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Short-Term Effects of Forest Fire on Water Quality along a Headwater Stream in the Immediate Post-Fire Period

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Abstract: Changes in water quality were examined during selected rainfall events in a headwater stream severely damaged by a forest fire on 21–23 February 2021. Seven water quality parameters were analyzed: pH, electrical conductivity, biochemical oxygen demand, chemical oxygen demand, total suspended solids (TSS), total nitrogen, and total phosphorous. First-flush effect and event mean concentration analyses were conducted in spring (dry season) and summer (wet season) immediately after the forest fire. In spring, the non-biodegradable organic matter concentrations increased along with pollutants related to ash-enhanced soil water repellency in water affected by first-flush effects. In summer, TSS and nutrient concentrations increased along with pollutants related to fire-induced soil surface disturbances after a series of rainfall events. First-flush analyses indicated that cumulative pollutant loads were greater in the spring than in the summer due to a higher concentration of forest fire ash in the early storm runoff immediately after the forest fire. The event mean concentrations revealed that pollutant loads were associated with both forest fire ash and storm events in the immediate post-fire period. Therefore, this study indicated that water quality along a headwater stream is affected by short-term effects of large and intense forest fires and rainfall seasonality.

Keywords: forest fire; pollutant parameters; first-flush effect; non-biodegradable organic matters; event mean concentration

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1. Introduction

The average annual temperature of the earth is currently rising owing to climate change events, such as global warming, El Niño, and La Niña [1]. Over the last century, the Republic of Korea (ROK) has experienced a temperature increase of 1.8 °C [2,3]. Rising temperatures have led to an increase in the frequency and intensity of extreme weather phenomena, such as floods and droughts [4–6], posing challenges in the stable supply of water resources [7,8]. In particular, the risk of large forest fires is expected to increase substantially because of the increased number of dry days [9,10]. Although the ROK has relatively small areas potentially affected by forest fire damage compared to other countries such as Australia and the United States [11–13], forest fires spread quickly and are difficult to extinguish [14,15] because it is located in the mid-latitude temperate climatic zone and exhibits clear and dry weather in the spring and autumn due to the effects of migratory anticyclones [5]. Moreover, increased erosion rates and changes in runoff occurrences and pollutant sources can considerably increase ash-related organic matter and the flux of sediment, nutrients, and other constituents from forest fires that affect water quality [13,16]. This could potentially contaminate the water supply from the forested headwater stream to the lowland river. Finally, considering that water quality management in polluted watersheds is expensive, it is more cost-effective to prevent contamination instead [17–20].

In the ROK, 63% of the land is covered by forests, and headwater streams (i.e., tertiary streams) account for 88.9% of the total length of the nationwide stream [21,22]. Therefore, streams play a significant role in freshwater supply and management [23]. Rivers in the forest basin play an important role as a source of water, soil, various nutrients, and organic matter, as well as an intermediate zone for supplying major rivers downstream [24]. Thus, forested headwater streams are an important source of potable water to communities worldwide and, in many cases, are managed specifically for this purpose [25]. Meyer et al. [26] reported that the upstream is diverse and species-rich, helping to maintain healthy mountain stream ecosystems throughout the water system. Moreover, water flowing from the headwater stream, which is as first-class water quality standards, flows into the downstream rivers and lakes and affects drinking water [27]. Therefore, the sustainable supply of clean water in the entire water system is determined by water purification [28,29].

Despite their role in freshwater supply, headwater streams in the ROK is managed by 43% of coniferous forests, increasing the risk of the spread of forest fires [30]. In addition, owing to overlapping mountains, the ROK shows irregular topography [5]. The mountains are close to villages and have high slopes, with an average elevation and slope of 450 m and 5.7°, respectively [5]. Therefore, the ROK is vulnerable to outbreaks and spread of forest fires [31], which may generate additional pollutants (e.g., polycyclic aromatic hydrocarbons) in negligible amounts or concentrate pre-existing contaminants (via ash de-posits) that may be transmitted into forested headwater streams [13]. Ash is not identified as an individual water pollutant because it contains a variety of constituents; however, its contributes to post-fire water quality as a non-point source (NPS) pollutant [32–34]. Particularly, excessive concentrations of biological nutrients and hazardous chemicals in water bodies in the post-fire period introduces various water quality problems, including shortage of safe drinking water, toxic algal blooms, oxygen loss, and biodiversity loss [13,32,35]. NPS pollution caused by forest fire deteriorates the health of the aquatic community, and it has been reported that it can change the species composition from up to downstream in a watershed [36–38]. Therefore, to prepare mid- to long-term water quality management measures for forest fires, it is necessary to first understand the headstream water quality in the post-fire period.

Compared to other disturbances, forest fires vary in the intensity and concentration of pollutants that affect water quality over time [39], which are associated with altering the range of physical and biogeochemical properties of the soil [40,41] as well as key hydro-logical factors controlling infiltration and surface runoff [42,43]. Forest fires are associated with the effects of ash; however, the analysis of factors to be investigated is limited owing to the short duration of the effects. The combustion of vegetation and soil organic matter (resulting in the breakdown of metal-organic compounds) and the effects of fire on the soil surface lead to ash and charcoal deposition [44–48]. Under these circumstances, when rainfall occurs, it is difficult to identify pollutants from forest fires that contribute to water quality degradation, because the total suspended solids (TSS) and nutrients (Total Nitrogen (TN) and Total Phosphorous (TP)) also increase. Several studies have reported that the highest concentration of TSS in headwater streams post-fire generally occurs in response to erosion events triggered by intense summer storms [49–51]. Moreover, the effects of forest fire on overland flow increases the erosion rate and suspended sediment loads, consequently increasing the concentration of toxic compounds and metals in water resources [13,16,35].

Therefore, to understand the changes in water quality caused by forest fires, important water quality parameters must be determined. The subsequent processes from forest fires can affect parameters such as pH, electrical conductivity (EC), turbidity, dis-solved oxygen, major ions, and nutrient loading (e.g., nitrate, sulfate, phosphate) [43,52,53]. Studies evaluating the impacts of fire on headwater stream quality tend to focus on sus-pended solids, organic carbon, and nutrients, whereas other components have received less attention [13,43,54,55]. Biochemical oxygen demand (BOD), chemical oxygen de-mand (COD), and total organic carbon (TOC) are water quality standards that are used to indirectly estimate the concentration of organic matter in water, and TN estimates the amount of nitrogen, a eutrophic causative substance that allows multiplication of algae in wastewater [13,56]. These parameters are related to the elevated levels of direct and/or in-direct pollutants in the water supply after a fire [54,57]. From this viewpoint, our specific objectives were to (1) analyze the water quality in response to forest fires, (2) indicate potential factors affecting the degradation of water quality in the headwater stream, and (3) determine the timing of the reduction and/or elimination of the impact of ash on stream water quality from forest fires. For this approach, first-flush effect and event mean concentration (EMC) analyses were employed to measure the representative pollutants related to the initial post-fire response affecting seasonal changes in water quality. This allowed us to compare the water quality of the headwater catchment with the that of the stream water in the immediate post-fire period. Furthermore, the results of this study may be useful for adapting sustainable water management practices to climate warming.

2. Materials and Methods

2.1. Site Description

This study was conducted in a headwater catchment (32.4 ha) located in Andong-si, 206 km South of Seoul (37°33′ N, 128°54′ E) (Figure 1a,b). According to the Andong weather station of the Korea Meteorological Administration (KMA), the mean annual precipitation ± standard deviation (SD) in this region from 2002 to 2021 was 1015.3 ± 200.8 mm (range: 737.9–1579.3 mm), of which 55% occurred in the summer. The mean annual temperature ± SD was 12.4 ± 0.5 °C (range: 11.3–13.2 °C). The elevation of the monitoring catchments ranges from 161 to 395 m above sea level, with hillslope gradients ranging from 0.4 to 47° with a mean of 27°. The underlying geology consists of sedimentary rocks. The catchment is vegetated by 21–50-year-old Korean red pine (*Pinus densiflora* S. et Z.), which facilitated the ignition and propagation of fires in the catchment. The stream channel was 0.9 km length, 4.0 m wide, and had a 0.25 m/m slope. This region was severely damaged by a forest fire from 21 February, 15:20 to 23 February 2021 7:20 KST (Korean Standard Time), and due to strong winds of up to 13 m/s, 419 ha of forest in the sur-rounding area was burned, causing property damage of KRW 17.7 billion [58]. Subsequently, the entire catchment was burnt out with stem and crown damage (Figure 1c–e).

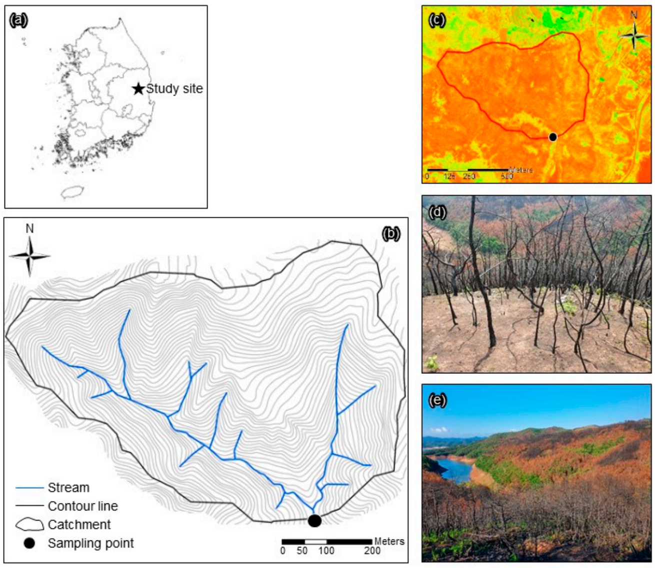

Figure 1. (**a**) Location of study site and (**b**) sampling point. (**c**) Normalized Difference Vegetation Index (NVDI) in the study catchment on 17 August 2021. Images (**d**,**e**) overview of the study catchment after the forest fire.

2.2. Field Experiment and Laboratory Analysis

Precipitation data were obtained from mountain meteorology observations of the Korea Forest Service (KFS). The runoff volume (mm) was divided by the projected area of the catchment. Antecedent dry days (ADDs), total precipitation, maximum 1 h precipitation, and 7- and 30-day antecedent precipitation indices (API_7 and API_{30}) were calculated from the precipitation data [59]. API_7 reflects soil moisture conditions near the surface, whereas the API_{30} represents moisture in the deep soil matrix [60,61].

An ISCO automatic water sampler (Teledyne ISCO Inc., Lincoln, NE, USA) was installed to collect water samples at 1 h intervals during rainfall events. Some events include the peak runoff and recession limb of the hydrograph as stormflow samples. The water sample preservation and analysis methods conformed to the standard methods of the Ministry of the Environment [62].

Physicochemical water quality parameters (pH, EC, BOD, COD, TOC, TSS, TN, and TP) were used to represent changes in stream water quality for NPS pollution monitoring. The pH and EC were determined using a pH meter (HM-30R, DKK-TOA Corp., Tokyo, Japan) and an EC meter (CM-30R, DKK-TOA Co., Tokyo, Japan), respectively. BOD was measured using the BOD_5 method, which requires five days of incubation at 20 °C using a specially designed incubator [63]. COD_{Mn} was determined using the acid titration method. The TSS content was measured by weighing after filtration and drying at 105–110 °C. TOC content was determined by high-temperature combustion using a TOC analyzer (TOC-L, Shimadzu Co., Kyoto, Japan). TN content was determined using the continuous-flow method of an autoanalyzer (SYNCA, BLTEC Co., Tokyo, Japan). TP content was measured using a UV-Vis Spectrometer (Cary 60, Varian Co., Palo Alto, CA, USA).

2.3. Data Calculation and Analysis

The EMC is known to be useful in interpreting complex patterns and comparing different events at different times or sites [64]. The EMC was calculated according to the relationship between the total water quality mass and total runoff volume during each rainfall event:

$$\mathrm{EMC} = \frac{\text{Mass of pollutant contained in the runoff event}}{\text{Total volume of flow in the event}} = \frac{\sum \mathrm{Q_i C_i}}{\sum \mathrm{Q_i}} \quad (1)$$

where EMC is the event mean concentration (mg/L), Q_i indicates the discrete flow coordinates on the event hydrograph, and C_i is the corresponding discrete concentration on the pollution graph. It should be noted that instead of measuring the discrete flows and concentrations throughout the different sites, the EMC represents the concentration of a flow-weighted composite sample of the runoff event [65]. All statistical analyses were performed using R version 4.1.2.

3. Results and Discussion

3.1. Temporal Variation in Water Quality of Headwater Stream in the Immediate Post-Fire Period

Table 1 lists the temporal changes in the observed water quality parameters (pH, EC, BOD, COD, TOC, TSS, TN, and TP), runoff, and rainfall responses for 10 rainfall events. Total precipitation and runoff during the rainfall events were 11.5–80.5 and 0.18–49.55 mm, respectively, with seven antecedent dry days (Figure 2a,b).

The mean pH value ranged from 7.7 to 8.2, and EC ranged from 191.9 to 345.8 μS/cm (Figure 2c). The mean values for organic matter were 0.8–9.0 mg/L for BOD, 6.5–17.6 mg/L for COD, and 6.1–15.6 mg/L for TOC (Figure 2d). The mean TSS concentrations ranged from 3.0 to 653.6 mg/L (Figure 2b). The nutrient concentrations ranged from 0.8 to 2.5 mg/L for TN and 0.01 to 0.03 mg/L for TP (Figure 2e). The increased COD and TOC concentrations indicated a concomitant increase in non-biodegradable organic matter induced soil water repellency in the spring immediately after the forest fire [13,39,66]. An increase in TSS, TN, and TP concentrations was associated with the combined impacts of fire-induced soil surface disturbance by the loss of surface cover during storm events, particularly during the flood season (June–September) [67,68]. In addition, summer monsoons can deliver seasonal rainfall and runoff, which affect sediment deposition on hillslopes and the transport of fluvial sediment [68–70].

Table 1. Summary of rainfall events and runoff volumes from which water samples were collected.

Date	No	Time Period (Days) *	Total Precipitation (mm)	Max. 1 h Precipitation (mm)	ADDs (Days)	API_7 (mm)	API_{30} (mm)	Duration of Rain (h)	Total Runoff (mm)	Peak Flow (mm/h)
12 March 2021	E1	17.2	12.5	4.5	0.0	7.0	68.5	5	0.26	0.06
27–29 March 2021	E2	32.4	23.0	2.5	7.0	0.0	83.5	14	1.17	0.05
3–4 April 2021	E3	39.3	80.5	10.0	0.0	15.0	48.5	18	35.65	6.59
12–13 April 2021	E4	48.3	21.0	4.0	0.0	7.0	116.5	18	1.60	0.10
15–21 May 2021	E5	81.2	59.0	6.5	0.0	17.5	50.0	40	10.89	0.33
28–29 May 2021	E6	94.3	11.5	5.8	0.0	5.5	112.5	2	1.31	0.08
3–4 July 2021	E7	130.4	45.5	10.2	0.0	7.5	53.0	11	23.95	8.02
7–8 July 2021	E8	134.5	37.0	14.3	0.0	81.0	113.0	6	17.15	4.76
23–25 August 2021	E9	181.4	67.3	8.6	0.0	18.0	47.0	21	30.71	11.64
31 August–1 September 2021	E10	189.6	46.8	10.9	0.0	43.2	159.5	12	49.55	13.14

Note: ADDs: Antecedent dry days, API_7 and API_{30}: 7- and 30-day antecedent precipitation indices, Asterisk (*) denotes the time period (days) in the immediate post-fire period.

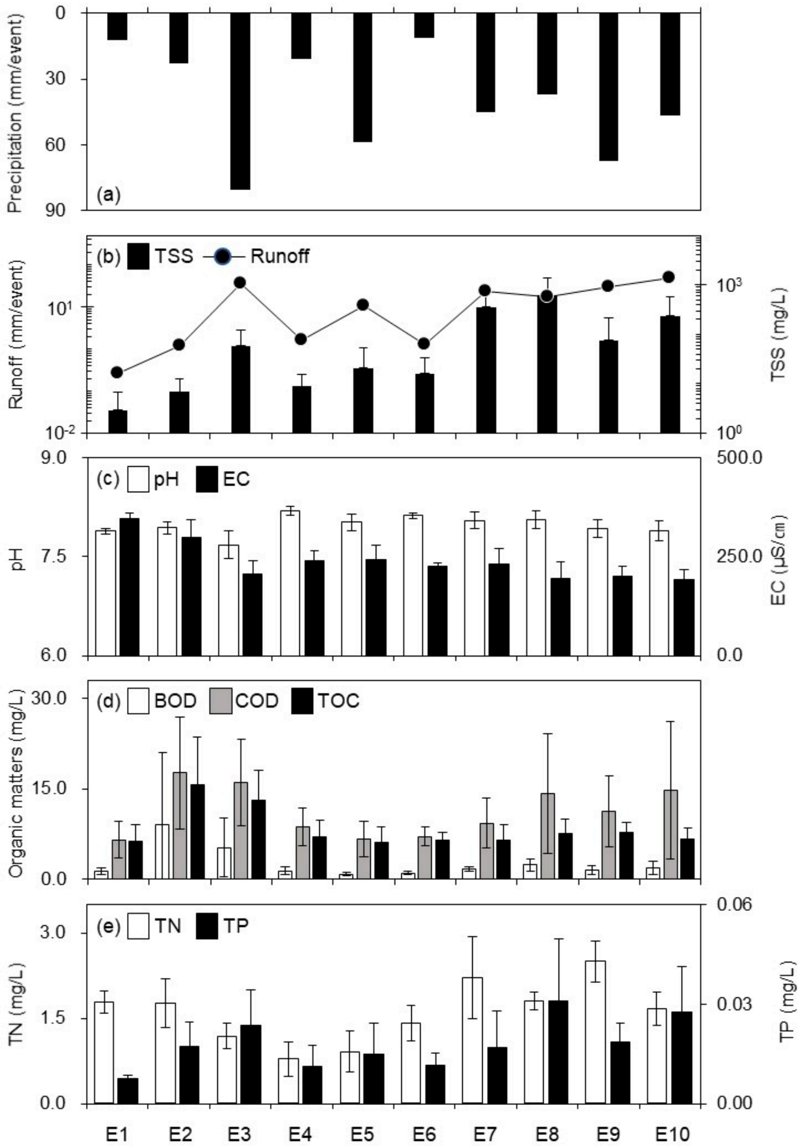

Figure 2. (**a**) Precipitation, (**b**) runoff and TSS, (**c**) pH and EC, (**d**) organic matter (BOD, COD, and TOC), and (**e**) TN and TP in a forested headwater stream during rainfall events (E1–E10) in the immediate post-fire period. TSS: total suspended solids, EC: electrical conductivity, BOD: biological oxygen demand, COD: chemical oxygen demand, TOC: total organic carbon, TN: total nitrogen, TP: total phosphorus.

As the characteristics of rainfall events can considerably affect pollutant emissions, two rainfall events (i.e., E3 and E9) with similar rainfall intensities and du-rations were selected in this study (Figure 3). Total precipitation and maximum 1 h precipitation were 80.5 mm and 10.0 mm for E3, respectively (Figure 3a) and 67.3 mm and 8.6 mm for E9, respectively (Figure 3b). The patterns of water quality parameters and runoff also occurred similarly for the two selected rainfall events from spring to summer in the immediate post-fire period. The runoff events responded quickly to precipitation inputs during the post-fire period. No distinctive time lag was observed between the peak rainfall input and peak flow. Event runoff receded progressively after the rainfall ceased.

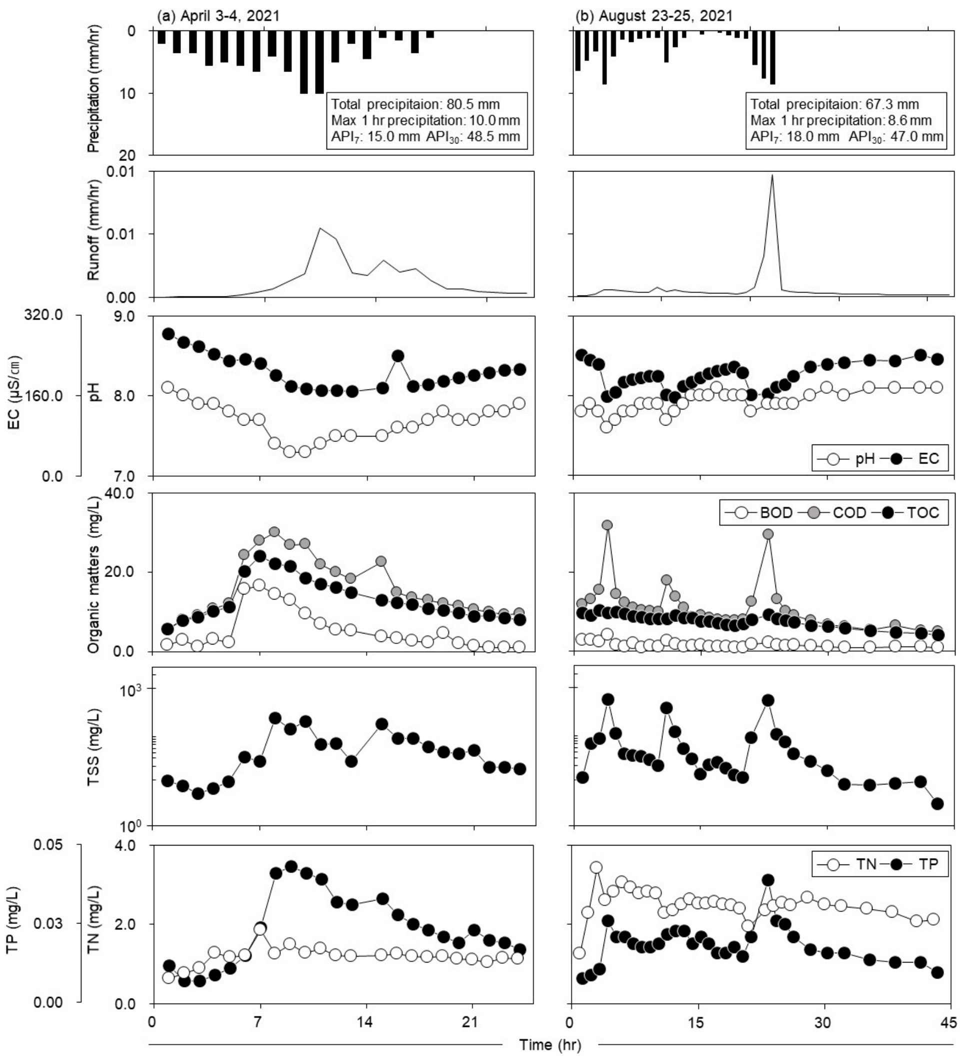

Figure 3. Changes in headwater stream quality in selected rainfall events in the immediate post-fire period. (**a**) E3 (3–4 April 2021) and (**b**) E9 (23–25 August 2021). Less increase in organic matter (BOD, COD, and TOC) was observed during E3 and a greater increase in TSS and nutrients (TN and TP) was observed during E9. EC: electrical conductivity, BOD: biological oxygen demand, COD: chemical oxygen demand, TOC: total organic carbon, TSS: total suspended solids, TN: total nitrogen, TP: total phosphorus.

Among the water quality parameters, the non-biodegradable organic matter components represented by COD and TOC were compared in E3 and E9, regardless of the runoff response (Figure 3).

For rainfall events, the maximum TSS and TP concentrations with peak flow quickly responded to increased rainfall amounts in the post-fire periods. For most sampled rainfall events, a close relationship was found between runoff and both TSS and nutrients (TN and TP). Similar to other studies, the maximum TSS and TP concentrations were found before peak flow [71,72]. These results suggest that particulate phosphorous is the predominant form of transported phosphorous during rainfall events and is associated with soil erosion [73,74].

3.2. First-Flush Effects of Forest Fire on Water Quality in the Headwater Stream

This study was performed to assess stormwater pollution parameters (BOD, COD, TOC, TSS, TN, and TP) in the first-flush runoff in the immediate post-fire period. As shown in Figure 4, the cumulative pollutant load ratio was used to identify the first-flush effects in organic matter (BOD, COD, and TOC), TSS, and nutrients (TN and TP) in the post-fire period.

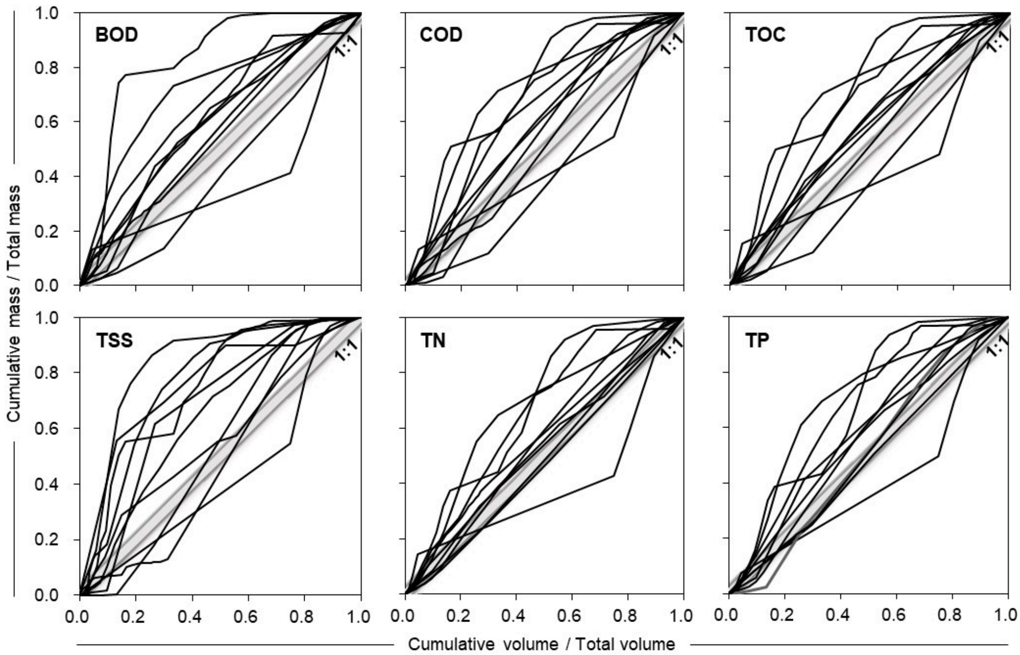

Figure 4. Cumulative load ratio for pollutant parameters in the immediate post-fire period. BOD: biological oxygen demand, COD: chemical oxygen demand, TOC: total organic carbon, TSS: total suspended solids, TN: total nitrogen, TP: total phosphorus.

Most pollutant constituents were discharged intensively during the early stages of rainfall with the persistent spring drought in the ROK [75,76]. As shown in Figure 4, the pollution parameter loads for most of the monitoring period were above the 1:1 line. Thus, the first flush had strong effects, which is consistent with the results of previous studies [34,77,78]. The first flush, or the initial surface runoff after a rainfall event, comprises most of the pollution in streams [32,34]. In addition, the concentration of pollutants decreased as a response to increased rainfall and runoff volume [68]. According to Deletic [79], the first-flush effect (i.e., the initial runoff being more polluted than the subsequent runoff) may appear in some runoff events but not in others at the same sites.

In Table 2, cumulative pollutant loads were separated according to spring (dry season) and summer (wet season) in the immediate post-fire period. All cumulative pollutant loads relative to 30, 50, and 70% of the runoff flow in the spring were greater than that in the summer due to more concentrated pollutants in the first part of runoff in the immediate post-fire period during the spring [16,80]. The water quality parameters of the first flush during both seasons exhibited high values compared to the three lowland rivers in a previous study, which ranged from 32.3 to 33.9% of the average cumulative load [34]. Even the load ratios at 30 and 50% of the runoff flow were higher in spring compared to those previously reported in upstream-affected steep slopes with soil losses and fertilization, which ranged from 44.1 to 48.3% and 69.4 to 74.3%, respectively, [81].

Table 2. Average cumulative load relative to cumulative runoff in spring and summer in the immediate post-fire period.

Season	Period	Event No.	Cumulative Runoff (%)	Cumulative Load (%)		
				Organic Matters (BOD, COD, TOC)	TSS	Nutrients (TN, TP)
Spring	12 March–29 May	E1–E6	30	48.3	65.4	44.2
			50	75.0	81.0	70.9
			70	89.3	92.2	88.1
Summer	3 July–1 September	E7–E10	30	34.5	30.8	31.0
			50	61.6	62.9	54.5
			70	83.5	91.8	78.0

Note: BOD: biological oxygen demand, COD: chemical oxygen demand, TOC: total organic carbon, TSS: total suspended solids, TN: total nitrogen, TP: total phosphorus.

From this result, the first-flush effect of the pollutants was not only related to ash-enhanced soil water repellency in the immediate post-fire periods [82,83] but also to the increased stormwater runoff when the intensity and duration of rainfall events increased during the flood season (June–September) [39,84]. However, it is difficult to apply existing first-flush formulae to other catchments, because the formulae are complex and varies widely depending on the characteristics of the catchment [79,85].

3.3. Water Quality in the Headwater Stream in Response to Post-Fire and Seasonal Changes

Figure 5 illustrates the changes in the water quality of the headwater stream separated by spring and summer in the immediate post-fire period. The pH and COD were similar in the spring and summer (Figure 5a,f). High pH values (7.3–8.3) were observed in the immediate post-fire period because wood ash, which is highly alkaline, increases soil pH by up to 3 units immediately after burning compared to that of unburned soils [86]. The EC, BOD, and TOC tended to be higher in spring than in summer (Figure 5b,e,g), whereas TN, TP, and TSS tended to be higher in summer than in spring (Figure 5c,d,f). The differences in the six parameters (i.e., EC, TN, TP, BOD, TOC, and TSS) between the two seasons were also significant according to the Mann–Whitney U test ($p < 0.05$) (Figure 5b–e,g,h). The chemical composition of ash is highly variable, which is affected by vegetation type, part of the plant (bark, wood, or leaves) burned, climate, soil type, and combustion conditions [87,88]. Water quality could be affected by seasonal changes, which increase in the dry season (November–April) and wet season, particularly in the summer (June–September), owing to the effect of the East Asian monsoon [89–91].

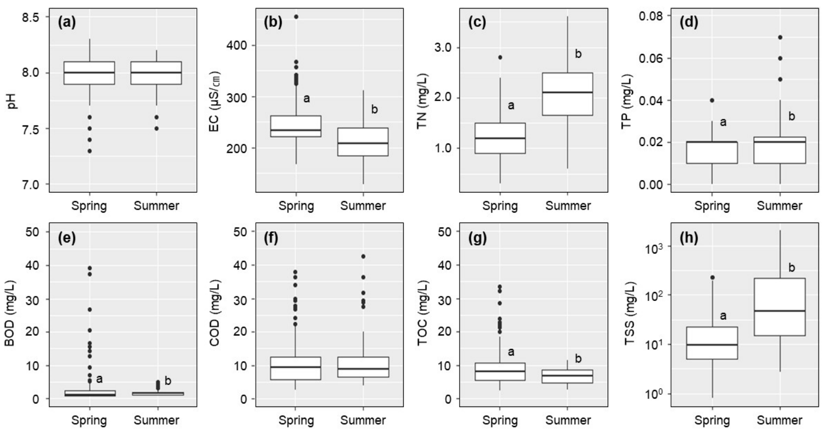

Figure 5. Comparison of observed water quality parameters (i.e., (**a**) pH, (**b**) EC, (**c**) TN, (**d**) TP, (**e**) BOD, (**f**) COD, (**g**) TOC, and (**h**) TSS) between spring (E1–E6) and summer (E7–E10) in the immediate post-fire period. Mann-Whitney U test is indicated in separate bold letters (a and b) above the bar graph ($p < 0.05$). EC: electrical conductivity, TN: total nitrogen, TP: total phosphorus, BOD: biological oxygen demand, COD: chemical oxygen demand, TOC: total organic carbon, TSS: total suspended solids.

Principal component analysis (PCA) was used to analyze the eight water quality parameters monitored during spring and summer (Figure 6). The loadings of various water quality parameters considered for each factor are listed in Table 3. The three main factors in the two seasons accounted for 87.5 and 87.2% of the total variance, respectively. In spring, Factor 1, accounting for 56.6% of the total variance, showed high loadings for BOD, COD, and TOC (Figure 6a). However, in summer, Factor 1, accounting for 60.9% of the total variance, showed high loadings for EC, BOD, COD, TSS, and TP (Figure 6b). In particular, the pollution load factors in spring were affected by organic matter-related ash, and pollution load factors in summer were influenced by organic matter and nitrogen and phosphorus. The ash-related organic matter enhanced soil water repellency [39]; thus, water repellency was induced in time due to fluctuations in soil moisture and the breakdown of water-repellent compounds [92].

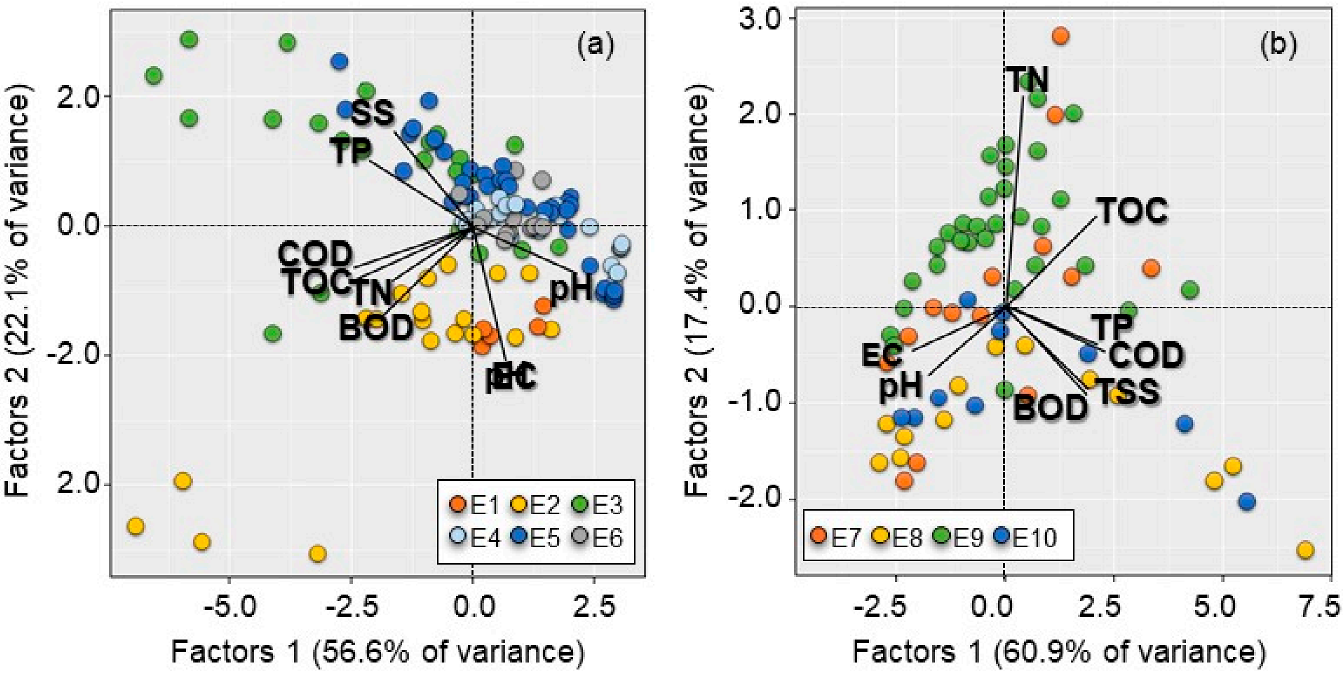

Figure 6. Biplot of principal components for observed water quality parameters in (**a**) spring (E1–E6) and (**b**) summer (E7–E10) in the immediate post-fire period. EC: electrical conductivity, BOD: biological oxygen demand, COD: chemical oxygen demand, TOC: total organic carbon, TSS: total suspended solids, TN: total nitrogen, TP: total phosphorus.

Table 3. Principal component loadings of observed water quality parameters in the immediate post-fire period.

Parameters	Spring (E1–E6)			Summer (E7–E10)		
	Factor 1	Factor 2	Factor 3	Factor 1	Factor 2	Factor 3
pH	−0.420	**0.679**	−0.363	−0.153	**−0.934**	−0.154
EC	0.232	**−0.820**	0.020	**−0.636**	**−0.550**	−0.320
BOD	**0.963**	−0.038	0.111	**0.578**	**0.577**	−0.324
COD	**0.872**	0.310	0.338	**0.716**	**0.621**	−0.089
TOC	**0.856**	0.237	0.419	0.496	**0.662**	0.462
TSS	0.309	**0.830**	−0.092	**0.923**	0.129	−0.057
TN	0.317	0.030	**0.928**	−0.034	0.102	**0.943**
TP	0.310	**0.763**	0.438	**0.902**	0.271	0.103

Note: EC: electrical conductivity, BOD: biological oxygen demand, COD: chemical oxygen demand, TOC: total organic carbon, TSS: total suspended solids, TN: total nitrogen, TP: total phosphorus. Bold numbers indicate a strong correlation coefficient.

In addition, most parameters returned to levels similar to the reference stream within 24 h, and concentrations in burned catchment streams returned to pre-fire levels within four months [82]. Thus, the results showed that atmospheric deposition of ash may have short-term impacts on stream water quality [93–95]. However, it was difficult to identify the exact origin of the pollutants for the 10 monitored periods with eight water quality characteristics. Therefore, the differences between spring and summer in terms of rainfall seasonality and export pollution must be classified to study water quality degradation in the immediate post-fire period.

3.4. Short-Term Effects of Initial Post-Fire Responses to Water Quality in the Headwater Stream

The EMCs of pollutant parameters (BOD, COD, TOC, TSS, TN, and TP) were compared between spring and summer in the immediate post-fire period. Most EMCs for the six parameters during the 10 rainfall events represent the general pollution status during the washing process with increased runoff (Table 4 and Figure 7).

Table 4. Summary of event mean concentrations of pollutant parameters (BOD, COD, TOC, TSS, TN and TP) in the immediate post-fire period.

Season	Period	No. Event	Organic Matters (mg/L)			TSS (mg/L)	Nutrients (mg/L)	
			BOD	COD	TOC		TN	TP
Spring	12 March–29 May	E1–E6	2.5 ± 1.9 (0.8–5.6)	10.6 ± 4.7 (6.6–19.4)	9.1 ± 3.4 (6.1–14.8)	23.5 ± 28.9 (2.4–85.5)	1.3 ± 0.4 (0.8–1.8)	0.02 ± 0.01 (0.01–0.03)
Summer	3 July–1 September	E7–E10	2.4 ± 0.4 (1.9–2.9)	19.6 ± 3.2 (14.5–23.2)	8.7 ± 0.6 (8.0–9.6)	713.6 ± 354.4 (278.9–1219.4)	2.3 ± 0.5 (1.8–3.0)	0.04 ± 0.01 (0.03–0.04)

Note: Mean ± standard deviation, Bracket: minimum–maximum values. BOD: biological oxygen demand, COD: chemical oxygen demand, TOC: total organic carbon, TSS: total suspended solids, TN: total nitrogen, TP: total phosphorus.

The mean EMC of organic matter (BOD, COD, and TOC) was 0.8–9.4 mg/L in the spring (E1–E6) and 1.9–23.2 mg/L in the in the summer (E7–E10) (Table 4). The mean EMC of TSS was 2.4–85.5 and 278.9–1219.4 in the spring and summer, respectively. The mean EMC of nutrients (TN and TP) was 0.01–1.8 mg/L and 0.03–3.0 mg/L in the spring and summer, respectively (Table 4).

As shown in Figure 7, the EMCs of organic matter (BOD and TOC) in spring tended to be greater than those in summer. In contrast, higher EMCs of the four pollutant parameters were observed in summer than in spring. This is because higher pollutant loads and increased runoff induce soil surface disturbances due to the loss of surface cover in the post-fire periods [39]. Costa et al. [48] indicated that the greatest volume of surface runoff flow resulted in greater EMCs, probably because this flow of suspended solids at the bottom of the riverbed releases pollutants.

The degree of water quality degradation induced by forest fires was compared to those with unburned streams (Figure 7a–e). For instance, in a study by Yur and Kim [96], the mean of EMCs (mg/L) of pollutant parameters ranged from 0.3 for TP to 6.0 for BOD in the forested watershed (338 ha) (Figure 7a,e). Kang et al. [97] showed mean EMCs from 0.2 for TP to 31.7 for TSS in a deciduous forest catchment (21.7 ha). Yoon et al. [98] also indicated mean EMCs from 0.03 for TP to 30.0 for TSS in a mixed-forest catchment (15.1 ha). NIER [99] reported mean EMCs from 0.02 for TP to 12.2 for TSS in three forested catchments (18–19 ha) (Figure 7c,e).

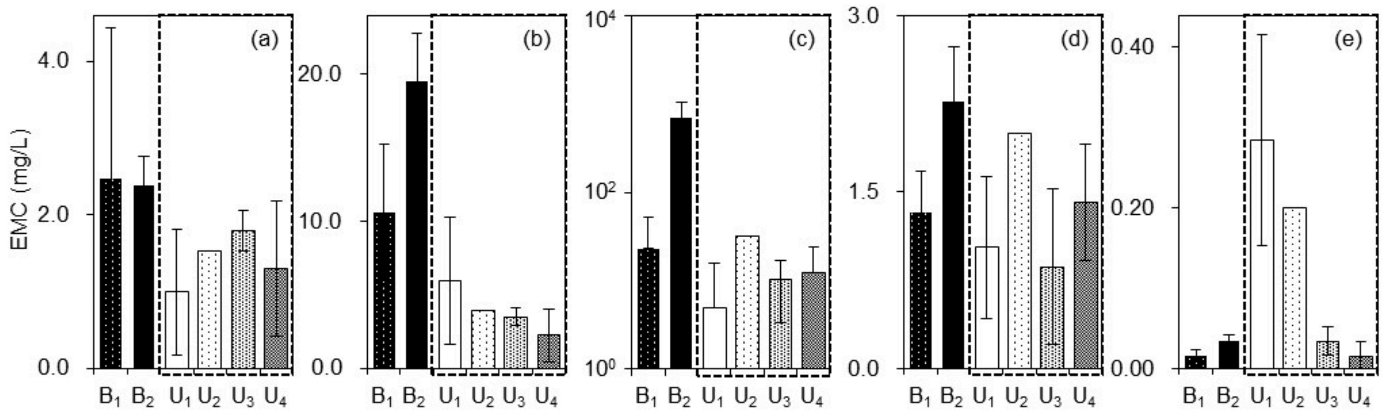

Figure 7. Event mean concentration (EMC) of pollutant parameters ((**a**) BOD, (**b**) COD, (**c**) TSS, (**d**) TN and (**e**) TP) between burned (in this study, B_1 and B_2) and unburned (in previous studies, U_1, U_2, U_3, and U_4) headwater catchments. B_1 and B_2 indicate EMC of pollutant parameters in the spring and summer, respectively. U_1, U_2, U_3, and U_4 indicate the EMC of pollutant parameters in Yur and Kim [97], Kang et al. [98], Yoon et al. [99], and NIER [100], respectively. Four unburned catchments were focused on forested headwater catchments from spring to summer. BOD: biological oxygen demand, COD: chemical oxygen demand, TSS: total suspended solids, TN: total nitrogen, TP: total phosphorus.

The EMCs of BOD, TN, and TP from spring to summer in the post-fire period were similar and/or slightly higher than the values reported in previous studies [48,93–95]. The EMCs of only non-biodegradable organic matter (COD and TOC) in the spring were 1.8- to 6.2-fold greater than those of the forested catchments, which signifies that pollutant parameters were related to ash-enhanced soil water repellency [13,100]. The EMCs of the pollutant parameters in summer increased by 3.3- to 11.4-fold for COD and TOC, and 22.5- to 143.0-fold for TSS, compared to that of the forested catchment. This is due to the combined impacts of forest fire ash and the series of storm events in the immediate post-fire period [101–103]. Furthermore, the pollutant parameters from the forest fire concentrated in spring may establish a methodological and theoretical basis for the development of sustainable water management strategies by accounting for relevant factors such as ash-enhanced soil water repellency in spring (dry season) and soil surface disturbance caused by the loss of surface cover in summer (wet season) and the East Asian monsoon circulation [91,104–106].

4. Summary and Conclusions

The short-term impact of forest fires and seasonal changes on water quality was examined using first-flush effects and event mean concentration analyses. The findings are summarized as follows: (1) Increased COD and TOC concentrations indicated a concomitant increase in non-biodegradable organic matter-induced soil water repellency in spring immediately after the forest fire; (2) the increase in TSS, TN, and TP concentrations was associated with the combined impacts of fire-induced soil surface disturbance and the loss of surface cover during storm events, particularly during the wet season in the summer because of the East Asian monsoon; (3) cumulative pollutant loads in the spring was greater than that in the summer due to a higher concentration of pollutants in the first flush immediately after the fire; and (4) event mean concentrations revealed that pollutant loads were induced by the combined impact of forest fire ash and the series of storm events in the immediate post-fire period. Therefore, this study indicated that large and intense forest fires have direct and indirect short-term effects on water quality in response to fire and rainfall seasonality. In particular, the increase in pollutant concentration in the dry and wet seasons because of the summer monsoon can degrade water quality by flooding, soil erosion, and altering hydrologic regimes within a forested headwater. This study focused only on the changes in water quality in one headwater stream within one year after a forest fire. Further, the study needs to consider influence of the timing of forest fires and pollutant dynamics for determining the long-term effects of forest fires on water quality along the spatial variation of headwater streams.

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