Original Article

Runoff Load Estimation Model for Dissolved Organic Carbon that Considers Soil and Hydrologic Processes in Forested Watersheds

Kazunori Ebata\(^a\), Yutaka Ichikawa\(^b\), Hiroshi Ishidaira\(^c\), Yoshitaka Matsumoto\(^d\), Kei Nishida\(^e\)

\(^a\) Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, Kofu, Japan
\(^b\) Graduate School of Engineering, Kyoto University, Kyoto, Japan
\(^c\) Interdisciplinary Centre for River Basin Environment, University of Yamanashi, Kofu, Japan
\(^d\) Department of Civil Engineering, National Institute of Technology, Toyota College, Toyota, Japan

ABSTRACT

Estimation of dissolved organic carbon (DOC) runoff load in forested watersheds is important for the assessment of the global carbon cycle as well as for the local water quality control. A few process-based models previously proposed exhibited difficulties with the availability of input data and applicability to short time-scale rainfall-runoff processes in the Asian monsoon area. With the four years’ data from two nested study areas in Yamanashi, Japan, this study developed a new numerical model that consists of two processes for determining DOC loads. For the hydrologic process, a semi-distributed hydrological model (modified TOPMODEL) was installed. For the soil process, a wet-dry cycle was successfully simulated by an advection-diffusion and dissolution formulation. Finally, cumulative DOC loads were also successfully estimated during baseflow and stormflow periods separately, showing reasonable matching between the simulations and the observations for both study sites. Considering the storm periods, from 27% to 47% of high flows contributed to 50% of the total DOC load at the two monitoring areas, respectively. In essence, the proposed model was expected to identify and evaluate the importance of DOC production potentially linked with internal processes within forested river systems.

Keywords: DOC source area, modified TOPMODEL, river runoff, storm flow, wet-dry cycle

INTRODUCTION

In stream ecosystems, dissolved organic carbon (DOC) is an essential biogeochemical component of water quality that serves as a major energy substrate for aquatic ecosystems [1–3]. In contrast, with regard to global carbon issue and local water quality control, the estimation of DOC fluxes from forestland to river is of equal importance. Forests often serve as non-point sources for runoff through which many nutrients are exported to water bodies; during this process, however, the export often exceeds capacity of the ‘river auto purification’ resulting in undesired eutrophication and water pollution.

A number of researches have been performed with regard to how DOC is generated in the landscape and transported to streams. Freshwater DOC concentrations are controlled by various natural factors such as geographic location, catchment topography, season, climate and upland-wetland flow paths. Dissolved Organic Carbon exports from catchments are also strongly influenced by storm events [4–7]. Japan belongs to the Asian monsoonal region, distinct from the maritime climatological locations of Europe and the United States, and short-term intensive rainfall episodes derived from typhoon events mainly occur during the period of June to October. In addition, it is suspected that global warming has increased the frequency of heavy rainfall. Due to such rainfall characteristics, DOC fluxes would be expected to proportionally increase considerably in the region.
As an estimation of DOC flux, empirical calculation has been widely introduced based on regression against river flow [8]. However, this method has an inherent drawback that the regression curves are not identical temporally and spatially due to lack of internal process. In order to solve this problem, several process-based models have been previously developed to simulate DOC production in soils and DOC export at catchment scale. Seibert et al. [9] proposed a simple riparian flow-concentration integration model (RIM), asserting that the riparian zone plays a key role in the control of DOC dynamics in a forested hillslope. Winterdahl et al. [10] developed a dynamic RIM model that included soil process. Both models captured the control factors but the applications were restricted at small hillslope scale. Futter et al. [11] proposed an integrated catchment model for carbon (INCA-C); this model successfully simulated seasonal and inter-annual patterns in DOC concentrations [12] and has been widely applied to areas in northern Sweden [13,14] and Canada [15] whereas, it consisted of numerous parameters for effectively characterizing the biogeochemical and hydrological processes. Jutras et al. [16] proposed a DOC runoff model (DOC-3) combined with a forest hydrological model, which requires only three fundamental parameters, calculated soil temperature and moisture and resultantly simulated DOC exports at catchment scale in Canada. Birkel et al. [17] and Dick et al. [18] proposed a coupled hydrology-biogeochemistry model for simulating DOC exports that incorporates the dominant factor controlling DOC dynamics with less parameterisation and indicated high contribution of riparian zone hydrologically connecting to total DOC flux. Lessels et al. [19] applied the coupled DOC model to a sub-arctic alpine catchment with a permafrost influence in Canada. However, all these models presented the calculation results on a monthly scale only, and were hence not applicable to episodic rainfall events typically found in Asian monsoon area.

In this study, a DOC runoff model was developed that considered soil process and hydrologic process by using lab-scale data as well as long-term monitoring data collected from a forested watershed in central Japan. The hydrologic sub-model was structured by ‘modified TOPMODEL’ [20] that was simple and characterized DOC source area (DSA) by considering hydrological connectivity and topographic feature of the catchment. The soil sub-model calculated temporal variation of DOC concentrations caused by rainwater infiltration and subsequent wet-dry cycle in upper soil. The results from the two sub-models were combined then DOC load to a stream was eventually calculated. Evaluating the impact of episodic rainfalls on the DOC runoff load was specifically focused at short-term (storm) scale as well as long-term (yearly) scale.

**STUDY AREA**

Mizugaki Experimental Watershed is located in the northern part of Yamanashi Prefecture, Japan (Fig. 1). There are two nested monitoring sites, MD (98 ha) and K2 (1,796 ha). The soil type is Andosol and the underlying geology is primarily granitic rock, with elevations ranging from 1,150 to 2,412 metres above sea level. The mean annual air temperature and rainfall in the region are 6.7°C and 1,631 mm, respectively. There is typically a snowpack from the end of December through early April, and peak stream discharges usually occur during frontal rains and typhoon-derived rains during the summer period. The forest overstory is occupied...
by Japanese larch (Larix kaempferi), while the understory is composed of deciduous broadleaf trees (Quercus mongolica, Ostrya japonica and Weigela japonica) [21].

HYDROLOGICAL AND GEOCHEMICAL DATA

Rainfall, discharge and DOC concentrations of river water and soil water were thoroughly monitored. Rainfall data were collected by a rain gauge (Rain Collector II, Davis Instruments, California, United States of America) and recorded at 10-minute intervals for each site. Stream discharges were calculated from water levels monitored by a water-pressure-level gauge (HM-500, Field Pro, Tokyo, Japan) and were recorded using a data logger (CR1000, Cambell Scientific, Utah, United States of America) at 10-minute intervals for each site. Based on the observed discharge, stormflow period and baseflow period were classified through the hydrograph separation using recession limb analysis [22]. Stream water samples were collected biweekly at both sites during baseflow in the period of 2009 – 2012, and were also collected during storm every hour on the rising limb of the hydrograph and every two hours on the falling limb using water samplers (6712 Portable Sampler, Teledyne ISCO, Nebraska, United States of America). All the continuous data logging for hydrology and sampling for water quality were controlled by a real-time monitoring system (GEORGE-I, Field Pro, Tokyo, Japan). Throughfalls were measured monthly using a two-liter bottle attached with a 10-cm diameter polyethylene funnels covered by a 5-mm plastic mesh screen at each site. Soil waters were sampled after the rain events from 2007 to 2012 by zero-tension lysimeters at soil surface and tensio lysimeters at 10 cm, 20 cm, 30 cm, 50 cm and 150 cm depths from the soil surface. The collected samples were filtered through 0.45μm glass fibre filters (Whatman GF/F, GE Healthcare Life Sciences, Tokyo, Japan) on site and then brought back to the laboratory for DOC analysis using a TOC analyser (Sievers900, General Electric, Connecticut, United States of America). Air temperature was also recorded at 10-minute intervals by meteorograph (Box car pro 4.3.1.1, Onset Computer Corporation, Massachusetts, United States of America). Potential evapotranspiration (ET) was estimated using the Penman–Monteith method derived from the National Institute for Agro-Environmental Sciences open data. A 10-m mesh DEM data batch was extracted by the Geospatial Information Authority of Japan and a calculated topographic index (TI) was used for the quantitative assessment of the runoff system in the modified TOPMODEL, where TI was determined as $\ln (a/tan\beta)$, $a$ is an upsloping contributing area of a given site based on drainage directions calculated via the D-infinity algorithm [23] and $\beta$ is the local slope angle [24].

MODELING METHODOLOGY

Hydrologic model for surface and subsurface water flows

Figure 2 provides a conceptual illustration of a DOC load calculation for both baseflow and stormflow periods. A semi-distributed hydrological modelling unit (modified TOPMODEL [20,25]) was installed to simulate the rainfall-runoff process where total stream discharges were separated into three components of flow pathways: overland flow ($E_x$), subsurface flow ($Q_{sf}$) and baseflow ($Q_b$). Input data required for the model were rainfall and ET, and outputs were depicted as water flux for each pathway every one hour. The calculated water fluxes in root zone were converted to volumetric water content and water velocity to be input to the following soil process calculation. $E_x$ and $Q_{sf}$ were considered to be correspondent to the water fluxes flowing through DSA located in the top or upper soil layer. Modified TOPMODEL was manually calibrated repeatedly during 2009 – 2010 at both sites and applied to validation at each site during 2011 – 2012. Model performance was assessed using Nash-Sutcliffe efficiency (NSE) and PBIAS.

Soil model for DOC generation

There have been many prior studies concerning the production and release of DOC from uplands and wetlands. In this present study, a ‘soil process’ describes the major physical factors and processes controlling DOC generation dominated in wetland soil surfaces which correspond to DSA. Dissolved Organic Carbon concentration of surface soil water is cumulatively increased by dissolution during baseflow period and is momently decreased by advection-diffusion during stormflow period. The soil process of this study employs an advection-diffusion equation for solute transportation at mobile water layer and a dissolution equation from immobile water layer to mobile water layer, as in equation (1) [26],

$$\frac{\partial (\theta C)}{\partial t} = -\frac{\partial (u\theta C)}{\partial z} + \frac{\partial}{\partial z}
\left(\theta D \frac{\partial C}{\partial z}\right) - D_s (C - C_{im}) \tag{1}$$

where $\theta$ is the volumetric water content expressed with Eq. (2), $C$ is the DOC concentration in surface soil water (mg/L),
\[ u \] is the water velocity in soil (m/h) expressed with Eq. (3), \( D_c \) is the diffusion coefficient (m\(^2\)/h), \( D_d \) is the dissolution coefficient (1/h), \( C_{im} \) is the DOC concentration in immobile water (mg/L), \( z \) is the vertical column length (m) and \( t \) is the time (h).

\( \theta \) and \( u \) are calculated from the modified TOPMODEL as follows,

\[
\theta = \begin{cases} 
\theta_{\text{min}} + \left( \theta_{\text{max}} - \theta_{\text{min}} \right) \left( 1 - \frac{\text{SRZ}}{\text{SRZ}_{\text{max}}} \right), & \text{SRZ} \geq 0 \\
\theta_{\text{max}}, & \text{SRZ} < 0 
\end{cases}
\]  \hspace{1cm} (2)

\[
u = \begin{cases} 
0, & \text{SRZ} \geq 0 \\
- \frac{\text{SRZ}}{\Delta t}, & \text{SRZ} < 0 
\end{cases}
\]  \hspace{1cm} (3)

where \( \theta_{\text{min}} \) is the minimum observed volumetric water content (60.6%), \( \theta_{\text{max}} \) is the maximum observed volumetric water content (80.5%) in wetland, \( \text{SRZ} \) is the storage deficit of root zone and \( \text{SRZ}_{\text{max}} \) is the maximum storage at root zone, \( D_c \) is the calculated with Equation (4) \([27]\),

\[ D_c = 4.3 \times 10^{-4} + 0.545 u^{1.355} \]  \hspace{1cm} (4)

There are one unknown initial value for \( C: C_{\text{rain}} \) (DOC concentration in throughfall) and two unknown parameters: \( D_d \) and \( C_{im} \). \( C_{\text{rain}} \) was calculated to have an average DOC concentration of throughfall during the period of 2009 – 2010 via field observations. \( C_{im} \) is dependent upon soil condition (e.g. wet or dry) and \( D_d \) varies with the soil type. Both were obtained from soil-column experiments, using intact surface soils collected from the study site in 2007, to minimize root-mean-square error (RMSE) between observation and calculation. In addition, parameter \( D_d \) in this study was modified as \( D_d^* \) to incorporate seasonal effect as in Equation (5),

\[ D_d^* = D_d e^{kT} \]  \hspace{1cm} (5)

where \( T \) is the air temperature (°C) and \( k \) is the constant value. The value \( k \) was calibrated to minimize RMSE between observed surface soil water DOC concentrations and estimated ones in 2007. The parameterised model was subsequently applied to the hourly calculation for validation during 2008 – 2010.

**DOC loading calculation**

The surface soil water DOC concentration calculated from the soil model was converted to the average value at 0 to 30 cm depth at MD and 0 to 60 cm at K2 using an exponentially curved vertical profile of the observed soil DOC concentrations. \( E_x \) or \( Q_{sf} \) calculated from the hydrologic
model and the averaged soil water DOC concentration were multiplied to produce a DOC runoff load from upper layer. In parallel, $Q_b$ was multiplied by the DOC concentration, similarly averaged at 30 to 100 cm depth at MD and 60 to 100 cm at K2, to produce a DOC runoff from deeper layer. Finally, the two results were combined to obtain total DOC load. The calculated total DOC loads were compared with the values from observation, which were prepared by load-discharge relationship each year during both periods. The DOC load-discharge relationship at each site was developed using the 10-min interval observed discharge data and the observed DOC load. Overall model performance was evaluated by PBIAS at the two sites in both baseflow period and stormflow period.

### RESULTS

#### Observation of hydrology and DOC concentrations

Table 1 shows the observed data for rainfall, stream discharge and observed DOC concentrations from 2009 to 2012. During the study period, maximum rainfall was observed in 2011 and minimum rainfall was observed in 2012. Mean stream discharges in baseflow and stormflow were 0.019 m$^3$/s and 0.036 m$^3$/s at MD, respectively, and those were 0.45 m$^3$/s and 0.73 m$^3$/s at K2. Mean stream DOC concentrations in baseflow and stormflow were 2.0 mg/L and 5.5 mg/L at MD, respectively, and were 1.1 mg/L and 1.7 mg/L at K2, respectively.

#### Hydrologic process modelling

Hydrologic processes were analysed via modified TOPMODEL and reasonable results were obtained in a yearly scale. The associated model parameters are provided in Table 2. After the calibration steps, the model was then run again for the validation (Fig. 3 and Fig. 4). The timing of the peak flow and the variation pattern of simulation fitted well with those of observation throughout the years at both sites, though the simulated discharges tend to be slightly overs-
estimated during the descending limb. Regarding the model evaluation criteria in Table 3 [28], the simulation performance at MD was very good for validation period. Also, the simulation performance at K2 was very good for validation period based on NSE except for stormflow period in 2011, and very good based on PBIAS (Table 4). After confirming the model quality, the calculated water flux from root zone to unsaturated zone and the overland flow ($E_d$), subsurface flow ($Q_{sf}$) and baseflow ($Q_b$) were exported to the following soil model and total DOC load calculation, respectively.

Soil process modelling

Table 5 shows the parameters for soil DOC model calculation. Figure 5 shows the validation results of simulated soil water DOC concentrations and observed ones in 2010. The soil model successfully demonstrated the wet-dry cycle in soil surface for each year. The criteria for nitrogen and phosphorus concentrations in Table 3 [28] were used for the evaluation of soil model performance. Using the criteria, the simulated results of the model were ‘very good’ for validation period (Table 6).

DOC load simulations for yearly and storm scales

After confirming the sufficient performances of modified TOPMODEL and soil model, daily DOC loads were calculated in 2009 – 2012 at both sites during baseflow and stormflow periods. The errors between observation and simulation were within a range of −22% to 43% and −47% to 58% in PBIAS values at MD site and K2 site, respectively (Table 7), and were equivalent to the results from a previous study [16] aiming long-term pattern analyses (−44% to 18%, −46% to 22% and −42% to 33% at each of three forest streams). The simulation results show that DOC loads during stormflow were, at maximum, 3.1 times and 1.4 times larger than those during baseflow at MD site and at K2 site, respectively. The simulated daily DOC loads were mostly underestimated at MD and were mostly overestimated at K2 during baseflow, while most of the daily DOC loads were underestimated at both sites during stormflow. In addition, the simulated mean daily DOC loads were low at MD (0.041 kg/(ha·d)) and K2 (0.027 kg/(ha·d)) during baseflow, while the mean value at MD was 3.6 times higher than that at K2 during stormflow. Annual DOC loads were also estimated at both sites as 21.2 – 25.1 kg/(ha·yr) at MD and 10.8 – 11.4 kg/(ha·yr) at K2, respectively. Comparing to the values previously reported [29],
the estimated annual DOC loads at both sites were within the range in temperate forest zone.

### DISCUSSION

#### Wet-dry cycle in soil process

In general, the upper soil horizons have higher DOC concentrations than those seen in lower, mineral horizons [11] and DOC is mainly carried by overland and subsurface flow. DOC-generation models in forest catchments were set by employing key inherent parameters such as air temperature and soil hydrological factors. Among a number of process-based DOC models, INCA-C [11] and DOC-3 [16] considered both parameters in daily calculation of DOC concentrations. These models reasonably simulated soil DOC dynamics,

---

**Table 3** General performance ratings for selected statistics on a hydrologic and soil process modeling [28].

<table>
<thead>
<tr>
<th>Performance ratings</th>
<th>NSE</th>
<th>PBIAS(%) streamflow</th>
<th>N, P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very good</td>
<td>0.75 &lt; NSE ≤ 1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Good</td>
<td>0.65 &lt; NSE ≤ 0.75</td>
<td>10 ≤</td>
<td>PBIAS</td>
</tr>
<tr>
<td>Satisfactory</td>
<td>0.50 &lt; NSE ≤ 0.65</td>
<td>15 ≤</td>
<td>PBIAS</td>
</tr>
<tr>
<td>Unsatisfactory</td>
<td>NSE ≤ 0.50</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 4** Performance of modified TOPMODEL simulation.

<table>
<thead>
<tr>
<th>Base flow</th>
<th>Calculation period(day)</th>
<th>Storm flow</th>
<th>Calculation period(day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration 2009</td>
<td>0.95</td>
<td>-4.8</td>
<td>257</td>
</tr>
<tr>
<td>Validation 2011</td>
<td>0.91</td>
<td>-7.2</td>
<td>271</td>
</tr>
<tr>
<td>K2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration 2009</td>
<td>0.79</td>
<td>1.2</td>
<td>211</td>
</tr>
<tr>
<td>Validation 2011</td>
<td>0.94</td>
<td>-1.0</td>
<td>202</td>
</tr>
<tr>
<td>Validation 2012</td>
<td>0.92</td>
<td>1.0</td>
<td>207</td>
</tr>
</tbody>
</table>

**Table 5** Parameters for soil model simulation.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crain</td>
<td>mg/L</td>
<td>4.8</td>
</tr>
<tr>
<td>Dd</td>
<td>1/h</td>
<td>3.5×10⁹</td>
</tr>
<tr>
<td>Cim</td>
<td>mg/L</td>
<td>9.5×10⁴</td>
</tr>
<tr>
<td>k</td>
<td></td>
<td>3.5×10⁻⁴</td>
</tr>
</tbody>
</table>

**Fig. 5** Soil DOC model simulation for validation in 2010 (Validation).

**Table 6** Performance of soil model simulation.

<table>
<thead>
<tr>
<th>Year</th>
<th>PBIAS(%)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>2.7</td>
<td>28</td>
</tr>
<tr>
<td>2008</td>
<td>5.6</td>
<td>25</td>
</tr>
<tr>
<td>2009</td>
<td>-7.4</td>
<td>30</td>
</tr>
<tr>
<td>2010</td>
<td>-16.7</td>
<td>22</td>
</tr>
</tbody>
</table>

Note: Year 2007 for calibration and year 2008-2010 for validation.
Table 7 DOC loads from observation and simulation and overall model performance.

<table>
<thead>
<tr>
<th>Year</th>
<th>Obs.</th>
<th>Sim.</th>
<th>PBIAS(%)</th>
<th>Duration(day)</th>
<th>Obs.</th>
<th>Sim.</th>
<th>PBIAS(%)</th>
<th>Duration(day)</th>
<th>LQ</th>
<th>PM</th>
<th>PBIAS(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD</td>
<td>2009</td>
<td>0.040</td>
<td>0.035</td>
<td>12.6</td>
<td>259</td>
<td>0.094</td>
<td>0.114</td>
<td>-21.5</td>
<td>106</td>
<td>20.3</td>
<td>21.2</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>0.061</td>
<td>0.043</td>
<td>30.0</td>
<td>254</td>
<td>0.122</td>
<td>0.124</td>
<td>-1.6</td>
<td>111</td>
<td>29.2</td>
<td>24.7</td>
</tr>
<tr>
<td></td>
<td>2011</td>
<td>0.050</td>
<td>0.044</td>
<td>12.2</td>
<td>268</td>
<td>0.243</td>
<td>0.138</td>
<td>43.2</td>
<td>97</td>
<td>37.0</td>
<td>25.1</td>
</tr>
<tr>
<td></td>
<td>2012</td>
<td>0.039</td>
<td>0.042</td>
<td>-7.1</td>
<td>281</td>
<td>0.108</td>
<td>0.129</td>
<td>-19.3</td>
<td>85</td>
<td>20.2</td>
<td>22.7</td>
</tr>
<tr>
<td>K2</td>
<td>2009</td>
<td>0.029</td>
<td>0.028</td>
<td>4.6</td>
<td>208</td>
<td>0.051</td>
<td>0.036</td>
<td>30.0</td>
<td>153</td>
<td>13.9</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>0.025</td>
<td>0.027</td>
<td>-11.4</td>
<td>184</td>
<td>0.051</td>
<td>0.034</td>
<td>33.9</td>
<td>181</td>
<td>13.8</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>2011</td>
<td>0.020</td>
<td>0.029</td>
<td>-46.5</td>
<td>200</td>
<td>0.082</td>
<td>0.034</td>
<td>57.8</td>
<td>165</td>
<td>17.4</td>
<td>11.4</td>
</tr>
<tr>
<td></td>
<td>2012</td>
<td>0.019</td>
<td>0.025</td>
<td>-32.4</td>
<td>205</td>
<td>0.047</td>
<td>0.035</td>
<td>25.4</td>
<td>161</td>
<td>11.4</td>
<td>10.8</td>
</tr>
</tbody>
</table>
however, there were restricted use for the simulations to recognise the temporal variations in long-term period only, i.e. at seasonal or inter-annual scales. The model newly developed in the present study hourly simulated the soil and stream water DOC concentrations and succeeded in demonstrating the DOC concentration decrease by rainfall and increase after the rain at short-term scale. As a consequence, stormflow contribution to DOC runoff can be effectively assessed with consideration of the wet-dry cycle and thereby highly accurate estimation of overall runoff load can be expected, particularly in areas with episodic rainfalls such as monsoon region.

**Impact of episodic rainfall on DOC runoff**

Stormflow had a tremendous impact on DOC export. Dissolved Organic Carbon concentrations during stormflow were constantly higher than those during baseflow, and the model simulation accordingly presented a large potential of stormflow in overall DOC runoff (Table 1 and Table 7). Contribution of stormflow was quantitatively analysed by delineating relationships between cumulative percentage of water flow period and correspondent cumulative percentage of DOC runoff load in the order of flow value from lowest to highest for four years (Fig. 6). The result showed that the relationship was not necessarily linear, and upper 27% and 47% of high flows were responsible for 50% of the total DOC load at MD and K2, respectively. Some researchers reported that between 41 – 61% of the total DOC exports were associated with the highest 10 – 22% of stream discharge [8,30]. Also, Bass et al. [31] indicated that 84% of total organic carbon was exported during significant discharge events that occurred only 9% of the time. These results were obtained based on intensively monitored data in limited number of seasons. However, they are still supportive to the results from our modelling, implying the persistent impact of episodic rainfall on an overall DOC runoff at yearly or even inter-yearly time scale.

**Development of DSA concept**

After undergoing DOC production processes in the soil, DOC is exported into the river as the water moves induced by rainfall runoff process. A “Variable Source Area (VSA)” concept was developed by Hewlett and Hibbert [32], which hypothesized that runoff contributing area changes in time because of expansion and shrink of saturated zone near land surface. The VSA concept has been actively referred by the researchers who applied it to the DOC runoff process analyses with consideration of the topography and landscape effects. Aitkenhead et al. [33] and Hope et al. [34] showed the strong correlation between DOC load and peat coverage rate. Another studies discussed the importance of organic-rich riparian soils [35,36] and wetland distribution [37,38] that significantly contribute to DOC export in forest catchments. In this study, a “DOC source area (DSA)” concept was newly proposed based on the hydrologic VSA and was introduced to the modelling system integrating soil and hydrology pro-
cesses for DOC runoff load estimation, in which subsurface flow \( (Q_{sf}) \) represented the DSA variability. The contribution of stormflow to total DOC load at MD was obviously larger than that at K2 as shown in Fig. 6 because of the different topography and landscape between the two sites. The site MD is located upstream with moderate slope and the riparian area alongside the stream channel is mostly in wet condition over the catchment. On the other hand, K2 consists of steeper slope and drier soil compared to MD and, consequently, DSA is not able to expand flexibly in response to rainfall. DOC Source Area was assumed to be adjacent to both soil surface and stream channel, and DOC generated in upper soil layer was exported by the subsurface flow through DSA as a major pathway. Although several researches previously emphasized the importance of wetland within a catchment [37,38], Hinton et al. [9] presented a conclusion that baseline DOC concentration was at high level and relative increase in DOC during storms was smaller in catchments with wetlands than in ones without wetlands. Spatial disconnection between wetland and stream channel, or remaining capacity of wetland to increase the DOC generation potential, were possible reasons in their study. The results from this study suggest that DSA is a useful concept for the interpretation of DOC runoff processes and also a critical factor for precisely estimating the runoff load in forested watershed.

**CONCLUSION**

A new numerical model was developed for determining DOC loads from forest streams via an estimation protocol that consists of two separate processes: runoff process and soil process. For runoff process, a semi-distributed hydrological modelling unit, ‘modified TOPMODEL,’ was installed through which surface and subsurface water flows that represent DOC source area (DSA) were sequentially simulated. For soil process, a wet-dry cycle was reasonably simulated by an advection-diffusion and dissolution formulation integrated with a root-zone water flux provided from a modified TOPMODEL calculation. Dissolved Organic Carbon runoff loads during baseflow periods were eventually estimated for both of the assessed study sites. The model results exhibited that stormflow clearly had a large impact on total DOC load, supposedly important implication in monsoon region with high frequency of episodic rainfalls. In addition, despite insufficient quantification in the present structure, DSA employed in the modelling could be a useful concept to evaluate the DOC runoff potential.

**ACKNOWLEDGMENTS**

The authors are thankful to Mr. Taihei Hanayama, Mr. Suguru Ishikura, Mr. Shuhei Hasumi and other laboratory members for supporting the field surveys and experimental efforts in this study. Gratitude is also due to Dr. Takuo Nagaike and Yamanashi Prefecture, as a whole, for providing the field in which the study was conducted. This research was funded by Research Grants from the Kurita Water and Environment Foundation (No. 15E041), the River Foundation from The River Foundation (No. 285311013) and Support for Regional Collaboration from the University of Yamanashi.

**REFERENCES**

[8] Hinton MJ, Schiff SL, English MC: The significance of storms for the concentration and export of dis-


