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Shifts in stream hydrochemistry in responses to typhoon and non-typhoon precipitation

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Abstract. Climate change is projected to increase the intensity and frequency of extreme climatic events such as tropical cyclones. However, few studies have examined the responses of hydrochemical processes to climate extremes. To fill this knowledge gap, we compared the relationship between stream discharge and ion input-output budget during typhoon and non-typhoon periods in four subtropical mountain watersheds with different levels of agricultural land cover in northern Taiwan. The results indicated that the high predictability of ion input-output budgets using stream discharge during non-typhoon periods largely disappeared during the typhoon periods. For ions such as Na^+, NH_4^+, and PO_4^{3-}, the typhoon periods and non-typhoon periods exhibited opposite discharge-budget relationships. In other cases, the discharge-budget relationship was driven by the typhoon period, which consisted of only 7% of the total time period. Watersheds with a 17–22% tea plantation cover showed large increases in NO_3^- export with increases in stream discharge. In contrast, watersheds with 93–99% forest cover showed very mild or no increases in NO_3^- export with increases in discharge and very low levels of NO_3^- export even during typhoon storms. The results suggest that even mild disruption of the natural vegetation could largely alter hydrochemical processes. Our study clearly illustrates significant shifts in hydrochemical responses between regular and typhoon precipitation. We propose that hydrological models should separate hydrochemical processes into regular and extreme conditions to better capture the whole spectrum of hydrochemical responses to a variety of climate conditions.

1 Introduction

One of the major concerns of global climate change is increases in extreme climatic events such as flooding, droughts, and tropical cyclones (Phillips, 2017). Mounting evidence suggests that such events have strong effects on ecosystem function such as biodiversity, productivity, phenology, nutrient cycling, and community resistance to invasion (Holmgren et al., 2006; Fay et al., 2008; Jentsch and Beierkuhnlein, 2008; Smith, 2011; Chang et al., 2017a; Sinha et al., 2017). Predicting ecological effects of climate extremes is challenging because their effects on ecosystems could be dramatically different from "typical" or "normal" climatic variability (Smith, 2011).

Land use change has been considered a potential environmental threat at both local and global scales (Foley et al., 2005; Tang et al., 2005). A large number of studies have reported that replacing natural forests with agriculture lands causes large

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increases in surface runoff, sediment yield and nutrient export (Kosmas et al., 1997; Hill et al., 1998; Gessesse et al., 2015). Locally, in a study of nutrient cycling in upstream watersheds of northern Taiwan, the replacement of 22% of the natural forests by tea plantations reduced the nitrogen retention ratio by 50% (Lin et al., 2015). The consequences of land use change on nutrient retention is likely most dramatic during extreme events such as tropical cyclones when precipitation exceeds soil infiltration capacity. A study on paired watersheds in Taiwan indicated that sediment yield was one order of magnitude lower in plantations with gentler slopes than natural forests with steeper slopes during base flow (Tsai et al., 2009). However, during the peak flow of a typhoon event, the sediment yield was one order of magnitude greater in the plantations than the natural forests (Tsai et al., 2009).

Studies of nutrient input and output in both temperate and subtropical regions reported that hydrological control of the net nutrient input-output budget could override the effect of plant growth, leading to greater nutrient export in the growing season when biological demand is high (Likens and Bormann, 1995; Chang et al., 2017a). Although rarely examined, it can be expected that differences in nutrient export between disturbed and undisturbed watersheds are most dramatic during extreme storm events, relative to less extreme, typical periods.

With the projected increases in climate extremes in many parts of the world (Elsner et al., 2010; Donat et al., 2016; Borodina et al., 2017; Pfahl et al., 2017), the relationship between precipitation or stream discharge and nutrient export could shift to a new phase, which cannot be extrapolated from relationships that are mostly driven by "typical" storms. In a previous study, we illustrated differences in monthly nutrient input and output among four mountain watersheds differing in levels of tea plantation cover in northern Taiwan (Lin et al., 2015). Here, we report the differences in the ion input-output budget between "regular" flow periods and typhoon periods in the four watersheds. The objectives of this study are to 1) test if typhoon storms will cause distinct alternation in nutrient input-output budget due to the nonlinear nature of many ecological processes in response to disturbance (Burkett et al., 2005; Jentsch, 2007); and, 2) to examine differences in the relationship between stream discharge and input-output budget among ions and among watersheds with different levels of agricultural land cover.

2 Materials and Methods

2.1 Study region

This study was conducted at the 303 km^2 subtropical Feitsui Reservoir Watershed (FRW) in northern Taiwan (Fig. 1a). This area is covered mostly by natural secondary forests dominated by tree species within the Fagaceae and Lauraceae families (Chen, 1993). Because the FRW is a water resource protection area, agricultural activities are limited to pre-existing agriculture lands, mostly tea plantations (1200 ha). Tea plantations comprise approximately 15.8% of the FRW (Chang and Wen, 1997; Chou et al., 2007). Fertilizer applications are heavy in the tea plantations, reaching 786 kg-N ha^{-1} yr^{-1} (Lin et al., 2015). The FRW has a rough topography with an elevation ranging from 45 m to 1127 m and a mean slope of 42% (Fig. 1b). The complex topography and seasonal monsoons contribute to high precipitation variability. Soils in the FRW are mostly Entisols and Inceptisols with high silt contents developed from argillite and slate with sandstone interbeds (Zehetner et al., 2008).

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2.2 Sampling scheme

We sampled stream water at four subwatersheds (A1, A2, F1, and F2) and precipitation water at two of the four subwatersheds (A1 and F2) within FRW on a weekly basis between September 2012 and August 2015 (Fig. 1a). Natural forest is the major land cover type of all watersheds (> 68%); however, agricultural lands are also important at A1 (22%) and A2 (17%). A1, A2, and F2 are small watersheds (< 3 ha) drained by first order streams while the F1 watershed (86-ha) is drained by a second-order stream that drains through A1 and A2 (Fig. 1).

Precipitation was collected with a 20-cm diameter polyethylene (PE) bucket. Stream water was collected by immersing a PE bucket into the stream. For both precipitation and stream water, a 600 mL subsample was taken using a PE bottle and transported to the laboratory with conductivity and pH being measured the same day of collection. All the samples were stored at 4ºC without chemical preservatives prior to chemical analysis. Concentrations of major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}, NH_4^+) and anions (Cl^-, SO_4^{2-}, NO_3^-) were analyzed by ion chromatography on filtered samples (0.45 μm filter paper) using Dionex ICS 1000 and DX 120 (Thermo Fisher Scientific Inc. Sunnyvale, CA, USA). PO_4^{3-} concentration was measured using the standard vitamin C-molybdenum blue method with a detection limit of 0.01 μM (Rice et al., 2012).

2.3 Precipitation and stream flow estimation

The weekly precipitation of the four subwatersheds was directly measured by the nearest rain gauge maintained by the Central Weather Bureau (CWB). The weekly stream discharge was estimated from two discharge gauges maintained by the Water Resource Agency using the area ratio method (Huang et al., 2012). The distance between the four subwatersheds and their nearest rain gauges was 1.0–8.5 km, and the distance to their corresponding discharge gauges was 3.0–5.0 km (Lin et al., 2015). The paired weekly ion concentrations and water volume of precipitation and streamflow were used for the ion input-output budget calculations (i.e., output via stream discharge – input through precipitation).

2.4 Definition of typhoon-affected samples

Because we did not sample precipitation and stream water on a storm-by-storm basis, we separated the weekly samples into typhoon samples and non-typhoon samples to examine the effects of typhoon storms on hydrochemistry. Following Chang et al. (2013), weekly samples collected between the first and last typhoon warnings issued by the Central Weather Bureau (CWB) of Taiwan are considered typhoon samples, and such a week was referred as a typhoon-affected week. Although there is a time lag between precipitation and streamflow, this lag was typically only a few hours in mountain watersheds of Taiwan (Huang et al., 2012), so this short lag has only limited effects on the division of typhoon and non-typhoon samples. This definition may overestimate the total quantity of precipitation and stream discharge associated with typhoon storms because typhoons rarely lasted for a week; thus, part of the weekly samples classified as typhoon samples included water before or after the typhoon storm periods. In contrast, this definition diluted the extreme nature of typhoon storms, as the weekly samples included some water from small storms or base flow. Although a storm-based sampling would better capture the effects of typhoon

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storms on hydrochemistry, it is dangerous to collect samples during typhoons, and it would also miss the base flow hydrochemistry.

3 Results

3.1 Basic storm information

There was a total of 11 typhoon-affected weeks based on our definition. The 11 typhoon-affected weeks contributed 3284 mm or 30% of total precipitation (10835 mm) and 2264 mm or 24% of total stream discharge (9481 mm) for the three sampling years (Table 1). The quantity of precipitation and discharge of typhoon-affected weeks ranged from 184 and 112 mm for typhoon Jelawat (26-29 September 2012) to 664 and 525 mm for typhoon Soudelor (7-9 August 2015), respectively (Table 1). Typhoons contributed 87–98% of the weekly precipitation and 82–90% of the weekly discharge, respectively, of the 11 typhoon-affected weeks (Table 1). The mean weekly precipitation (± standard deviation) for the typhoon-affected weeks, 298 (± 124) mm, was approximately 5 times of that for the non-typhoon weeks, 61 (± 64) mm. The mean weekly stream discharge for the typhoon-affected weeks, 205 (± 105) mm, was approximately 3.6 times of that for the non-typhoon weeks, 57 (± 49) mm.

The weekly maximal hourly, 6-hr, 12-hr and 24-hr precipitation of the typhoon-affected weeks were generally considerably greater than those of the non-typhoon weeks and the differences were greater with greater time intervals. The greatest value of maximal hourly, 6-hr, 12-hr and 24-hr precipitation during the typhoon period reached 54, 43, 33, and 19 mm hr^{-1}, respectively, based on the records in rain gauge COA530 (Fig. 2). There were 5, 8, 9 and 9 typhoon weeks that were ranked in the uppermost ten for the highest precipitation intensity for hourly, 6-hr, 12-hr and 24-hr records, respectively (Fig. 2).

3.2 Stream discharge as a predictor of watershed ion export

One striking pattern during the typhoon period (i.e., the 11 typhoon-affected weeks) is the lack of predictability of stream discharge on input-output budget for many ions in most watersheds. This lack of predictability is in contrast to the high level of predictability during the non-typhoon period (Figs. 3, 4 and Table 2). During non-typhoon periods, stream discharge is a good predictor of net export of all ions except NH_4^+ for all watersheds, and for NO_3^- and PO_4^{3-} in F2 only (Figs. 3 and 4). In contrast, during the typhoon period, discharge was not a significant predictor for 20 of the 36 ion budgets (4 watersheds x 9 ions) (Figs. 3 and 4). In addition to the low predictability, variability in input-output as indicated by their standard errors was several times greater during typhoon periods, relative to non-typhoon periods (Fig. 5).

3.3 Differences between typhoon and non-typhoon periods

In addition to the lack of predictability of stream discharge for input-output budgets during typhoon periods, there were distinct differences in the discharge-budget relationship between typhoon and non-typhoon periods for many ions. There was a positive relationship between stream discharge and the Na^+ budget during the non-typhoon period, with greater discharge associated with greater net Na^+ export in all watersheds (Fig. 3). However, the relationship was negative during the typhoon period for watersheds A1 and F2, with greater discharge associated with greater Na^+ retention (Fig. 3). Similarly, there was also a positive relationship between stream discharge and PO_4^{3-} budget during the non-typhoon period for watersheds A2 and F1, but during the typhoon period the relationship was negative (Fig. 4). The distinct difference between the two periods was also reflected in the overall net export of Cl^- during the non-typhoon periods and net retention during the typhoon periods (Fig. 5).

In addition to the opposite directions of the relationship between discharge and ion budget between typhoon and non-typhoon periods, the 11 typhoon-affected weeks also affected the overall relationship between discharge and ion budget. The positive relationship between discharge and Cl^- budget during the non-typhoon period disappeared in all watersheds when the 11 typhoon-affected weeks were included in the analysis (Fig. 4). Similarly, the positive relationship between discharge and Na^+ budget in watersheds A2 and F1 disappeared when the typhoon-affected weeks were included (Fig. 3). In contrast, the relationship between discharge and NH_4^+ budget changed from non-significant to significantly negative when the typhoon-affected weeks were included (Fig. 3). For the PO_4^{3-} budget of A2, including the typhoon-affected weeks changed the relationship from positive to negative (Fig. 4).

3.4 Differences among watersheds with different proportions of agricultural land

Nitrate exhibited a unique pattern in the relationship between stream discharge and input-output budget. Stream discharge was an excellent predictor of net NO_3^- export in watersheds A1 and A2 during non-typhoon period with R^2 of linear regression of 0.98 in A1 and 0.92 in A2 (Fig. 4 and Table 2). Although there was also a significant positive relationship between stream discharge and NO_3^- budget (net export) during non-typhoon period in F1, the predictability was considerably lower ($R^2 = 0.25$) than those of A1 and A2 (Fig. 4). For watershed F2, stream discharge was not a significant predictor of NO_3^- input-output budget during non-typhoon periods (Fig. 4). The mean input-output budget of F1 and F2 was an order of magnitude lower than that of A1 and A2, and the mean weekly NO_3^- budget of F2 was only -0.07 kg ha^{-1} w^{-1}, which was not different from zero ($p = 0.489$).

The input-output budget of PO_4^{3-} and K^+ was also dramatically different among the four watersheds (Figs. 3 and 4). During non-typhoon periods there was a positive relationship between K^+ budget and stream discharge with greater net export associated with greater discharge in all watersheds. However, this relationship was not significant in A1, A2 and F1 during typhoon periods and there was a significantly negative relationship during typhoon periods at watershed F2 (Fig. 3). Moreover, the typhoon-affected weeks changed the relationship from positive (without typhoon data) to negative (with typhoon data) for watershed F2 (Figs. 3 and 4). In addition, the mean weekly budget of watersheds A1 and A2 was greater during typhoon periods than during non-typhoon periods, but for watersheds F1 and F2 this budget was greater during non-typhoon periods than during typhoon periods (Figs. 3 and 4). There was a negative relationship between stream discharge and PO_4^{3-} budget during the typhoon-affected period at all watersheds, with greater discharge associated with greater retention, but this relationship was weakest at F2, which had a weekly budget of PO_4^{3-} near zero at F2 (Fig. 4). However, there was an overall net retention during typhoon periods at all watersheds (Fig. 4).

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For Ca^{2+}, there were positive relationships between discharge and weekly input-output budgets across different watersheds for non-typhoon periods, typhoon periods and when all data were combined; however, the R^2 and the slopes of the regression lines decreased with increases in forest cover. For example, for the entire data set, the R^2 and slope decreased from 0.95 and 0.041 in A1 to 0.75 and 0.031 in F2 (Fig. 3 and Table 2). Similar patterns were also found for Mg^{2+} and SO_4^{2-} during the non-typhoon periods and when all data were combined, but the relationship was not significant during the typhoon periods (Figs. 3 and 4).

4 Discussion

4.1 Unpredictability of hydrochemical response to climate extremes

The large differences in weekly precipitation, stream discharge and weekly maximal hourly, 6-hr, 12-hr and 24-hr precipitation between the typhoon and non-typhoon periods (Table 1) clearly illustrate the extreme effects of typhoon storms. The lack of predictability of stream discharge on ion input-output budgets for the typhoon period is attributable to the high variability of ion budgets associated with typhoon storms (Figs. 3, 4 and Table 2). High variability associated with typhoons is not limited to ion budgets but also to water resources. In a study of long-term biogeochemistry in a natural hardwood forest in northeastern Taiwan, the 20-year average annual precipitation was 3840 mm, but was 3240 mm when precipitation associated with typhoon storms was excluded, with annual contributions from typhoon storms varying from 0% (0/2770 mm) in 1995 to 42% (1711/4033 mm) in 2008 (Chang et al., 2017b).

Many hydrological models are constructed primarily based on non-extreme conditions or on a combination of both extreme and non-extreme conditions (Wade et al., 2006; Shih et al., 2016; Lu et al., 2017). However, our results showed that in many cases such models would not perform well during extreme conditions such as during typhoons. There are at least three ways that extreme events could lead to model failure. First, in many cases the pattern seen during the more regular period does not exist during extreme conditions, such as a loss of predictability of the budgets of many ions when using stream discharge during the typhoon period (Figs. 3 and 4). Second, in some cases such as the budget of Na^+ the models built using non-typhoon data would mistakenly predict the patterns to be in the wrong direction in extreme conditions (Fig. 3). Third, in other cases, the pattern revealed by the models may be driven by only several extreme events, as evident from the cases of NH_4^+ at F2, and PO_4^{3-} at A1, A2, and F1 (Figs. 3 and 4).

Climate change will increase the frequency and intensity of extreme climate events such as flooding, drought, and tropical cyclones (Emanuel, 2005; Elsner et al., 2010; Hirabayashi et al., 2013; Cook et al., 2015; Pfahl et al., 2017). Many studies report increases in extreme precipitation events and flooding from observations over the past half century, particularly in the tropics and subtropics (Hirabayashi et al., 2013; Fischer and Knutti, 2016). Furthermore, the upward trends in frequency and intensity of tropical cyclones due to warming climate is expected to lead to the development of more destructive cyclones (Emanuel, 2005; Elsner et al., 2010). A recent analysis indicated that there was a manifest westward shift of tropical cyclones in the Northwest Pacific (Wu et al., 2015), such that risks of extreme precipitation and flooding events are expected to rise in this region, which includes Taiwan. Our results show that hydrological consequences of extreme events can not be directly extrapolated from non-extreme conditions. Because rare but extreme events can cause abrupt changes (Müller et al., 2014), separation of hydrochemical processes into more regular and extreme conditions is more likely to capture the whole spectrum of hydrochemical responses to a variety of climate conditions. In addition, regime shifts could invalidate future predictions calibrated on past trends (Müller et al., 2014). Thus, hydrological models must recognize and incorporate the unpredictability and even chaotic nature of extreme storms to make model predictions more reliable.

4.2 Extreme storms intensify the impact of land use change

The differences in the input-output budgets of NO_3^-, PO_4^{3-}, and K^+, the three elements that are the primary ingredients of commercial fertilizers, between A1, A2 and F1, F1 illustrate the effects of replacing natural vegetation with agricultural land use on watershed hydrochemistry. The differences for NO_3^- are most striking. Throughout the three-year period, the budget is close to zero for F1 and F2 (Fig. 4) illustrating the very high hemostasis of forested watersheds. In contrast, although tea plantations cover only 22% and 17% of the area of A1 and A2, respectively, the dramatic increases in NO_3^- export illustrate that the effects of replacing natural vegetation by agricultural land use is intensified during heavy storms. The results also illustrated that hydrochemistry is distinctly different between forested and agricultural watersheds. More importantly, our results indicate that even mild changes (22% or less) of the land use could have profound effects on critical ecological processes. Many studies have illustrated negative ecological consequences caused by replacing natural vegetation with agricultural land use (Howarth et al., 2012; Michalak et al., 2013), but few studies have examined the impact during extreme storms when the impact could be maximized. Our results illustrate that when natural vegetation is intact as in the case of F2, hydrochemical processes are relatively stable even during most intense storms (Fig. 4).

The close relationship between stream discharge and NO_3^- export from watersheds A1 and A2 across a wide range of stream discharge (Fig. 4) highlights hydrological control on nutrient export. This implies that there was an ample NO_3^- supply from sources other than precipitation input, which can mostly, if not entirely, be attributed to heavy fertilization, amounting > 700 kg-N ha^{-1} yr^{-1} at our study sites (Lin et al., 2015). This level of fertilization deposits large quantities of NO_3^- in the watersheds, greater than what could be removed by all except the most extreme storms associated with Typhoon Sudelor (2015) leading to the proportional increases in NO_3^- export with increases in stream discharge seen here (Fig. 4). It is important to note that the weekly export of NO_3^- from watershed A1 reached 40 kg ha^{-1} w^{-1}. The consequences of such a high nitrogen input rate to these aquatic systems deserve further investigations.

4.3 Unexpected ion retention

The increases in net retention of NH_4^+ and PO_4^{3-} (all watersheds), Na^+ (A1 and F2), and K^+ (F2) with increases in stream discharge during the typhoon period are unexpected. The pattern of PO_4^{3-} at all watersheds and the pattern of Na^+ at A1 and F2 were driven by a single extreme event which had an extremely negative budget (i.e., output much smaller than input) (Fig. 3). This extreme event was due to Typhoon Sudelor (2015), which set a new record for wind speed (237 km hr^{-1}) in northern

Taiwan, causing a serious deterioration in household water quality in Taipei (Taiwan's largest city) (Fakour et al., 2016). This storm also caused a record of sidewalk tree mortality in northern Taiwan. It is not clear if this extreme storm affected the measurement of precipitation and stream flow or damaged the forest to the level that changed the hydrochemical processes in previously unknown ways. However, we could not find any good reason to exclude the data because neither the concentration nor the precipitation: discharge ratio of the week was an outlier. It is the product of the two that makes it significantly different from the general pattern of other typhoon-affected weeks. Thus, perhaps the input-output budget of this most extreme week represents a hydrochemical process phase-shift between the regular extreme events and the most extreme event, as such, the response of the most extreme event cannot be predicted using the data from the regular extreme events. In a study of the effects of typhoons on forest leaf area index in northeastern Taiwan, leaf area index could return to pre-typhoon levels within one year but the decreases associated with a record high number of six typhoons within a year (1994) took approximately one decade to recover (Lin et al., 2017). In other words, the ecological and hydrological effects of record-setting extreme events could be fundamentally different from "regular extreme" events. The most extreme climate events often attract attention and much research has been conducted on them, but based on the current study, results from these studies should be interpreted with caution as they may not represent the overall patterns of extreme events.

However, the greater retention of NH_4^+ at all watersheds cannot be attributed to the single week associated with Typhoon Sudelor because the pattern persisted even after this event was excluded ($p = 0.039$). The pattern of NH_4^+ retention was caused by the smaller slope of output vs. discharge compared to input vs. discharge, which was possibly related to slow nitrification rates during extremely large storms.

5 Conclusions

Our analysis of ion input-output budget illustrates that hydrochemistry during typhoon storms are highly variable, and models built from regular periods have low predictability of ion budgets during extreme storm periods. Hydrochemical responses to typhoon storms are distinctly different from those of regular storms and have the potential to dominate the long-term hydrochemical patterns. Much greater increases in NO_3^- export associated with increases of stream discharge at watersheds with 17–22% agricultural land cover, relative to NO_3^- exports in watersheds with 93–99% forest cover, indicate that even mild land use change may have large impacts on hydrochemical processes. Climate change is predicted to increase the intensity and frequency of climate extremes. Based on the results of this study, we suggest separating hydrochemical processes into regular and extreme conditions to better capture the whole spectrum of hydrochemical responses to a variety of climate conditions.

6 Data availability

All observational data used in this study necessary to compare with or to reproduce the work are available on request from the corresponding author Teng-Chiu Lin (tclin@ntnu.edu.tw).

Author contributions. T.C. Lin designed and performed the research. C.T. Chang, J.C. Huang, and T.C. Lin conducted the field and laboratory work. C.T. Chang and T.C. Lin analysed the data. C.T. Chang, J.C. Huang, L. Wang and T.C. Lin contributed to the discussion and interpretation of the results. C.T. Chang and T.C. Lin wrote the first draft and all authors contributed substantial edits.

Competing interests. The authors declare that they have no conflict of interest.

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Table 1. The basic information of the typhoon affected weeks.

Name of typhoons	Date	Accumulated Prec. of specific typhoons (mm, A)	Total Prec. of typhoon week (mm, B)	C = A/B (%)	Accumulated discharge of specific typhoons (mm, D)	Total discharge of typhoon week (mm, E)	F = D/E (%)
Jelawat	26-29 Sep. 2012	181	184	98	96	112	86
Soulik	12-14 Jul. 2013	334	345	97	156	173	90
Trami	20-22 Aug. 2013	296	321	92	172	200	86
Kong-Rey	28-30 Aug. 2013	258	286	90	185	225	82
Usagi	20-22 Sep. 2013	265	304	87	173	194	89
Fitow	5-7 Oct. 2013	305	324	94	210	242	87
Matmo	22-23 Jul. 2014	170	184	92	126	150	84
Fung-Wong	20-23 Sep. 2014	180	187	96	77	92	84
Chan-Hom	9-11 Jul. 2015	243	252	96	125	150	83
Soudelor	7-9 Aug. 2015	632	664	95	446	525	85
Goni	21-24 Aug. 2015	224	233	96	176	201	88
Average		280	298	94	177	205	86

1. The accumulated precipitation of typhoons were summed from first and last typhoon warnings issued and the total precipitation (mm) of typhoon week is the average value of two rain gauges (COA530 and COA540) during the week of typhoon influenced, and same as the discharge (the average value of four watersheds, A1, A2, F1, and F2).

Table 2. The significant regression models between stream discharge (x) and ion budgets (y) for non-typhoon, typhoon and all data, respectively (referring to plots in Fig. 3 and 4).

Ions		A1	A2	F1	F2
Na^+	Non-typhoon	y = 0.043x - 0.28, R^2 = 0.49**	y = 0.043x - 0.38, R^2 = 0.49**	y = 0.041x - 0.46, R^2 = 0.56**	
	Typhoon	y = -0.065x + 0.28, R^2 = 0.37*			y = -0.027x + 2.95, R^2 = 0.12**
	All data				y = -0.065x + 14.06, R^2 = 0.57**
K^+	Non-typhoon	y = 0.009x - 0.11, R^2 = 0.66**	y = 0.007x - 0.13 R^2 = 0.55**	y = 0.004x - 0.16, R^2 = 0.38**	y = 0.003x - 0.11, R^2 = 0.32**
	Typhoon				y = -0.017x + 2.71, R^2 = 0.73**
	All data	y = 0.007x + 0.01 R^2 = 0.51**	y = 0.003x + 0.05, R^2 = 0.21**	y = 0.001x - 0.01, R^2 = 0.04**	y = -0.005x + 0.29, R^2 = 0.20**
Ca^{2+}	Non-typhoon	y = 0.046x + 0.41, R^2 = 0.95**	y = 0.026x + 0.29, R^2 = 0.92**	y = 0.022x + 0.27, R^2 = 0.90**	y = 0.039x + 0.40, R^2 = 0.86**
	Typhoon	y = 0.030x + 3.36, R^2 = 0.82**	y = 0.013x + 2.43, R^2 = 0.57**	y = 0.022x +03.36, R^2 = 0.60**	y = 0.012x + 5.08, R^2 = 0.24*
	All data	y = 0.041x + 0.69, R^2 = 0.93**	y = 0.022x + 0.52, R^2 = 0.86**	y = 0.022x + 0.29, R^2 = 0.88**	y = 0.031x + 0.84, R^2 = 0.75**
Mg^{2+}	Non-typhoon	y = 0.024x + 0.14, R^2 = 0.92**	y = 0.016x + 0.12, R^2 = 0.87**	y = 0.013x + 0.07, R^2 = 0.84**	y = 0.019x + 0.13, R^2 = 0.84**
	All data	y = 0.018x + 0.46, R^2 = 0.78**	y = 0.011x + 0.40 R^2 = 0.63**	y = 0.009x + 0.24, R^2 = 0.60**	y = 0.009x + 0.59, R^2 = 0.35**
NH_4^+	Typhoon	y = -0.003x + 0.37, R^2 = 0.60*	y = -0.003x + 0.22, R^2 = 0.50*	y = -0.004x + 0.56, R^2 = 0.53*	y = -0.009x + 1.15, R^2 = 0.79*
	All data				y = -0.004x + 0.04, R^2 = 0.26*
Cl^-	Non-typhoon	y = 0.049x - 1.03, R^2 = 0.24**	y = 0.042x - 1.08, R^2 = 0.20**	y = 0.053x - 1.43, R^2 = 0.34**	y = 0.043x - 0.92, R^2 = 0.25**
NO_3^-	Non-typhoon	y = 0.129x - 0.88, R^2 = 0.98**	y = 0.093x - 0.63, R^2 = 0.92**	y = 0.013x - 0.80, R^2 = 0.25**	
	Typhoon				y = 0.020x - 2.96, R^2 = 0.59**
	All data	y = 0.096x + 1.25, R^2 = 0.67**	y = 0.076x + 0.44, R^2 = 0.80**	y = 0.013x - 0.75, , R^2 = 0.30**	y = 0.008x - 0.57, R^2 = 0.20**
SO_4^{2-}	Non-typhoon	y = 0.057x + 0.43, R^2 = 0.67**	y = 0.026x - 0.14, R^2 = 0.32**	y = 0.030x - 0.17, R^2 = 0.42**	y = 0.054x + 0.17, R^2 = 0.60**
	All data	y = 0.040x + 1.49, R^2 = 0.45**	y = 0.018x + 0.42, R^2 = 0.24**	y = 0.026x + 0.11, R^2 = 0.37**	y = 0.028x + 1.38 R^2 = 0.17**
PO_4^{3-}	Non-typhoon		y = -2*10^{-4}x - 0.008, R^2 = 0.15**	y = -1*10^{-4}x - 0.009, R^2 = 0.11**	
	Typhoon	y = -4*10^{-4}x + 0.07, R^2 = 0.55**	y = -4*10^{-4}x + 0.06, R^2 = 0.54**	y = -6*10^{-4}x + 0.08, R^2 = 0.41*	y = -5*10^{-5}x + 0.01, R^2 = 0.34*
	All data	y = -5*10^{-9}x + 0.005, R^2 = 0.05*	y = -1*10^{-4}x + 0.005, R^2 = 0.05*		

P-value: * < 0.05 < ** < 0.01.

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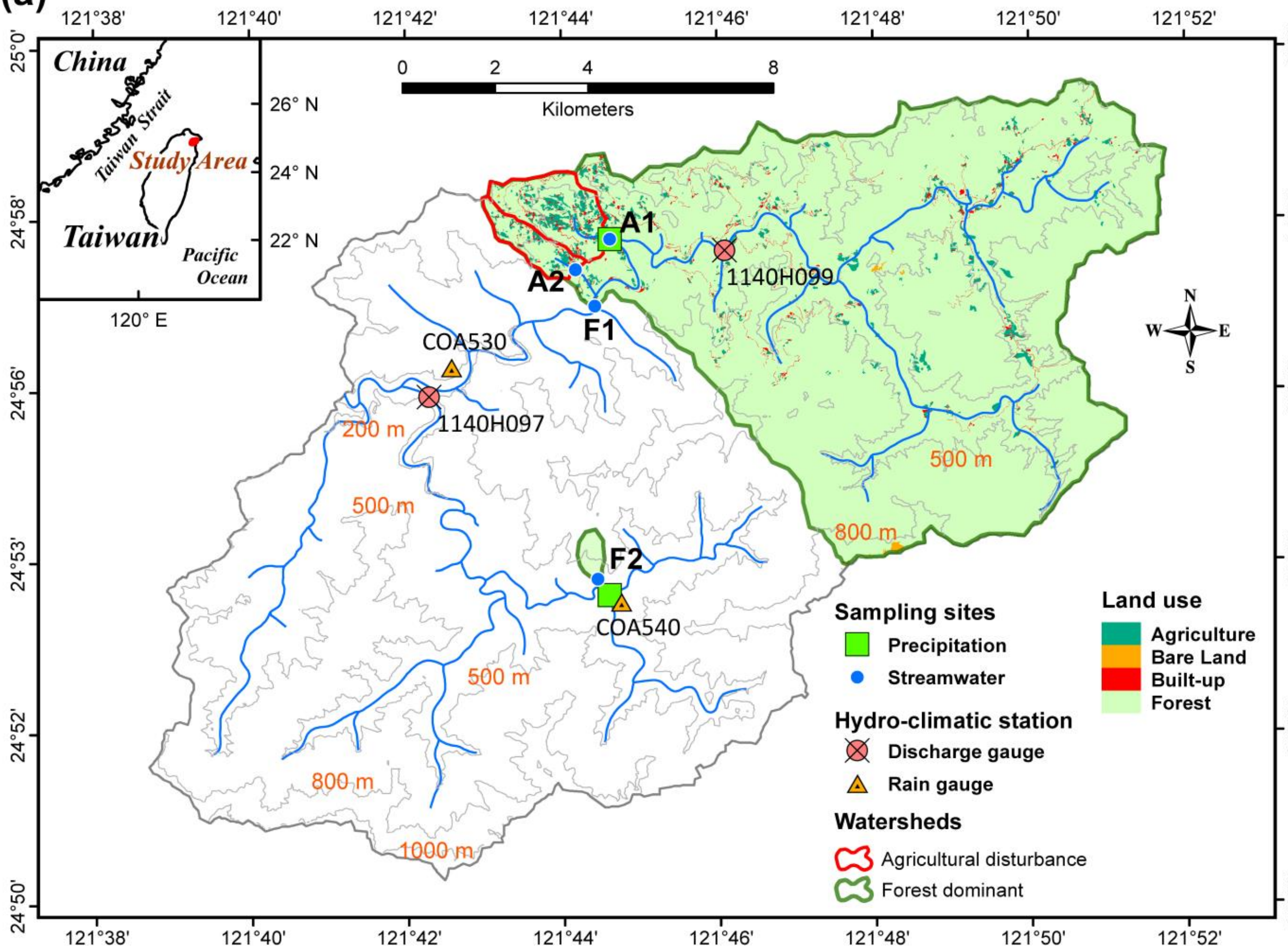
(a)



(b)

Watersheds	Area (km²)	Slope (%)	Land use (%)					
			Natural Forest	Agriculture	Road	Building	Water body	Others
A1	2.92	39.3	68.0	22.1	3.61	1.54	0.69	4.11
A2	1.36	34.8	75.5	17.1	2.96	1.31	0.19	2.96
F1	86.04	38.7	93.5	2.87	0.77	0.35	1.12	1.44
F2	0.67	48.1	99.2	0.38	0.00	0.00	0.00	0.38

Figure 1: Location and land use distribution of the studied watersheds at the Feitsui Reservoir Watershed (a), and the basic information of four studied watersheds (b).

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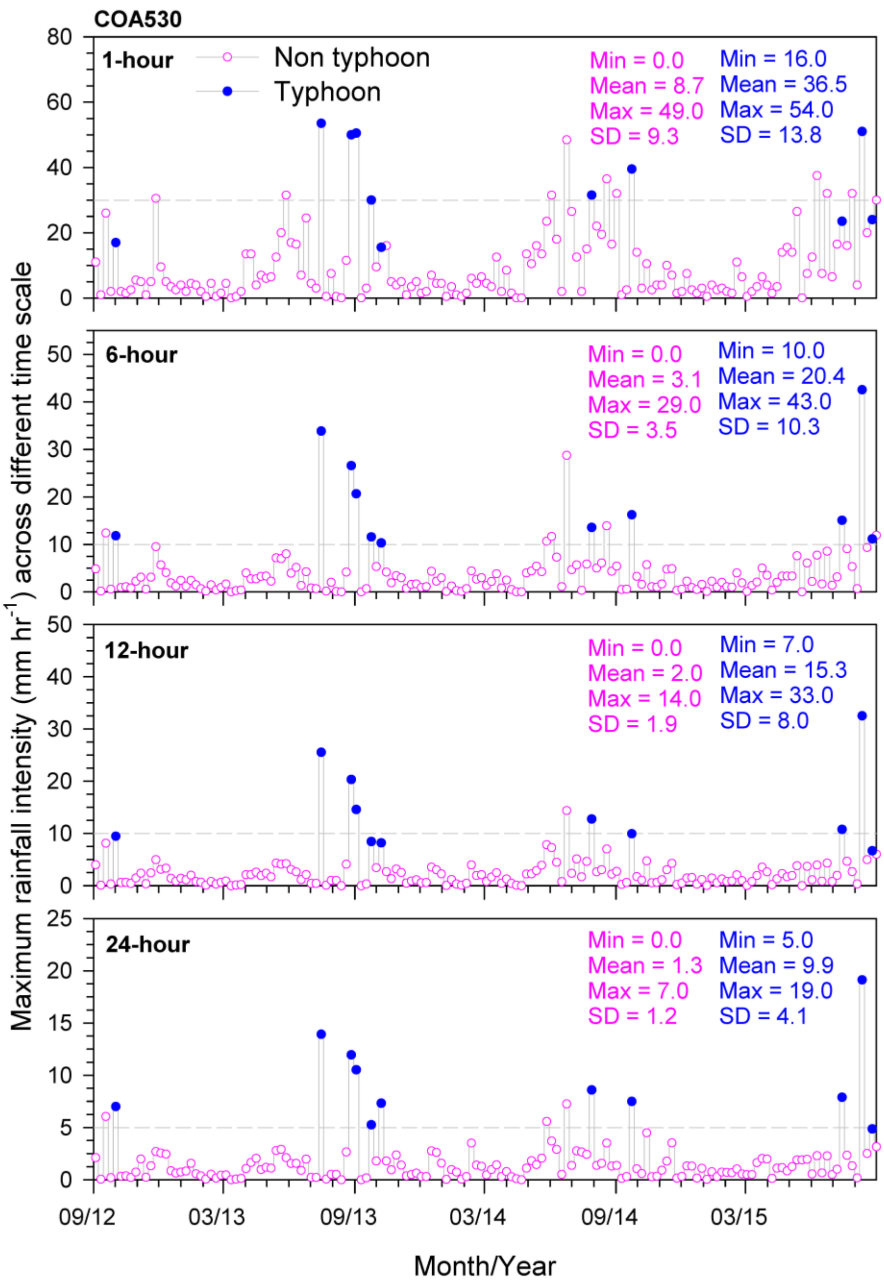

Figure 2: Weekly maximum 1-hr, 6-hr, 12-hr, and 24-hr precipitation of the two rain gauge stations (referring to the location COA530 in Fig. 1) used in this study.

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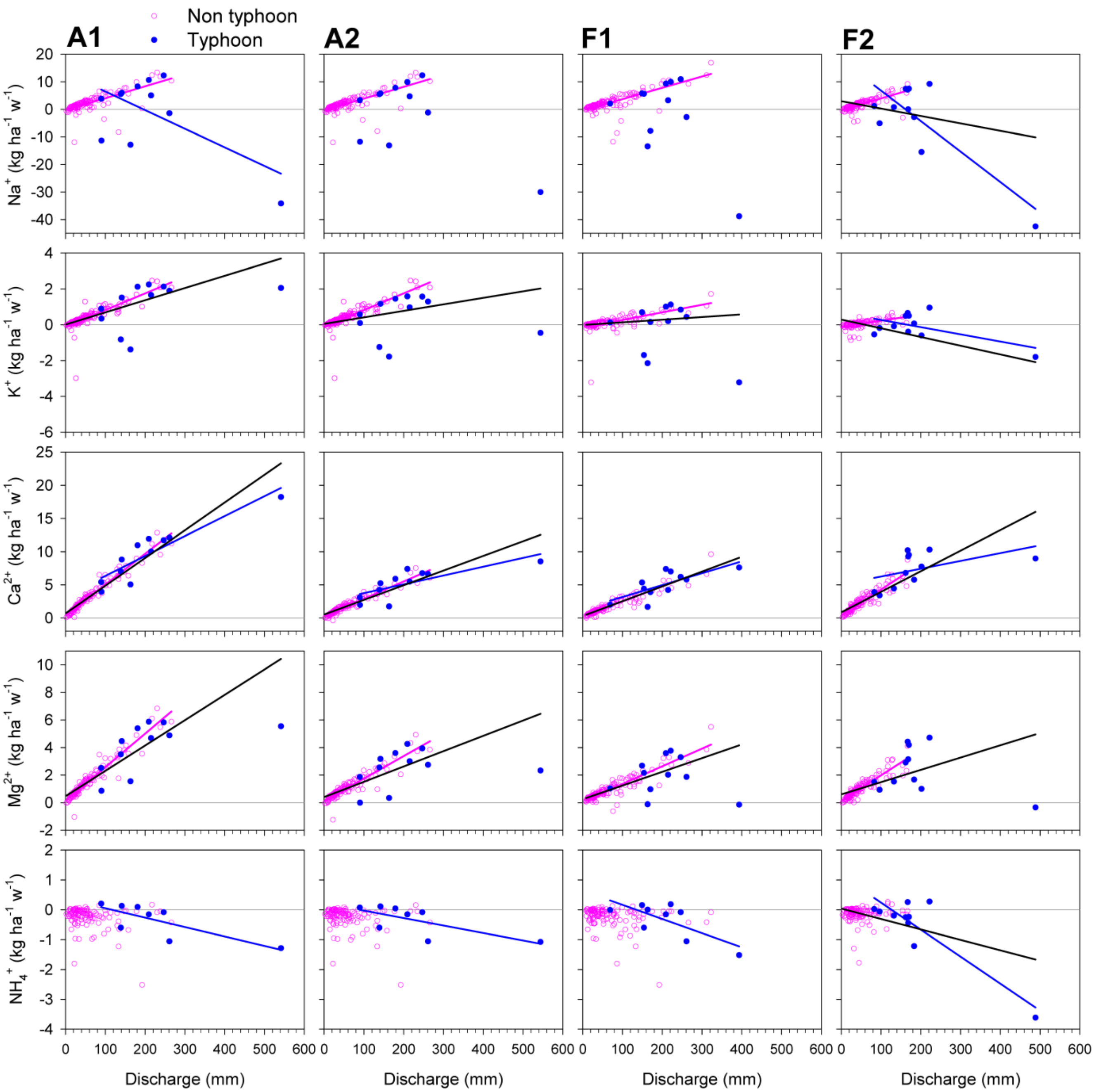

Figure 3: Relationship between stream discharge and nutrient budget (stream output – precipitation input) of cations (Na^+, K^+, Ca^{2+}, Mg^{2+}, and NH_4^+). The purple, blue, and black lines indicate significant linear regressions between discharge and ions budgets for non-typhoon, typhoon and all data, respectively. Please refer to Table 2 for the regression models and R^2s.

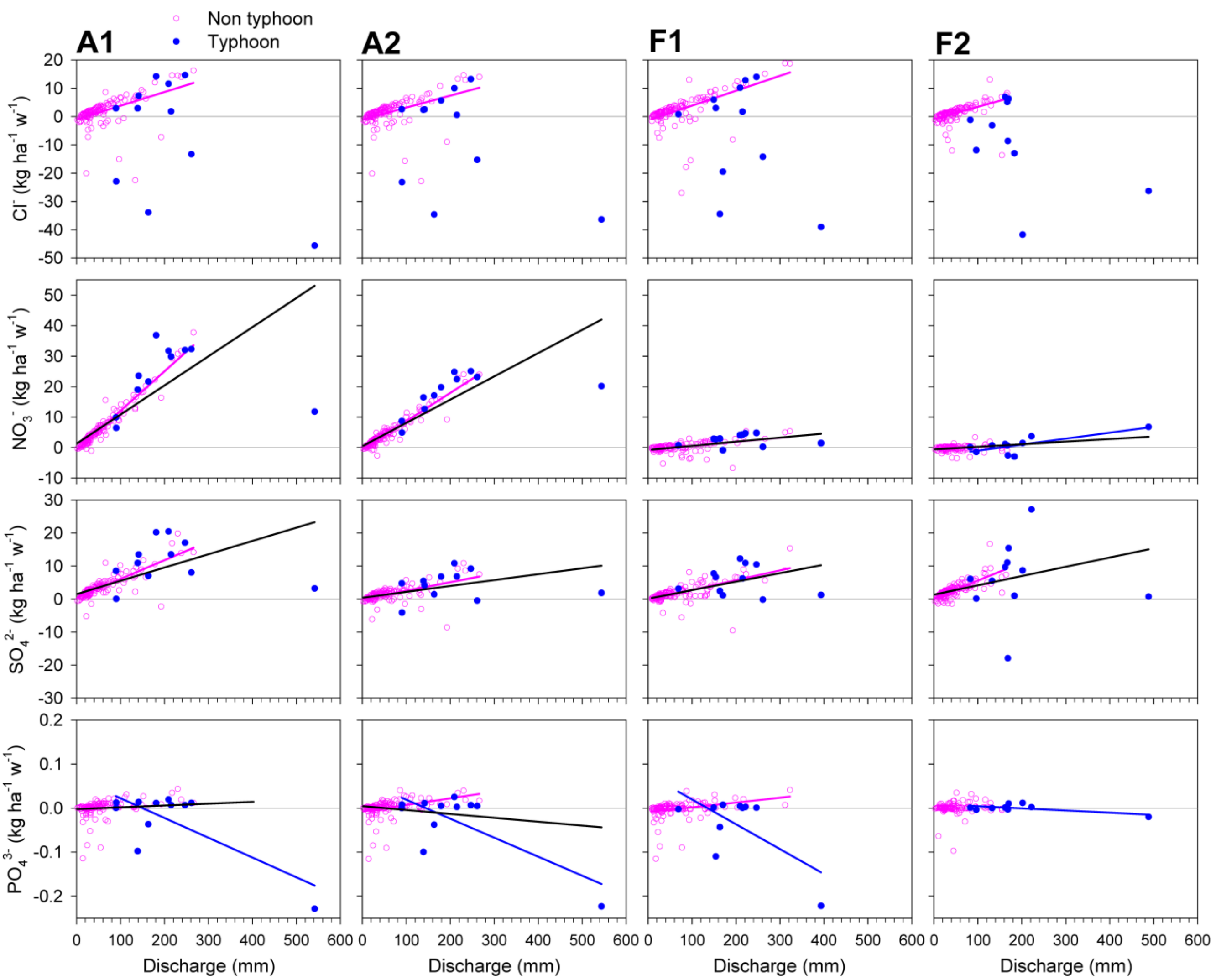

Figure 4: Relationship between stream discharge and nutrient budget (stream output – precipitation input) of anions (Cl^-, NO_3^-, SO_4^{2-}, and PO_4^{3-}). The purple, blue, and black lines indicate significant linear regressions between discharge and ions budgets for non-typhoon, typhoon and all data, respectively. Please refer to Table 2 for the regression models and R^2s.

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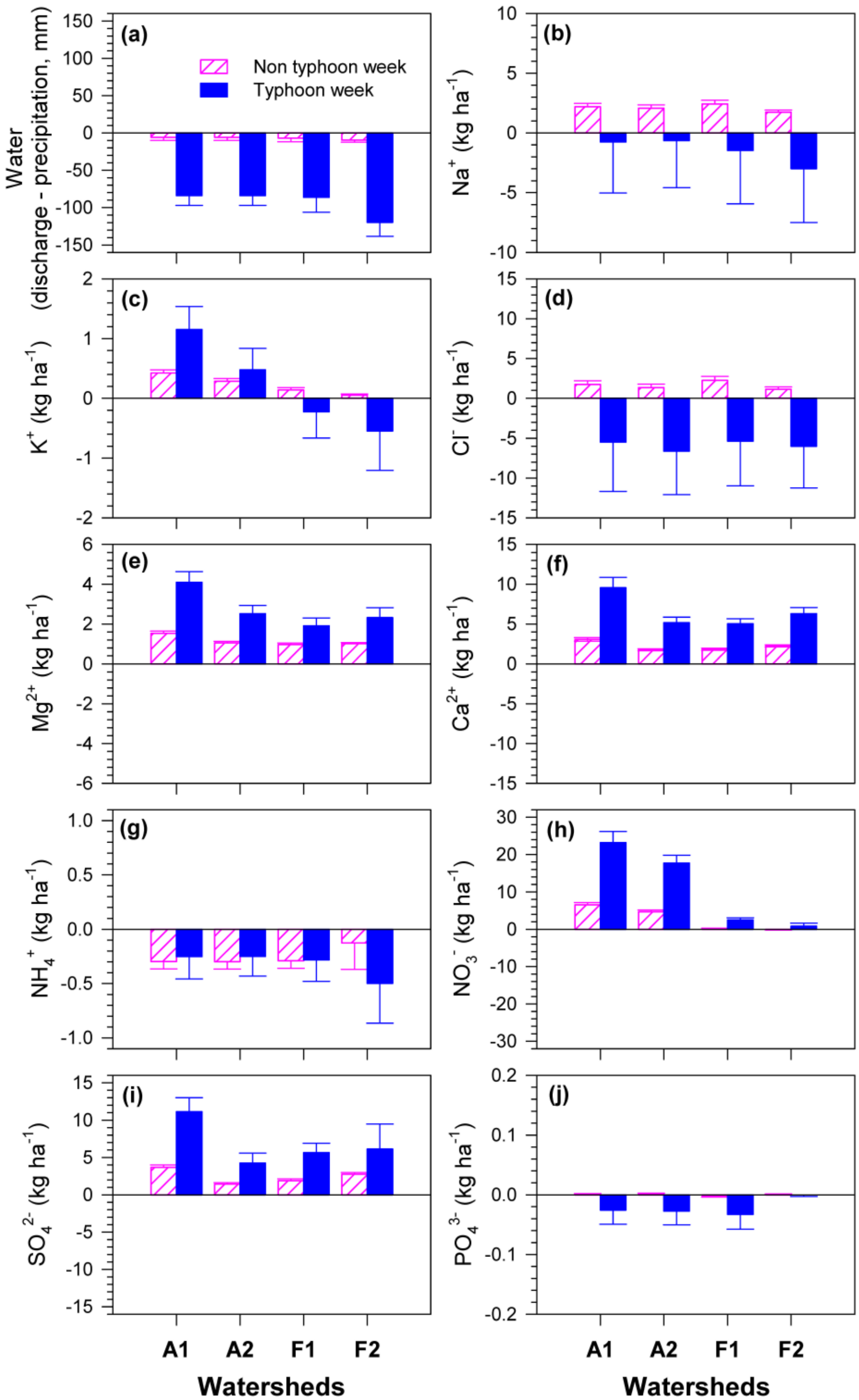

Figure 5: Mean weekly budget for non-typhoon and typhoon periods. (a) Water quantity (stream discharge – precipitation), (b) Na^+, (c) K^+, (d) Cl^-, (e) Mg^{2+}, (f) Ca^{2+}, (g) NH_4^+, (h) NO_3^-, (i) SO_4^{2-}, and (j) PO_4^{3-}.