

Article

Effects of Forest Logging Systems on the River Flow Regime Indices Using Graphical Techniques: A Case Study in a Small Natural Forest

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Abstract: This study aims to investigate the impact of forest exploitation methods on monthly discharge and hydrological indices of river flow using graphical methods in a forested watershed in North Iran. To achieve this, 10 hydrological index changes related to river flow regime influenced by the Shelterwood/clear cutting, Femel cutting, and the Near Nature approach forest cutting methods were assessed. According to the results, it can be stated that the Shelterwood/clear cutting method influenced monthly flow indices by increasing the coefficient of variations and intensifying runoff production, while the Femel cutting and the Near Nature approach methods contributed to regulating the flow regime and sustaining river flow. The influence of various tree-cutting techniques on river flow values and fluctuations is more evident during the wettest months compared to low-water months. The period of Shelterwood/clear cutting disrupted the natural correlation between precipitation and runoff production. Furthermore, the shift from Shelterwood/clear cutting to Femel cutting and the Near Nature approach progressively diminished the slope of the curve, indicating a reduction in monthly runoff at both measurement stations. In conclusion, opting for an appropriate method, such as the Near Nature approach, is preferable from both ecological and hydrological perspectives when managing forest areas in the study region and similar conditions involving comparable topography, climate, soil, and forest stands. The index-based coupled with graphical methodology employed appropriately demonstrates the influence of logging techniques on monthly flow patterns, which provides valuable insights into evaluating the repercussions of alternative management interventions on river flow dynamics.

Keywords: forest exploitation; flow regime; hydrological indicators; double mass curve; wood harvesting



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1. Introduction

The destruction of vegetation cover and intensified forest exploitation pose detrimental consequences to the environmental resources of watershed areas, notably escalating flood potential and runoff production. Decreased forest and plant cover due to exploitation lead to increased surface runoff [1,2]. The rise in runoff due to land use changes can serve as a significant indicator for assessing potential flood occurrences within a watershed. Moreover, increased runoff contributes to elevated suspended sediments, resulting in decreased water quality in rivers and downstream areas [3,4]. Land use alterations and vegetation cover profoundly influence hydrological outcomes at local, regional, and global scales. The hydrological impacts of land use change and vegetation cover management manifest in alterations in runoff depth, minimum and maximum discharge, soil moisture,

and evapotranspiration [5]. Changes in canopy cover, root systems, and litter layers of vegetation cover can notably affect the hydrological cycle [6]. Forest cover loss particularly augments runoff and annual peak discharge, notably during moist seasons, leading to decreased streamflow persistence during dry periods [7,8]. As the percentage of forest cover has a direct relationship with river base flow, a reduction in forest cover exacerbates occurrences like destructive flooding and soil erosion [9,10]. Reinstating natural vegetation cover and afforestation are pivotal measures for restoring degraded ecosystems. Compared to artificial forests, restoring natural vegetation cover is a significantly long-term process for ecosystem restoration [11]. Runoff generated from deforested forested areas increases in the short term [1,12].

Cheng [13] utilized the paired watershed technique to evaluate streamflow changes in Camp Creek, British Columbia, following clear-cut logging across 30% of its 33.9 km² watershed. Post-logging observations revealed consistent increases in annual and monthly water yields, annual peak flows, and earlier occurrences of annual peak flow and half flow volume. Hartanto et al. [14] examined how ecological factors impact runoff and soil erosion via runoff plot monitoring in Central Kalimantan, Indonesia. They found that skid trail plots had the highest runoff and soil loss, followed by control and harvest plots. Jones and Post [15] investigated the streamflow responses post forest cutting in conifer and deciduous forests across the US. They noted increased streamflow within 1 to 5 years after cutting, especially prominent in conifer forests. While conifer sites maintained spring surpluses for up to 35 years, deciduous forests exhibited winter and spring streamflow deficits after 10 to 15 years. Wei and Zhang [16] quantified the impacts of large-scale forest disturbance and climatic variability on streamflow in the Willow River watershed, British Columbia, Canada. Their approach, employing modified double mass curves, showed an average annual streamflow increase of +58.7 mm due to forest disturbances and a −72.4 mm decrease linked to climatic variability. Zhang, Wei, Sun, and Liu [17] investigated hydrological effects in the Upper Zagunao River watershed, China, and found that harvesting increased annual runoff by 38 mm/yr, while climatic variability caused a variation of −38.3 mm/yr. Schelker et al. [18] studied how forest clear cutting affected snow dynamics and stream responses in northern Sweden. They found that clear cutting increased snow accumulation by 27%, prompting earlier snowmelt and faster stream responses in certain years. Ide et al. [12] assessed clear-cutting effects on annual and seasonal runoff in an eastern Finland forest over 18 years and found a substantial changes in runoff patterns due to clear cutting, notably in spring and summer. Wei et al. [19] found that forest harvesting at stand level increased spring freshets and modified surface water–ground water interactions, usually boosting annual streamflow, except in some Siberian regions with conflicting outcomes, while at larger scales, cumulative forest disturbance interacting with climate generated diverse and intricate hydrological responses, involving complex interactions among forest disturbance, climate, and watershed properties [19]. Balocchi et al. [20] through a review on Chilean forest hydrology, found that post-timber harvesting streamflow increases and found differences in water usage between native forests and plantations. Vilhar et al. [21] highlighted the importance of interdisciplinary research in karst regions to better understand groundwater flow, infiltration, and recharge processes impacted by large-scale forest disturbances on hydrology within karst aquifer systems.

This literature review underscores the varied impacts of distinct logging methods on flow components. Post-clear-cutting observations consistently demonstrate heightened streamflow, increased peak flows, and alterations in seasonal flow patterns across diverse global watersheds. Despite this understanding, there exists a notable research gap in comprehensive comparative studies among different cutting techniques, particularly in regions varying in topography, climate, and forest stand types. This lack of comprehensive analysis hinders a holistic understanding of the nuanced hydrological impacts of various tree-cutting methods [22,23].

Efficient utilization and management of water resources, forests, and their optimal management require a better understanding of hydrological relationships and components,

along with the selection of an appropriate forest exploitation system. The present research aims to evaluate the comparative effects of diverse logging techniques (Shelterwood/clear cutting, Femel cutting, and the Near Nature approach) on hydrologic responses. By comparing the hydrologic responses associated with different logging techniques using graphical methods, this research attempt to offer some insights beneficial to informed decision-making within forest management and conservation strategies. This investigation evaluated the influence of forest management and exploitation on hydrological indicators of streamflow within a representative Hyrcanian forest located in Northern Iran.

2. Materials and Methods

2.1. Study Area

The study area in this research is the Navroud Asalem watershed located in Gilan Province. The study area covers an area of 307 km² and spans over 83.47 km in the western region of Gilan. The highest elevation relative to sea level is 3016 m, while the lowest point stands at 118 m. The watershed's minimum and maximum elevations are 1378 and 2549 m above sea level, respectively. The Navroud Asalem watershed predominantly comprises Iran's Hyrcanian moist forests. According to the Modified De Martonne climatic classification, the higher elevations are characterized as "moist" and cold, while the lower sections fall under the classification of "very moist" [24]. Figure 1 illustrates the location of the Navroud Asalem watershed on the map of Iran and Gilan Province.

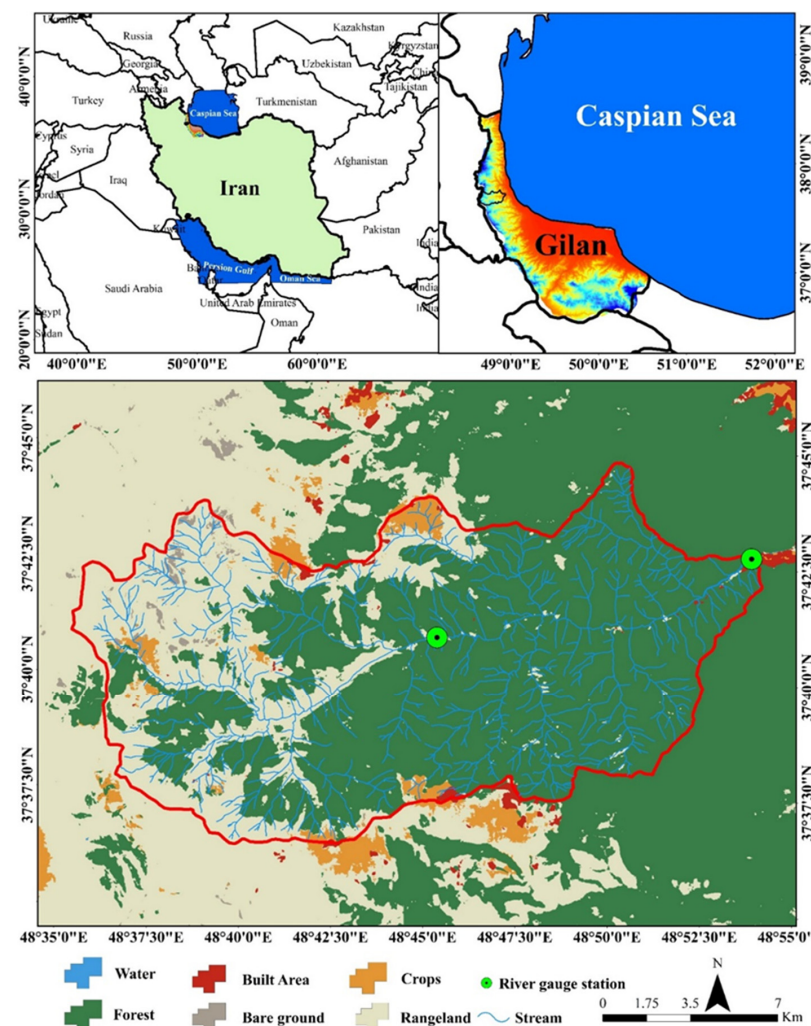


Figure 1. Geographical location and the stream network and river gauge stations in Navroud Asalem Forested area.

2.2. Methodology

2.2.1. Data Used

In the current study, the precipitation and river flow data statistics for the study area spanning a 30-year period (1986–2016) in Gilan province were obtained from the Gilan Regional Water Company. In this research, the daily discharge statistics of two river gauge stations Khalian (located upstream of the study area) and Kharjegil (located downstream of the study area) were used to analyze the hydrological effects caused by changes in the periods of forest management and exploitation. Subsequently, the details and durations of the diverse forest management practices were obtained from the Shafaroud Forest Management based on information and documents provided. The first period employed Shelterwood/clear cutting (1986–1996) as the forest management method, the second period utilized Femel cutting (1997–2006), and the third period adopted the Near Nature approach (2007–2016), all of which were analyzed and compared in this research. The upstream area of the Khalian river gauge station is 142 km², and the Kharjegil river gauge station drains an area of about 266 km². The Khalian and Kharjegil stations are located at 710 and 140 m above sea level, respectively. It is worth mentioning that in the different periods under study, exploitation methods were implemented in the mentioned areas, and therefore the hydrological response was evaluated for each management period.

Shelterwood/clear cutting method: in this method, timber harvesting includes removing trees in stages while leaving some trees to create shelter and encourage natural regeneration, which is highly effective in reducing the production of surface runoff and subsurface flow.

Femel cutting method: The Femel method is a selective method of timber harvesting, which involves the removal of individual trees or small groups of trees, and in this method, large parts of the forest remain intact. This method can help improve the long-term health of the forest and at the same time reduce the ecological effects of wood harvesting.

Near Nature cutting method: the Near Nature approach to forest exploitation is an effective way to harvest timber that can promote the long-term health of the forest while minimizing the ecological impacts of timber harvesting.

It should be mentioned that in the upstream of Kharjegil station, three periods of forest exploitation Shelterwood/clear cutting, Femel cutting and the Near Nature approach were applied. This is despite the fact that in the upstream of Khalian station, only two periods of forest exploitation Femel cutting and the Near Nature approach were carried out, which were analyzed separately in this research in the mentioned stations.

In addition to flow rate data, rainfall data from rain gauge stations in Khalian and Kharjegil stations were used in calculating some indicators such as runoff coefficient. The data in a common statistical period were selected based on the availability of measured data, and the rain gauge stations are located in the vicinity of the river gauge stations. It should be mentioned that the existence of auxiliary data such as soil moisture levels and evapotranspiration rates can help to complete the interpretations, which were not available in this research. It should be mentioned that according to the purpose of the research, which was to evaluate the impact of different methods of forest exploitation on the river flow regime, the available data provided an acceptable analysis of watershed response and hydrologic signals.

2.2.2. Hydrologic Indices

We assessed the changes in the hydrological regime and river stream characteristics using data from Kharajgil and Khalian hydrometric stations, employing 10 hydrological indices. These indices fall into two categories: the first emphasizes the components of the flow regime, while the second uses dimensionless indices, removing the effects of precipitation values and fluctuations to test the net impact of management practices [25].

Group 1: the indices chosen for evaluating changes in the river stream regime include Minimum Flow (m³/s), Maximum Flow (m³/s), Average Flow (m³/s), Median-Flow Index

(m^3/s), Low-Flow Conditions Index (m^3/s), High-Flow Conditions (m^3/s), Water Yield (MCM), Runoff Height (mm) [26,27].

Group 2: the dimensionless indices used in this study include the Coefficient of Variations (%), and Runoff Coefficient (-).

In this study, we calculated the Low-Flow Conditions Index by dividing the minimum monthly flow values by the mean, and the High-Flow Conditions Index was derived by dividing the maximum flows by the mean. Water yield values were determined by dividing the accumulated unit area over time in measured flow. Runoff height values were obtained by dividing the runoff by the watershed area. The Coefficient of Variation was obtained by dividing the standard deviation by the mean. Moreover, the Runoff Coefficient Index values were calculated by dividing the runoff height by the average monthly precipitation [28].

2.2.3. Graphical Assessment of Logging Effects on River Flow Regime

Subsequently, we created graphical representations to explore the relationship between precipitation and flow values during three distinct logging periods.

Our study assumes that various forest management operations will exert diverse effects on different hydrological components of streamflow. Furthermore, the impact of these operations on flow characteristics may vary from minimal to substantial. Consequently, we compared and evaluated changes in hydrological indices of flow during three distinct forest management periods, namely Shelterwood/clear cutting, Femel cutting, and the Near Nature approach.

Graphical techniques are useful tools in assessing the impact of changes in land use/cover on river flow patterns, as they provide a clear visual representation of changes in hydrological indicators. These techniques help to show changes in monthly discharge, flow variability, and runoff characteristics associated with different forest exploitation methods, changes in flow hydrograph components such as magnitude, rate of change, frequency, and timing. For example, the use of box plots and double mass curves highlights differences in flow regimes and the relationship between precipitation and runoff, making it easier to detect the effects of forest harvesting and exploitation practices on river dynamics. In addition, graphical representations enable the identification of trends and anomalies over time, which are important for understanding the long-term impact of logging on river flow. By visually comparing the results, it is possible to recognize the impact of various disturbances, intensification or adjustment of the flow regime and different components of the river's hydrology. Therefore, graphical methods along with statistical and numerical methods can be effective for making informed decisions about forest management and reducing the adverse effects of forest destruction and exploitation from a hydrological point of view.

The double mass curve evaluates the distribution of variations between cumulative precipitation and flow values. In the event of a sudden increase in the trend of changes, a shift in slope becomes evident in the double mass curve [29]. The slope of the double mass curve reflects the intensity of runoff increase based on precipitation. If a statistically significant change in the slope of the double mass curve occurs, it indicates a rising trend in monthly runoff values [30,31]. The DMC theory states that plotting two quantities during the same period results in a straight line when the data are proportional. A break in this slope indicates a change in this proportionality, showing a shift in the relationship between the variables. This helps identify when this change occurs and measure the degree of alteration in their relationship, while aligning the curve's general direction at a 45° angle relative to the axes optimizes the detection of slope changes [32]. The DMC's application and interpretation of results vary with the type of data being analyzed [32,33]. For the analysis of the double mass curve, cumulative monthly precipitation and monthly flow values were plotted for different periods.

3. Results

The results of changes in the average of monthly values of hydrological characteristics during three logging periods at the Kharjegil station are presented in Table 1 and Figure 2.

Table 1. Comparison of hydrological indices among different tree cutting methods in Kharjegil station.

Tree Cutting Method	Month	Minimum Flow (cms)	Maximum Flow (cms)	Average Flow (cms)	Median-Flow Index (cms)	Low-Flow Conditions Index (cms)	High-Flow Conditions (cms)	Coefficient of Variations (%)	Water Yield (MCM)	Runoff Height (mm)	Runoff Coefficient (-)
Shelterwood/clear cutting	Oct.	2.53	12.68	6.23	5.10	0.50	25.56	53.04	16.70	75.89	0.37
Femel cutting		2.08	8.41	4.70	4.00	0.52	16.18	40.69	12.60	57.26	0.38
Near Nature approach		2.30	6.49	4.26	4.10	0.56	11.58	31.08	11.41	51.88	0.27
Shelterwood/clear cutting	Nov.	3.69	10.40	6.07	5.83	0.63	16.43	40.75	16.25	73.84	0.54
Femel cutting		2.35	9.25	5.02	4.53	0.52	17.87	47.49	13.44	61.11	0.48
Near Nature approach		2.18	11.41	6.00	4.81	0.45	25.17	57.31	16.06	72.99	0.37
Shelterwood/clear cutting	Dec.	2.07	10.28	4.64	3.72	0.56	18.50	54.21	12.42	56.45	0.56
Femel cutting		2.29	6.32	4.28	4.41	0.52	12.15	28.95	11.47	52.13	0.48
Near Nature approach		1.91	7.97	4.49	4.00	0.48	16.70	39.97	12.03	54.69	0.51
Shelterwood/clear cutting	Jan.	2.72	9.79	4.56	4.22	0.64	15.19	44.79	12.21	55.49	0.67
Femel cutting		2.06	5.13	3.33	3.15	0.65	7.84	29.61	8.92	40.54	0.58
Near Nature approach		2.05	5.97	3.52	3.20	0.64	9.33	36.77	9.42	42.81	0.57
Shelterwood/clear cutting	Feb.	3.10	7.15	4.54	4.29	0.72	9.89	25.69	12.16	55.27	0.60
Femel cutting		2.73	5.54	3.85	3.66	0.74	7.44	25.55	10.32	46.92	0.54
Near Nature approach		2.68	5.24	3.82	3.65	0.73	7.14	23.01	10.23	46.52	0.53
Shelterwood/clear cutting	Mar.	4.32	12.06	7.17	7.13	0.61	19.93	33.58	17.97	81.69	0.86
Femel cutting		2.25	10.66	5.72	5.54	0.41	26.26	43.84	14.32	65.09	0.77
Near Nature approach		3.05	7.63	5.61	5.43	0.56	13.58	23.81	14.06	63.91	0.57
Shelterwood/clear cutting	Apr.	3.57	11.71	8.66	9.32	0.38	30.58	32.29	23.19	105.43	1.38
Femel cutting		3.21	9.82	7.01	7.78	0.41	23.85	33.87	18.77	85.31	0.86
Near Nature approach		3.01	13.78	7.52	6.92	0.43	31.70	48.13	20.15	91.57	0.92
Shelterwood/clear cutting	May.	3.02	10.94	6.12	5.79	0.52	21.01	38.84	16.39	74.51	1.02
Femel cutting		2.81	10.84	5.74	4.82	0.58	18.60	47.76	15.37	69.87	0.69
Near Nature approach		2.31	9.24	5.09	4.40	0.52	17.64	42.80	13.63	61.95	0.86

Table 1. Cont.

Tree Cutting Method	Month	Minimum Flow (cms)	Maximum Flow (cms)	Average Flow (cms)	Median-Flow Index (cms)	Low-Flow Conditions Index (cms)	High-Flow Conditions (cms)	Coefficient of Variations (%)	Water Yield (MCM)	Runoff Height (mm)	Runoff Coefficient (-)
Shelterwood/clear cutting	Jun.	2.46	5.78	4.00	4.00	0.62	9.39	27.72	10.71	48.68	0.94
Femel cutting		2.41	6.20	3.65	3.10	0.78	7.97	36.50	9.76	44.39	0.56
Near Nature approach		1.85	4.39	3.22	3.03	0.61	7.19	27.19	8.64	39.25	0.72
Shelterwood/clear cutting	Jul.	1.83	5.83	3.36	2.78	0.66	8.85	40.84	9.01	40.96	0.56
Femel cutting		2.02	4.33	2.81	2.63	0.77	5.65	26.15	7.52	34.17	0.41
Near Nature approach		2.05	6.10	3.08	2.75	0.75	8.19	41.70	8.25	37.52	0.44
Shelterwood/clear cutting	Aug.	2.05	4.16	2.86	2.74	0.75	5.57	23.42	7.65	34.79	0.28
Femel cutting		1.74	3.42	2.31	2.20	0.79	4.31	25.24	6.18	28.10	0.38
Near Nature approach		1.60	2.96	2.29	2.24	0.71	4.14	20.70	6.15	27.94	0.38
Shelterwood/clear cutting	Sep.	2.16	6.01	3.45	2.91	0.74	8.12	37.80	9.24	41.98	0.26
Femel cutting		2.01	9.32	4.48	4.14	0.48	19.26	51.63	12.01	54.57	0.28
Near Nature approach		1.59	7.64	3.67	2.89	0.55	13.87	57.09	9.83	44.66	0.23

Table 1 presents a comprehensive analysis of various hydrological parameters across three distinct forestry practices: Shelterwood/clear cutting, Femel cutting, and the Near Nature approach. Noteworthy differences in several indices elucidate the significant variances in hydrological characteristics among these logging methods.

Minimum and Maximum Flow:

- Shelterwood/clear cutting: demonstrates substantial variations in both minimum and maximum flows compared to Femel cutting and the Near Nature approach, notably in April (Shelterwood/clear cutting: $2.30 \text{ m}^3/\text{s}$; Femel cutting: $13.78 \text{ m}^3/\text{s}$).
- Femel cutting: generally displays lower minimum and maximum flow values across several months in comparison to the other methods, indicating reduced flow variability.

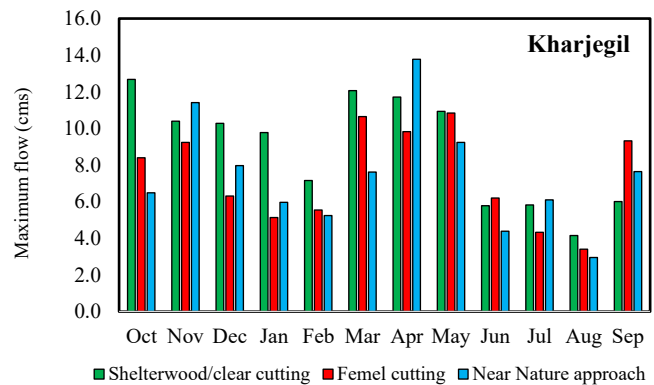
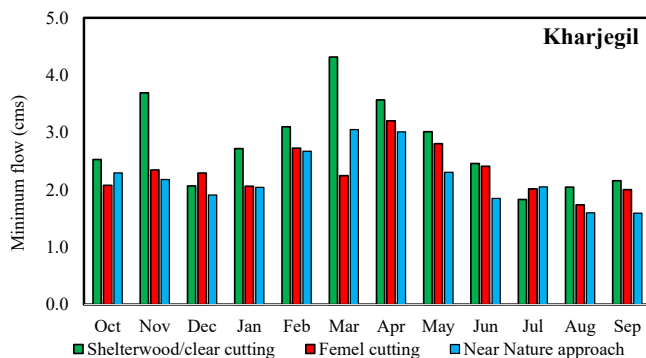


Figure 2. Cont.

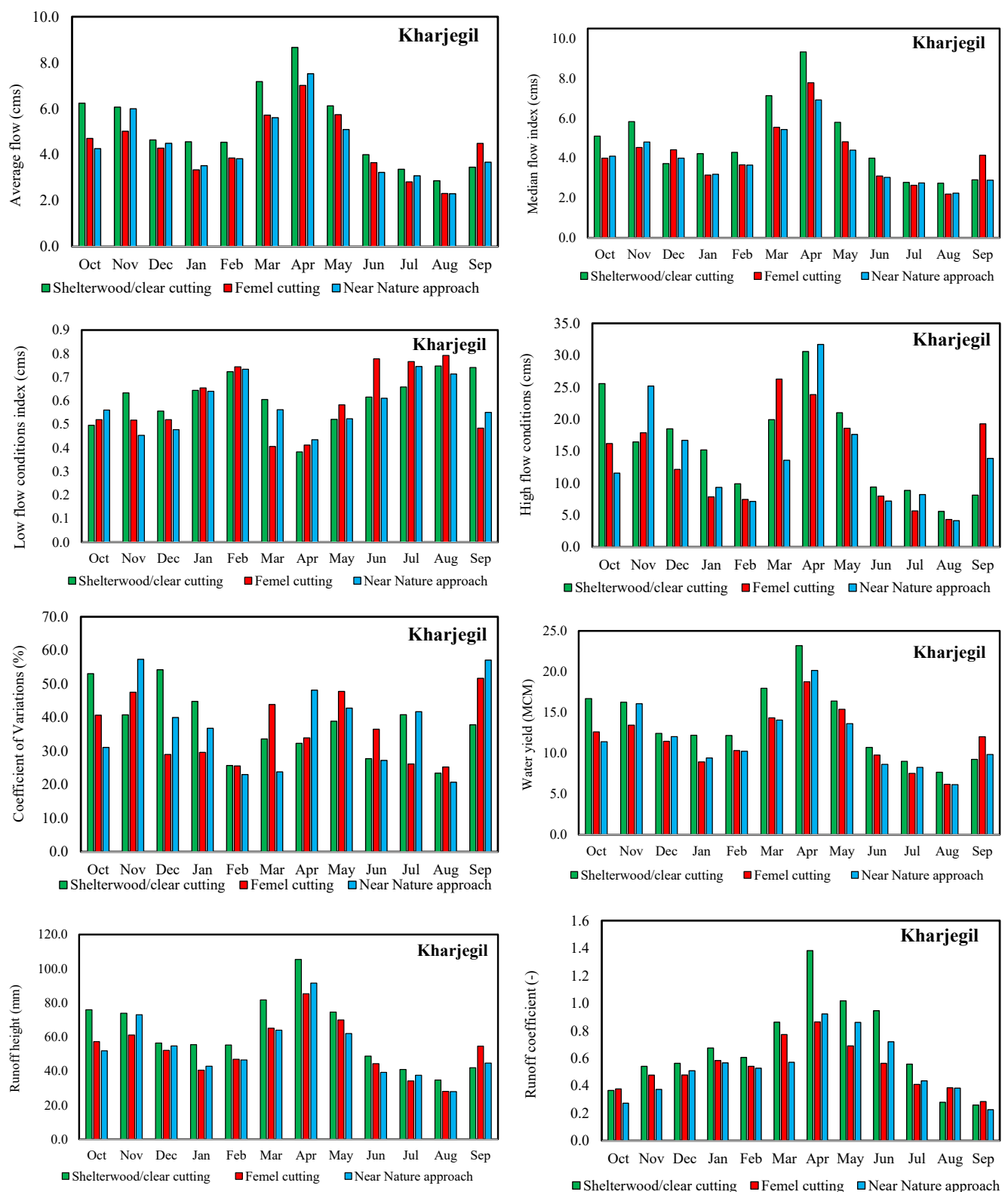


Figure 2. Changes in hydrological characteristics during three logging periods at Kharjegil station.

Average Flow and Variability:

- Near Nature approach: exhibits consistently higher average flow values in various months (e.g., May: 6.12 m³/s) compared to Shelterwood/clear cutting (e.g., May: 3.02 m³/s) and Femel cutting (e.g., May: 2.81 m³/s).
- Coefficient of Variations: highlights greater flow variability in Shelterwood/clear cutting, with higher percentages (e.g., October: 53.04%) compared to Femel cutting (e.g., October: 25.17%).

Median-Flow Index and Low-Flow Conditions:

- Shelterwood/clear cutting: presents notable differences in median-flow index and low-flow conditions compared to Femel cutting and the Near Nature approach across various months (e.g., March: 7.13 m³/s for Shelterwood/clear cutting and 5.43 m³/s for Near Nature approach).
- Femel cutting: shows consistent trends of lower values in these indices, signifying differences in flow characteristics during lower flow periods.

High-Flow Conditions and Runoff Characteristics:

- Near Nature approach: reveals higher values for high-flow conditions and runoff coefficients in several months (e.g., April: 105.43 MCM for Near Nature approach) compared to Shelterwood/clear cutting (e.g., April: 30.58 MCM) and Femel cutting (e.g., April: 31.70 MCM).
- Shelterwood/clear cutting: exhibits diverse runoff heights and coefficients in different months compared to the other methods, suggesting varying effects on water yield and runoff.

The substantial discrepancies in flow indices among these forestry practices underscore their diverse impacts on hydrological dynamics.

The results of variations in the average of monthly values of hydrological characteristics during two logging periods at the Khalian station are presented in Table 2 and Figure 3.

Table 2. Comparison of hydrological indices among different logging methods in Khalian station.

Logging Method	Month	Minimum Flow (cms)	Maximum Flow (cms)	Average Flow (cms)	Median-Flow Index (cms)	Low-Flow Conditions Index (cms)	High-Flow Conditions (cms)	Coefficient of Variations (%)	Water Yield (MCM)	Runoff Height (mm)	Runoff Coefficient (-)
Femel cutting	Oct.	1.07	1.80	1.36	1.32	0.81	2.22	15.92	3.65	17.40	0.28
Near Nature approach		0.83	2.56	1.41	1.25	0.67	3.85	36.74	3.79	18.04	0.29
Femel cutting	Nov.	0.97	2.26	1.56	1.49	0.65	3.46	26.24	4.18	19.91	0.23
Near Nature approach		0.91	3.11	1.78	1.66	0.55	5.65	42.55	4.78	22.76	0.20
Femel cutting	Dec.	1.02	1.74	1.39	1.42	0.72	2.42	17.14	3.73	17.77	0.24
Near Nature approach		0.92	2.65	1.60	1.72	0.54	4.93	34.70	4.28	20.39	0.31
Femel cutting	Jan.	0.86	1.80	1.31	1.30	0.66	2.73	23.34	3.50	16.66	0.32
Near Nature approach		0.69	2.34	1.27	1.22	0.56	4.17	37.97	3.39	16.15	0.38
Femel cutting	Feb.	0.88	2.09	1.35	1.31	0.67	3.10	23.38	3.63	17.27	0.33
Near Nature approach		0.85	2.47	1.38	1.39	0.61	4.07	34.54	3.70	17.64	0.32

Table 2. Cont.

Logging Method	Month	Minimum Flow (cms)	Maximum Flow (cms)	Average Flow (cms)	Median-Flow Index (cms)	Low-Flow Conditions Index (cms)	High-Flow Conditions (cms)	Coefficient of Variations (%)	Water Yield (MCM)	Runoff Height (mm)	Runoff Coefficient (-)
Femel cutting	Mar.	1.06	4.62	2.04	1.74	0.61	7.62	50.02	5.12	24.39	0.46
Near Nature approach		1.26	4.20	2.55	2.49	0.50	8.34	34.98	6.40	30.48	0.39
Femel cutting	Apr.	1.26	4.28	2.70	2.89	0.44	9.78	34.18	7.23	34.41	0.53
Near Nature approach		1.98	7.08	3.71	3.42	0.58	12.21	45.93	9.95	47.37	0.70
Femel cutting	May.	1.42	5.22	2.68	2.50	0.57	9.18	44.38	7.17	34.16	0.44
Near Nature approach		1.28	4.98	2.75	2.39	0.54	9.29	45.97	7.38	35.13	0.65
Femel cutting	Jun.	1.11	3.30	1.89	1.78	0.62	5.32	37.56	5.05	24.05	0.76
Near Nature approach		1.03	3.39	1.81	1.60	0.64	5.29	38.36	4.86	23.13	0.60
Femel cutting	Jul.	1.01	2.53	1.56	1.50	0.67	3.76	31.31	4.17	19.86	0.61
Near Nature approach		1.01	2.80	1.48	1.22	0.83	3.36	38.67	3.95	18.83	0.48
Femel cutting	Aug.	0.72	1.79	1.25	1.28	0.56	3.20	26.02	3.36	15.99	0.66
Near Nature approach		0.81	2.35	1.28	1.11	0.73	3.21	37.33	3.42	16.29	0.67
Femel cutting	Sep.	0.90	2.18	1.37	1.28	0.70	3.11	30.83	3.66	17.42	0.31
Near Nature approach		0.81	2.45	1.28	1.15	0.71	3.47	37.36	3.42	16.27	0.28

Table 2 provides a comparative overview of various hydrological parameters between Femel cutting and the Near Nature approaches in logging. Significant differences exist in numerous indices, highlighting contrasting hydrological characteristics between these practices.

Minimum and Maximum Flow:

- Femel cutting: displays lower minimum and maximum flow values compared to Near Nature approach, notably in May (Femel cutting: 1.28 m³/s; Near Nature approach: 9.29 m³/s).
- Near Nature approach: exhibits consistently higher minimum and maximum flow values across several months, indicating greater flow variability (e.g., April: 1.98 m³/s for Femel cutting; 7.08 m³/s for Near Nature approach).

Average Flow and Median-Flow Index:

- Femel cutting: shows lower average flow values on most months compared to Near Nature approach (e.g., June: 1.89 m³/s for Femel cutting; 3.39 m³/s for Near Nature approach).
- Median-Flow Index: demonstrates higher values for Near Nature approach, suggesting greater stability in flow conditions (e.g., May: 2.75 m³/s for Femel cutting; 4.98 m³/s for Near Nature approach).

Low-Flow Conditions and Coefficient of Variations:

- Femel cutting: reflects higher low-flow conditions and coefficients of variations, indicating lower flow stability across different months (e.g., July: 0.83 m³/s for Femel cutting; 0.48 m³/s for Near Nature approach).

- Near Nature approach: presents lower values for low-flow conditions and coefficients of variations, signifying more consistent flow patterns.

High-Flow Conditions and Runoff Characteristics:

- Near Nature approach: displays substantially higher values for high-flow conditions on numerous months, suggesting higher peak flows (e.g., April: 47.37 MCM for Near Nature approach; 9.95 MCM for Femel cutting).
- Femel cutting: indicates comparatively lower values for runoff height and coefficients, reflecting differences in water yield and runoff patterns.

The considerable disparities in these hydrological indices between Femel cutting and the Near Nature approach underscore the diverse impacts of the logging methods on water flow dynamics.

Box plots of monthly flow values during different logging periods at Kharjegil are illustrated in Figure 4.

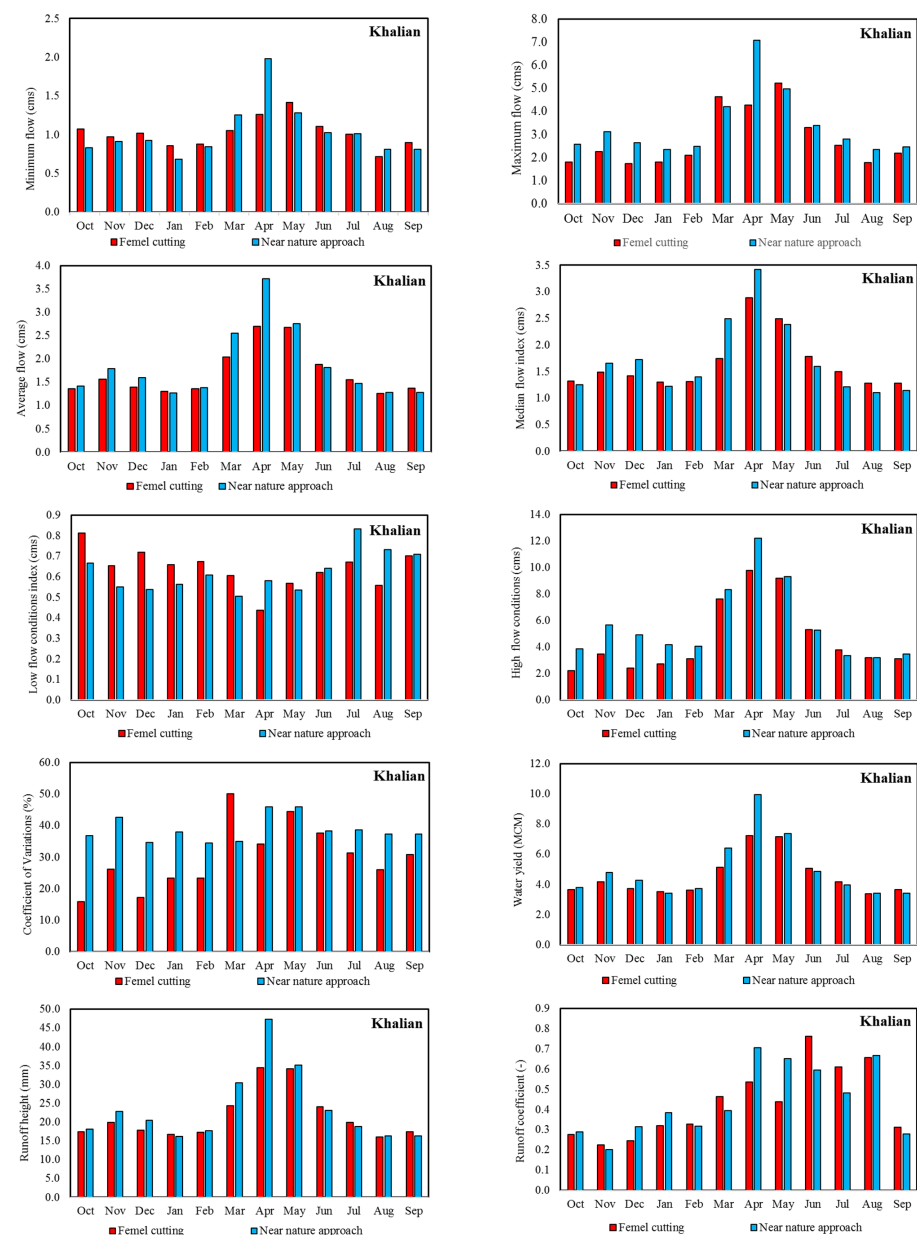


Figure 3. Changes in hydrological characteristics during three logging periods at Khalian station.

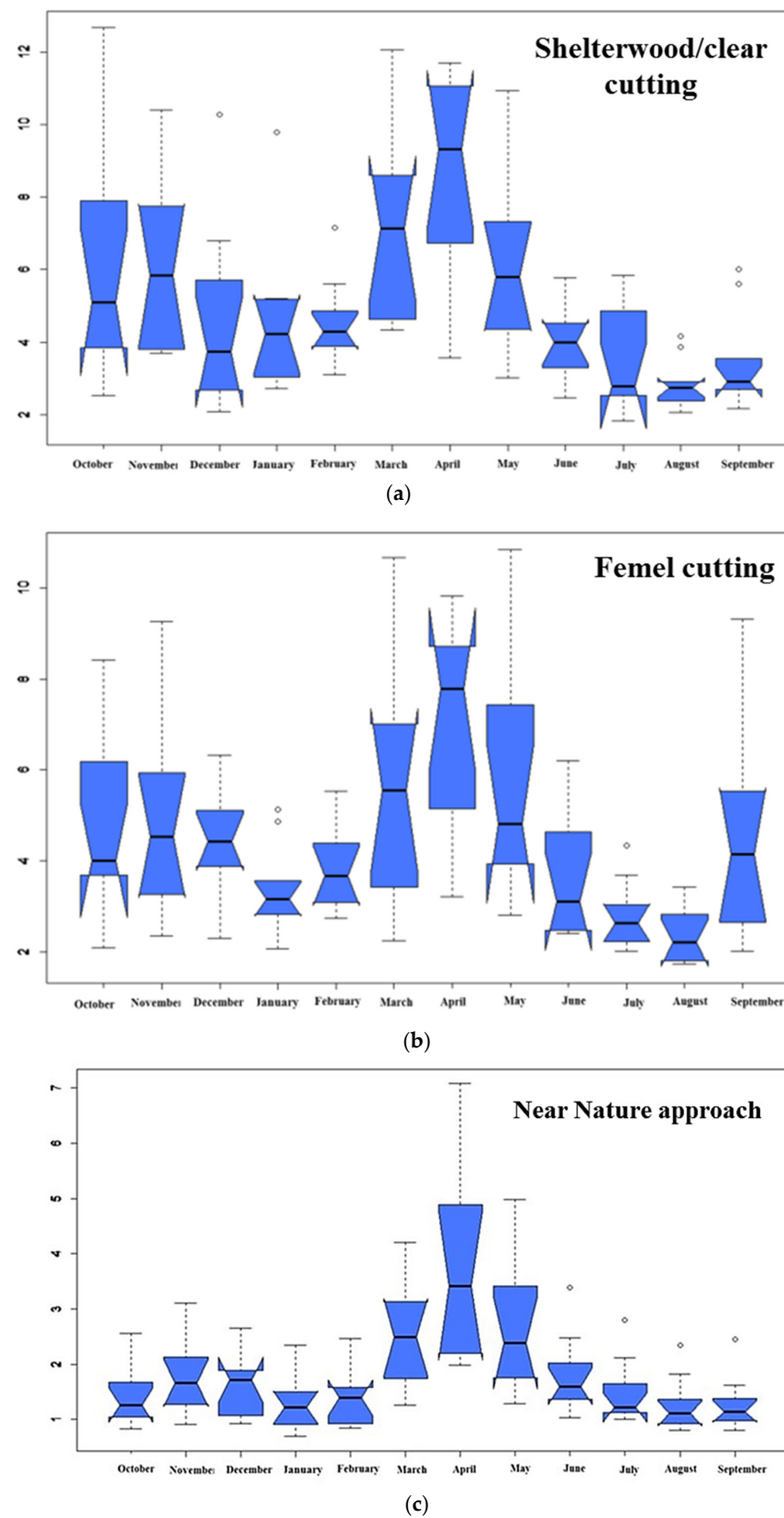


Figure 4. Box plots of monthly flow values during different logging periods at Kharjegil station, (a) Shelterwood/clear cutting, (b) Femel cutting, (c) Near Nature approach.

Based on the results in Figure 4, the monthly flow rates during the Shelterwood/clear cutting period were higher across various months of the year, while in the second (Femel cutting) and third periods (Near Nature approach), these decreased.

Box plots of monthly flow values during different logging periods at Khalian are presented in Figure 5.

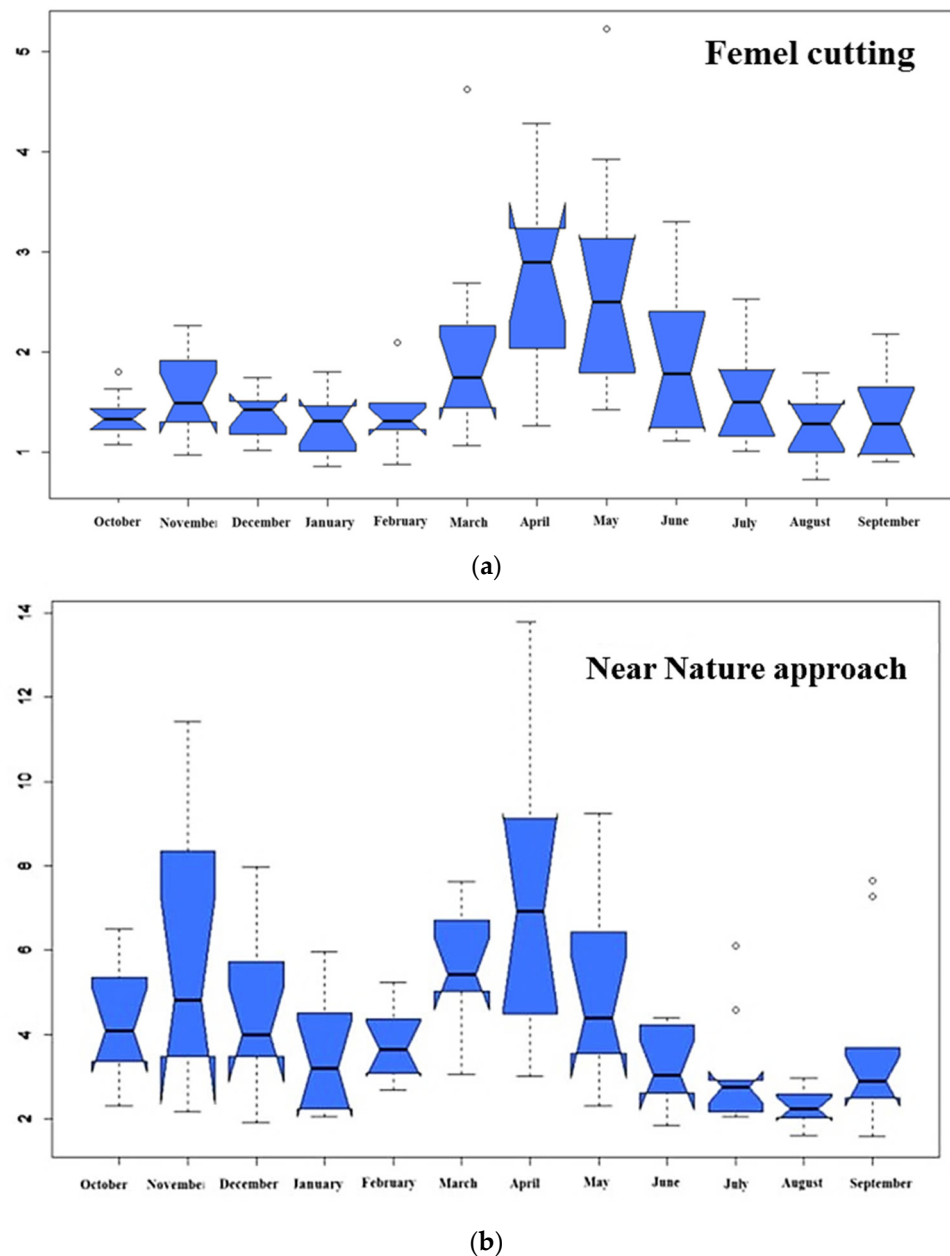


Figure 5. Changes in monthly discharge values in the second and third periods of logging at Khalian station: (a) Femel cutting, (b) Near Nature approach.

Considering the results of Figure 5, there is no significant change in the monthly flow values between forest management methods, Femel cutting and the Near Nature approach, across different months of the year.

The correlation between precipitation values and monthly flow in three logging periods at Kharjegil and Khalian stations is depicted in Figures 6 and 7.

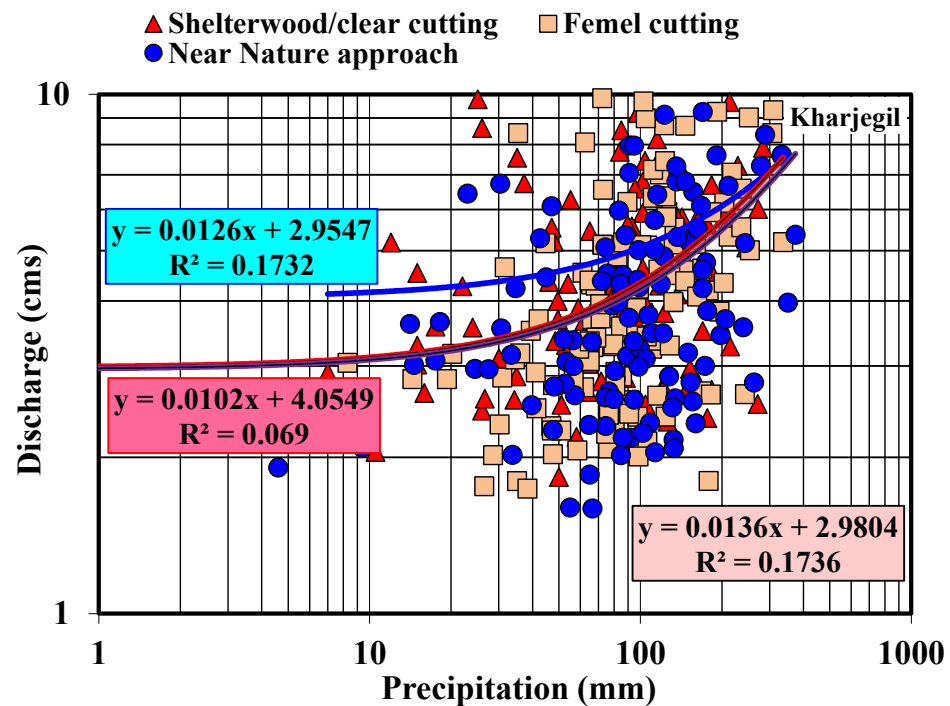


Figure 6. Correlation between precipitation and monthly flow values in three logging periods at Kharjegil station.

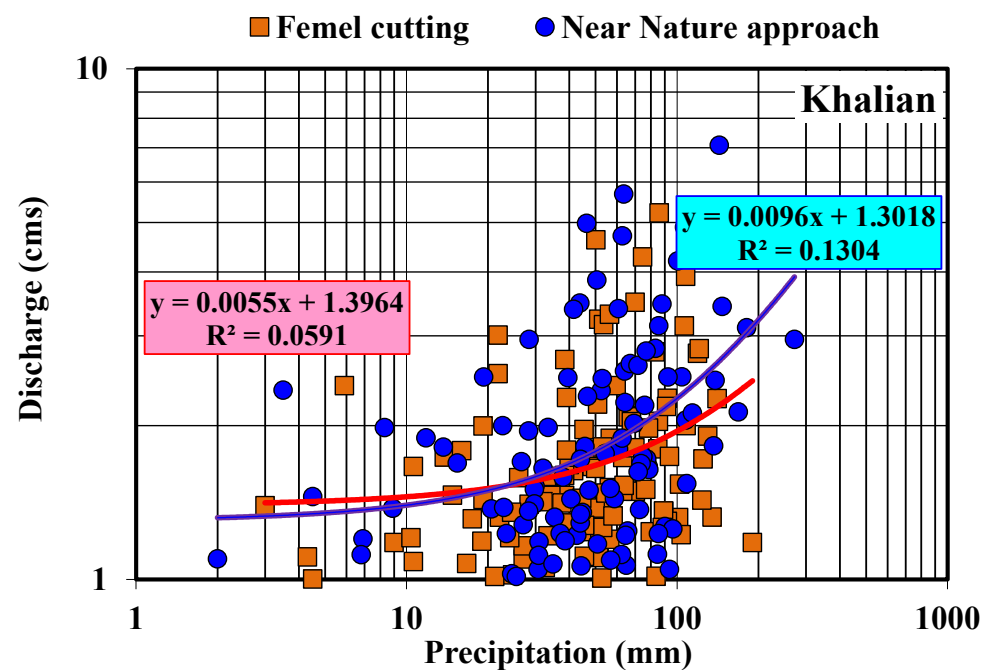


Figure 7. Correlation between precipitation and monthly flow values in three logging periods at Khalian station.

Considering the results of Figure 6, a higher correlation between precipitation and monthly flow values at Kharjegil station was observed in the second logging period (Femel cutting), with a coefficient of determination of 0.173, and in the third period (Near Nature approach), with a coefficient of determination of 0.173, compared to the first period (Shelterwood/clear cutting), with a coefficient of determination of 0.069.

Considering the results shown in Figure 7, a higher correlation between precipitation and monthly flow values at Khalian station was observed in the Femel cutting logging

period, with a coefficient of determination of 0.059, while the correlation between precipitation and monthly flow values in the Near Nature approach logging period had a higher value of 0.130.

To evaluate the changes in cumulative annual precipitation and flow values at the studied stations during different logging periods, graphical representations of the double mass curve are presented in Figures 8 and 9.

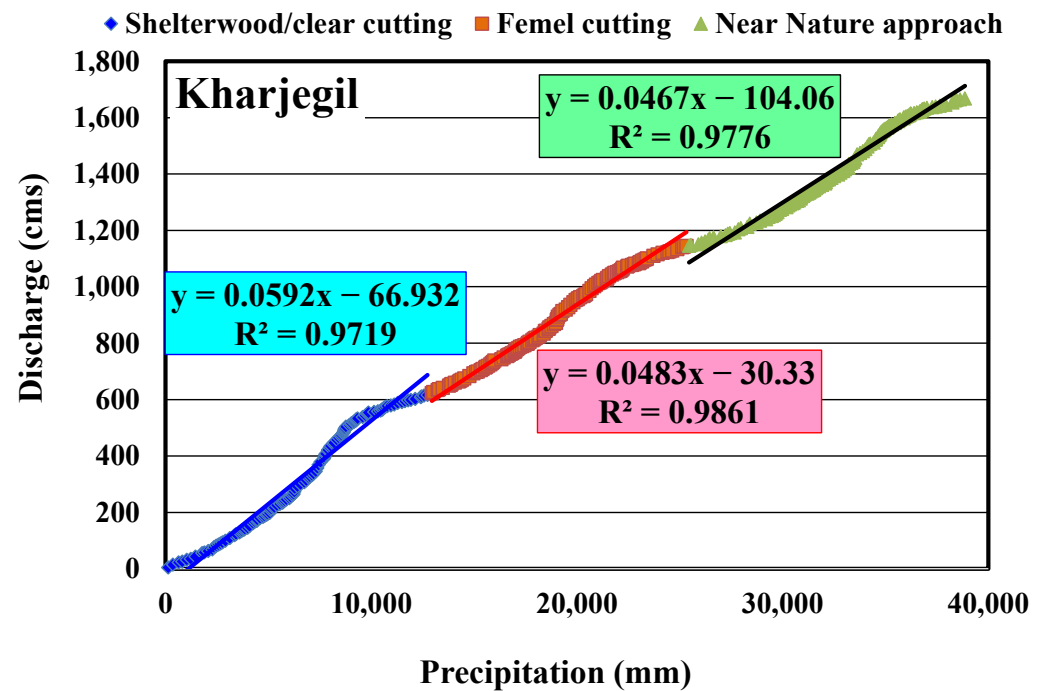


Figure 8. Double mass curve of cumulative flow values for precipitation at Kharjegil station in different logging periods.

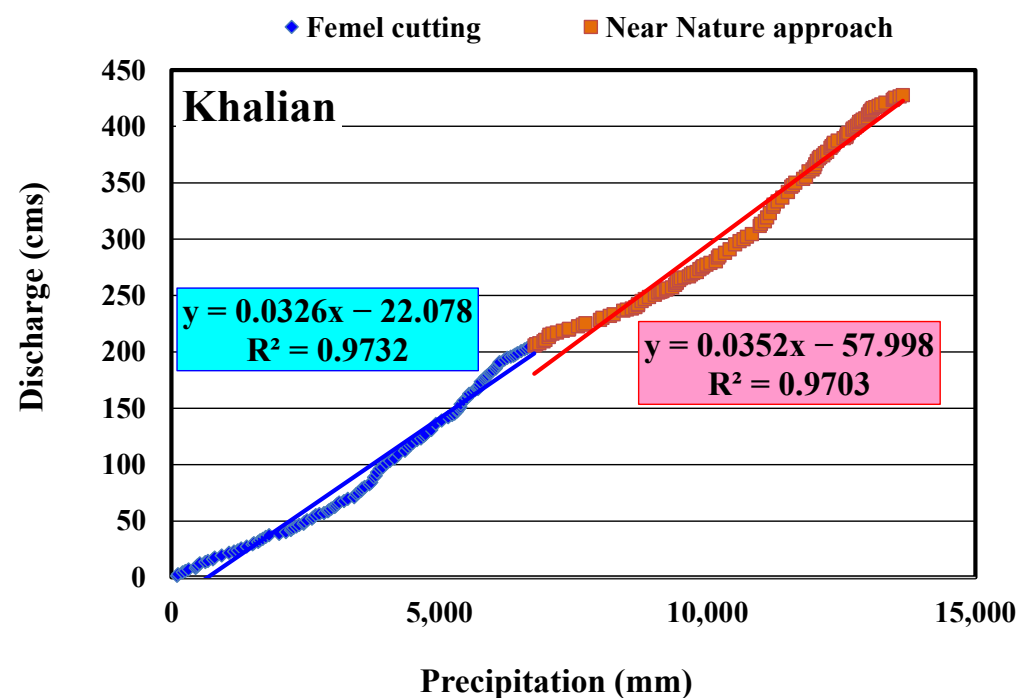


Figure 9. Double mass curve of cumulative flow values for precipitation at Khalian station in different logging periods.

According to the results in Figure 8, the slope of the double mass curve (DMC) at Kharjegil station is not consistent across the three logging periods, indicating the relative impact of different logging methods on changing the precipitation–runoff relationship. Moreover, the shift from the Shelterwood/clear cutting technique to Femel cutting and the Near Nature approach leads to a gradual decline in the curve’s slope, indicating a decrease in monthly runoff. In other words, at Kharjegil station, the slope of the DMC during the Shelterwood/clear cutting period decreased from 0.0592 to 0.0483 in the Femel cutting period and further decreased in the third logging period (Near Nature approach).

However, at Khalian station (Figure 9), the slope of the double mass curve (DMC) increased.

4. Discussion

According to Figure 4, in the month of April, as a month of high precipitation, the flow rates in Shelterwood/clear cutting, Female cutting and the Near Nature courses were about 9, 8 and 78 m³/s, respectively. This is despite the fact that in August (as a month with low precipitation), the discharge values in the mentioned periods were equal to 3, 2.4 and 2.2 m³/s, respectively. In other words, in the Shelterwood/clear cutting management, where a large number of trees are harvested simultaneously, forest clear cutting led to an increase in surface runoff. Additionally, the interpretation of the box plots indicates that the range of variations in monthly flow values in the first period (Shelterwood/clear cutting) was greater, while in the second and third periods (Femel cutting and the Near Nature approach), the range of variations in monthly flow values decreased, which can be considered as regulating the flow regime and reducing fluctuations. A similar pattern can be observed for median-flow values, which decreased in the third period (Near Nature approach). Another important point inferred from Figure 4 is that the impact of different tree-cutting methods on river flow values and fluctuations is more pronounced in months with higher water levels than in low-water months.

The comparison of the box plots in Figure 5 indicates a reduction in the range of flow values (fluctuations) in different months of the year for the Near Nature approach compared to Femel cutting. Additionally, the pattern of changes in flow values among different months in the two logging periods, Near Nature and Femel cutting, is almost similar.

From Figure 6, it can be stated that during the Shelterwood/clear cutting period, the tree clear cutting significantly altered the natural relationship between precipitation and runoff production. The R square values presented in Figures 6 and 7 only show the relationship between discharge and precipitation. In other words, it can be said that the lower the value of R square obtained based on the data from a specific exploitation period, the more changes occurred in the internal correlation of the discharge and precipitation variables, which may be very low.

Although the change in slope on the curve in Figures 8 and 9 indicates the influence of differences in logging methods, regarding the increase in runoff, it is likely associated with an increase in the climatic factor of precipitation. According to Hartanto et al. [14], closely monitoring responsive factors is essential for forest managers to reduce soil erosion risks during logging operations by minimizing disturbances to these ecological components. If there were no human disturbances, DMCs’ slope changes are due to natural causes; otherwise, they may be the result of human activities, and a more in-depth study can be conducted to quantitatively evaluate the impact of natural causes [34].

In Figures 8 and 9, each part of the graph corresponds to one operation/exploitation period, and as mentioned in the research method, all three forest exploitation periods were applied at Kharjegil station, and there were only two forest exploitation periods at Khalian station. In other words, the different periods separated on the graphs show the values of cumulative precipitation per cumulative discharge related to each period of forest exploitation. It is clear that the separation of periods will help to evaluate the different impact of exploitation methods on the relationship between cumulative precipitation and cumulative discharge. In the comparison between different periods, it is possible to

point out the effect of different methods of exploitation on the change in the slope of the DMC curve.

When using DMCs, it is important to consider a strong correlation between the analyzed elements, the consistency of the observed data of the reference or benchmark variables over the study period, and a positive relationship between the two variables [35]. The DMCs identify trend changes in the variables' relationship and pinpoint the point of abrupt change based on the slope [33]. A generalized DMC could be used to analyze trends in the hydrological elements as long as the variables are closely related by cause and effect [35].

In another study, Zheng et al. [36] aimed at assessing the impact of the long-term precipitation and land use changes on runoff variations in a humid subtropical river basin of China using the DMC approach, and showed that the slope of the DMC changed in a specific year, indicating that the change in surface runoff was obviously also influenced by human activities.

The decreasing slope of the double mass curve (DMC) over three consecutive periods, corresponding to different logging methods, suggests a change in the relationship between rainfall and runoff. This decreasing slope indicates a diminishing proportionality between the two variables, potentially implying reduced rainfall efficiency in generating runoff over time. The shift in logging methods influenced this trend, altering hydrological processes and watershed response. Further analysis could quantitatively evaluate the impact of logging methods on infiltration, interception, and hydrological dynamics that regulate runoff generation in forested watersheds.

In the graphic methods used, the time changes in the precipitation factor and its effect on the discharge in different periods are considered. In addition, in some of the indices used that are dimensionless (such as runoff coefficient), the effect of changes in precipitation was included. However, the statistical evaluation of the process of changes can contribute to the richness of the research, which is mentioned in the section on research limitations.

Due to the fact that, in most watersheds with hydrometric stations, flow data are recorded on a daily scale, it is possible to calculate the used indicators. The approach can be used without any restrictions in other similar regions with different climates to evaluate the impact of forest exploitation practices. In artificial or natural afforested areas under exploitation, it is possible to quantify the impact of forest growth and dynamics on various water balance components in the long term. In addition, the present approach can be used to evaluate the impact of human activities (such as forest destruction, urban development) and natural variabilities (such as drought and climate change, occurrence of extreme rainfall, changes in the timing of snow melting) on changes in the flow regime. It should be noted that the framework used in this research can be used in other areas with rangeland, agricultural and urban use, provided that environmental changes can affect hydrological signals. It is noteworthy that, with long-term data evaluation, the cumulative effects of various activities on river flow variability and water yield components can be assessed.

This study significantly contributes to the understanding of the hydrological impacts of different forest logging methods on river flow regimes and emphasizes the need for appropriate forest management practices. Through the analysis of hydrological indicators resulting from the application of forest management practices including Shelterwood/clear cutting, Femel cutting, and the Near Nature approach, this study shows how these methods affect monthly flow indicators, runoff production, and flow variability. Shelterwood/clear cutting increases the coefficient of variation and runoff and disrupts the natural rainfall-runoff relationship, especially in wet months. In contrast, the Near Nature approach and the Femel cutting method show more stable and regular flow patterns, indicating their suitability for sustainable forest management. In addition, graphical techniques used in this study, such as histograms, box plots and dual mass curves, and logarithmic scatterplots provide a clear pattern of the effects of logging on flow dynamics. The results show that the change from the Shelterwood period to a Near Nature approach decreases the slope of the dual mass curve, indicating reduced runoff and improved flow regulation. The

findings of this study emphasize the ecological and hydrological benefits of adopting a Near Nature approach, which maintains more consistent flow patterns and minimizes fluctuations. These insights are critical for policymakers and forest managers in choosing logging practices that balance forest exploitation with maintaining hydrological stability.

4.1. Implications

Through assessing different hydrological index changes influenced by various logging techniques, this research explains the complex relationship between forest management/exploitation methods, river flow regime and hydrologic dynamics in forested watersheds in North Iran. According to the results, Shelterwood/clear cutting intensifies runoff production, disrupting the natural correlation between precipitation and runoff, while Femel cutting and the Near Nature approach contribute to regulating flow regime and sustaining monthly river flow. Water resource management in forested watersheds necessitates careful consideration of logging practices to mitigate adverse environmental impacts. The findings emphasize the importance of adopting sustainable methods like the Near Nature approach to maintain ecological integrity and hydrological balance. Policymakers and forest managers can formulate effective strategies that balance economic interests with environmental conservation goals. This study's policy implications emphasize the need for sustainable forestry practices aligned with logging methods based on ecological and hydrological objectives. Incorporating the Near Nature approach into forest management policies can enhance water production sustainability and minimize runoff fluctuations. Implementing these strategies requires interdisciplinary collaboration among policymakers, scientists, and stakeholders to develop adaptive management strategies aligned with river flow regime and economic gains through forest exploitation. The findings prove the relationship between forest exploitation methods and changes in hydrological signals in an evidence-based selection of appropriate forest logging method for ensuring long-term water production in similar forested regions in northern Iran.

To maintain the stability of the river flow and reduce hydrological disturbances, it is recommended for end users and policy makers to use the Near Nature approach or Femel cutting over Shelterwood/clear cutting. These methods have been shown to better regulate flow regimes by reducing the Coefficient of Variation, reducing runoff production and maintaining river flow, especially during high-water months, which not only increases the ecological health of the watershed, but also provides more sustainable water availability for downstream uses. Policymakers should prioritize the implementation of the Near Nature approach in forest management programs as this approach shows greater stability in flow conditions and less variability in runoff patterns. This approach is well coordinated with sustainable forest management practices, promoting ecological balance and reducing the adverse effects of wood on water dynamics. Incorporating these findings into the forestry laws and policies related to northern Iran can have a significant positive impact on maintaining natural hydrological processes and reducing the risks associated with severe flow changes.

4.2. Limitations

One of the limitations of this study is its reliance on 30-year historical data, which may not fully reflect climate changes or extreme weather events affecting river flow patterns and hydrological indicators. In addition, the focus of this study on a specific region in northern Iran means that the findings (not the methodology) may not be directly applicable to other forested watersheds with different climatic, topographic, and ecological conditions. Another limitation is the potential for unspecified variables, such as soil type, land use changes, or human impacts, which may also affect river flow dynamics, but were not explicitly controlled for in this research. The use of graphical methods, although effective in visualizing trends, together with statistical and numerical methods (like trend test of different hydrometeorological data) can provide a more comprehensive understanding of the complex interactions between forest management practices and river flow regimes.

5. Conclusions

Forest management practices have both positive and negative effects on the forest, the environment, and ecosystems. In this study, employing an index-based and graphical approach, the hydrological response and changes in river flow patterns during three different tree-cutting periods, namely Shelterwood/clear cutting, Femel cutting, and the Near Nature approach, were compared and evaluated. The results suggest that tree-cutting methods such as Femel cutting and the Near Nature approach, which involve scattered and selective tree removal, are more sustainable and have fewer impacts on changing river flow patterns and hydrological indices. A similar emphasis on the impact of various tree-cutting methods on flow characteristics is found in the study by Suryatmojo et al. [37].

Shelterwood/clear cutting, particularly in April, demonstrates substantial flow variations, emphasizing its impact on flow variability compared to the consistently lower flow values in Femel cutting and the Near Nature approach, indicating reduced variability. The analysis of average flow and variability underscores Near Nature approach's superiority, consistently exhibiting higher average flow values. Shelterwood/clear cutting, conversely, displays greater variability, as indicated by higher a Coefficient of Variation in specific months. Shelterwood/clear cutting exhibits diverse runoff heights and coefficients, suggesting varying effects on water yield and runoff. These findings emphasize the importance of careful consideration when selecting tree-cutting techniques due to their diverse impacts on water-flow patterns. The graphical results indicate that Shelterwood/clear cutting significantly disrupted the natural correlation between precipitation and runoff. Additionally, the analysis of double mass curves reveals a diminishing slope at Kharjgil station when transitioning from Shelterwood/clear cutting to Femel cutting and the Near Nature approach, suggesting a decline in monthly runoff. In contrast, at Khalian station, the increasing slope suggests the influence of various logging methods, potentially affected by heightened climatic precipitation factors. Given the negative effects of tree-cutting methods in the forest on hydrological indices related to susceptibility to flood and high flows, it is recommended to choose a tree-cutting method with the goal of sustaining minimum flows and reducing high-flow indices. Furthermore, selecting an appropriate method like the Near Nature approach is preferable both ecologically and in terms of its impact on the hydrological pattern of river flow for managing forest areas in the study region. It is worth noting that the negative effects of forest-cutting methods on the ecological balance of the forest, soil characteristics, and the reduction in the protective role of trees, along with the synergistic effects, are crucial aspects that require comprehensive assessment.

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