Postprint: Effects of Forest Disturbance on Runoff Regime of Forested Small Watersheds in Northern Daxing' anling

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Abstract

To understand the response of hydrological processes in Daxing' anling forested watersheds to forest disturbance, this study employed the near-paired watershed method to exclude spatiotemporal differences in climatic variables and comparatively investigated the changing trends of flow regimes of high flow and low flow in typical small forested watersheds (<100 km^2) in northern Daxing' anling after forest disturbance. The results showed that forest disturbance had a significant impact on low flow regimes. Compared with the control watershed (Xiaobeigou watershed), forest disturbance (accounting for 6.74% of the total watershed area) reduced the average low flow discharge in the Laogou River watershed by 26.58%, increased the average coefficient of variation of low flow by 36.77%, and the differences reached extremely significant levels ($P < 0.01$). On the other hand, forest vegetation disturbance relatively increased the peak flow, duration, and variability of small forested watersheds, but the differences compared with the control watershed did not reach statistically significant levels, indicating that small-area forest vegetation disturbance failed to cause significant changes in watershed high flow regimes. Further analysis of the Flashiness Index for the paired watersheds revealed that forest disturbance significantly increased the flashiness of small forested watersheds. The flashiness index of the disturbed watershed during the study period was 0.078, which was 1.37 times that of the control watershed (0.057). The natural flow regimes of small forested watersheds in northern Daxing' anling are relatively sensitive to forest disturbance. In areas closely linked to the hydrological cycle (such as riparian zones), small-scale forest disturbance can cause significant changes in flow regimes, which requires special attention in future forest and water resource management in this region.

Full Text

Preamble

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The Effects of Forest Disturbance on Flow Regimes of a Small Forested Watershed in Northern Daxing' anling, China

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Abstract

Natural flow regimes of rivers have been threatened by climate change and increased human activities, which consequently affect their health and integrity. Forest disturbance and climate variability are two of the most critical drivers affecting hydrological processes in forested watersheds. Despite an increased understanding of the relationship between climate change and flow regimes, few investigations have been conducted on how forest disturbance influences flow regimes. Moreover, existing research has not accounted for the effects of climate variability on flow regimes when assessing the effects of forest disturbance.

In the present study, the paired watersheds approach, which can account for temporal and spatial variations of climate, was applied to a typical small forested watershed (<100 km^2) in northern Daxing' anling to investigate the effects of forest disturbance on flow regimes. The results showed that low-flow regimes were more sensitive than high-flow regimes to forest disturbance. Even though the area of forest disturbance was only 6.74% of the total watershed area (Laogouhe watershed), the average magnitude (0.47 mm) of low flows was lower by 26.58% and the average variability (0.39) of low flows was higher by 36.77% than those of low flows (0.60 mm and 0.28, respectively) in the control watershed (Xiaobeigou watershed). Besides, the differences in low flow magnitude and variability between the paired watersheds were statistically significant ($P < 0.01$).

In contrast, the magnitude, duration, and variability of high flows in the disturbed watershed were greater than those in the control watershed, but no statistical significance was found, suggesting that the small forest disturbance did not significantly affect the flow regimes of high flows in the study region. Based on the results of the flashiness index, the flashiness of flows was significantly increased by forest disturbance. The flashiness index in the disturbed watershed was 0.078 during the whole study period, which is 1.37 times larger than that of the control watershed (0.057). These results indicate that the natural flow regimes of small forested watersheds in northern Daxing' anling are sensitive to forest disturbance. Since small-scale disturbance in the study area

can lead to significant changes in flow regimes, more focus should be applied to forest disturbance and water resources in future management.

Keywords: flow regimes; forest disturbance; low flow; high flow

Introduction

Flow regimes, including magnitude, frequency, duration, timing, and variability of discharge, reflect the characteristics of specific hydrological events such as floods and low flows. Stable flow regimes are crucial for maintaining aquatic biodiversity and the functional integrity of river ecosystems [2-3]. Climate change and forest disturbance are two major drivers altering streamflow in forested watersheds [4], with forest disturbance playing a key role in modifying flow regimes [5]. Climate change directly affects watershed water input and evapotranspiration through alterations in precipitation and temperature, thereby influencing flow regimes [6]. For instance, Masih et al. [7] found that reduced monthly precipitation in the Karkheh watershed decreased low flows, while increased winter precipitation raised peak flows during 1961-2001. Forest disturbance directly impacts watershed flow regimes by altering canopy interception, soil water infiltration, and evapotranspiration [8]. Following complete clear-cutting of a forest in British Columbia, Canada, annual runoff increased by 79.4% [10]. Zhang et al. [11] discovered that during the forest disturbance period (1964-1990) in Baker Creek, the timing of annual peak flows advanced significantly, average peak discharge increased by 110%, and low flow variability decreased markedly, while during 1990-2009, peak and low flows increased by 31.4% and 16.0%, respectively. Schnorbus and Alila [12] found that in the Columbia Mountains of southeastern British Columbia, only when clear-cut areas reached 6%-14% of watershed area at specific elevation ranges did significant changes in hourly and daily peak flows occur within 1.25-100 year return periods.

Despite these contributions to understanding relationships between climate change, forest disturbance, and flow regimes, most studies have not considered interactive effects, particularly the confounding influence of spatial and temporal differences in meteorological factors (e.g., precipitation and air temperature) when assessing forest disturbance impacts [6]. Removing climatic variability effects is a major challenge in studying forest disturbance-flow regime relationships. The paired watershed approach offers an effective solution by using two adjacent forested watersheds with similar characteristics but different disturbance histories, using the undisturbed watershed as a control. This method effectively eliminates climatic variability and has been widely applied to study hydrological changes from vegetation alteration [13-14].

Daxing' anling represents China' s only cold-temperate bright coniferous forest region. Although mean annual precipitation is not high, the area has a well-developed river system closely related to forest water conservation functions [15-16]. Forest disturbance can reduce evapotranspiration and increase runoff coefficients, potentially increasing surface runoff in the short term. However, reduced canopy interception, thinner litter layers, and damaged soil structure increase soil erosion [17], decrease soil water-holding capacity, and compromise forest water conservation, thereby increasing extreme hydrological events such as floods and droughts [18]. Moreover, as a high-cold region with slow plant community succession, vegetation recovery is difficult once destroyed. Revealing relationships between forest disturbance and hydrological processes is therefore crucial for forest management and sustainable water resource utilization in Daxing' anling.

This study employs the paired watershed approach to investigate two typical small forested watersheds (<100 km^2) in northern Daxing' anling: Laogouhe watershed (disturbed) and Xiaobeigou watershed (control). The objective is to reveal relationships between forest change and hydrological processes, providing theoretical support for forest and water resource management and regional ecological security in Daxing' anling, focusing on gold mining-induced forest vegetation and soil structure disturbance along riverbanks in Laogouhe.

Study Area Overview

The study area is located in northern Daxing' anling, Heilongjiang Province. The region has a cold-temperate monsoon climate. According to Mohe meteorological station data (1959-2012), mean annual temperature is -4.29°C, mean annual maximum temperature is 4.31°C, mean annual minimum temperature is -11.81°C, mean annual precipitation is 433.57 mm, mean annual sunshine duration is 2426.97 h, and mean annual wind speed is 2.03 m/s. The terrain consists primarily of low mountains and hills, with elevations ranging 550-791 m. Zonal soil type is brown coniferous forest soil with thickness of 15-40 cm, and permafrost is present. The region belongs to the Pan-Arctic flora' s Eurasian subregion of Daxing' anling flora. Zonal vegetation is cold-temperate bright coniferous forest dominated by *Larix gmelinii*, with other tree species including *Pinus sylvestris* var. *mongolica*, *Betula platyphylla*, and *Populus davidiana*.

Watershed Selection

Based on extensive preliminary surveys, two typical small forested watersheds with similar topographic characteristics were selected as paired watersheds: Laogouhe watershed and Xiaobeigou watershed. Laogouhe watershed (99.23 km^2) is a disturbed watershed (LGH) where historical gold mining caused extensive damage to riparian forest vegetation and soil structure, creating typical disturbance zones along both sides of the riverbed (6.69 km^2, 6.74% of total watershed area) based on 2013 remote sensing imagery, field surveys, and national forest resource inventory data. Xiaobeigou watershed (66.44 km^2) serves as the control watershed (XBG) with undisturbed forest vegetation. The paired watersheds share similar geomorphology, vegetation conditions, and soil types (Table 1), and both lie within the continuous permafrost zone of the Xing' an-Baikal permafrost region [20], ensuring consistent permafrost distribution that can be excluded as a confounding factor.

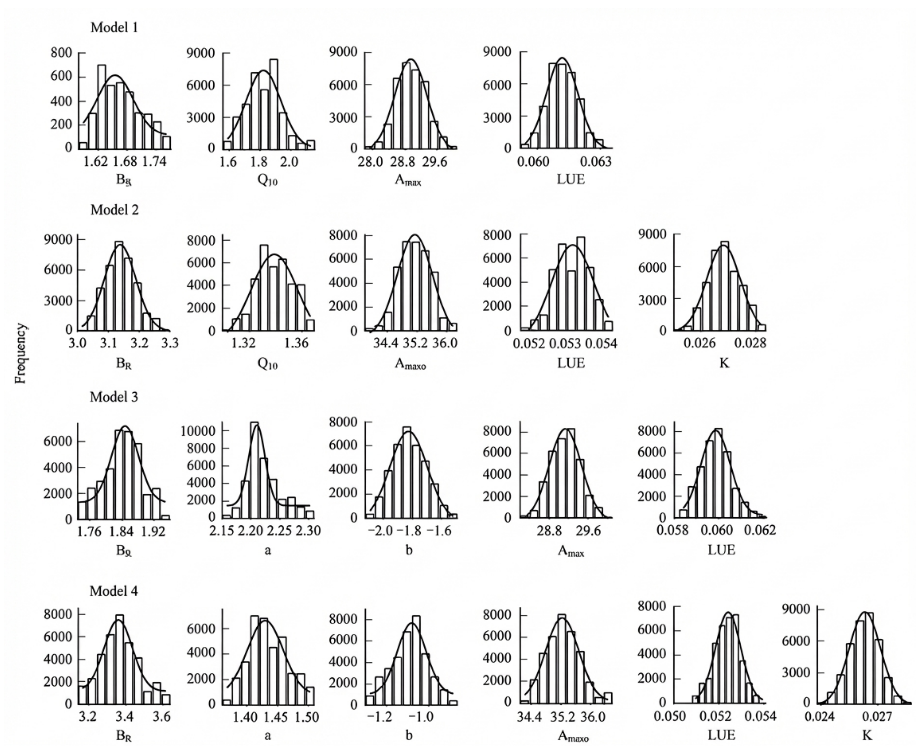

Figure 1: Figure 1

Location of paired watersheds and disturbance in Laogouhe watershed

Characteristics of the paired watersheds

Watersheds	Area (km^2)	Elevation (m)	Tree Species Composition	Canopy Density	Soil Type
Laogouhe	99.23	550-791	*Larix gmelinii*, *Pinus sylvestris* var. *mongolica*	0.6	Brown coniferous forest soil
Xiaobeigou	66.44	550-791	*Larix gmelinii*, *Betula platyphylla*	0.65	Brown coniferous forest soil

LGH: Laogouhe watershed; XBG: Xiaobeigou watershed

Data Collection

Water level recorders (Onset HOBO U20-001-04, R1, R2) were installed at narrow, regular river cross-sections downstream of both watersheds. Observation period was 2014-2015 with 30-minute recording intervals. Continuous discharge data were obtained by establishing stage-discharge rating curves. Daily runoff was calculated from continuous flow data and converted to watershed runoff depth based on catchment area.

To reduce rainfall observation errors, a rain gauge (Onset HOBO RG3-M) was installed in an open area (P1) at the center of the paired watersheds. Given the small watershed areas (<100 km^2) and minimal topographic differences, spatial heterogeneity of precipitation is small. Reliability of rainfall observations was verified using double mass curves of daily runoff from the paired watersheds.

Research Indicators

Peak flow and low flow are important hydrological variables that reflect river water resources status and hydrological processes [22]. Flow duration curves, which show the cumulative frequency of exceeding certain discharge values during a period, are widely used to define peak and low flows [13, 23]. In this study, peak flow is defined as discharge equaling or exceeding the 10% frequency value on the flow duration curve, while low flow is defined as discharge equaling or below the 90% frequency value [10, 24].

Three indicators—magnitude, duration, and variability—were selected to characterize peak and low flow regimes. Magnitude (mm) represents daily watershed runoff depth during peak or low flow events. Duration is the total time of peak or low flow occurrence. Variability is the absolute difference between peak/low flow discharge and mean runoff depth. Box-plots were created for each indicator and non-parametric Mann-Whitney U tests were performed to examine differences between paired watersheds.

To further investigate runoff variability, the flashiness index was introduced. Flashiness represents the rate of runoff change, with high flashiness indicating rapid change and stable flows showing slower change rates [1]. The study period was divided into rising and recession phases, with flashiness index calculated for each phase and the entire period using Formula (1):

$$FIndex = \frac{q_i - q_{i-1}}{q}$$

where q_i is runoff depth on day i, q_{i-1} is runoff depth on day $i-1$, q is mean runoff depth, and n is total number of days in the study period.

Results and Analysis

Runoff Characteristics of Paired Watersheds

Double mass curves plot cumulative values of two hydrological variables to assess consistency in trends [26] and disturbance effects [27]. The double mass curve of cumulative daily runoff depth for the paired watersheds showed an extremely significant linear relationship (R^2 = 0.99, P < 0.000) throughout the study period without obvious inflection points, indicating proper watershed selection and consistent hydrological responses.

Both watersheds are rainfall-dominated. During the study period, three major rainfall events occurred. Before each event, both watersheds were in low-flow periods with similar runoff depths (0.53-0.67 mm). During rainfall, runoff depths increased sharply to peak values (1.53-2.12 mm). After the summer' s largest rainfall event (42.4 mm single-day precipitation), both watersheds reached their annual peak flows (1.87 mm for Laogouhe, 2.12 mm for Xiaobeigou). Subsequently, runoff gradually decreased, entering autumn low-flow periods in September.

Overall, the paired watersheds showed consistent rainfall responses. However, during rising periods, Laogouhe' s runoff depth was 5.92-25.17% higher than Xiaobeigou' s, while during recession and low-flow periods, Laogouhe' s runoff depth was lower.

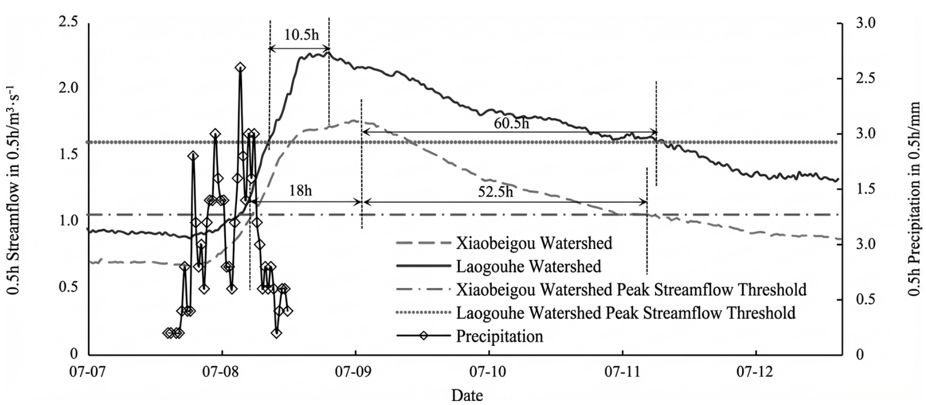

Figure 2: Figure 2

Double mass curve of cumulative daily flows for Laogouhe versus Xiaobeigou watersheds with best-fitted linear regression

[FIGURE:3] Relationship between daily flows of paired watersheds and precipitation

Peak and Low Flow Magnitude Characteristics

Flow duration curves were plotted for the paired watersheds. In the high-flow region (exceeding 10% frequency), runoff was similar between watersheds. However, in the low-flow region (below 90% frequency), Laogouhe' s runoff was significantly lower than Xiaobeigou' s, indicating that forest disturbance substantially reduced low flows while having minimal impact on high flows.

Specifically, peak flow magnitudes were nearly identical between disturbed (1.54 mm) and control (1.55 mm) watersheds ($P = 0.60$). In contrast, low flow magnitude in the disturbed watershed (0.47 mm) was 26.58% lower than the control (0.60 mm), with the difference being highly significant ($P < 0.01$).

[FIGURE:4] Daily flow duration curves for paired watersheds

[FIGURE:5] Magnitude of high and low flows for paired watersheds and Mann-Whitney U test results

Peak and Low Flow Duration Characteristics

Using 0.5 h intervals, statistics showed forest disturbance significantly increased peak flow duration. Peak flow duration in the disturbed watershed (239.5 h) was 37 h longer than the control (202.5 h), while low flow duration (163.0 h) was 14.5 h shorter than the control (148.5 h), though the latter difference was not statistically significant.

Using the largest peak flow event (July 8-12, 2014) as an example, the disturbed watershed reached peak flow threshold faster (10.5 h) than the control (18.0 h), but recession was slightly longer (60.5 h vs. 52.5 h). This demonstrates that forest disturbance reduced the rainfall response time for peak generation but increased recession duration.

[FIGURE:6] Analysis of high flow duration characteristics for paired watersheds from July 8-12, 2014

Peak and Low Flow Variability Characteristics

Peak flow variability (coefficient of variation) was slightly higher in the disturbed watershed but not statistically significant ($P = 0.125$). However, low flow variability increased significantly, with the coefficient of variation (0.39) being 36.77% higher than the control (0.28), reaching statistical significance ($P < 0.01$).

The flashiness index further revealed runoff variability. All rising and recession periods showed higher flashiness in the disturbed watershed, particularly during low-flow periods. The rising-phase flashiness index (0.160) was 1.71 times the control (0.074), while the recession-phase index (0.078) was 1.59 times the control (0.049). The overall study period flashiness index (0.078) was 1.37 times the control (0.057).

[FIGURE:7] Variability of high and low flows for paired watersheds and Mann-Whitney U test results

[FIGURE:8] Schematic diagram of rising and recession phase division for paired watersheds

Flashiness index of different phases for paired watersheds

Study Period	Laogouhe (Rising)	Laogouhe (Recession)	Xiaobeigou (Rising)	Xiaobeigou (Recession)
Whole study period	0.086	0.078	0.069	0.057
Low-flow period	0.243	0.160	0.044	0.049
Peak period	0.163	0.174	0.054	0.039
Other periods	0.078	0.109	0.052	0.037

Discussion

Effects of Forest Disturbance on Low Flow Regimes

Forest disturbance in Laogouhe watershed caused significant changes in low flow regimes. Mean low flow magnitude decreased by 26.58% and variability increased by 36.77% compared to the control watershed, with highly significant differences ($P < 0.01$). These findings align with Liu et al. [24], who reported that reduced forest cover decreased low flow magnitude by 30.1% and increased variability by 3.2% in a 266 km^2 Ethiopian watershed during 1968-1984. Conversely, Zhang et al. [10] found opposite results in British Columbia’ s Baker Creek, where low flow magnitude increased by 16.0% and variability decreased from 0.86 to 0.06 after forest disturbance. Such contrasting results indicate that forest disturbance effects on low flows vary across watersheds.

Although the disturbed area was small (6.74% of watershed), it concentrated in riparian zones. Reduced forest vegetation decreased canopy interception and litter water storage [33-34], while damaged soil structure from mining reduced soil permeability and water-holding capacity [36]. During dry periods, this prevented hillslope subsurface flow from recharging streamflow, significantly reducing low flow magnitude and increasing variability. However, if soil structure remains intact after disturbance, reduced evapotranspiration and canopy interception could increase soil moisture and potentially enhance low flows [23]. Thus, low flow regime changes depend on disturbance intensity, location, and soil conditions.

Effects of Forest Disturbance on Peak Flow Regimes

This study found that while forest disturbance slightly increased peak flow magnitude, duration, and variability, differences were not statistically significant. Previous research shows forest disturbance generally increases peak flow magnitude [9, 37-38], duration [24], and variability [10, 24], but responses vary significantly with disturbance area and location. Peak flow increases with disturbance area and intensity [39], but watershed characteristics and runoff generation mechanisms create different responses across watersheds [40].

In this study, the small disturbance area (6.74%) and high watershed resilience [41] may have limited peak flow impacts. Peak flows typically accompany intense rainfall events when canopy interception rates decrease [14, 42-43] and litter layers and soils rapidly saturate [34, 42]. Since disturbance concentrated in riparian zones while peak flows primarily originate from hillslope runoff rather than low-elevation riparian areas [32], impacts on peak flow regimes were minimal.

Conclusion

Using the paired watershed approach, this study investigated vegetation disturbance effects on flow regimes in small forested watersheds of Daxing' anling. Key findings include:

1. Low flow regimes in Daxing' anling' s small forested watersheds are highly sensitive to forest disturbance. Despite the small disturbance area (6.74% of watershed), mean low flow magnitude decreased by 26.58% and variability increased by 36.77% compared to the control watershed, with highly significant differences ($P < 0.01$).
2. Forest disturbance slightly increased peak flow magnitude, duration, and variability, but differences were not statistically significant. This indicates that small-scale forest disturbance (6.74% of watershed) did not significantly alter peak flow regimes in this region.
3. Forest disturbance significantly increased overall runoff flashiness. The flashiness index in the disturbed watershed (0.078) was 1.37 times that of the control (0.057), indicating more rapid runoff changes.

These results demonstrate that natural flow regimes of small forested watersheds in northern Daxing' anling are sensitive to forest disturbance. Even small-scale disturbances can cause significant flow regime changes, particularly for low flows. This sensitivity should be carefully considered in future forest and water resource management, especially in areas closely linked to hydrological cycles such as riparian zones.

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