the difference is not strong enough to be conclusive. However, it still reflects a trend toward higher discharge under the Near nature cutting system. While both methods show comparable hydrological responses, the Near nature cutting method appears to slightly enhance streamflow compared to Selective cutting. This difference, though not significant, may indicate subtle variations in canopy cover and soil infiltration capacity resulting from the two management techniques.

Figure 3 shows the variations in the mean monthly streamflow at the Khalian station under two logging methods: Selective cutting (No. 2) and Near nature cutting (No. 3). As seen in the graph, the seasonal flow pattern for both methods is almost identical,

Tab. 1. The results of the Tukey HSD test in multiple comparisons of the effects of silviculture methods on monthly flow values in Kharjegil station

(I) Cutting method	(J) Cutting method	Mean Difference (I-J)	Std. Error	Sig.	Lower B, 95% CI	Upper B, 95% CI
1	2	0.79*	0.24	0.004	0.20	1.37
	3	0.84*	0.24	0.002	0.26	1.43
2	1	-0.79*	0.24	0.004	-1.37	-0.20
	3	0.05	0.24	0.970	-0.52	0.64
3	1	-0.84*	0.24	0.002	-1.43	-0.26
	2	-0.05	0.24	0.970	-0.64	0.52

1= Shelterwood/clear cutting, 2= Selective cutting, 3= Near nature cutting, The error term is Mean Square = 3.998, *= The mean difference is significant at the 0.05 level.

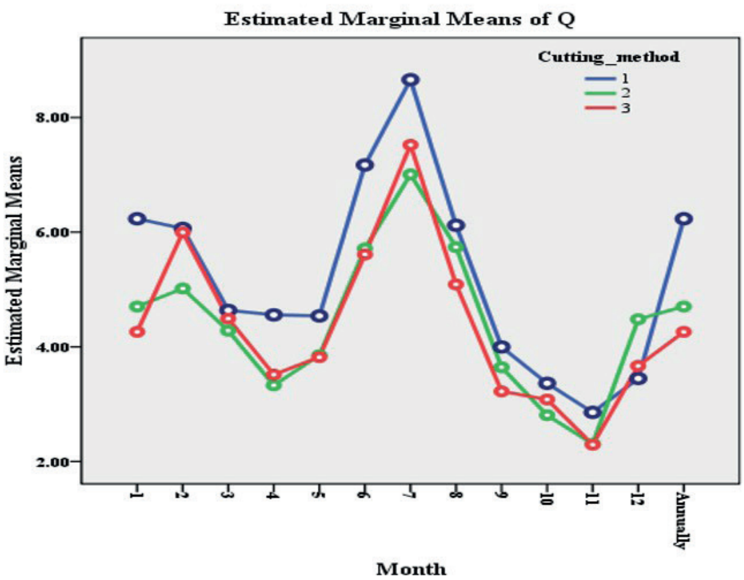

Fig. 2. The interactions of monthly flow values across different silviculture methods at Kharjegil station, (1= Shelterwood/clear cutting, 2= Selective cutting, 3= Near nature cutting)

Tab. 2. The results of the Tukey HSD test in multiple comparisons of the effects of silviculture methods on monthly flow values in Khalian station

(I) Cutting method	(J) Cutting method	Mean Difference (I-J)	Std. Error	Sig.	Lower B, 95% CI	Upper B, 95% CI
2	3	-0.154	0.089	0.085	-0.330	0.021
3	2	0.154	0.089	0.085	-0.021	0.330

2= Selective cutting, 3= Near nature cutting

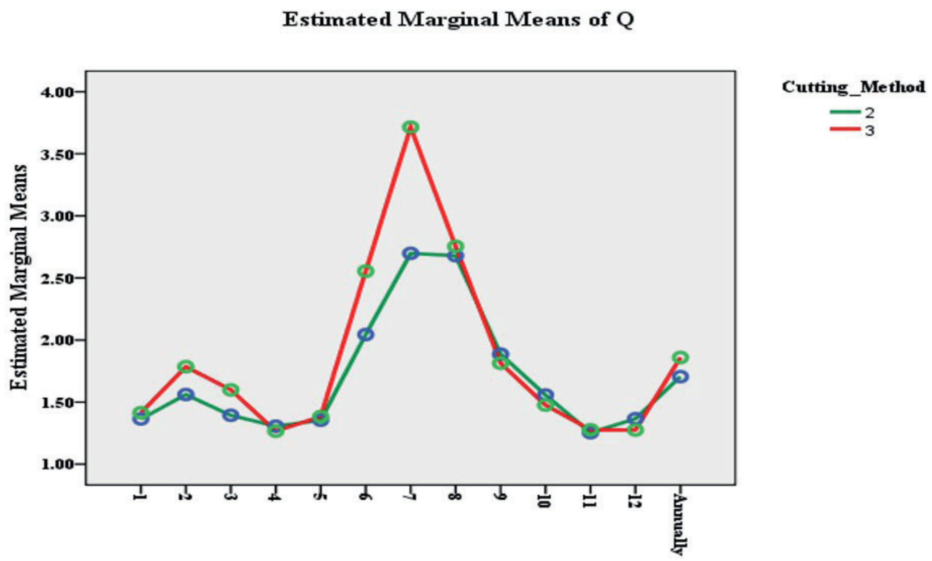

Fig. 3. The interactions of monthly flow values across different silviculture methods at Khalian station, (2= Selective cutting, 3= Near nature cutting)

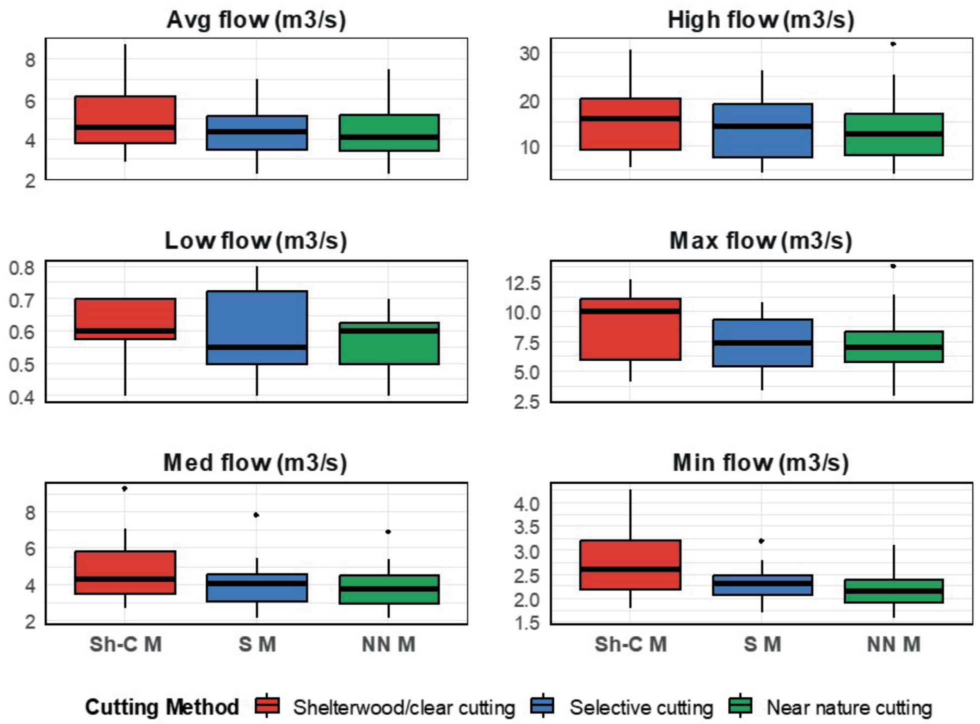

Fig. 4. The comparison of monthly flow characteristics over different silviculture methods in Navroud forest at Kharjegil station

with peak flows occurring in March, April, and May (corresponding to the snowmelt and spring rainfall period) and the lowest discharges observed in late summer and autumn. Notably, the curves of the two methods largely overlap, showing no distinct differences between them. This overlap indicates that, statistically, the effects of these two methods on monthly discharge at the Khalian station are similar and not significantly different.

Table 3 compares annual hydrological indices across three silviculture methods at two Navroud forest stations: Kharjegil and Khalian

As seen in Table 3, at Kharjegil, Shelterwood/clear cutting had higher flows, notably min (4.0 vs. 2.8), max (7.0 vs. 5.1), and yield (162.0 vs. 138.2 MCM). Near nature cutting had the highest high flow (10.2) and largest CV (23.5%). At Khalian, near nature cutting exceeded selective cutting in max flow (3.2 vs.

Tab. 3. Comparison of annual hydrological indices at two Navroud stations under different silviculture methods

Index	Navroud (Kharjegil)			Navroud (Khalian)	
	Shelterwood/ clear cutting	Selective cutting	Near nature cutting	Selective cutting	Near nature cutting
Min flow (m^3/s)	4.0	3.4	2.8	1.2	1.3
Max flow (m^3/s	7.0	5.1	6.8	2.3	3.2
Avg flow (m^3/s)	5.1	4.4	4.4	1.7	1.9
Med flow (m^3/s	5.1	4.4	4.3	1.7	1.7
Low flow (m^3/s)	0.8	0.8	0.7	0.7	0.8
High flow (m^3/s)	8.8	6.6	10.2	3.1	4.3
CV (%)	19.7	13.2	23.5	19.2	30.1
WY (MCM)	162.0	139.0	138.2	53.8	58.6
RH (mm)	736.5	631.8	628.1	256	279
RC (-)	0.6	0.5	0.5	0.4	0.4

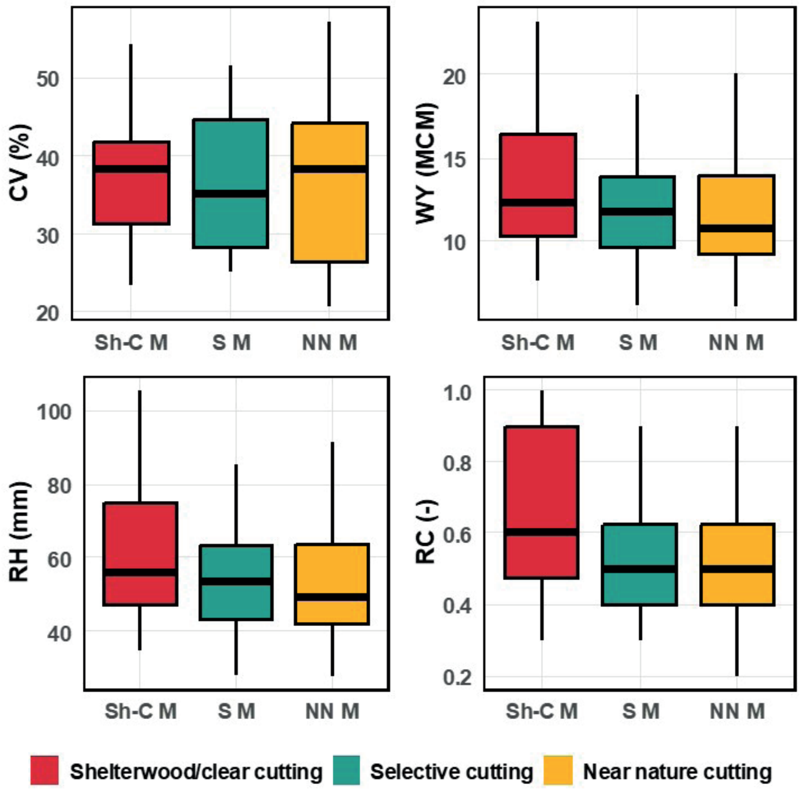

Fig. 5. The comparison of hydrological variability and water balance indices over different silviculture methods in Navroud forest at Kharjegil station

2.3), high flow (4.3 vs. 3.1), and CV (30.1% vs. 19.2%), with slightly higher yield (58.6 vs. 53.8 MCM).

The comparison of monthly hydrological indices values over different silviculture methods at Kharjegil station has been presented in Figure 4 and 5.

Figure 4 compares monthly flow characteristics under three silvicultural methods at the Kharjegil station. The Shelterwood/clear cutting method exhibits the highest values across most flow indices, including average flow, maximum flow, and high flow, indicating enhanced surface runoff due to extensive vegetation removal. In contrast, both Selective cutting and Near nature cutting show similar and relatively lower flow magnitudes with smaller variability. Minimum flow values are also lowest under these two methods, reflecting greater water retention and evapotranspiration. Overall, these results highlight the pronounced hydrological impact of the Shelterwood/clear cutting method in increasing monthly discharge compared to more conservative management approaches.

Figure 5 presents a comparison of hydrological variability and water balance indices (CV, W/T, RH, and RC) among the three cutting methods. The Shelterwood/clear cutting method records the highest CV (around 35%) and RH values, reflecting substantial fluctuations in monthly flow and increased runoff generation. Conversely, the Near nature cutting method displays the lowest CV and RC values, suggesting more stable hydrological conditions and improved soil moisture retention. The Selective cutting method falls between the two extremes. In general, higher harvesting intensity leads to greater hydrological instability and a decline in water balance efficiency across the watershed.

The comparison of monthly hydrological indices values over different silviculture methods in Navroud forest at Khalian station has been presented in Figure 6 and 7.

Figure 6 illustrates the variations in monthly flow indices under Selective cutting and Near nature cutting methods at the Khalian station. Both methods follow a nearly identical seasonal pattern, with comparable values for minimum, average, and maximum flows. However, Near nature cutting shows slightly higher maximum flow (around 2.0 m^3/s), possibly due to more efficient subsurface flow pathways and moderated canopy interception. The relatively small differences and overlapping ranges suggest that these two silvicultural systems exert similar influences on streamflow dynamics. Statistically, the hydrological responses of the two methods are not significantly different.

Figure 7 compares the variability and water balance indices (CV, W/T, RH, and RC) under the two silvicultural methods at the Khalian station. The Near nature cutting method demonstrates slightly higher CV and RC values compared to Selective cutting, indicating marginally greater fluctuations in monthly discharge. Meanwhile, W/T values remain close between the two treatments, suggesting comparable water balance conditions. Overall, the Near nature cutting approach maintains relatively stable hydrological behavior, preserving forest hydrological functions with minimal disturbance. These findings reinforce its suitability as a sustainable silvicultural practice in temperate forested catchments.

ANOVA was conducted to compare the effect of silviculture methods on the river flow indices in Kharjegil station, and the results are presented in Table 4.

ANOVA results show only minimum flow (MinF) differed significantly between silviculture methods ($p = 0.037$, $F = 3.623$), while other indices showed no significant changes ($p > 0.3$). This indicates cutting methods mainly affect low-flow conditions, with little impact on other hydrologic characteristics.

In the following, the results of differences in hydrological indices over different silviculture methods by conducting the LSD post hoc test has been presented in Table 5.

The LSD test shows a significant difference in minimum flow between Shelterwood/clear cutting and Near nature cutting (0.62, $p = 0.01$), with Shelterwood maintaining higher minimum flows. Other flow indices like maximum and average flow show no significant differences despite some numeric variations. This suggests that silviculture methods mainly affect low-flow conditions, while overall water yield and flow variability remain similar across methods. Minimum flow is the most sensitive index to cutting practices at Kharjegil station.

The descriptive statistics of the hydrological indices resulted from different silviculture methods in Khalian station has been shown in Table 6.

The results of Table 6 show that the mean values of most indices are slightly higher under the Near nature cutting method. For example, maximum flow (MaxF) and average flow (AvgF) are greater in the Near nature cutting treatment (3.35 vs. 2.76 m^3/s and 1.87 vs. 1.72 m^3/s, respectively), indicating a modest increase in flow magnitude under this approach. A considerable difference is observed in the variability index (CV), where Near nature cutting exhibits considerably higher variability (38.09%) compared to Selective cutting (29.18%). This suggests that despite similar average flow conditions, the Near nature method may produce more fluctuating monthly discharges. Similarly, the high-flow index (HighF) also shows a marked increase (5.54 vs. 4.53 m^3/s), further emphasizing enhanced flow peaks under the Near nature regime. While the two methods show relatively close hydrological behavior, the Near nature cutting approach tends to generate slightly higher and more variable flow conditions. This pattern may be attributed to differences in canopy cover and soil infiltration capacity, where partial disturbances under the Near nature system promote episodic runoff while maintaining overall flow stability.

The results of independent t-test to show the differences in hydrological flow indices resulted from different silviculture methods in Khalian station has been shown in Table 7.

According to Table 7, most hydrological indices at Khalian station show no significant difference between silviculture methods, except for the coefficient of variation (CV), which significantly decreased (mean difference = -8.90, $p = 0.00$). Other indices like MinF and MaxF showed little change. This means that while flow amounts remain similar, flow variability is notably lower under some silviculture

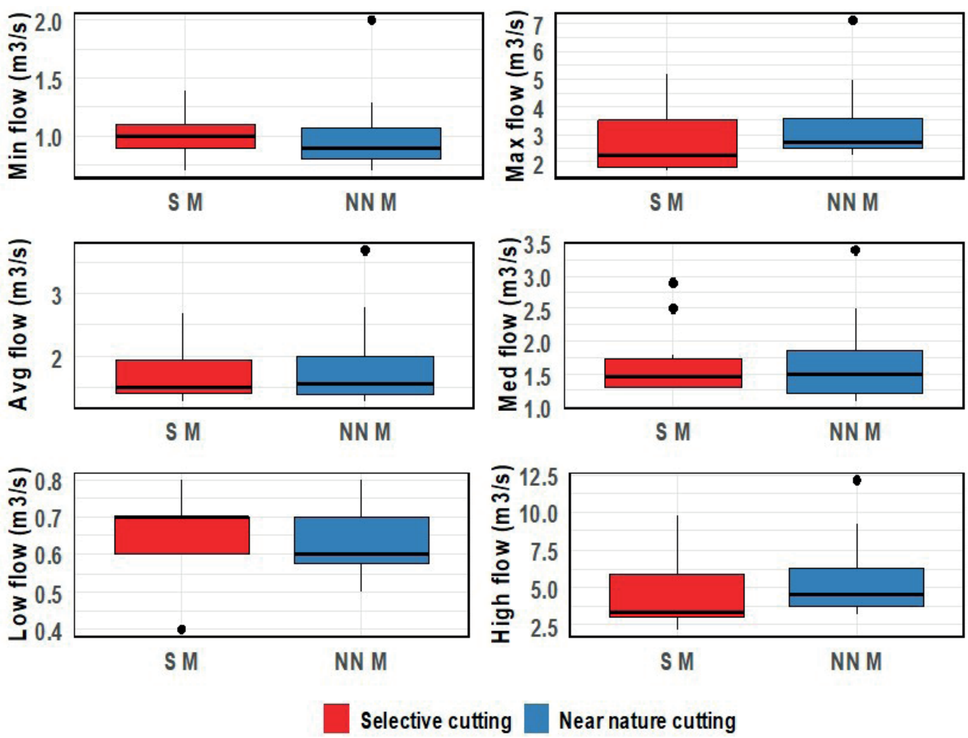

Fig. 6. The comparison of monthly flow characteristics over different silviculture methods in Navroud forest at Khalian station

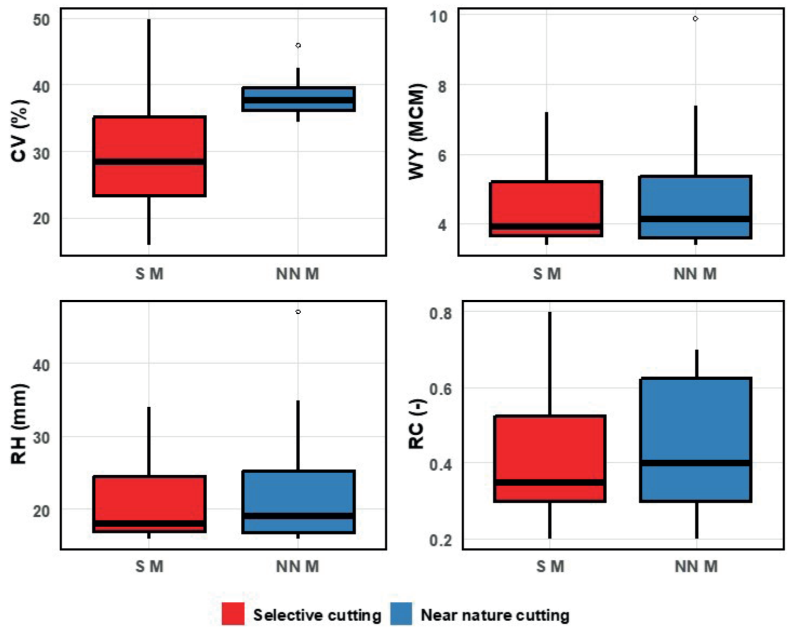

Fig. 7. The comparison of hydrological variability and water balance indices over different silviculture methods in Navroud forest at Khalian station

Tab. 4. The results of the analysis of variance (One-way ANOVA) test of different hydrologic indices resulted from silviculture methods at Kharjegil station

Index	Source of Variation	Sum of Sq.	df	Mean Sq.	F	Sig.
MinF	Between Groups	2.78	2	1.38	3.623	0.037
	Within Groups	13.8	36	0.38		
MaxF	Between Groups	18.24	2	9.11	1.196	0.314
	Within Groups	274.48	36	7.62		
AcgF	Between Groups	4.79	2	2.39	1.131	0.334
	Within Groups	76.22	36	2.11		
MedF	Between Groups	5.27	2	2.63	1.107	0.341
	Within Groups	85.72	36	2.38		
LowF	Between Groups	0.008	2	0	0.263	0.77
	Within Groups	0.548	36	0.01		
HighF	Between Groups	26.43	2	13.21	0.23	0.796
	Within Groups	2071.29	36	57.53		
CV	Between Groups	25.64	2	12.82	0.096	0.909
	Within Groups	4833.84	36	134.27		
WY	Between Groups	114.95	2	57.47	0.041	0.96
	Within Groups	50529.99	36	1403.61		
RH	Between Groups	2375.03	2	1187.51	0.041	0.96
	Within Groups	1044008.08	36	29000.22		
RC	Between Groups	0.082	2	0.04	0.911	0.411
	Within Groups	1.61	36	0.04		

methods, suggesting a more stable hydrologic regime that could benefit water management.

4 DISCUSSION

Comparative Effects of Silviculture Methods on River Flow

The statistical analysis revealed distinct hydrological impacts from different silviculture methods. At the Kharjegil station, the most intensive method, Shelterwood/clear cutting, resulted in significantly higher monthly flow values compared to both Selective cutting (mean difference = 0.79 m^3/s, $p < 0.05$) and Near nature cutting (mean difference = 0.84 m^3/s, $p < 0.002$) (Tab. 1, Fig. 2). This pattern was consistent across several hydrological indices, where Shelterwood/clear cutting yielded the highest maximum flow (7.0 m^3/s) and high flow (8.8 m^3/s, Tab. 3). These results align with numerous studies that have documented increased streamflow following intensive canopy removal. For instance, Moore and Wondzell (2005) concluded that forest harvesting typically increases annual runoff and peak flows, a pattern strongly echoed in our results from the more intensive Shelterwood/clear cutting system. Similarly, Lavigne et al. (2004) reported a 57% increase in annual runoff after deforestation, underscoring the profound impact of significant canopy reduction on watershed hydrology. The mechanism is primarily attributed to reduced evapotranspiration and interception losses, leading to increased water availability for runoff (Bosch & Hewlett, 1982).

Conversely, the hydrological effects of Selective cutting and Near nature cutting were statistically similar at both the Kharjegil and Khalian stations for monthly flow values (Tab. 1 and 2, Fig. 2 and 3). This similarity suggests that these less intensive methods impose a comparable and more moderate influence on the river flow regime. This result is consistent with the principles of sustainable forest management, which advocate for harvesting techniques that mimic natural

Tab. 5. The result of multiple comparisons of river flow index over different silviculture methods according to LSD post hoc test at Kharjegil station

Dep. Var	(I)	(J)	Mean Diff (I-J)	Std. Error	Sig.	Lower B 95% CI	Upper B 95% CI	Dep. Var	(I)	(J)	Mean Diff (I-J)	Std. Error	Sig.	Lower B 95% CI	Upper B 95% CI
MinF	1	2	0.47	0.24	0.05	-0.01	0.96	HighF	1	2	1.08	2.97	0.54	-4.19	7.86
		3	0.62*	0.24	0.01	0.13	1.11			3	1.64	2.97	0.58	-4.39	7.67
	2	1	-0.47	0.24	0.05	-0.96	0.01		2	1	-1.83	2.97	0.54	-7.86	4.19
		3	0.15	0.24	0.53	-0.34	0.64			3	-0.19	2.97	0.94	-6.22	5.84
	3	1	-0.62*	0.24	0.01	-1.11	-0.13		3	1	-1.64	2.97	0.58	-7.67	4.39
		2	-0.15	0.24	0.53	-0.64	0.34			2	0.19	2.97	0.94	-5.84	6.22
MaxF	1	2	1.49	1.08	0.17	-0.70	3.69	CV	1	2	1.70	4.54	0.71	-7.51	10.92
		3	1.40	1.08	0.20	-0.79	3.59			3	-0.03	4.54	0.99	-9.25	9.18
	2	1	-1.49	1.08	0.17	-3.69	0.70		2	1	-1.7	4.54	0.71	-10.92	7.51
		3	-0.09	1.08	0.93	-2.29	2.10			3	-1.73	4.54	0.70	-10.95	7.48
	3	1	-1.40	1.08	0.20	-3.59	0.79		3	1	0.03	4.54	0.99	-9.18	9.25
		2	0.09	1.08	0.93	-2.10	2.29			2	1.73	4.54	0.70	-7.48	10.95
AvgF	1	2	0.72	0.57	0.20	-0.42	1.88	WY	1	2	3.57	14.69	0.80	-26.22	33.37
		3	0.75	0.57	0.19	-0.40	1.91			3	3.70	14.69	0.80	-26.09	33.50
	2	1	-0.72	0.57	0.20	-1.88	0.42		2	1	-3.57	14.69	0.80	-33.37	26.22
		3	0.02	0.57	0.96	-1.13	1.18			3	0.12	14.69	0.99	-29.67	29.93
	3	1	-0.75	0.57	0.19	-1.91	0.40		3	1	-3.70	14.69	0.80	-33.50	26.09
		2	-0.02	0.57	0.96	-1.18	1.13			2	-0.12	14.69	0.99	-29.93	29.67
MedF	1	2	0.65	0.60	0.28	-0.57	1.88	RH	1	2	16.25	66.79	0.80	-119.21	151.71
		3	0.86	0.60	0.16	-0.36	2.08			3	16.84	66.79	0.80	-118.62	152.30
	2	1	-0.65	0.60	0.28	-1.88	0.57		2	1	-16.25	66.79	0.80	-151.71	119.21
		3	0.20	0.60	0.73	-1.02	1.43			3	0.58	66.79	0.99	-134.87	136.05
	3	1	-0.86	0.60	0.16	-2.08	0.36		3	1	-16.84	66.79	0.80	-152.30	118.62
		2	-0.20	0.60	0.73	-1.43	1.02			2	-0.58	66.79	0.99	-136.05	134.87
LowF	1	2	0.012	0.04	0.79	-0.08	0.11	RC	1	2	0.09	0.08	0.27	-0.07	0.26
		3	0.03	0.04	0.47	-0.06	0.13			3	0.10	0.08	0.23	-0.06	0.26
	2	1	-0.01	0.04	0.79	-0.11	0.08		2	1	-0.09	0.08	0.27	-0.26	0.07
		3	0.02	0.04	0.65	-0.07	0.12			3	0.00	0.08	0.92	-0.16	0.17
	3	1	-0.03	0.04	0.47	-0.13	0.06		3	1	-0.10	0.08	0.23	-0.26	0.06
		2	-0.02	0.04	0.65	-0.12	0.07			2	-0.00	0.08	0.92	-0.17	0.16

*= The mean difference is significant at the 0.05 level, I= Cutting_method, J= Cutting_method
1= Shelterwood/clear cutting, 2= Selective cutting, 3= Near nature cutting

Tab. 6. The descriptive statistics of the hydrological indices over different silviculture methods in Khalian station

	Cutting method	Mean	Std. Deviation	Std. Error Mean
MinF	2	1.04	0.18	0.05
	3	1.04	0.35	0.09
MaxF	2	2.76	1.19	0.33
	3	3.35	1.37	0.38
AvgF	2	1.72	0.48	0.13
	3	1.87	0.72	0.20
MedF	2	1.65	0.50	0.13
	3	1.71	0.67	0.18
LowF	2	0.65	0.09	0.02
	3	0.63	0.10	0.02
HighF	2	4.53	2.62	0.72
	3	5.54	2.72	0.75
CV	2	29.18	10.31	2.86
	3	38.09	4.51	1.25
WY	2	8.36	13.71	3.80
	3	9.10	14.99	4.15
RH	2	39.79	65.29	18.11
	3	43.36	71.46	19.82
RC	2	0.42	0.18	0.05
	3	0.44	0.17	0.04

2= Selective cutting, 3= Near nature cutting

Tab. 7. The results of independent t-test against the hydrological indices over different silviculture methods in Khalian station

Index	Var. Assump.	Sig. (Levene)	t	Sig. (2-tailed)	Mean Diff.	Lower	Upper
MinF	EQ var assm	0.09	0.00	1.00	0.00	-0.22	0.22
	EQ var not assm	-	0.00	1.00	0.00	-0.23	0.23
MaxF	EQ var assm	0.97	-1.17	0.25	-0.59	-1.63	0.45
	EQ var not assm	-	-1.17	0.25	-0.59	-1.63	0.45
AvgF	EQ var assm	0.28	-0.63	0.53	-0.15	-0.65	0.34
	EQ var not assm	-	-0.63	0.53	-0.15	-0.65	0.35
MedF	EQ var assm	0.42	-0.26	0.79	-0.06	-0.54	0.42
	EQ var not assm	-	-0.26	0.79	-0.06	-0.54	0.42
LowF	EQ var assm	0.60	0.58	0.56	0.02	-0.05	0.10
	EQ var not assm	-	0.58	0.56	0.02	-0.05	0.10
HighF	EQ var assm	0.89	-0.96	0.34	-1.00	-3.17	1.15
	EQ var not assm	-	-0.96	0.34	-1.00	-3.17	1.15
CV	EQ var assm	0.01	-2.85	0.00	-8.90	-15.35	-2.46
	EQ var not assm	-	-2.85	0.01	-8.90	-15.51	-2.30
WY	EQ var assm	0.87	-0.13	0.89	-0.73	-12.37	10.89
	EQ var not assm	-	-0.13	0.89	-0.73	-12.37	10.89
RH	EQ var assm	0.87	-0.13	0.89	-3.57	-58.99	51.83
	EQ var not assm	-	-0.13	0.89	-3.57	-59.01	51.86
RC	EQ var assm	0.94	-0.32	0.74	-0.02	-0.17	0.12
	EQ var not assm	-	-0.32	0.74	-0.02	-0.17	0.12

disturbances and maintain forest structure to preserve hydrological functions (Clarke et al., 2015; Keivan Behjou et al., 2024).

Hydrological Indicator Response and Spatial Variability

The response of specific hydrological indicators provided deeper insights into the silvicultural impacts. The most sensitive indicator was the minimum flow (MinF), which showed a significant difference between silviculture methods at Kharjegil ($p = 0.037$, Tab. 4). The LSD post-hoc test confirmed a significant difference specifically between Shelterwood/clear cutting and Near nature cutting (mean difference = 0.62, $p = 0.01$), with the intensive method maintaining a higher minimum flow (4.0 m^3/s vs. 2.8 m^3/s, Tab. 3). This result contrasts with some studies, such as Coble et al. (2020), who noted decreased low-flow severity after harvest. The higher minimum flow observed here under Shelterwood/clear cutting could be linked to a reduction in baseflow contribution due to altered soil infiltration, a phenomenon discussed by Robinson et al. (2003) in the context of deforestation reducing streamflow continuity in dry seasons.

Furthermore, a notable spatial variability was observed between the two stations. At the upstream Khalian station, the coefficient of variation (CV) was the only indicator to show a significant difference, being lower under Selective cutting compared to Near nature cutting (mean difference = -8.90, $p < 0.01$, Tab. 7). This indicates that Selective cutting promoted a more stable flow regime at this location. The differences in station response can be partly explained by their location within the watershed; the upstream Khalian station is likely more sensitive to direct harvesting effects, while the downstream Kharjegil station integrates more complex influences, including other human activities. This scale-dependent response to forest management has been emphasized in other watershed studies, such as Dung et al. (2012).

Implications for Sustainable Forest Management

The overarching result of this study is that less intensive silviculture methods, namely Selective and Near nature cutting, have a markedly lower and more stable impact on the river flow regime compared to Shelterwood/clear cutting. The significantly altered flow patterns and higher peak flows associated with Shelterwood/clear cutting pose potential risks, such as increased soil erosion and flashier streamflow, which are well-documented consequences of intensive harvesting (Picchio et al., 2021). Therefore, to minimize hydrological disruption, particularly concerning baseflow stability and overall flow variability, the use of Selective cutting or Near nature cutting is recommended over Shelterwood/clear cutting in the Hyrcanian forests. This recommendation supports a growing body of evidence advocating for close-to-nature silviculture to sustain hydrological ecosystem services (del Campo et al., 2022).

Limitations

This study provides a robust long-term assessment, yet some limitations should be acknowledged. The analysis was based on monthly flow data, which is suitable for identifying long-term trends but may smooth over short-term hydrological dynamics and extreme events that daily data could capture. Furthermore, while the two stations provided valuable insights, the results are specific to the Navroud watershed within the Hyrcanian forest ecoregion. The hydrological response can vary significantly with soil type, topography, climate, and forest composition. Finally, this study focused on flow indices; incorporating data on sediment load, water quality, and direct measurements of evapotranspiration and soil moisture would provide a more comprehensive understanding of the hydrological impacts.

Implications

The results have direct implications for forest management policy and practice in the Hyrcanian region and similar temperate forest ecosystems. By demonstrating the superior hydrological performance of Selective and Near nature cutting, this study provides empirical evidence to support policies that incentivize these less disruptive methods. Forest managers can use these results to design harvesting plans that better protect water resources, maintain baseflow during critical dry periods, and reduce the risk of flooding and erosion. From a research perspective, this study underscores the value of long-term, indicator-based statistical assessments for evaluating silvicultural impacts. The methodological framework applied here can be adapted to other forested watersheds to build a broader comparative understanding, ultimately contributing to more sustainable and evidence-based forest management worldwide.

5 CONCLUSIONS

Evaluating the hydrological effects of forest harvesting methods can predict future effects and inform appropriate management methods in forested areas. This study evaluates the impact of tree harvesting methods on hydrological aspects of river flow regime, using monthly flow data and nine hydrological indices. The effects of Shelterwood/ clear cutting, Selective cutting, and Near nature approaches on river flow were assessed in three periods in the Caspian forests of northern Iran. The statistical analysis using Two-way ANOVA and GLM revealed that Selective cutting had a higher impact on monthly flow values with an increase of about 0.79 m^3/s compared to Shelterwood/clear cutting at Kharjegil, and Near nature cutting had a more significant effect than Shelterwood/clear cutting with an increase of about 0.84 m^3/s in the same location. There was no significant difference between Selective cutting and Near nature cutting methods at Kharjegil. At Khalian, there was no significant difference between the two methods in terms of their effect on monthly flow values. Additionally, One-way ANOVA (Tukey post-hoc test) against nine hydrological indicators for the three types of harvesting in different periods showed a significant difference between silviculture methods for the „MinF“ indicator (minimum flow), where Shelterwood/ clear cutting had a higher minimum flow (4.0 m^3/s) compared to Selective cutting (3.4 m^3/s) and Near nature cutting (2.8 m^3/s) ($p < 0.05$) at Kharjegil station. The independent t-test to assess significant differences in nine hydrological indicators for two types of harvesting in Khalian station showed that most indicators had no significant difference between the two cutting methods, except for the „CV“ indicator ($p < 0.05$), where the Selective cutting method yielded lower values than the Near nature cutting method. Overall, the results indicate that the effects of different tree harvesting and cutting methods vary between the two study stations. The effects of different tree harvesting and cutting methods vary between the two study stations, with Khalian station showing generally lower flows (e.g., MinF around 1.2 m^3/s) and higher variability (CV up to 30.1%), while Kharjegil shows higher absolute flows (MinF up to 4.0 m^3/s) but lower variability.

The difference between the two stations can be partly explained by their location. Khalian, being upstream, is more sensitive to harvesting effects on river flow, while Kharjegil, downstream, may experience overlapping influences from human activities. Monthly flow data was used, which is suitable for forested areas dominated by base and groundwater flow, though daily data could better capture rapid changes. Selective cutting and Near nature cutting show similar effects on most flow indicators, but Selective cutting results in significantly lower flow variability (CV: 13.2% vs. 23.5% at Khalian). Shelterwood/clear cutting leads to a higher minimum flow (4.0 m^3/s) compared to the other methods. Thus, Selective and Near nature cutting are recommended to minimize impacts on minimum flow. Effects may vary by forest type and location, so further research on long-term impacts and other hydrological processes is needed to support sustainable forest management. This study provides key indicatios for managing Hyrcanian and similar temperate broad-leaved forests where silviculture affects river flows. It shows how different harvesting methods (shelterwood/clear cutting, selective cutting, and near-nature cutting) impact hydrology, especially during critical low-flow periods. Selective and near-nature cutting methods help maintain flow stability, supporting less disruptive practices for sustainable water yield and base flow maintenance. Though site-specific, the approach and indicators used can be applied elsewhere to assess forestry impacts on hydrology. Overall, the results can guide adaptive management and policy in forested watersheds balancing timber use and tuning river flow regime.

Acknowledgement

The authors sincerely thank the two anonymous reviewers for their valuable time, insightful comments, and constructive suggestions, which greatly contributed to improving the quality and clarity of this manuscript. Their careful and thorough review is deeply appreciated.

REFERENCES

Armstrong, W. H., Collins, M. J., & Snyder, N. P. (2014). Hydroclimatic flood trends in the northeastern United States and linkages with large-scale atmospheric circulation patterns. Hydrological Sciences Journal, 59(9), 1636–1655. https://doi.org/10.1080/02626667.2013.862339

Asbjornsen, H., Wang, Y., Ellison, D., Ashcraft, C. M., Atallah, S. S., Jones, K., Mayer, A., Altamirano, M., & Yu, P. (2022). Multi-targeted payments for the balanced management of hydrological and other forest ecosystem services. Forest Ecology and Management, 522, 120482. https://doi.org/10.1016/j.foreco.2022.120482

Borcard, D., Gillet, F., & Legendre, P. (2018). Exploratory data analysis. In R. Gentleman, K. Hornik, & G. Parmigiani (Eds.), Numerical ecology with R (pp. 11–34). Springer. https://doi.org/10.1007/978-3-319-71404-2

Bosch, J. M., & Hewlett, J. D. (1982). A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology, 55(1-4), 3–23. https://doi.org/10.1016/0022-1694(82)90117-2

Clarke, N., Gundersen, P., Jönsson-Belyazid, U., Kjonaas, O. J., Persson, T., Sigurdsson, B. D., Stupak, I., & Vesterdal, L. (2015). Influence of different tree-harvesting intensities on forest soil carbon stocks in boreal and northern temperate forest ecosystems. Forest Ecology and Management, 351, 9–19. https://doi.org/10.1016/j.foreco.2015.04.034

Coble, A. A., Barnard, H., Du, E., Johnson, S., Jones, J., Keppeler, E., ... & Wagenbrenner, J. (2020). Long-term hydrological response to forest harvest during seasonal low flow: Potential implications for current forest practices. Science of the Total Environment, 730, 138926. https://doi.org/10.1016/j.scitotenv.2020.138926

Cook, T. L., Snyder, N. P., Oswald, W. W., & Paradis, K. (2020). Timber harvest and flood impacts on sediment yield in a postglacial, mixed-forest watershed, Maine, USA. Anthropocene, 29, 100232. https://doi.org/10.1016/j.ancene.2019.100232

Cui, X., Liu, S., & Wei, X. (2012). Impacts of forest changes on hydrology: A case study of large watersheds in the upper reaches of Minjiang River watershed in China. Hydrology and Earth System Sciences, 16(11), 4279–4290. https://doi.org/10.5194/hess-16-4279-2012

Moore, R. D., & Wondzell, S. M. (2005). Physical hydrology and the effects of forest harvesting in the Pacific Northwest: A review. JAWRA Journal of the American Water Resources Association, 41(4), 763–784. https://doi.org/10.1111/j.1752-1688.2005.tb03770.x

del Campo, A. D., Otsuki, K., Serengil, Y., Blanco, J. A., Yousefpour, R., & Wei, X. (2022). A global synthesis on the effects of thinning on hydrological processes: Implications for forest management. Forest Ecology and Management, 519, 120324. https://doi.org/10.1016/j.foreco.2022.120324

Du, E., Link, T. E., Wei, L., & Marshall, J. D. (2016). Evaluating hydrologic effects of spatial and temporal patterns of forest canopy change using numerical modelling. Hydrological Processes, 30(2), 217–231. https://doi.org/10.1002/hyp.10591

Dung, B. X., Gomi, T., Miyata, S., Sidle, R. C., Kosugi, K., & Onda, Y. (2012). Runoff responses to forest thinning at plot and catchment scales in a headwater catchment draining Japanese cypress forest. Journal of Hydrology, 444, 51–62. https://doi.org/10.1016/j.jhydrol.2012.03.040

Eisenbies, M. H., Aust, W. M., Burger, J. A., & Adams, M. B. (2007). Forest operations, extreme flooding events, and considerations for hydrologic modeling in the Appalachians—A review. Forest Ecology and Management, 242(2-3), 77–98. https://doi.org/10.1016/j.foreco.2007.01.051

Esfandyari Darabad, F., Mostafazadeh, R., Shahmoradi, R., & Khiavi, A. N. (2020). The effect of dam construction on flood and low flow indices in south of Lake Urmia. Journal of Natural Environment Hazard, 9(24), 1–14. https://doi.org/10.22111/JNEH.2018.23157.1355

Field, A. (2013). Discovering statistics using IBM SPSS statistics. Sage.

Gelman, A., & Hill, J. (2006). Data analysis using regression and multilevel/hierarchical models. Cambridge University Press.

Ghasemi, A., & Zahediasl, S. (2012). Normality tests for statistical analysis: A guide for non-statisticians. International Journal of Endocrinology and Metabolism, 10(2), 486–489. https://doi.org/10.5812/ijem.3505

Gyssels, G., Poesen, J., Bochet, E., & Li, Y. (2005). Impact of plant roots on the resistance of soils to erosion by water: A review. Progress in Physical Geography: Earth and Environment, 29(2), 189–217. https://doi.org/10.1191/0309133305pp443ra

Hou, Y., Wei, X., Zhang, M., Creed, I. F., McNulty, S. G., & Ferraz, S. F. B. (2023). A global synthesis of hydrological sensitivities to deforestation and forestation. Forest Ecology and Management, 529, 120718. https://doi.org/10.1016/j.foreco.2022.120718

Jones, J. A., & Grant, G. E. (1998). Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon. Water Resources Research, 32(4), 959–974. https://doi.org/10.1029/98WR02500

Keivan Behjou, F., Mostafazadeh, R., & Alaei, N. (2024). Effects of forest logging systems on the river flow regime indices using graphical techniques: A case study in a small natural forest. Hydrology, 11(7), 94. https://doi.org/10.3390/hydrology11070094

Kuchment, L. S., Gelfan, A. N., & Demidov, V. N. (2011). Modeling of the hydrological cycle of a forest river basin and hydrological consequences of forest cutting. The Open Hydrology Journal, 5(1), 9–18.

Lavigne, M. P., Rousseau, A. N., Turcotte, R., Laroche, A. M., Fortin, J. P., & Villeneuve, J. P. (2004). Validation and use of a semidistributed hydrological modeling system to predict short-term effects of clear-cutting on a watershed hydrological regime. Earth Interactions, 8(3), 1–19. https://doi.org/10.1175/1087-3562(2004)008%3C0001:VAUOAS%3E2.0.CO;2

Mehry, S., Mostafazadeh, R., EsmaliOuri, A., & Ghorbani, A. (2017). Spatial and temporal variations of base flow index (BFI) in the Ardabil Province rivers, Iran. Earth and Space Physics, 43(6), 623–634. https://doi.org/10.22059/jesphys.2017.60293

Mostafa, M., Shataee Jouibary, S., Lotfalian, M., & Sadoddin, A. (2017a). Comparison of geometric characterizes Chehel-chay forest watershed roads with rural road standards with an emphasis of run off product. Journal of Wood and Forest Science and Technology, 23(2), 123–145. https://doi.org/10.22069/jwfst.2017.10736.1560

Mostafa, M., Shataee Jouibary, S., Lotfalian, M., & Sadoddin, A. (2017b). Watershed road network analysis with an emphasis on fire fighting management. Journal of Environmental Engineering and Landscape Management, 25(4), 342–353. https://doi.org/10.3846/16486897.2017.1281816

Mostafazadeh, R., Esfandyari Darabad, F., Mohammadirad, L., & Haji, K. (2020). Quantitative changes and statistical comparison of river flow hydrological indicators after the construction of Yamchi Dam, Ardabil, Iran. Environment and Water Engineering, 6(2), 107–121. https://doi.org/10.22034/jewe.2020.230926.1359

National Research Council. (2008). Hydrologic effects of a changing forest landscape. National Academies Press. https://nap.nationalacademies.org/resource/12223/forest_hydrology_final.pdf

Neter, J., Kutner, M. H., Nachtsheim, C. J., & Wasserman, W. (1996). Applied linear regression models. McGraw-Hill.

Ning, L., Riddle, E. E., & Bradley, R. S. (2015). Projected changes in climate extremes over the northeastern United States. Journal of Climate, 28(8), 3289–3310. https://doi.org/10.1175/JCLI-D-14-00150.1

Nordén, B., Rorstad, P. K., Magnér, J., Götmark, F., & Löf, M. (2019). The economy of selective cutting in recent mixed stands during restoration of temperate deciduous forest. Scandinavian Journal of Forest Research, 34(8), 709–717. https://doi.org/10.1080/02827581.2019.1679876

Picchio, R., Jourgholami, M., & Zenner, E. K. (2021). Effects of forest harvesting on water and sediment yields: A review toward better mitigation and rehabilitation strategies. Current Forestry Reports, 7(4), 214–229. https://doi.org/10.1007/s40725-021-00146-7

Poudyal, B. H., Maraseni, T. N., & Cockfield, G. (2019). Implications of selective harvesting of natural forests for forest product recovery and forest carbon emissions: Cases from Tarai Nepal and Queensland Australia. Forests, 10(8), 693. https://doi.org/10.3390/f10080693

Robinson, M., Cognard-Plancq, A. L., Cosandey, C., David, J., Durand, P., Führer, H. W., ... & Zollner, A. (2003). Studies of the impact of forests on peak flows and baseflows: A European perspective. Forest Ecology and Management, 186(1-3), 85–97. https://doi.org/10.1016/S0378-1127(03)00238-X

Swank, W. T., Swift Jr, L. W., & Douglass, J. E. (1988). Streamflow changes associated with forest cutting, species conversions, and natural disturbances. In Forest Hydrology and Ecology at Coweeta (pp. 297–312). Springer New York. https://doi.org/10.1007/978-1-4612-3732-7_22

Tague, C. L., Moritz, M., & Hanan, E. (2019). The changing water cycle: The eco-hydrologic impacts of forest density reduction in Mediterranean (seasonally dry) regions. Wiley Interdisciplinary Reviews: Water, 6(4), e1350. https://doi.org/10.1002/wat2.1350

Talebi Khiavi, H., & Mostafazadeh, R. (2021). Land use change dynamics assessment in the Khiavchai region, the hillside of Sabalan mountainous area. Arabian Journal of Geosciences, 14(22), 2257. https://doi.org/10.1007/s12517-021-08690-z

Vose, J. M., Sun, G., Ford, C. R., Bredemeier, M., Otsuki, K., Wei, X., Zhang, Z., & Zhang, L. (2011). Forest ecohydrological research in the 21st century: What are the critical needs? Ecohydrology, 4(2), 146–158. https://doi.org/10.1002/eco.193

Article first received: 12 June 2025
Article accepted: 08 December 2025