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Differences in N loading affect DOM dynamics during typhoon events in a forested mountainous catchment

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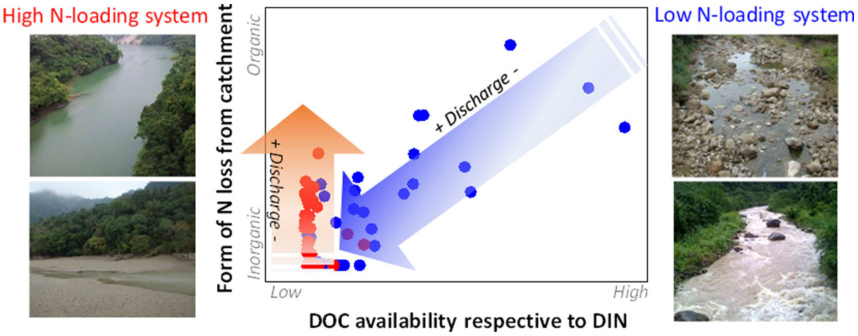
HIGHLIGHTS

- We investigated the interaction between organic and inorganic solutes during typhoons.
- Lateral transport during typhoons enhances local catchment feature.
- Flow paths determined the transport mechanisms between DOM and inorganic nutrients.
- DOM quality and N loading are internal forces driving riverine system to be *active* or *passive pipe*.

GRAPHICAL ABSTRACT



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ABSTRACT

The dissolved organic matter (DOM) and nutrient dynamics in small mountainous rivers (SMRs) strongly depend on hydrologic conditions, and especially on extreme events. Here, we investigated the quantity and quality of DOM and inorganic nutrients during base-flow and typhoon events, in a chronically N-saturated mainstream and low N-loaded tributaries of a forested small mountainous reservoir catchment in Taiwan. Our results suggest that divergent transport mechanisms were triggered in the mainstream vs. tributaries during typhoons. The mainstream DON increased from 3.4 to 34.7% of the TDN pool with a static DOC:NO_3-N ratio and enhanced DOM freshness, signalling a N-enriched DOM transport. Conversely, DON decreased from 46 to 6% of the TDN pool in the tributaries and was coupled with a rapid increase of the DOC:NO_3-N ratio and humified DOM signals, suggesting the DON and DOC were passively and simultaneously transported. This study confirmed hydrology and spatial dimensions being the main drivers shaping the composition and concentration of DOM and inorganic nutrients in small mountainous catchments subject to hydrologic extremes. We highlighted that the dominant flow paths largely controlled the N-saturation status and DOM composition within each sub-catchment, the effect of land-use could therefore be obscured. Furthermore, N-saturation status and DOM composition are not only a result of hydrologic dynamics, but potential agents modifying the transport mechanism of solutes export from fluvial systems. We emphasize the importance of viewing elemental dynamics from the perspective of a terrestrial-aquatic continuum; and of taking hydrologic phases and individual catchment characteristics into account in water quality management.

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1. Introduction

Since the last decade, inland waters have been recognised as active sites processing organic carbon (Cole et al., 2007). About 2.7 Pg C yr^{-1} is transported, mineralised, and buried in inland waters, similar to the amount of the terrestrial C sink for anthropogenic emissions (2.8 Pg C yr^{-1}, Battin et al., 2009; Tranvik et al., 2009). The source material and processing of dissolved organic matter (DOM) determine the fate of carbon (Hansen et al., 2016), which in fluvial systems is controlled by the interdependence between the spatial and hydrologic dimensions along the terrestrial-aquatic continuum (Ejarque et al., 2017). Building upon the idea of inland waters as active components of the global C cycle (Cole et al., 2007), the *Pulse-shunt Concept* further articulates that the catchments alternate between base-flow and episodic hydrologic events, such as snow melt or storms (Raymond et al., 2016). The drainage systems shift between instream process-dominant "*active pipes*" and export-dominant "*passive pipes*" in terms of DOM reactivity, depending on factors which affect residence time (e.g. hydrology) and decomposition kinetics (e.g. temperature) (Raymond et al., 2016). DOM is the largest organic matter pool in riverine systems (Tank et al., 2010). This ubiquitous and complex source of organic compounds composed of both dissolved organic carbon (DOC) and nitrogen (DON) is closely linked to the ecosystem metabolism (Bertilsson and Jones, 2003; del Giorgio and Williams, 2005). In small mountainous streams (SMRs), the highly variable flow paths not only extensively determine the DOM characteristics (Yang et al., 2015) but also the magnitude of N export (Zhang et al., 2007) during extreme hydrologic events. However, to our knowledge, the interactions between riverine organic and inorganic C and N components during hydrologic extremes are rarely investigated.

Anthropogenic influences often act as the third dimension of disturbances on fluvial dynamics in addition to hydrology and longitudinal dimensions (Ward and Stanford, 1995). The influence of anthropogenic N enrichment (e.g. atmospheric-deposition, fertilization, etc.) on organic N loss has remained controversial (Pellerin et al., 2006). Several field studies suggested DON dominates over dissolved inorganic N (DIN) in N-limited forest ecosystems receiving low anthropogenic N inputs (Qualls, 2000; Perakis and Hedin, 2002; Park and Matzner, 2006; Schmidt et al., 2010). Dissimilarly, plot-scale N fertilization studies concluded that the majority of N is lost as DON from N-saturated systems (Brookshire et al., 2007; Fang et al., 2009), and that a higher labile DON demand occurs in the face of lower DIN availability (Brookshire et al., 2005). However, data synthesis has suggested that the catchment N-saturation status is not the only attribute of DON loss, but the variability in catchment characteristics and climate are probably also important factors, and that the evaluation of the changes in the composition and reactivity of DON associated with increased N loading is crucial (Pellerin et al., 2006).

The processing and fate of organic C is fundamentally and synergistically linked to the N cycle (Taylor and Townsend, 2010; Ghosh and Leff, 2013). Lability of DOM influences the tendency of DIN or DON to be the dominant N source for heterotrophic bacterial growth (Manzoni et al., 2010; Ghosh and Leff, 2013). With low N-loading, the ecosystem loss of DOC couples with DON (Aber et al., 1998; Vitousek et al., 2002), as hypothesised by the "*Passive Carbon Vehicle*" theory, and the quality of DOM is static (Brookshire et al., 2007). For chronically N-saturated catchments, however, N-enriched DON loss exceeds and decouples from DOC concentrations (Brookshire et al., 2007; Fang et al., 2009), and has been hypothesised as complying with the "*Stoichiometric Enrichment*" theory (Brookshire et al., 2007).

To our knowledge, there is scarce field evidence resolving the transport mechanisms of DOM and inorganic nutrients simultaneously, especially in montane forest systems subjected to drastic changes in hydrologic phases. In this study, we hypothesised that these kinds of catchments will shift between "*active pipe*" and "*passive pipe*" during low and extreme hydrologic regimes, respectively. Moreover, streams with different discharge per unit area will generate divergent flow paths during extreme events; that the N-saturation state and quality of DOM will be reflected on the respective transport mechanism. That is, DOM quality will not only be a result of the interplay between hydrologic and spatial dimensions but is also an internal force driving the system to export DOM and nutrients passively (coupled) or actively (decoupled).

2. Material and methods

2.1. Study site

Tsengwen Reservoir, (23°14′53″N, 120°32′11″E) with a capacity of 708 million m^3, is the largest operating reservoir for irrigation, flood regulation, hydropower generation, domestic and recreational use for southern Taiwan (Fig. 1). The mainstream, Tsengwen River, runs 56.2 km from headwater (Wangsuishan Mountain, 2440 m) and has a total catchment area of 481 km^2 with a mean elevation of 963 m and a mean slope of 54.4%. The whole catchment is characterized by a humid sub-tropical climate with a mean annual temperature of 24.3 °C with 27.7 °C in summer and 17.8 °C in winter (Southern Region Water Resources Office, Taiwan). In southern Taiwan, about 89% of annual rainfall (2525 mm) and 88% of subsequent riverine discharge ($17{,}436 \times 10^6$ m^3) are concentrated between May and October, showing the distinct seasonality to which monsoon frontal rains and typhoons are the main contributors. This distinct seasonality marks the intra-annual dry-wet cycle with drastic differences in hydrologic regimes. For base-flow sampling, two tributary stations, *Shalun* "Tri-S" situated north and *Datung* "Tri-D" situated central-east of the reservoir, one main river station, *Tzjing* "Main-T", and the reservoir downstream-dam site were sampled (Fig. 1). However, due to limited accessibility during typhoon Matmo, samples from another mainstream station which was about 3 km downstream of Main-T, *Dapu* "Main-P", was sampled along with Tri-D and Tri-S. During typhoon Soudelor, Tri-D and Main-T were sampled. In general, the two tributary catchments have higher percentages of agricultural lands. Tri-S features steeper slopes and a higher percentage of bare-land area, which is probably due to old landslide scars (Table 1). According to the land-use survey in 2012 (National Land Surveying and Mapping Center, Taiwan), 77% of the total catchment area was made up of forest, while other land-use categories included betel nut plantation (4.3%), bare-land (3.6%), grassland (3%), tea plantation (1.5%), fruit trees (1%), and dry farming (1.1%). In recent years, increased betel nut and tea cultivation has accelerated the clearance of forest cover.

2.2. Field sampling and laboratory measurement

Base-flow sampling was conducted biweekly or monthly over the course of 2.5 years, leading to a total $N = 108$ for low flow and $N = 91$ for high flow periods. Additionally, typhoon samplings were conducted intensively at 2–3 h intervals during two complete typhoon events, each for 45–50 h (total $N = 110$). Two typhoons, *Matmo* (moderate scale, 135 km h^{-1}, 22–24 Jul 2014) and *Soudelor* (severe scale, 210 km h^{-1}, 7–10 Aug 2015) were sampled. Matmo and Soudelor totalled 286.8 mm rainfall in 49 h and 313.4 mm in 51 h, respectively. However, sites were not accessible during the maximum impact period due to a road blockage caused by slump and trees, resulting in a 9-h gap in the Soudelor sampling. The discharge of the mainstream was measured at Main-P Dapu gauging station (Fig. 1). A modified 3-layer TOPMODEL was applied to estimate the discharge of ungauged tributaries following the methods described in Huang et al. (2009). The results were presented as runoff depths (mm d^{-1}) by taking the catchment area into account.

At each site, 3 L of free-flowing surface river water were collected from the middle of the bridge using rinsed polyethylene bottles mounted to a set of stainless steel racks. Physical-chemical parameters