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# Organic carbon sequestration and discharge from a deciduous forest catchment in Korea

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## Abstract

Soil infiltration and surface discharge of precipitation are critical processes that affect the sequestration and discharge of dissolved organic carbon (DOC) and particulate organic carbon (POC) in forested catchments. Both DOC and POC are highly concentrated in the soil surface in most forest ecosystems and their discharge may not be negligible particularly under the monsoon climate. In East Asia, however, there are little data available to evaluate the role of such processes in forest carbon budget. In this paper, we address two basic questions: 1) how does stream discharge respond to storm events in a forest catchment? and 2) how much DOC and POC are discharged from the catchment particularly during the summer monsoon period? To answer these questions, we collected hydrological data (e.g., precipitation, soil moisture, runoff discharge, groundwater level) and conducted hydrochemical analyses (including DOC, POC, and six tracers) for a deciduous forest catchment in Gwangneung National Arboretum in west-central Korea. Based on the end-member mixing analysis of the six storm events during the summer monsoon in 2005, the surface discharge was estimated as 30 to 80% of the total runoff discharge. The stream discharge responded to precipitation within 12 h during these storm events. The annual discharge of DOC and POC from the catchment was estimated as 0.04 and 0.05 tC ha<sup>-1</sup> yr<sup>-1</sup>, respectively. Approximately 70% of the annual organic carbon efflux occurred during the summer monsoon period. Overall, the annual discharge of organic carbon was estimated to be 4 to 14% of the net ecosystem carbon exchange (NEE) obtained by eddy covariance technique at the same site. Considering the current trends of increasing intensity and amount of summer rainfall and the large interannual variability in NEE, ignoring the organic carbon discharge from forest ecosystems would result in an overestimation (underestimation) of the strength of forests as a carbon sink (source) in the monsoon East Asia.

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## 1 Introduction

A significant portion of carbon stored in terrestrial ecosystems is exported with water movement in both organic and inorganic forms, which are defined as particulate organic carbon (POC), dissolved organic carbon (DOC), and dissolved inorganic carbon (DIC).

5 The transport of terrestrial carbon into streams, rivers and eventually the oceans is an important link in the global carbon cycle (Ludwig et al., 1996; Warnken and Santschi, 2004; Battin et al., 2009). Of the organic carbon entering rivers globally, about 50% is transported to the ocean, 25% is oxidized within the system, and 25% stored as POC in the system as sediment (Hope et al., 1994). As compared to the terrestrial carbon  
10 sinks (of  $1.9\text{--}2.8\text{ Gt C yr}^{-1}$ ), the organic carbon transport from terrestrial ecosystems to oceans has been estimated to be  $0.4\text{--}0.9\text{ Gt C yr}^{-1}$  (Meybeck, 1982; Hope et al., 1994; Prentice et al., 2001; Canadell et al., 2007; Battin et al., 2009), representing a substantial component of the ecosystem carbon balance. Hydrological processes strongly affected organic carbon discharge from terrestrial ecosystems especially in  
15 the monsoon climate regions. In East Asia, for example, 60 to 80% of annual organic carbon is exported to the ocean during the summer monsoon (Tao, 1998; Liu et al., 2003; Kawasaki et al., 2005; Zhang et al., 2009).

Forests are the major terrestrial biome, in which soils and vegetation are the primary sources of DOC and POC in the streamwater. Within the forest soil profile, concentrations of DOC are highest typically in the interstitial waters of the organic-rich upper  
20 soil horizons (McDowell and Likens, 1988; Richter et al., 1994; Dosskey and Bertsch, 1997). A significant portion of DOC is transported by the preferential flow, given that the state of adsorption equilibrium cannot be reached owing to the reduced contact time between DOC and the soil surface (e.g., Jardine et al., 1989; Hagedorn et al.,  
25 1999). Understanding the flow paths of DOC discharge from forested catchments to streams is important because DOC provides a source of energy to microorganisms in water systems and carbon fixation in the soil (Stewart and Wetzel, 1982; Neff and Asner 2001; Kawasaki et al., 2005).

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The identification of flow paths in forested catchments has been elusive because of difficulties in measuring subsurface flow. Forested catchments are spatially complex and subsurface flow is invisible. Hence, one can only infer the movement and mixing of water from the natural tracer elements that the water carries (Pinder and Jones, 1969).

5 Using various tracers, the end-member mixing analysis has been used to elucidate flow paths and hydrological processes in several catchments (e.g. Hooper et al., 1990; Christophersen et al., 1990; Elsenbeer et al., 1995; Katsuyama et al., 2001). Numerous conceptual models have adopted the flow path dynamics proposed by Anderson et al. (1997), i.e., both pre-event soil water and bedrock groundwater contribute to the  
10 formation of a saturated zone in the area adjacent to the stream (e.g., McGlynn et al., 1999; Bowden et al., 2001; Uchida et al., 2002).

Storm events can alter DOC and POC concentrations and fluxes significantly by shifting dominant flow paths toward preferential flow through macropores, runoff, and lateral flow (Tipping et al., 1997; Katsuyama and Ohte, 2002; McGlynn and McDonnell,  
15 2003). The concentration of POC depends notably on stream discharge and the concentration of suspended particulates, suggestive of particle mobilization when physical thresholds are exceeded (Tipping et al., 1997). The higher pore water velocity leads to the shorter contact time between soil water and the solid matrix, which creates conditions of chemical and physical non-equilibrium. Thus, adsorption of DOC is diminished  
20 in mineral soil horizons. Flushing of DOC adsorbed on aggregate surfaces and concentrated in subsurface micropores also contributes to increasing DOC concentrations and efflux at the beginning of storm events (e.g., Kalbitz et al., 2000).

In Korea, more than 50% of annual precipitation falls in the summer monsoon season, which discharges quickly to the ocean due to steep slopes and short river lengths (<500 km). However, the paucity of observation data hinders our scrutiny of flow paths,  
25 DOC and POC discharge from Korean forested catchments especially during the summer monsoon period. Accordingly, we conducted an intensive hydrological and hydrochemical experiment from June to October in 2005 in the Gwangneung deciduous forest catchment in west-central Korea. Throughout this study period, we observed

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DOC concentrations in throughfall, soil water, groundwater, and streamwater during the storm events with two questions in mind: 1) how does stream discharge respond to storm events in this forest catchment? and 2) how much DOC and POC are discharged from the catchment particularly during the summer monsoon period? In this paper, we present the results of our analyses and demonstrate the importance of the water cycle in the carbon budget estimation in a forested catchment under the monsoon climate.

## 2 Materials and methods

### 2.1 Study site

The study was conducted in a deciduous forest catchment (22.0 ha) at the Gwangneung catchment (221 ha) located in the west-central part of the Korean Peninsula (37° 45' 25.37" N, 127° 9' 11.62" E) with an elevation ranging from 90 to 470 m (Fig. 1). This forest catchment is a core flux measurement site where long-term ecological, meteorological and hydrological studies have been conducted to ascertain water and carbon exchanges (<http://www.koflux.org>). The (30-yr normal) annual air temperature at the site is 11.5°C; mean annual precipitation and runoff (from 1982 to 2004) are 1332 and 809 mm, respectively. The Gwangneung catchment is a tributary drainage of the Bongsunsa, the Toegyewon, and the Han River basin in an increasing order (Fig. 1).

The study area is dominated by an old natural forest of *Quercus sp.* and *Carpinus sp.* (80–200 yr old), and represents a typical montane landscape of the country. The catchment is covered with weathered gneiss, and the hillsides are dominated by slopes of 10–20°, with a maximum slope of 51°. The soil texture is sandy loam, and soil depth is 0.4 to 0.8 m with a notable H horizon. We selected four locations (SP1, SP2, R1, and R2) at the headwater catchment with normalized difference vegetation index (NDVI) of 0.65 for hydro-biogeochemical analysis of soil- and groundwater (Fig. 1c).

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2.2 Hydrological measurements

Stream discharge at the site was measured continuously at a 120° V-notch weir located downstream of a spring through which groundwater emerges to the surface. Precipitation was measured using a tipping bucket near the gauging station. Water-filled porosity was recorded every 5 min. at two sites with time-domain-reflectometry (TDR) rods at 0–0.1, 0–0.3, and 0.3–0.6 m in depth (Fig. 1c).

Based on a hydrological perspective, we classified the groundwater into two categories, i.e., the responses of the groundwater level to storm events and on the usual groundwater condition. The SP1 and SP2 sites for the sampling of hillslope groundwater (HGW) were located in the upper slope of the catchment where the groundwater level changed noticeably. During the dry season, the saturated groundwater table did not appear in HGW, and the response to storm events was the same as that for the riparian groundwater. The R1 and R2 sites for the sampling of riparian groundwater (RGW) were located in the riparian zone in the middle slope of the catchment. This zone was saturated with groundwater throughout the year.

In April 2005, we installed the wells made of bore pipes with 0.05 m in diameter, perforated with small holes around their bottoms (Table 1). The R1 area was adjacent to the stream and was saturated with groundwater throughout the year. The SP1 area was not saturated except during the storm events. The groundwater levels at R1-G1 and R1-G4 were measured by automatic multi-probe data loggers (CTD-diver, Van Essen Instruments, The Netherlands) at 1 min. intervals. The groundwater levels at R1-G3, R1-G5, R1-G6, SP1-G1, and SP1-G2 were measured by the water-level logger before sampling.

2.3 Sampling and chemical analysis

Samples of throughfall, soil water, hillslope groundwater, riparian groundwater, spring water, stream water, and hillslope runoff (HR) were collected for chemical analysis. An automated throughfall collector (SL12020, Shinill Science, Korea) was set up near

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the gauging station. To collect soil water, we installed two tension-free lysimeters at a depth of 0.05 m at SP1, SP2, R1, and R2 in April 2005. The lysimeters were made of PVC funnel (0.2×0.3×0.05 m) attached to two outlets with silicon sample extraction tubes. Groundwater was collected weekly using a silicon tube and 50 ml injector. The spring water was collected weekly using a 50 ml injector. The stream water samples during the storm events were collected by automated water sampler (6712FR, ISCO, USA) every 2 h for 48 h, except DOC samples between 1 and 3 July 2005. We collected events samples for six storms: 26–28 June (E050626), 1–3 July (E050701), 9–10 July (E050709), 24–26 August (E050824), 13–15 September (E050913), and 30 September–2 October (E050930) in 2005. Hillslope runoff samples were collected at SP1, SP2, and R1 during the storm events (i.e., E050626, E050701, and E050913).

The electric conductivity (EC) of water samples was measured with an electrode probe (013010MD, Thermo Electron Co., USA). Samples for ion analysis were sealed in 200 ml polyethylene bottles, and were refrigerated until analysis. The concentrations of  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Na}^+$ ,  $\text{Mg}^{2+}$ , and  $\text{Ca}^{2+}$  were analyzed by ion chromatography ( $\text{Cl}^-$  and  $\text{SO}_4^{2-}$ , DE/S-135, Sykam, Germany;  $\text{Na}^+$ ,  $\text{Mg}^{2+}$ , and  $\text{Ca}^{2+}$ , DX-320, Dionex, USA) after filtering through a cellulose acetate filter with 0.45  $\mu\text{m}$  pore. The DOC and POC samples were collected in 150 ml glass bottles wrapped with aluminum foil, and 0.01 g HgCl was added to inhibit bacterial decomposition. Samples were refrigerated until analysis. We used glass microfiber filter with 0.7  $\mu\text{m}$  pore (GF/F, Whatman, USA) after combusting at 500°C for two hours to remove organic contaminants in the filter. The samples were filtered through this contaminant-free glass microfiber filter, and added with 1 ml of 1 M HCl to remove inorganic carbon before analysis. DOC concentration was analyzed by carbon analyzer (Multi N/C 3000 analyzer, Analytik Jena, Germany). Suspended particulate was collected by filtering known volumes (30–110 ml) of water through fused GF/F filter papers. The samples were fumed with 4 M HCl to remove inorganic carbon, and then analyzed for POC with an elemental analyzer (EA1112 CHNS analyzer, Thermo Finnigan, Italy).

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## 2.4 Hydrographic separation

The end-member mixing analysis (EMMA) with principal components analysis (PCA) was applied to each storm event to evaluate quantitatively the contribution of each water component (Christophersen and Hooper, 1992; Burns et al., 2001). The dataset consisted of six tracers ( $\text{EC}$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Na}^+$ ,  $\text{Mg}^{2+}$ , and  $\text{Ca}^{2+}$ ) for 146 samples of stream water from the headwater catchment. The data were standardized into a correlation matrix, and a PCA was performed on the correlation matrix using all six tracers, and all combinations of six tracers. A model was selected that accounted for the greatest amount of variability with two principal components.

The PCA chosen for the use of EMMA incorporated six tracers, because the first two principal components from the covariance matrix explained 94% of the variability in these data. We selected three end-members with large spatial and temporal concentration variations within the catchment. We used the hillslope runoff as an end-member, which was collected at SP1, SP2, and R1 areas during the storm events (i.e., E050626, E050701, and E050913). The solutes for hillslope and riparian groundwater end-members were collected at SP1 and R1 areas before individual storm events (Fig. 1).

The contribution of each end-member was calculated by solving the following simultaneous mass balance equations (e.g., Hooper et al., 1990; Burns et al., 2001; Katsuyama et al., 2001):

$$Q_{\text{HR}} + Q_{\text{HGW}} + Q_{\text{RGW}} = Q_{\text{st}} \quad (1)$$

$$U1_{\text{HR}}Q_{\text{HR}} + U1_{\text{HGW}}Q_{\text{HGW}} + U1_{\text{RGW}}Q_{\text{RGW}} = U1_{\text{st}}Q_{\text{st}} \quad (2)$$

$$U2_{\text{HR}}Q_{\text{HR}} + U2_{\text{HGW}}Q_{\text{HGW}} + U2_{\text{RGW}}Q_{\text{RGW}} = U2_{\text{st}}Q_{\text{st}} \quad (3)$$

where  $Q$  is the discharge; subscripts HR, HGW, RGW, and st denote hillslope runoff, hillslope groundwater, riparian groundwater, and stream water, respectively; and  $U1$  and  $U2$  refer to the first and second principal components.

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## 2.5 Time lag calculation

We quantified the time lag between the precipitation and stream discharge by calculating the cross correlation ( $C_{AB}$ ), which measures the persistence of two signals ( $A$  and  $B$ ) during the measurement period and is defined as (Stull, 1988):

$$C_{AB}(L) = \frac{\sum_{k=0}^{N-j-1} \left[ (A_k - \overline{A_k}) (B_{k+j} - \overline{B_{k+j}}) \right]}{\left[ \sum_{k=0}^{N-j-1} (A_k - \overline{A_k})^2 \right]^{1/2} \left[ \sum_{k=0}^{N-j-1} (B_{k+j} - \overline{B_{k+j}})^2 \right]^{1/2}} \quad (4)$$

where  $L$  is time lag ( $=j\Delta t$ ),  $\Delta t$  is measurement interval,  $\overline{A_k} = \frac{1}{N-j} \sum_{k=0}^{N-j-1} A_k$  and

$$\overline{B_{k+j}} = \frac{1}{N-j} \sum_{k=0}^{N-j-1} B_{k+j}.$$

## 2.6 Estimation of water and DOC infiltration

To estimate the water infiltration rate, we calculated the groundwater recharge rate from the groundwater table fluctuation following Moon et al. (2004):

$$\alpha = \frac{\Delta h}{\sum P} \times S_y \quad (5)$$

where  $\alpha$  is the recharge rate,  $\Delta h$  is the change of groundwater level,  $P$  is precipitation, and  $S_y$  is the specific yield.

DOC infiltration was calculated from multiplying the water infiltration and DOC concentration in soil water at R1 each precipitation.

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## 3 Results

### 3.1 Hydrological characteristics of the storm events

The hydrological characteristics of the six storm events observed during and after the monsoon season in 2005 are summarized in Table 2. The precipitation intensity and discharge intensity were highest on 1 July during E050701 with  $17.7 \text{ mm } 10 \text{ min}^{-1}$  and  $1.0 \text{ mm } 10 \text{ min}^{-1}$ , respectively. The proportion of stream discharge relative to the total precipitation ranged from 15 to 60% with an average of 30%. The maximum discharge rate was also observed during this period, which was associated with five days' antecedent precipitation.

Figure 2 shows precipitation, water-filled porosity, groundwater level, and stream discharge for the six storm events. As expected, the water-filled porosity in the shallow soil layer increased more quickly and to a greater extent than in the deeper soil layer. The groundwater level at R1-G4 sensitively responded to the precipitation. In E050626, the groundwater level in the beginning was 0.3 m below the surface, which gradually increased to the subsurface and then decreased.

Table 3 shows the time lags computed from the cross correlation analysis among stream discharge, precipitation, and water-filled porosity. The time lags between water-filled porosity and stream discharge were  $<10 \text{ min}$ , except for the 0.3–0.6 m soil layer in E050626 and E050913, which yielded time lags of 1 h 30 min and 30 min, respectively. When the maximum precipitation intensity was higher than  $7 \text{ mm } 10 \text{ min}^{-1}$ , the time lag between the stream discharge and precipitation was of the order of 20 to 30 min. Time lags between precipitation and water-filled porosity varied from 2 to 11 h with low correlations.

### 3.2 Flow paths of water during the storm events

The relative contributions of each flow paths are summarized in Table 4. In E050626, the groundwater components (HGW+RGW) accounted for more than 60% of the total

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stream discharge throughout the period, except for the time of the peak precipitation when the surface runoff component accounted for about 40%. In E050701, the HR component (which accounted for almost 50%) increased as the saturated zone spread out after the rainfall ceased. In E050709, the contributions of each component did not change significantly. Despite the low total precipitation and maximum precipitation intensity (as compared to those in E050626 and E050701), E050824 showed a relatively high surface discharge of nearly 80% in the early stage. The groundwater component, however, increased to 60% by the end of E050824. In the fall (i.e., E050913 and E050930), the surface discharge was high up to almost 80% (Table 4).

In E050913 and E050930, the values of water-filled porosity in the surface layer (0–0.1 m) was about 5% higher than the maximum observed during the previous storm events (Fig. 2). This higher water-filled porosity (as compared to prior storm events) led to a low water infiltration rate and an increase in the contribution of surface discharge (Tables 4 and 5). Previous studies suggested that a maintained precipitation expands the saturation zone and increases macropore flows in the forested catchment (e.g., McDonnell, 1990). Such macropore flows deliver new water in which dissolved ion concentrations are low because of the short contact time with soil and bedrock (Burns et al., 1998). Table 4 also suggests a potential contribution of the overland flow to the stream discharge in E050913 and E050930.

### 3.3 Variations of DOC and POC in stream water and soil profile

Temporal variations in DOC and POC concentrations during the individual storm events are shown in Fig. 3. The DOC concentrations in E050626 were higher than those in other storm events and were positively related to the discharge rate. The POC concentrations in the latter four storm events (i.e., E050709, E050824, E050913, and E050930) were higher than those in the former two storm events (i.e., E050626 and E050701). After the precipitation ceased, the DOC and POC concentrations returned to the pre-storm levels.

The averaged DOC concentration in soil water during the dry period in June in-

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creased to  $79 \text{ mg L}^{-1}$ , and drastically decreased to around  $10 \text{ mg L}^{-1}$  after first storm events (Fig. 4a,b). For the entire observation period, the concentrations of DOC in the groundwater at 0.5 m (R1-G3, R1-G6, and SP1-G2) were significantly higher ( $p < 0.0001$ ) than those in the groundwater at 0.8–1.0 m (R1-G5 and SP1-G1) (Fig. 5).  
 5 The DOC concentrations of groundwater at 0.5 m in the riparian area (R1-G3) also decreased after the storm events (Fig. 4c). The DOC and POC concentrations observed in the spring water and the stream water during the periods of baseflow conditions were consistently low at  $< 1.0 \text{ mg L}^{-1}$  (Fig. 4d).

## 4 Discussion

### 4.1 Effects of storm events on DOC and POC discharge

The DOC concentration in the soil water (0–0.05 m) was highest before the storm events (Fig. 4). Such a maximum concentration resulted from the increase in DOC concentrations following the rewetting due to small amount of precipitation (9.4 mm on 15 June) after dry periods (e.g., Tipping et al., 1999; Kalbitz et al., 2000), which was  
 15 discharged later during E050626 and E050701 (Table 2).

The results from the hydrographic separation during the storm events indicated that a large amount of water discharged through the surface and subsurface soil layers (HR+HW; Table 4). An inverse relationship between DOC concentrations and water fluxes in the organic soil horizons (Fig. 4b and Table 4) suggests that a simple leaching  
 20 model might explain some of the seasonal changes in DOC (e.g., McDowell and Wood, 1984). The contact time between the soil and the soil water is critical for the concentration of dissolved material. The calculated mean residence time of water based on the  $^{35}\text{S}$  analysis varied with changing water regime in the study area, ranging from 20 to 40 days during the summer monsoon period (Kim et al., 2009). Especially, for the  
 25 stream water sample taken on 15 September when the surface runoff increased due to the storm event, the mean residence time of water also decreased abruptly (Kim

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et al., 2009; Table 4). Thus, DOC concentrations were lower in the summer when more water passed through the forest floor with shorter contact time. On the contrary, the groundwater content with longer contact time may lead to higher DOC concentrations (e.g., Kalbitz et al., 2000).

The increase of POC concentration during the latter four storm events probably arose from both catchment erosional processes and the entrainment of particulate material accumulated in the stream bed over the former storm events (e.g., Tipping et al., 1993). We suppose that the increase of surface runoff would induce the sharp responses of POC concentration (Fig. 3 and Table 4).

To derive the annual DOC and POC fluxes for the entire year in 2005, a linear regression of DOC and POC discharge was used against the stream discharge as an alternative method of estimating values during the periods of missing observation (Fig. 6a,b). In this study, the annual DOC and POC discharge from the Gwangneung deciduous forest catchment was estimated as about 0.04 and 0.05 tC ha<sup>-1</sup> yr<sup>-1</sup>, respectively (Fig. 6c). These values are equivalent to 2% of the annual net primary production (NPP of 4.3 tC ha<sup>-1</sup> yr<sup>-1</sup>; Lim et al., 2003) and 4 to 14% of the net ecosystem carbon exchange (NEE of -2.46~0.66 tC ha<sup>-1</sup> yr<sup>-1</sup>; Kwon et al., 2009) of the Gwangneung deciduous forest (Fig. 7). Through the discharge processes as discussed previously, 50 and 80% of the annual DOC and POC efflux were transported out of this forest catchment during the summer monsoon period.

## 4.2 DOC infiltration during the summer monsoon

According to the results from the water infiltration rates, 0.44 tC ha<sup>-1</sup> DOC was infiltrated into the soil from late June to early October (Table 5), which represented approximately 8% of the stored carbon in the forest floor (5.6 tC ha<sup>-1</sup>; Lim et al., 2003) and 20 to 70% of NEE (-2.46 to 0.66 tC ha<sup>-1</sup> yr<sup>-1</sup>; Kwon et al., 2009) (Fig. 7). These results indicate that a considerable amount of decomposed organic matter is stored in the soil through water movement processes. If most of the infiltrated DOC were to accumulate as soil organic carbon in the shallow soil and to be decomposed in the deep soil, then

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0.5% of the soil carbon ( $92.0 \text{ tC ha}^{-1}$ ; Lim et al., 2003) would be retained from DOC during the summer monsoon (Fig. 7). While these values seem to be relatively small, soil organic carbon can be accumulated in the mineral soil for an extended period (e.g., Michalzik et al., 2003); potentially making the 0.5% of soil carbon retained from DOC during the summer monsoon an important component of the forest carbon budget to consider (e.g., Battin et al., 2009).

### 4.3 Effects of antecedent precipitation on DOC discharge

The antecedent precipitation index (API) can be used to examine the effect of temporal variation of precipitation on DOC concentration in the stream water during baseflow periods. This index is commonly used to model the residual effect of previous precipitation on current soil moisture and runoff and can be calculated as (Ziemer and Albright, 1987; Uchida et al., 2002; Kawasaki, 2005):

$$\text{API} = \sum_{i=1}^{\infty} 0.5^{i/T} P_i \quad (6)$$

where  $T$  is the “half-life” representing the decay characteristic of a particular recession and  $P_i$  is the daily precipitation during the  $i$  days beforehand. The values of  $T$  were tested from 5 to 120 days. Figure 8 represents the changes in correlation coefficient ( $r$ ) as a function of  $T$ , where the former is the relationship between stream water DOC concentration and API for the corresponding  $T$ . The  $r$  values did not change significantly with  $T > 10$  d, suggesting that the antecedent precipitation did not cause the temporal variation of stream water DOC concentration. This result indicates that the actual DOC movement was produced by the changes in soil moisture and contribution rate of surface discharge.

## 5 Conclusions

Based on our intensive field measurements for six storm events from June to October in 2005, 30 to 80% of water was discharged through surface runoff in a natural deciduous forest catchment in Korea. Consequent rises of DOC and POC concentration in streamwater were observed immediately upon the onset of these storm events. Through these discharging processes, 50 and 80% of the annual DOC and POC efflux (0.04 and 0.05 t C ha<sup>-1</sup> yr<sup>-1</sup>, respectively) was transported out of this forest catchment during the monsoon season. The annual organic carbon efflux was estimated to be 4 to 14% of the annual NEE of this forest ecosystem, that was small in terms of the total carbon budget of the whole ecosystem. However, 8% of litterfall carbon was estimated to be infiltrated into the soil as DOC during the same period, which was accumulated in soil through adsorption processes. To better understand the carbon cycling in this catchment, it is necessary to estimate the annual accumulation of DOC and the concurrent water movement in the soil. The organic carbon discharged from the ecosystems of the Korean river basin may constitute an important carbon sink through burial in coastal sea sediments or sea floor, which may be accelerated by the annually recurring and intensified monsoon in East Asia. In order to make an accurate estimation of the ecosystem carbon budget, these missing components should be taken into account particularly in the monsoon Asia. The data presented in our study can be used to calibrate and improve eco-hydrological schemes such as the Regional Hydrological and Ecological Simulation System (RHESSys) model to examine the sensitive couplings between carbon and water exchanges, which are currently in progress.

*Acknowledgements.* This research was supported by grants (code: 1-8-3) from Sustainable Water Resources Research Center for 21st Century Frontier Research Program, the Long-term Ecological Study and Monitoring of Forest Ecosystem Project of Korea Forest Research Institute, and the “CarboEastAsia” A3 Foresight Program of the Ministry of Education, Science and Technology of Korea.

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**Table 1.** The Hydrological characteristics and observation at the observation wells.

Point	Well depth (m)	Saturation condition	Chemistry observation	Groundwater level observation
R1-G1	0.502	permanent	none	automated
R1-G3	0.492	permanent	yes	manual
R1-G4	0.547	permanent	none	automated
R1-G5	0.817	permanent	yes	manual
R1-G6	0.547	permanent	yes	manual
SP1-G1	1.107	temporary	yes	manual
SP1-G2	0.502	temporary	yes	manual

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**Table 2.** Hydrological characteristics of the six storm events from June to October 2005.

	E050626	E050701	E050709	E050824	E050913	E050930
Observed period	26–28 Jun	1–3 Jul	9–10 Jul	24–26 Aug	13–15 Sep	30 Sep–2 Oct
Total precipitation (mm)	160.5	104.0	40.5	83.5	85.5	87.0
Max. precipitation intensity (mm 10 min <sup>-1</sup> )	11.1	17.7	2.5	4.5	7.5	2.5
Total discharge (mm)	23.6	61.5	11.5	22.8	18.1	29.1
Max. discharge intensity (mm 10 min <sup>-1</sup> )	0.32	1.05	0.06	0.14	0.28	0.16
Total discharge/total precipitation (%)	15	60	28	27	21	33
Antecedent precipitation (5 days)	0.0	161.9	1.3	1.5	7.0	1.0
Antecedent precipitation (10 days)	1.3	161.9	154.3	19.5	7.0	43.5

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**Table 3.** Estimated time lags among stream discharge (SD), precipitation (P), and water-filled porosity (WFP). The numbers in the parentheses indicate cross correlation coefficients.

	E050626	E050701	E050709	E050824	E050913	E050930
P and SD	0 h 30 m (0.43)	0 h 30 m (0.50)	8 h 40 m (0.38)	8 h 20 m (0.42)	0 h 20 m (0.65)	12 h 10 m (0.49)
P and WFP (0–0.1 m)	3 h 00 m (0.17)	3 h 00 m (0.40)	9 h 40 m (0.45)	9 h 00 m (0.40)	6 h 40 m (0.36)	11 h 00 m (0.56)
P and WFP (0.3–0.6 m)	7 h 50 m (0.14)	2 h 20 m (0.12)	9 h 10 m (0.48)	7 h 00 m (0.27)	6 h 00 m (0.29)	8 h 30 m (0.31)
WFP and SD (0–0.1 m)	0 h 10 m (0.73)	0 h 10 m (0.93)	0 h 00 m (0.92)	0 h 00 m (0.98)	0 h 10 m (0.80)	0 h 00 m (0.96)
WFP and SD (0.3–0.6 m)	1 h 30 m (0.56)	0 h 00 m (0.51)	0 h 10 m (0.93)	0 h 10 m (0.91)	0 h 30 m (0.67)	0 h 00 m (0.91)

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**Table 4.** The relative contribution and uncertainty (%) of hillslope runoff (HR), hillslope groundwater (HGW), and riparian groundwater (RGW) for the six storm events from June to October 2005.

	E050626	E050701	E050709	E050824	E050913	E050930
HR	32±0.9	49±1.0	47±0.9	54±0.9	79±1.0	78±1.0
HGW	38±3.9	16±0.9	28±0.6	30±0.4	11±0.5	11±0.5
RGW	30±0.1	35±0.7	25±0.5	16±0.6	10±0.5	12±0.5

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**Table 5.** The precipitation, water infiltration rate, amount of infiltrated water, soil water DOC concentration, and amount of in filtrated DOC for the each precipitation at R1.

Observed period		26–28 Jun (E050626)	1–3 Jul (E050701)	3 Jul	9–10 Jul (E050709)	13 Jul	25 Jul	1 Aug	2–3 Aug	7 Aug	24–26 Aug (E050824)	28 Aug	13–15 Sep (E050913)	17 Sep	21 Sep	30 Sep – 2 Oct (E050930)
Precipitation (mm)		160.5	104.0	32.6	40.5	58.5	51.6	30.0	93.5	33.0	83.5	20.0	85.5	64.0	39.0	87.0
Water infiltration rate (%)	R1-G1	15.4	12.5	17.0	25.1	17.0	36.8	18.4	6.9	30.9	30.6	91.5	16.0	16.5	29.3	13.2
	R1-G4	25.0	29.7	35.0	39.4	34.4	67.8	59.8	18.5	30.2	26.0	25.9	18.2	27.6	41.0	19.8
	Average	20.2	21.1	26.0	32.2	25.7	52.3	39.1	12.7	30.6	28.3	58.7	17.1	22.1	35.1	16.5
Amount of infiltrated water (mm)		32.4	21.9	8.5	13.1	15.0	27.0	11.7	11.6	10.1	23.6	11.7	14.6	14.1	13.7	14.3
Soil water DOC concentration (mgL <sup>-1</sup> )		13.4	8.9	2.2	10.9 <sup>a</sup>	10.9 <sup>a</sup>	8.1	7.5 <sup>a</sup>	7.5 <sup>a</sup>	5.8	6.2 <sup>a</sup>	6.2 <sup>a</sup>	6.9	6.0 <sup>a</sup>	6.0 <sup>a</sup>	7.0
Amount of infiltrated DOC (kg C ha <sup>-1</sup> )		95.6	42.9	4.1	31.2	36.0	47.8	19.4	19.6	12.9	32.0	15.9	22.2	18.6	18.0	22.1

<sup>a</sup> Mean concentration of immediate two precipitations.

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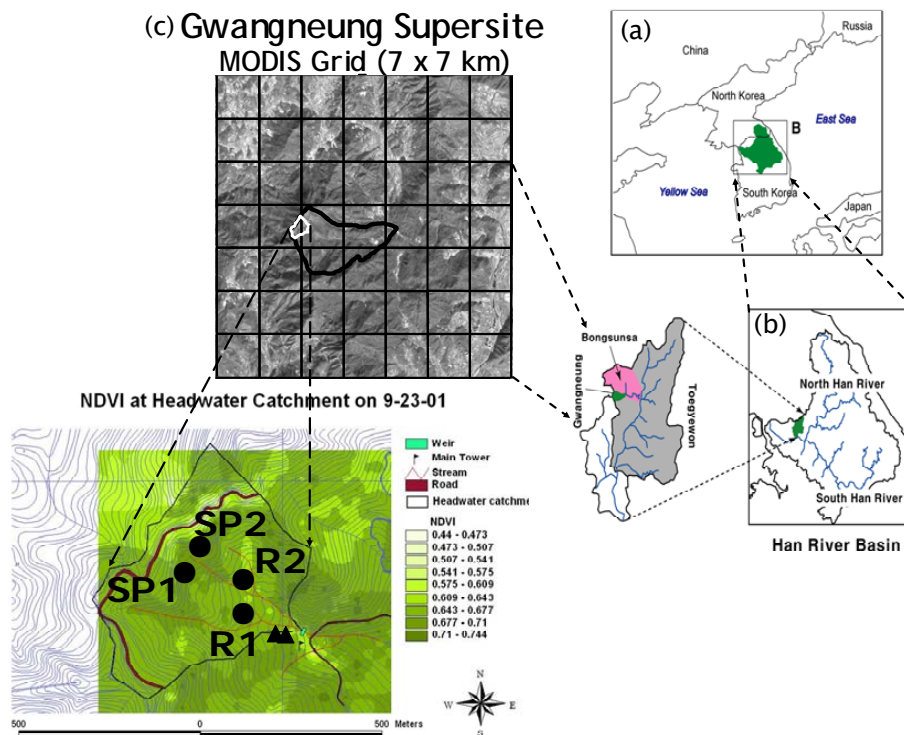
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**Fig. 1.** Maps showing (a) the location of the study site, (b) the topography of the Gwangneung catchment, and (c) the topography and normalized difference vegetation index of the headwater catchment (22 h). Black circles indicate the locations of tension free lysimeters and groundwater wells. Black triangles indicate the locations of water-filled porosity measurement.

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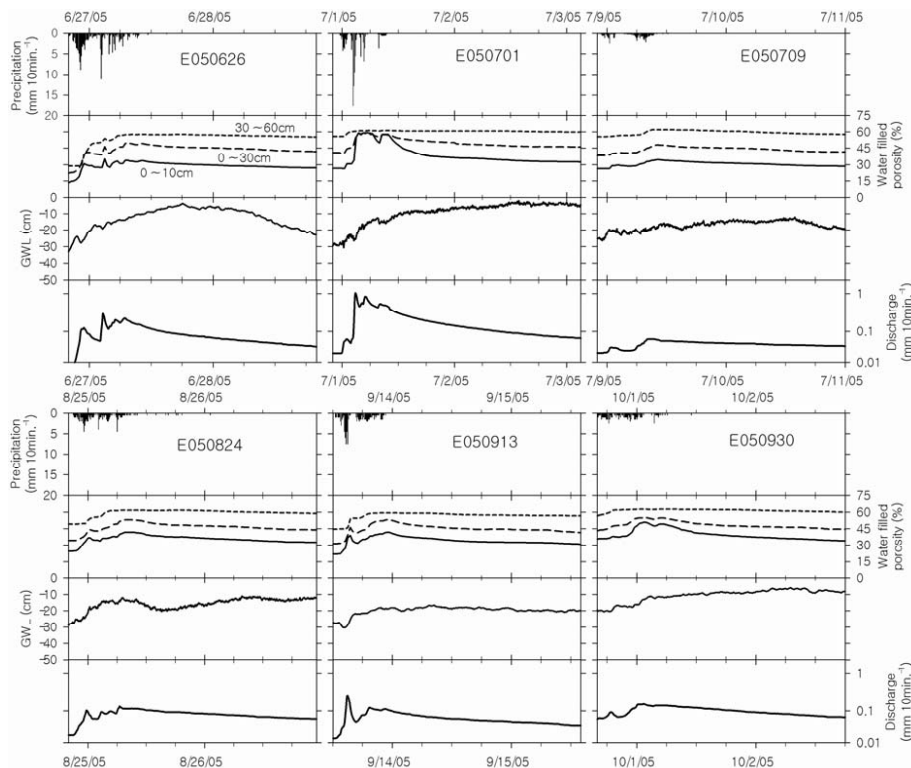
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**Fig. 2.** Temporal variations in precipitation, mean value of water-filled porosity, groundwater level (GWL) at R1-G1, and stream discharge during the six storm events from June to October 2005.

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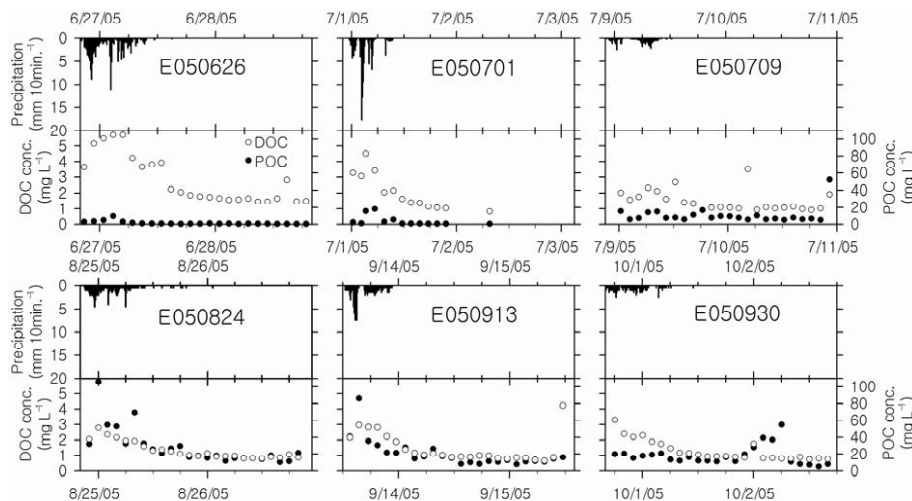
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**Fig. 3.** Precipitation and temporal variations of DOC and POC concentration in streamwater during the six storm events from June to October 2005.

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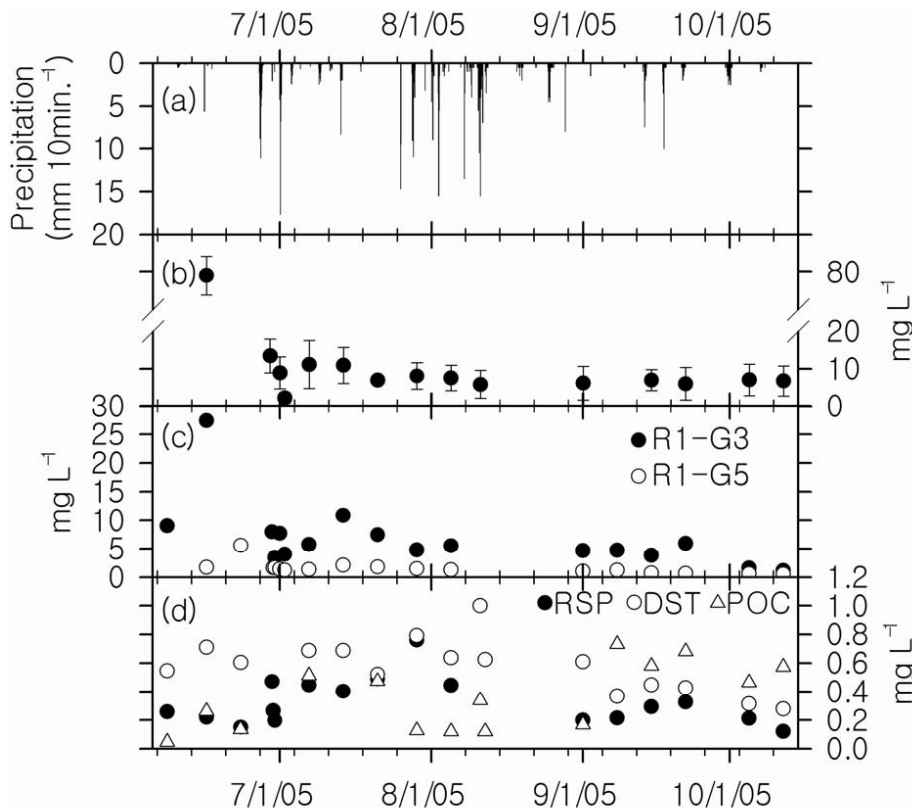
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**Fig. 4.** Variations in (a) precipitation and DOC concentrations in (b) soil water, (c) groundwater, and (d) spring water (RSP), streamwater (DST), and POC concentration (POC) in streamwater during the periods of baseflow conditions from June to October 2005. Vertical error bar in (b) soil water means standard deviation.

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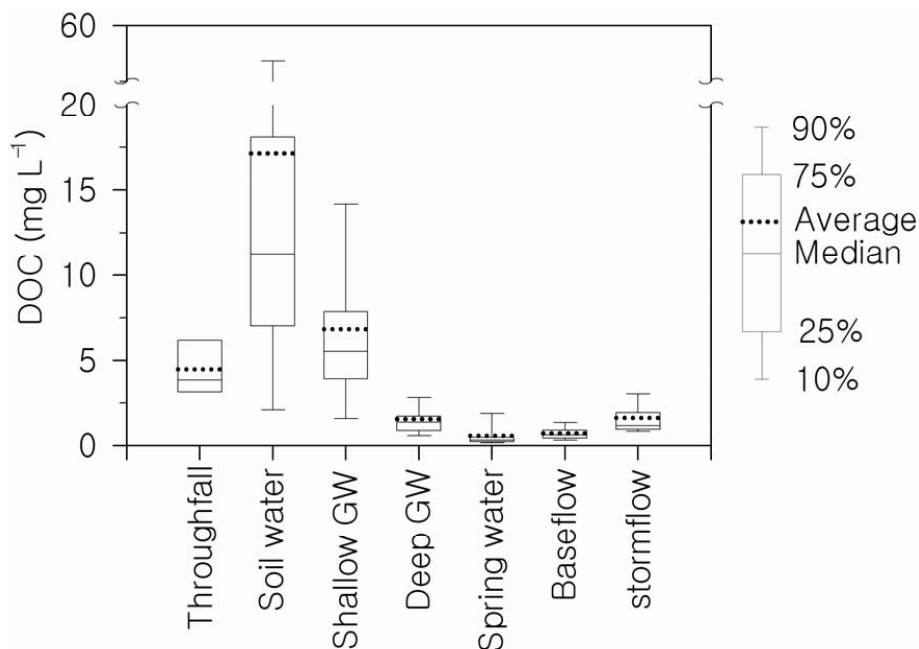
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**Fig. 5.** The concentrations of DOC from throughfall, soil water, shallow groundwater (0.5 m), deep groundwater (0.8–1.0 m), spring water, and baseflow, and stormflow for the period from April to October 2005.

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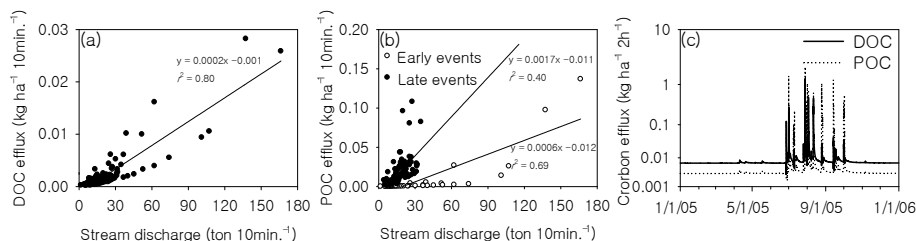
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**Fig. 6.** Relationship between (a) the stream discharge and DOC, (b) stream discharge and POC, and (c) the estimation of the annual organic carbon efflux from the Gwangneung deciduous forest catchment. Early events and Late Events in the (b) indicate E050626, E050701, and E050709, E050824, E050913, E050930, respectively.

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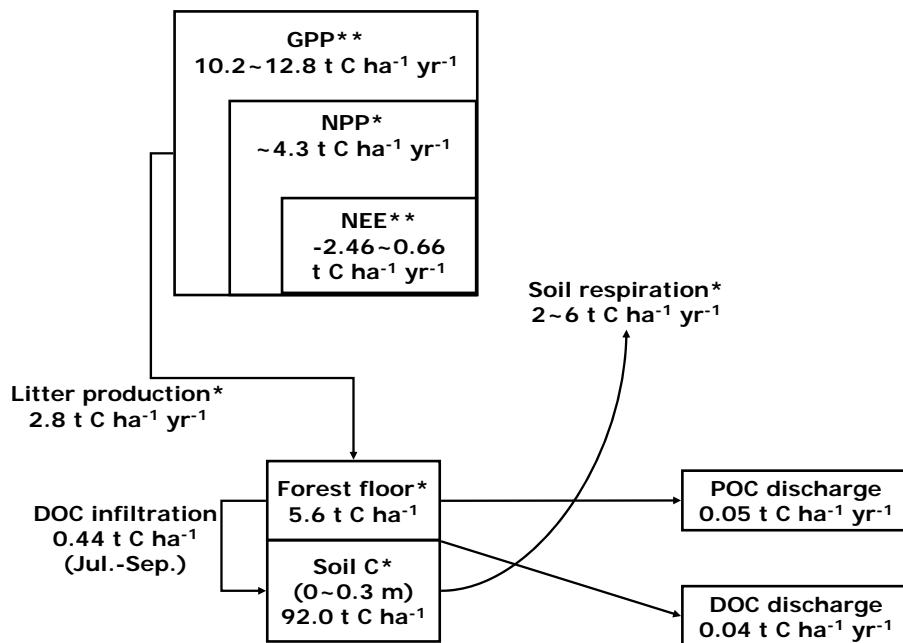
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**Fig. 7.** The contribution of DOC and POC to the carbon budget in the Gwangneung deciduous forest catchment. \* Lim et al. (2003; observation periods 1998 to 1999), \*\* Kwon et al. (2009; observation periods 2006 to 2008).

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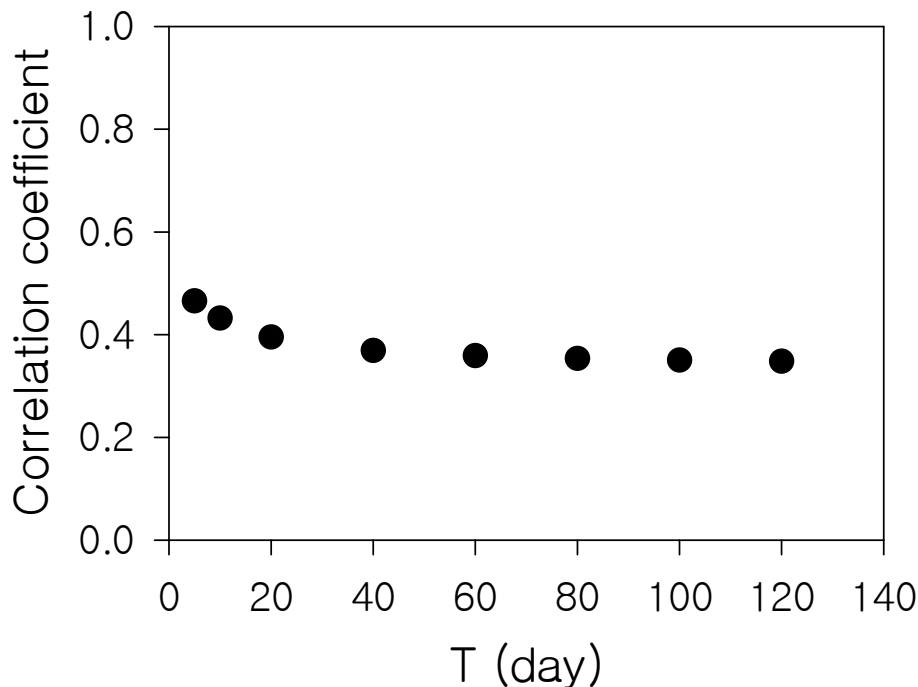
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**Fig. 8.** Relationship between  $T$  and correlation coefficient (derived from the relationship between stream water DOC concentration and API for the corresponding  $T$  value).

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