MODELLING HYDROLOGIC PROCESSES DISTRIBUTION IN A TROPICAL FOREST WATERSHED IN THE PHILIPPINES

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Received February 2009

INTRODUCTION

Recent concerns about global climate change have focused on the need to track the flow of water through the entire hydrologic cycle. Nowadays, hydrologic modelling has become an indispensable tool and cost-effective way in understanding the movement of water over the earth’s surface. A hydrologic process is described by Feng (2000) in various ways through mathematical equations. These may be empirical equations obtained by regression of data collected from the research area or systematic equations derived from physical laws and theories that describe the process. Maidment (1993) describes that the phenomena by these mathematical equations are a function of space, time and randomness which can either be modelled as a lumped or a distributed system. However, some authors tend to criticise the use...
of distributed and lumped models. Their main concern is the use of many parameters that can be altered during the calibration phase and may lead to subjectivity. Essentially, the application and adaptability of hydrologic models would always lead to confusion unless realistic calibration and parameter fittings are analytically accomplished in the given sites.

In the case of BROOK90 model, the model considered in this study, applications have been distinguished in the grassland and temperate evergreen and deciduous forests (Federer 2002), monoculture conifer stands into mixed or pure deciduous (Armbruster 2004), cultivated land (Wahren et al. 2007), silver fir-beech forest (Vilhar et al. 2006), mixed Norway spruce and European beech (Jost et al. 2005), and mixed coniferous forest (Combalicer et al. 2008) with satisfying agreement to its performance. Moreover, the application of this model is reliable in the tropical watersheds considering thorough evaluation of sensitive parameters suited to the local conditions. The hydrologic modelling studies under tropical conditions would have great response on small watershed such as in the case of the Molawin forest watershed.

The Molawin watershed is part of the Mount Makiling Forest Reserve, which is a densely vegetative secondary forest and well-researched ecosystem. Previous investigations have mostly focused on its water quality and sediment characteristics (Pasa 1997), hydrometeorological characterisation (Cruz 1982, Saplaco & Aquino 1991), microclimate profile (Saplaco 1983), landuse modelling (Anunciado 1993, Pudasaini 1993, Bantayan & Bishop 1998, Vallesteros 2002), carbon stocks assessment (Lasco et al. 2004, Han 2009), ecosystem structure and function (Lee 2008), and stand structure, soil respiration and properties (Bae 2008). The existing data sets may help to completely describe the hydrologic behaviour of the forest watershed. In addition, hydrologic processes have significant effects on the biotic and abiotic components of a watershed. Understanding these processes provides a logical viewpoint in analysing the watershed interaction with land, vegetation, water, man and other organisms.

The main purpose of this study was to assess the use of hydrologic model under a tropical forest’s watershed conditions. In addition, the study simulated the hydrologic processes distribution and described the inner track flow of water through the modelling process.

MATERIALS AND METHODS

The study area

The study was conducted at the Mount Makiling Forest Reserve located at 14° 9' to 14° 15' N latitude and 121° 9' to 121° 15' E longitude, and 65 km south-east of Metro Manila on Luzon Island in the Philippines (Figure 1). Specifically, the experimental site was situated within the Molawin watershed, a mountain landscape with fully vegetated areas and covering about 377 ha. The drainage pattern of the watershed is almost dentritic in appearance, in which most tributaries drain to the Laguna de Bay—the largest lake in the Philippines.

The climate is tropical monsoon with a short dry season. Annual rainfall and temperature range from 1645 to 2299 mm and 25 to 29.6 °C respectively. The topography of the site is moderately sloping and lies at the foot of Mount Makiling with an elevation of 100 m asl. The dominant soil type is clayey loam derived from the volcanic tuff with andesite and basalt base. The vegetation of the Molawin watershed is a gradient from lowland vegetation at the base, to a typical tall forest on lower elevations, to a crooked, stunted mossy forest at its peaks. Other characteristics of the watershed are summarised in Table 1.

The BROOK90 model

The BROOK90 model (Federer 2002) has a strong physically-based description, which simulates the above and below liquid phases of the precipitation–evaporation–streamflow–groundwater flow part of the hydrological cycle for a point scale stand on a daily time step. Further details are provided in the BROOK90 documentation files (Federer 2002, Federer et al. 2003). Mathematically, the BROOK90 model water distribution is expressed as follows:

\[ P = EVAP + FLOW + SEEP \]  

where P is the precipitation (mm), EVAP is the evaporation (mm), FLOW is the corresponding simulated total streamflow (mm) derived from surface flow and the groundwater flow, and SEEP is the deep seepage loss from groundwater (mm).

In the application of equation 1, the model calculates evaporation with the Shuttleworth–
Wallace equation (Shuttleworth & Wallace 1985), an improvement of the Penman–Monteith equation as well as the temporal and quantitative flow mechanisms within a catchment. It is considered as the sum of five components, namely, evaporation of intercepted rain, evaporation of intercepted snow, snow evaporation, soil evaporation and transpiration. However, evaporation in the study site was concentrated on three components in the absence of snow effects. For streamflow, it is given as:

\[
\text{FLOW} = \text{SRFL} + \text{GWFL}
\]  

(2)

where SRFL is the surface flow and GWFL is the groundwater flow. Equally, streamflow is generated using the following simplified processes: storm flow by source area flow or subsurface pipe flow and delayed flow from vertical or downslope soil drainage and first-order groundwater storage. Groundwater is assumed to be a first order reservoir as:

\[
\text{GWFL} = \text{GWAT}(1 - \text{GSP})
\]  

(3)

where GWAT is the groundwater storage below soil layers, GSC is the fraction of groundwater storage that is transferred to groundwater flow and deep seepage (SEEP) daily, and GSP is the fraction of groundwater discharge produced by GSC that goes to deep seepage and is not added to streamflow (FLOW). The soil–water
characteristics are defined using a modified approach of Brooks and Corey (1964), and Saxton et al. (1986) from 10 and 11 classified textural classes respectively. The water movement through the soil is simulated using the Darcy–Richards equation. The model considers water stored as intercepted rain, intercepted snow, snow on the ground, soil water from one to many layers and groundwater. Finally, in case of the seepage loss, it is calculated as:

$$SEEP = GWAT \times GSC \times GSP$$  \hspace{1cm} (4)

**Model calibration and parameterisation**

The calibration phase of the modelling was evaluated using a range of parameters along with the actual and derived values of variables related to streamflow, soil physical properties, watershed morphology, leaf area index and other canopy parameters. In principle, the calibration and parameterisation were done manually but most of the data and variable values were taken from the field, published documents, research outputs, and derived information through geographic information system and remote sensing. The approach was considered to avoid the subjectivity of model parameters especially at a watershed scale study. There was no generic optimisation method applied in this study. The fitting of parameters to measured data were only done as fine tuning. According to Federer (2002), in the case of the BROOK90 model, parameter fitting, whether done intuitively or mathematically can easily lead to incorrect parameterisation. The apparent effect of one parameter is used to correct for an incorrect value of a different parameter or for a poorly-functioning algorithm. Hence, it is important to clearly understand each parameter and what it does. Optimisation procedures generally should not be applied to models like the BROOK90 which uses many parameters.

The BROOK90 is a parameter rich model and lumped by six parameters, namely, location, flow, canopy, soil as well as fixed and initial parameters. The model is site specific and has given values for its initialisation run. The main concentration of the calibration and parameter fittings focused on the canopy, soil, location and flow parameter variables that conform to the appropriate local conditions of a watershed.

Values of different canopy variables were taken from published documents, land satellite imageries through remote sensing, and actual field observation and measurements (Table 2). The vegetation index using the ETM+ landsat imageries taken in 2002 was utilised to determine the degree of vigour and density of vegetation at the surface (Figure 2). In addition, the Normalised Difference Vegetation Index (NDVI), an index that provides a standardised method of comparing vegetation greenness among satellite imageries, was considered in correlating the overall maximum leaf area index (LAI) of the entire watershed. The LAI is one of the most important and probably sensitive parameters in the BROOK90 model. It is quite impossible to estimate in the field with complex vegetative types. In effect, vegetation index dynamics in time are correlated with the LAI and other functional variables (Wang et al. 2005). Pierce et al. (1993), as cited by Pullen (2000), described the NDVI–LAI relationship for broadleaf canopies that has been established empirically as follows:

$$LAI = \left(\frac{NDVI}{0.26}\right) \times 2$$  \hspace{1cm} (5)

In the case of soil parameters, values were generally estimated prior to running the model and were not fitted but were dependent on the soil profile and soil water properties. Composite soil sampling was considered by dividing the sampling area into subsampling areas based on the topographic locations along the drainage network. Soil samples were collected in varying soil depths considering the textural classes, organic matter and bulk density. These properties were all required information to determine the suitable parameter values in the BROOK90 model simulation. Soil parameter variables as presented in Table 3, namely, matric potential (PSIF), volumetric water content (THETAF), matrix porosity (THSAT), negative slope of the log (BEXP), and hydraulic conductivity at field capacity (KF) were derived from the Clapp and Hornberger (1978) soil water parameters table for forest soils in the BROOK90 documentation file. Further details were described by Federer (2002).

In this study, bulk densities ranged from 1.23 to 1.38 g cm\(^{-3}\), which THSAT values should be around 0.60. Forest soils have higher organic fraction in some horizons than agricultural soils. The THETA should be 0.40 to 0.85 of THSAT for each layer. Use of THETAF = 0.397 corresponds to silty clay loam, 0.425 equivalent to silty clay and 0.433 for clay texture in the watershed. The
Table 2  Final canopy parameter values suitable for the model in the Molawin watershed

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Range</th>
<th>Value from literature</th>
<th>Final value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALB</td>
<td>Albedo (f)</td>
<td>0.1–0.3</td>
<td>0.25&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.25</td>
</tr>
<tr>
<td>ALBSN</td>
<td>Surface reflectivity without and with snow on the ground (f)</td>
<td>0.1–0.9</td>
<td>0.15&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.10</td>
</tr>
<tr>
<td>KSNVP</td>
<td>Multiplier to reduce snow evaporation, arbitrary (f)</td>
<td>0.2–2.0</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td>Z0G</td>
<td>Ground surface roughness (m)</td>
<td>≥ 0.001</td>
<td>1.5&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.02</td>
</tr>
<tr>
<td>MAXHT</td>
<td>Maximum canopy height for the year (m)</td>
<td>&gt; 0.01</td>
<td>-</td>
<td>35</td>
</tr>
<tr>
<td>MAXLAI</td>
<td>Maximum projected LAI for the year (m&lt;sup&gt;2&lt;/sup&gt;/m&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>&gt; 0.00001</td>
<td>10.20&lt;sup&gt;c&lt;/sup&gt;</td>
<td>5.31</td>
</tr>
<tr>
<td>MXRTLN</td>
<td>Maximum length of fine roots per unit ground area (m m&lt;sup&gt;-2&lt;/sup&gt;)</td>
<td>1700–11000</td>
<td>3000&lt;sup&gt;e&lt;/sup&gt;</td>
<td>4000</td>
</tr>
<tr>
<td>MXKPL</td>
<td>Maximum plant conductivity (mm day&lt;sup&gt;-1&lt;/sup&gt; MPa&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>5–30</td>
<td>8&lt;sup&gt;e&lt;/sup&gt;</td>
<td>15</td>
</tr>
<tr>
<td>FXYLEM</td>
<td>Fraction of the internal plant resistance to water flow that is in the xylem (f)</td>
<td>0–0.99</td>
<td>0.5&lt;sup&gt;e&lt;/sup&gt;</td>
<td>0.5</td>
</tr>
<tr>
<td>CS</td>
<td>Ratio of projected stem area index (SAI) to height (f)</td>
<td>≥ 0</td>
<td>0.035&lt;sup&gt;e&lt;/sup&gt;</td>
<td>0.035</td>
</tr>
<tr>
<td>PSICR</td>
<td>Minimum plant leaf water potential (MPa)</td>
<td>-1.5–3.0</td>
<td>-2.0&lt;sup&gt;f&lt;/sup&gt;</td>
<td>-2.0</td>
</tr>
<tr>
<td>GLMAX</td>
<td>Maximum leaf conductance (cm s&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>0.2–2.0</td>
<td>2.0&lt;sup&gt;f&lt;/sup&gt;</td>
<td>0.53</td>
</tr>
<tr>
<td>LWIDTH</td>
<td>Average leaf width (m)</td>
<td>&gt; 0.01</td>
<td>-</td>
<td>0.25</td>
</tr>
<tr>
<td>CR</td>
<td>Extinction coefficient for photosynthetically-active radiation in the canopy (f)</td>
<td>0.5–0.7</td>
<td>0.6&lt;sup&gt;f&lt;/sup&gt;</td>
<td>0.6</td>
</tr>
</tbody>
</table>

<sup>a</sup> Ito & Oikawa (2002)  
<sup>b</sup> Oh (1999)  
<sup>c</sup> Luo et al. (2002)  
<sup>d</sup> Scurlock et al. (2001)  
<sup>e</sup> Federer (2002)  
<sup>f</sup> Federer et al. (1996)  
<sup>g</sup> Harris et al. (2004)

Figure 2  Leaf area index derived from the NDVI of the ETM+ land satellite imageries in 2002 at the Mt. Makiling Forest Reserve
hydraulic conductivity at some unsaturated water content was difficult to determine. In the absence of detailed soil information, representative values in BROOK90 model were utilised in the watershed. Applying values ranging from 4.2 to 4.9 mm day\(^{-1}\) were recommended representing the textural classes in the area.

Overall, data sets were prepared for the calibration (2004–2006) combining a final parameter set values appropriate to a watershed. Results of the calibration using final parameter sets were also used for the validation period (2007–2008) in the Molawin watershed. However, no data from January till June 2007 were taken because of the structural damage caused by a strong typhoon that happened in 2006.

**Streamflow monitoring**

Five-year’s measurement of the water level and flow velocity was considered in the experimental watershed. An OTT Thalimedes logger was installed to automatically monitor the daily water level. The digital flow probe was used for flow velocity measurement, which was mostly taken during wet seasons. In effect, the stage–discharge relationship was established over time by developing a rating curve.

**Rating curve development**

The stage–discharge relationship for the Molawin gauging station was derived using a set of discharge measurements and corresponding water levels on the flume with the zero stream gradient (Figure 3). Flow velocities were considered at the variation in water level at the time of measurements. Discharges were in good agreement with the water depths \( (r^2 = 0.97) \) and indicated the good reliability of the method employed. The derived regression model appeared to be not overestimating the stream discharges particularly during the high flow conditions. From the regression model, the daily observed stream discharge in the watershed found a range of 0.01 to 13.96 m\(^3\) s\(^{-1}\) with an annual mean discharge of about 0.11 m\(^3\) s\(^{-1}\) in the 5-year measurement. The derived local stage–discharge relationship is expressed in a power regression as:

\[
y = 2.271x^{1.804} 
\]

where \( y \) is the stream discharge (m\(^3\) s\(^{-1}\)) and \( x \) is the water depth (m).

**Sensitivity analysis**

The model sensitivity was tested under various conditions particularly to canopy variables, which evidently affected the entire simulation outcomes. Condition no. 1 denotes a 15% decrease to all variables having indirect response and 15% increase for variables with the direct response. Condition no. 2 means a 25% decrease to all variables having indirect response and 25% increase for variables with the direct response. Condition no. 3 is equivalent to a 15% increase to all variables having indirect response and 15% decrease for variables with the direct response. Condition no. 4 implies a 25% increase to all variables having indirect response and 25% decrease for variables with the direct response.

A sensitivity analysis was considered to determine how changes in the value of parameters and changes in the structure affect the model. It was performed to identify which parameters would be responsive during the
model predictions and what type of relationship they have for the water balance component simulation under the tropical forest watershed conditions. The BROOK90 model is composed of complex analytical parameters. A combination of the final parameter sets was utilised as baseline information responding to possible increased and decreased changes in parameter values in the model. Each variable was identified according to the lower and upper range of values to find the numerical input limitations of the model. For instance, canopy parameters were effectively examined under the two potential conditions and structures. Similarly, soil conditions according to soil series were considered as likely changes to the area. The equivalent soil textural range was estimated using the Clapp and Hornberger (1978), and Saxton and Rawls (2006) soil equations in different iterations.

RESULTS AND DISCUSSION

The BROOK90 model performance

Table 4 shows the model performance responding to streamflow values during calibration and validation periods at the Molawin watershed. The average annual rainfall during the calibration period was 1908 mm while during the validation, 1940 mm. The rainy season with average monthly precipitation values greater than 150 mm was very pronounced from June till December in both periods. For streamflow characteristics, the average annual streamflow was slightly lower during the calibration (899 mm) compared with the validation (1131 mm) events. Results of the total streamflow simulation showed a satisfying agreement against observed values using the final parameter sets of the BROOK90 model. Essentially, the seasonal relative error between observed and simulated values for the calibration period was very minimal at 1.0% on an annual average streamflow, 98.5% for summer flows and -8.5% for wet flows. Similarly, discrepancies for total streamflows were about 1.4% in the validation period but the seasonal performance has improved to 19.9% for summer flows and -4.4% for rainy flows. This situation was most likely attributed to the extended rains and early typhoon event that occurred in January 2008. Overall, streamflow simulation appeared slightly overestimated in dry seasons while the rest of the year was occasionally underestimated in both periods. Effects of groundwater below soil layers of the model were mainly the source of streamflows in response to the simulation for the period of low flows. Nevertheless, a small discrepancy on an annual basis could be distinguished in high flow simulations throughout observation periods.

The model efficiency criteria were described as statistical measurements of how well a model simulation fits the available observations (Beven 2001). In this study, the monthly coefficient of determination ($r^2$) was high (0.87) for both periods, while daily streamflows also indicated a better relationship between the measured and simulated streamflows (Figure 4). Similarly, the simulation demonstrated positive and high Nash–Sutcliffe coefficients on the daily and monthly

![Figure 3](image_url)  
**Figure 3** The derived rating curve in the Molawin watershed
Table 4 Model performance response to streamflow simulations for the Molawin tropical forest watershed during calibration and validation periods

<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured (mm)</td>
<td>Simulated (mm)</td>
</tr>
<tr>
<td></td>
<td>Measured (mm)</td>
<td>Simulated (mm)</td>
</tr>
<tr>
<td>Average annual streamflow</td>
<td>899.4</td>
<td>908.3</td>
</tr>
<tr>
<td>Seasonal flow variation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry (Jan–May)</td>
<td>83.8</td>
<td>162.5</td>
</tr>
<tr>
<td>Wet (June–Dec)</td>
<td>837.8</td>
<td>745.8</td>
</tr>
<tr>
<td>Average annual rainfall (mm)</td>
<td></td>
<td>1908</td>
</tr>
</tbody>
</table>

However, the daily coefficient during the validation had higher satisfying agreement compared with the calibration period. This condition probably leads to an underestimation of the model performance during peak flows and over estimation during low flows. It should be noted that the total precipitation on the site was lower during calibration. Results of fairly high Nash–Sutcliffe efficiency indices signified that the mean value of the observed streamflow would have a better relation to the modelled values.

**Sensitivity of the model**

Figure 5 exhibits sensitivity of the BROOK90 model that responds to changes in canopy variables. In case of the streamflow behaviour, the model has indicated inverse relationships of most sensitive variables into the variation of albedo, maximum canopy height, maximum leaf area index, plant conductivity, maximum leaf conductance and input parameters–temperatures (T
\(_2\)). In contrast, the average leaf width and length of fine roots per unit ground area as variables have shown their direct relationship to the streamflow simulation. Essentially, the calibrated model appeared highly responsive during high flows, while it was unaffected for the duration of flows. An opposite response against the flow simulation was also found in terms of evaporation losses wherein changes in input values were markedly reflected as evaporation fluctuations during months with high transpiration rate. The belowground response, especially seepage losses, was affected under conditions 3 and 4 in parameter variables input but not sensitive to changes in conditions 1 and 2 variable values. As a result, conditions 1 and 2 of the identified sensitive variables led to an increased mean annual streamflow ranging from 8 to 11%, declined evaporation losses of about 3 to 4%, and minimal decrease in seepage loss. In contrast, conditions 3 and 4 confirmed a minimal decrease in annual flow ranging from 2 to 4%, increase in evaporation rate of about 7%, and 20 to 21% annual losses turned into seepage. Moreover, changes in soil conditions greatly affected the simulation performance. Estimated flows reasonably increased when soil conditions on site changed to closer sand-clay-loam class, while a large disparity was observed when soil closely resembled the clay-loam textural type. Canfield and Lopez (2000) found the same observation relative to the recognised sensitive parameters. Overall, increase and decrease in streamflow, evaporation, surface flow and ground flow were influenced by these identified sensitive factors.

**Hydrologic processes distribution and partitioning**

Figure 6 shows the illustrative distribution and partitioning of the different hydrologic processes under the Molawin tropical forest watershed conditions. Precipitation is the immediate source of all water entering the land phase of all hydrologic cycles (Saterlund 1972). The average annual rainfall for the 5-year period (2004–2008) in the University of the Philippines National Agro-meteorological Station was 1908 mm. On an annual basis, approximately 41% of the precipitation turned into evaporation, 49% became streamflow and 10% turned into deep seepage. Outcomes of the streamflow simulation are likely affected by the increasing rate of surface flow (SRFL) and saturated groundwater.
The model mechanisms assume that upon reaching the floor, rainwater may enter the soil through infiltration (INFL) or flow over the surface as overland flow. A large portion of the precipitation remains streamflow mainly through SRFL and GWFL, which had contributed to roughly 583 mm (31%) and 359 mm (19%) respectively. For evaporation, a portion of rain falling on a forest was intercepted by the canopy, the understory and ground vegetation and then evaporated back to the atmosphere. Total evaporation losses in the watershed accounted for 773 mm, which were largely influenced by transpiration (TRAN) (25%), interception loss (RINT) (8.3%), and soil evaporation (SLVP) (7.2%). With regard to the belowground liquid component, the total seepage loss estimated was about 193 mm, which was derived from interactions of the GWAT, GSC and GSP.

The distribution of hydrologic components is primarily reflected on a pronounced seasonal variation and the fluctuating patterns in precipitation (Figure 7). It can be seen that the mean monthly streamflow for the study
period also fluctuates from month to month following closely that of mean monthly rainfall. However, streamflows during the later months were higher because of groundwater saturation, hence, strongly responded to high rainfall events. An average annual streamflow of 942 mm was accounted with two distinct peak flows that occurred in September (129 mm) and December (183 mm) while the lowest was recorded in April (17 mm). The groundwater flow and seepage had analogous patterns with high flow from November till February and declined the rest of the year. It was surprising that during the dry period (January–April), the streamflow amount remained higher as compared with evaporation losses due to the high groundwater flow contribution (39–98% of the flow) even though negligible surface flow. This unique occurrence is a characteristic of tropical rainforest watershed. Wu and Johnston (2008) further described that forests rely on soil moisture stores or have access to groundwater. A given watershed has favourable soil moisture measuring 33.9 ± 3.4 for dry season and 38.4 ± 3.7 for wet season (Bae 2008).

Figure 5  Sensitivity of the model on (a) streamflow, (b) evaporation and (c) seepage loss responded to changes in canopy variables.
Figure 6  The illustrative distribution and partitioning of different hydrologic processes in the Molawin tropical forest watershed. The RFAL = rainfall, RINT = rainfall catch rate, INTR = intercepted rain, RTHR = rain through fall, RNET = rain net to soil, SRFL = surface flow, SLFL = soil infiltration, BYFL = bypass flow, DSFL = downslope flow, VRFL = vertical flow layer, GWFL = groundwater flow, IRVP = evaporation rate of intercepted rain, SLVP = soil evaporation, TRAN = transpiration, SWAT = total soil water in all layers and GWAT = groundwater storage.

Figure 7  Simulated average monthly distribution of different hydrologic processes in the Molawin tropical forest watershed.
However, the streamflow greatly contributed about 31 to 85% for the duration of rainy seasons by high rate of the surface flow. Overall, there is a continuous streamflow throughout the year and its fluctuation pattern is directly dependent on the amount of precipitation in the watershed.

The monthly water distribution variations demonstrate how evaporative losses greatly affect streamflow components of a forested watershed. High evaporation losses (> 100 mm) regularly occurred from June till September and low for the rest of the year. Similarly, the amount of evaporation was higher than streamflow from April till September, equivalent to 47–74% of the precipitation. In essence, the significant increase in evaporation losses were mainly controlled by transpiration and evaporation from the intercepted rain throughout the rainy season while evaporation from the soil dominated during the dry season. Results indicated that 29 to 58% of the evaporation was caused by transpiration while 7 to 16% was released through evaporation from the intercepted rain. Correspondingly, about 14 to 63% of the evaporation was contributed by soil evaporation during the dry season. In this process, Federer (2002) further described that in vegetated systems, evaporation is dominated by transpiration and controlled largely by the maximum leaf conductance when soil remains reasonably wet. However, the decrease in the transpiration rate from September till December was probably due to microclimate conditions in the given forest watershed. Lee (2006) and Bae (2008) reported that onsite relative humidity, air temperature and soil temperature during the given months were on the average 76.9%, 26.3 °C and 24.9 °C respectively. These cooler microclimate conditions led to the decrease in transpiration and soil evaporation. In the BROOK90 model, the evaporation simulation is noted as the sum of five factors. The evaporation from the intercepted snow and snow evaporation were disregarded in which there was no significant interaction that took place in the watershed.

One way to evaluate outcomes of the hydrologic processes distribution in the Molawin watershed was to compare the results of other studies under tropical conditions. Results of these studies are summarised in Table 5. The

### Table 5
Comparison of annual estimates for various hydrologic processes in different tropical rainforest watersheds

<table>
<thead>
<tr>
<th>Location</th>
<th>Rainfall (mm)</th>
<th>Flow (mm)</th>
<th>Interception loss (mm)</th>
<th>ET (mm)</th>
<th>TRAN (mm)</th>
<th>Seepage / storage (mm)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>A hilly evergreen forest site in Kog-Ma, Thailand</td>
<td>1768</td>
<td>812</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tanaka et al. (2008)</td>
</tr>
<tr>
<td>Forested watersheds in central Taiwan</td>
<td>2500</td>
<td>1200</td>
<td>450</td>
<td>1350</td>
<td>650</td>
<td></td>
<td>Cheng et al. (2002)</td>
</tr>
<tr>
<td>Sungai Jelai watershed, Peninsular, Malaysia (1973–1985)</td>
<td>2058</td>
<td>748</td>
<td>1014</td>
<td></td>
<td></td>
<td></td>
<td>Mun (1987)</td>
</tr>
</tbody>
</table>

ET = evapotranspiration, TRAN = transpiration
CONCLUSIONS

Outcomes of the modelling have clearly shown the illustrative distribution of different hydrologic processes and characterised the hydrograph of the watershed. The iteration of the BROOK90 model under tropical watershed conditions is certainly easier since it deals only with two distinct seasons. The calibration approach offers great agreement at the catchment scale by avoiding the subjectivity of the parameter values.

Modelling remains a valuable tool that provides realistic estimates to quantify hydrologic processes involved in a watershed system. However, modellers are always encouraged to utilise multiple data sets and warned to keep away from using hypothetical values to generalise real situations. Application of the model to climate change investigations is highly recommended but it must also note the impact of land cover of the watershed through time. The comparison of the BROOK90 lumped modelling system with any distributed physically-based system and intermediate hydrologic model approach will surely be interesting.

ACKNOWLEDGEMENTS

This study was the initiative of the Center for Restoration of Forest Ecosystem Functions on Different Forest Zones (CERES) project headed by DK Lee, Seoul National University, with the support of Forest Science and Technology Projects (Project No. S210608L0101704C) provided by Korea Forest Service.

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