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

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COMBALICER EA, CRUZ RVO, LEE SH & IM S. 2010. Modelling hydrologic processes distribution in a tropical forest watershed in the Philippines. Hydrologic modelling has become an indispensable tool and cost-effective process in understanding the movement of water loss in the Molawin rainforest watershed, Philippines. The study aimed to optimise the use of a lumped BROOK90 model and simulate the hydrologic processes distribution in a given watershed. The rating curve model was developed as a basis for hydrologic modelling. The model was calibrated at catchment scale to avoid subjectivity of various variable parameters by considering the topography, morphology, climate, soil and canopy characteristics. Five years of streamflow discharge measurements were considered for the model sensitivity analysis, calibration and validation. Results showed a good agreement between observed and simulated streamflows during calibration (r = 0.87 and E = 0.87) and validation (r = 0.84 and E = 0.81) periods. As a consequence, the major hydrologic processes distribution accounted for 41% of the precipitation that turned into evaporation, while 49% became streamflow and 10% remained in deep seepage loss. Overall, the distribution of hydrologic components is primarily reflected during pronounced seasonal variations and fluctuating patterns in precipitation.

Keywords: BROOK90 model, lumped model, Molawin watershed, precipitation partitioning, water loss

COMBALICER EA, CRUZ RVO, LEE SH & IM S. 2010. Model taburan proses hidrologi di dalam legeh hutan tropika di Filipina. Model hidrologi telah menjadi alat yang sangat diperlukan dalam pemahaman tentang pergerakan air yang hilang di dalam legeh hutan tropika Molawin di Filipina. Model hidrologi juga merupakan satu proses keberkesanan kos dalam memahami kehilangan air. Kajian ini bertujuan untuk mengoptimumkan penggunaan model BROOK90 berkelompok dan merangsang taburan proses hidrologi di dalam sesuatu legeh. Model lekuk kadar dibangunkan sebagai asas bagi model hidrologi. Model ditentukurkan pada peringkat tadahan untuk mengelakkan kesubjektifan pelbagai parameter dengan mengambil kira topografi, morfologi, iklim, ciri-ciri tanah dan kanopi. Ukuran luahan aliran sungai selama lima tahun dipertimbangkan untuk analisis kepekaan model, tentukuran dan pengesahan. Keputusan menunjukkan persamaan antara nilai aliran sungai yang dicerap dengan nilai yang dikira semasa tentukuran (r = 0.87 dan E = 0.87) dan semasa pengesahan (r = 0.84 dan E = 0.81). Akibatnya, taburan proses hidrologi yang utama menunjukkan bahawa 41% daripada titisan akan hilang melalui sejatan, 49% menjadi aliran sungai dan 10% kekal sebagai peresapan dalam. Secara amnya, taburan komponen hidrologi jelas semasa perubahan musim yang ketara dan perubahan corak titisan.

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

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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), hydrometereological 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 2006), 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:

$$P = EVAP + FLOW + SEEP \qquad (1)$$

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–

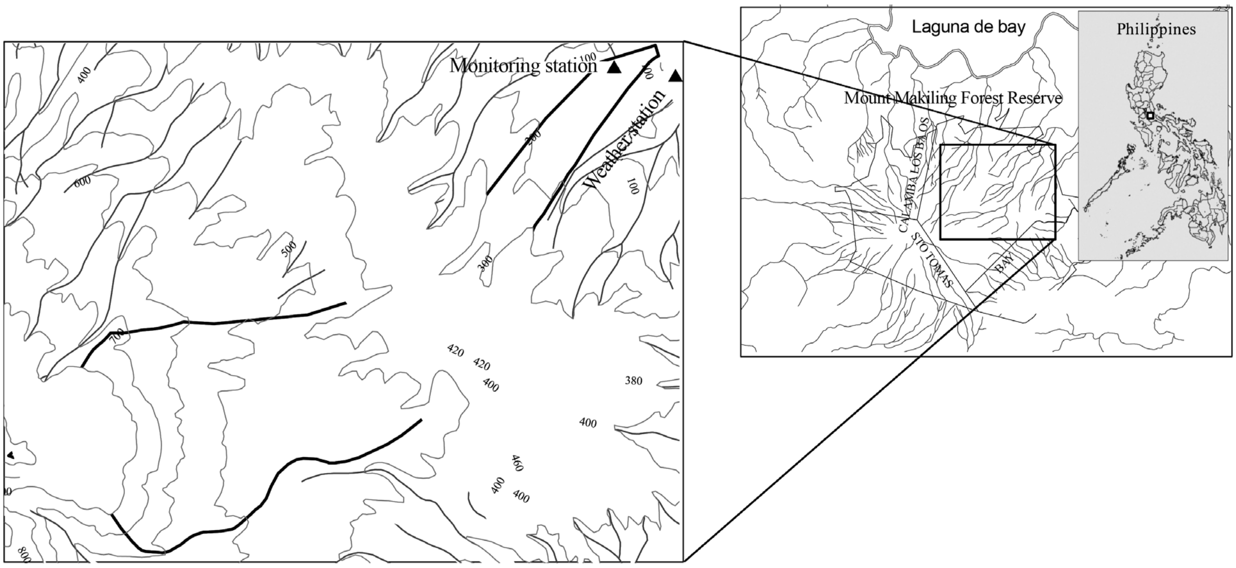

Figure 1 Location of the study site and monitoring station

Table 1 Principal and morphological characteristics of the Molawin watershed

Catchment area	377 ha
Average slope	31.8%
Elevation range	40–1040 m asl
Drainage density	1.71 km km^{-2}
Drainage pattern	Dentritic
Annual discharge range	29.8–59.3 $m^3 s^{-1}$
Annual rainfall range	1645–2299 mm
Mean temperature range	25–29.6 °C
Soil moisture regime	Andesite and basalt base
Soil texture	Dominantly clay loam
Forest type	Secondary forest

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:

$$FLOW = SRFL + GWFL \quad (2)$$

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:

$$GWFL = GWAT \times GSC \times (1 - GSP) \quad (3)$$

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:

$$\text{SEEP} = \text{GWAT} \times \text{GSC} \times \text{GSP} \qquad (4)$$

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:

$$\text{LAI} = \left(\frac{\text{NDVI}}{0.26}\right) \times 2 \qquad (5)$$

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 THETAF 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

Parameter	Description	Range	Value from literature	Final value
ALB	Albedo (f)	0.1–0.3	0.25[a]	0.25
ALBSN	Surface reflectivity without and with snow on the ground (f)	0.1–0.9	0.15[a]	0.10
KSNVP	Multiplier to reduce snow evaporation, arbitrary (f)	0.2–2.0	-	0.3
Z0G	Ground surface roughness (m)	≥ 0.001	1.5[b]	0.02
MAXHT	Maximum canopy height for the year (m)	> 0.01	-	35
MAXLAI	Maximum projected LAI for the year (m^2 m^{-2})	> 0.00001	10.20[c] 6.91[c] 5.91[d]	5.31
MXRTLN	Maximum length of fine roots per unit ground area (m m^{-2})	1700–11000	3000[e] 3500[f]	4000
MXKPL	Maximum plant conductivity (mm day^{-1} MPa^{-1})	5–30	8[g,e]	15
FXYLEM	Fraction of the internal plant resistance to water flow that is in the xylem (f)	0–0.99	0.5[e]	0.5
CS	Ratio of projected stem area index (SAI) to height (f)	≥ 0	0.035[e]	0.035
PSICR	Minimum plant leaf water potential (MPa)	-1.5–3.0	-2.0[e]	-2.0
GLMAX	Maximum leaf conductance (cm s^{-1})	0.2–2.0	2.0[g] 0.53[f]	0.53
LWIDTH	Average leaf width (m)	> 0.01	-	0.25
CR	Extinction coefficient for photosynthetically-active radiation in the canopy (f)	0.5–0.7	0.6[f]	0.6

[a] Ito & Oikawa (2002)
[b] Oh (1999)
[c] Luo *et al.* (2002)
[d] Scurlock *et al.* (2001)
[e] Federer (2002)
[f] Federer *et al.* (1996)
[g] Harris *et al.* (2004)

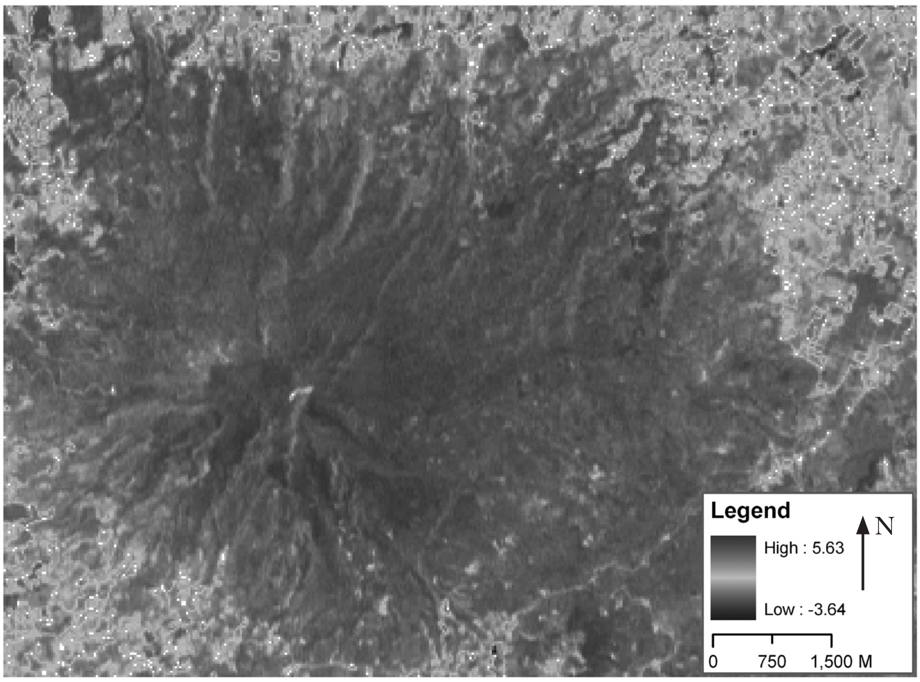

Figure 2 Leaf area index derived from the NDVI of the ETM+ land satellite imageries in 2002 at the Mt. Makiling Forest Reserve

Table 3 Derived soil parameter values for the model used in the watershed

Layer no.	Thickness (THICK), mm	Stone volume fraction (STONEF), f	Matric potential (PSIF), kPa	Volumetric water content (THETAF), $m^3 m^{-3}$	Matrix porosity (THSAT), $m^3 m^{-3}$	Negative slope of the log psi (BEXP)	Hydraulic conductivity (KF), mm day^{-1}
1	200	0	-6.0	0.397	0.60	7.75	4.9
2	400	0	-7.7	0.425	0.60	11.4	4.3
3	600	0	-7.7	0.425	0.60	11.4	4.3
4	800	0	-7.7	0.425	0.60	11.4	4.3
5	1000	0	-6.5	0.433	0.60	10.4	4.2

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:

$$y = 2.271x^{1.804} \quad (6)$$

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

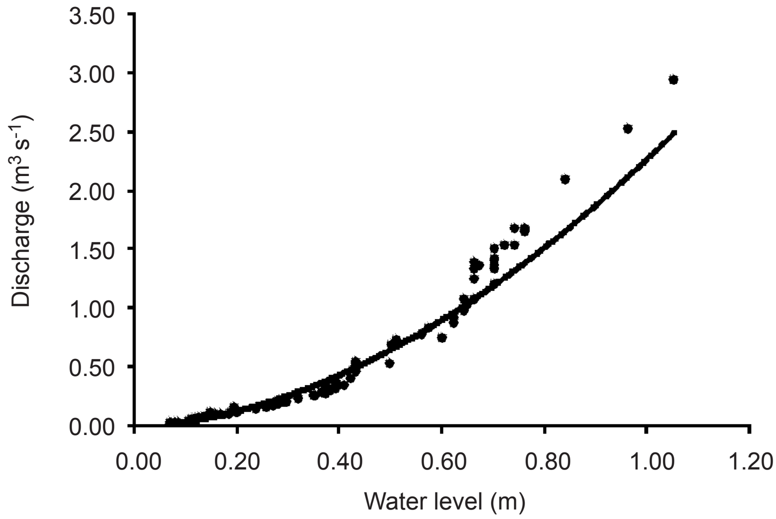

Figure 3 The derived rating curve in the Molawin watershed

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

Table 4 Model performance response to streamflow simulations for the Molawin tropical forest watershed during calibration and validation periods

Characteristic	Calibration (2004–2006)			Validation (2007–2008)		
	Measured (mm)	Simulated (mm)	Relative error (%)	Measured (mm)	Simulated (mm)	Relative error (%)
Average annual streamflow	899.4	908.3	1.0	1130.9	1146.8	1.4
Seasonal flow variation						
Dry (Jan–May)	83.8	162.5	98.5	270.1	323.9	19.9
Wet (June–Dec)	837.8	745.8	-8.5	860.8	822.9	-4.4
Average annual rainfall (mm)		1908			1940	

bases. 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 loss. Outcomes of the streamflow simulation are likely affected by the increasing rate of surface flow (SRFL) and saturated groundwater

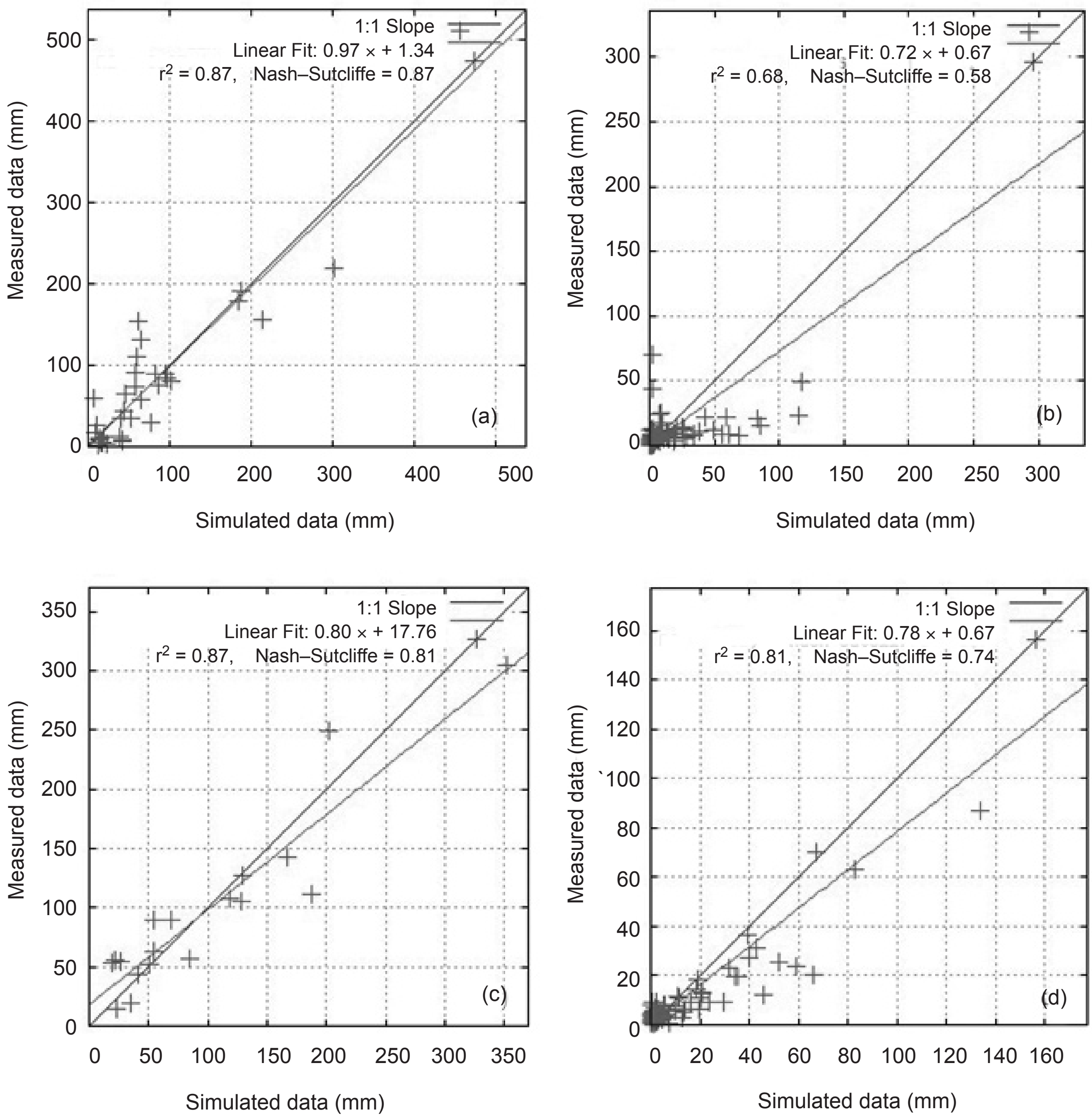

Figure 4 The model performance coefficient during monthly (a) and daily (b) calibration, and monthly (c) and daily (d) validation periods

flow (GWFL). 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 understorey 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

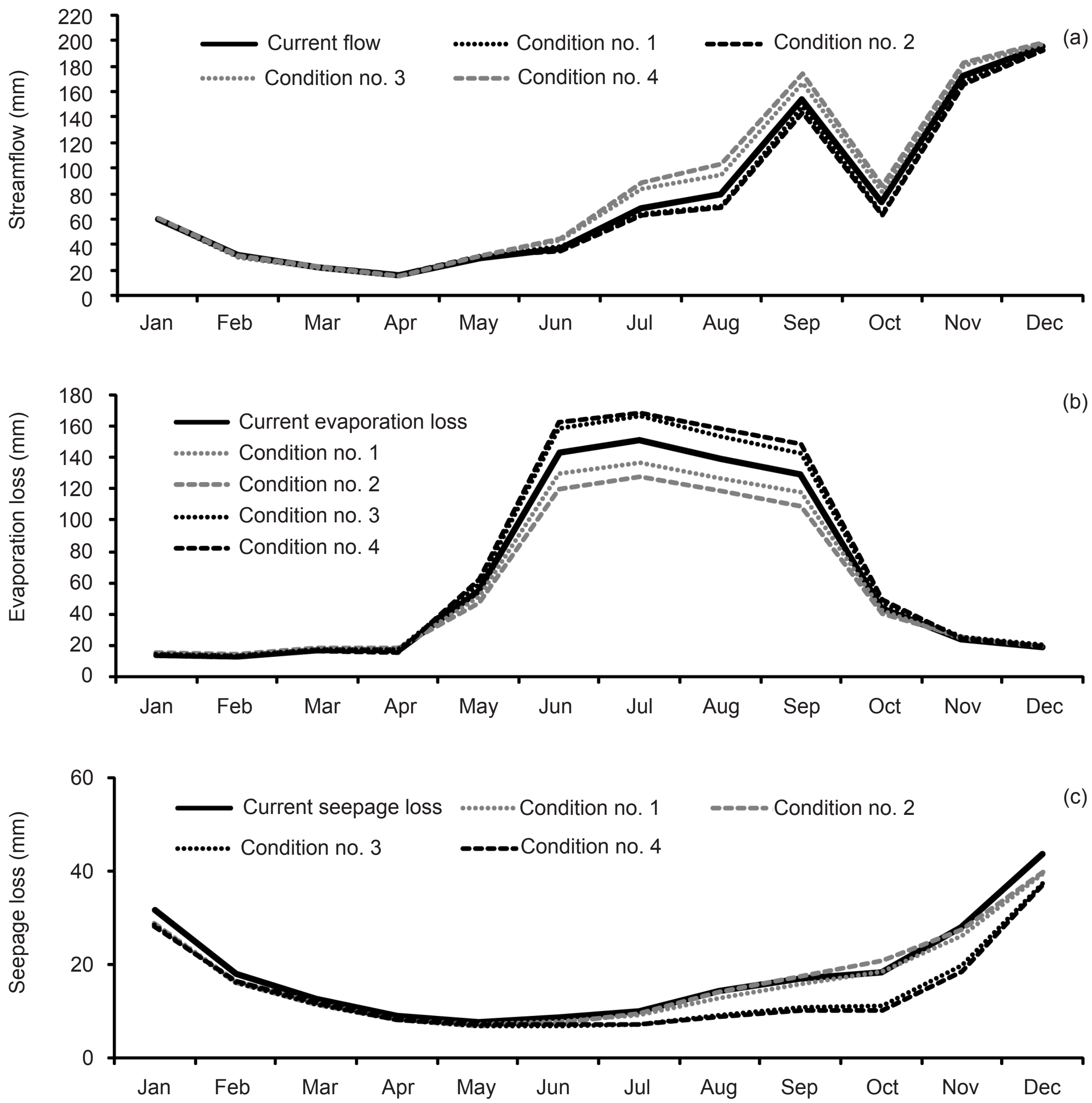

Figure 5 Sensitivity of the model on (a) streamflow, (b) evaporation and (c) seepage loss responded to changes in canopy variables

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).

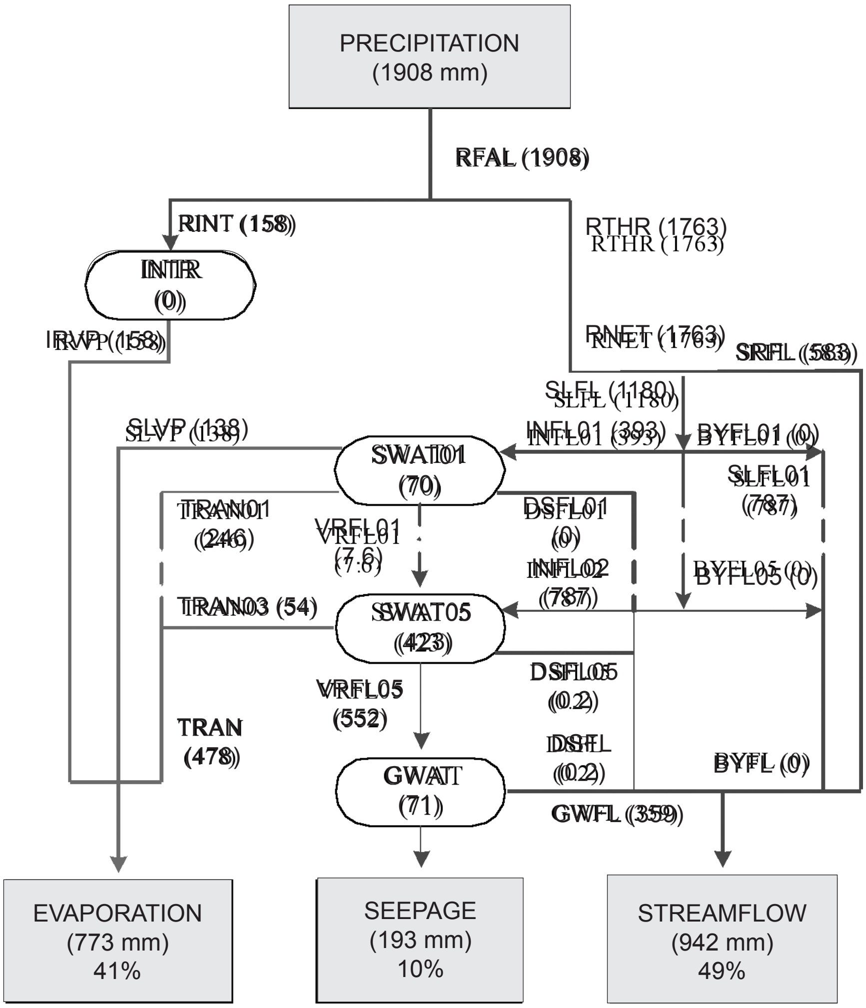

Figure 6 The illustrative distribution and partitioning of different hydrologic processes in the Molawin tropical forest watershed. The RFAL = rainfall, RINT = rainfall catch rate, INTR = intercepted rain, RTHR = rain through fall, RNET = rain net to soil, SRFL = surface flow, SLFL = soil infiltration, 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

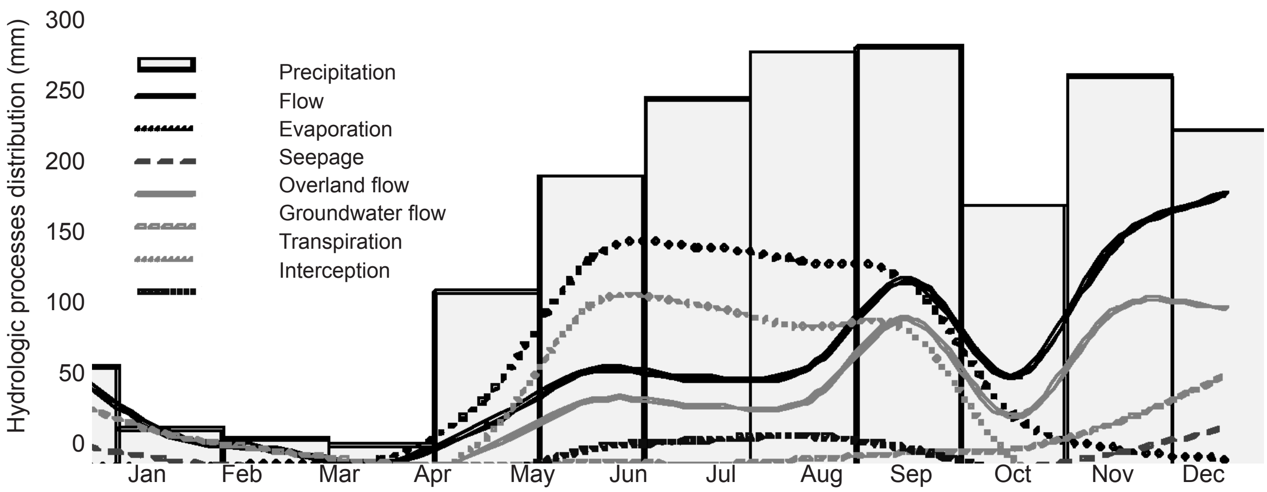

Figure 7 Simulated average monthly distribution of different hydrologic processes in the Molawin tropical forest watershed

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

Location	Hydrologic process						Source
	Rainfall (mm)	Flow (mm)	Interception loss (mm)	ET (mm)	TRAN (mm)	Seepage / storage (mm)	
Molawin watershed, Philippines (2004–2008)	1908	942 (49%)	158 (8%)	773 (41%)	478 (25%)	193 (10%)	Present study
A hilly evergreen forest site in Kog-Ma, Thailand	1768			812 (46%)			Tanaka *et al.* (2008)
Forested watersheds in central Taiwan	2500	1300 (52%)	450 (18%)	1200 (48%)	650 (26%)		Cheng *et al.* (2002)
A rain forest region of eastern Amazonia, Brazil (1992–1993)	2706		406 (15%)	1350 (50%)			Klinge *et al.* (2001)
Lien-Hua-Chi watershed, central Taiwan (1990–1991)	2708		307 (11%)				Lu & Tang (1995)
Sapulut watershed, Malaysia (1991–1992)	2418 - 2222		504 – 473 (21%)				Kuraji (1996)
Sungai Jelai watershed, Peninsular, Malaysia (1973–1985)	2058	748 (36%)		1014 (49%)		296 (14%)	Mun (1987)
Janlappa nature reserve, West Java, Indonesia (1980–1981)	2833		595 (21%)	1481 (52%)	886 (31%)		Calder *et al.* (1986)

ET = evapotranspiration, TRAN = transpiration simulated hydrologic processes distribution and partitioning over given periods were most likely within an acceptable range. For example, Tanaka *et al.* (2008) recently accounted 46% annual evapotranspiration (ET) at a hill evergreen forest site in Kog-Ma, Thailand. Cheng *et al.* (2002) found a comparable distribution of the streamflow (52%), interception loss (18%), ET (48%) and transpiration (26%) in four forested watersheds in Taiwan. However, the estimated interception loss of the present study was slightly lower than that of Lu and Tang (1995) in the natural hardwood forest in central Taiwan, Klinge *et al.* (2001) in a rainforest region of eastern Amazon, Brazil, Kuraji (1996) in the Sapulut watershed, Malaysia and Calder *et al.* (1986) in West Java Indonesia's tropical rainforest. The low interception loss can be attributed to the lower available amount of precipitation in the Molawin watershed as compared with watershed sites from previous investigations. Given the precipitation amount, a slightly lesser proportion of ET losses was estimated in the watershed while transpiration and seepage were close to the later outcomes.

In the Philippines, most of the investigations were reported decades ago and not in typically forested watershed setting. For example, Galvez (1976) accounted that 46% precipitation evaporated in the Central Luzon basin. Tingsanchali *et al.* (1976) reported that 54% of the annual rainfall contributed to streamflow, 43% turned into evapotranspiration and 3% recharged to groundwater in the Bicol river basin. Clemente (1991) reported 43% surface runoff, and 57% was shared by change in storage, evapotranspiration, paddy flow and deep percolation from a small agricultural watershed in Iloilo. Early *et al.* (1980), who investigated the upland water balance of a rice producing watershed, indicated that 13% of rainfall was measured as seepage outflow, 19% as controlled surface runoff, 54% potential ET and 10% residual deep percolation.

The above studies had all indicated that water loss through interception and transpiration in the forest watershed was large enough to cause a reduction in surface runoff and subsequently streamflow. Overall, it is reasonable to say that in tropical watersheds average loss of water was in the range of 36 to 52% for streamflow, 8 to 21% for interception, 41 to 52% for evapotranspiration, 25 to 31% for transpiration and 10 to 14% for deep seepage loss.

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.

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REFERENCES

Anunciado IML. 1993. Influence of forest land use change on agricultural production: the case of Sipit watershed Mount Makiling, Philippines. MSc thesis, University of the Philippines Los Banos, College.

Armbruster MK, Feger H & Seegert J. 2004. Effects of changes in tree species composition on water flow dynamics—model applications and their limitations. *Plant and Soil* 64: 13–24.

Bae KK. 2008. Stand structure, soil respiration and soil properties in secondary forest and agroforestry sites of *Gmelina arborea* and dipterocarps after forest fire at Mt. Makiling, Philippines. MSc thesis, Seoul National University, Seoul.

Bantayan NC & Bishop ID. 1998. Linking objective and subjective modeling for land use decision-making. *Landscape and Urban Planning* 43: 35–48.

Beven JK. 2001 *Rainfall-Runoff Modelling—the Primer.* John Wiley & Sons Ltd, Chichester.

Brooks RH & Corey AT. 1964. Hydraulic properties of porous media. *Hydrological Paper* 3: 1–27.

Calder IR, Wright IR & Murdiyarso D. 1986. A study of evaporation from tropical rain forest—West Java. *Journal of Hydrology* 89: 13–31.

Canfield HE & Lopez VL. 2000. Simulating soil moisture change in a semiarid rangeland watershed with a process-based water-balance model. Pp. 316–319 in Ffolliott P & Baker MB (Eds.) *Proceedings of the Conference on Land Stewardship in the 21st Century: The Contributions of Watershed Management.* 13–16 March 2000, Tucson.

Cheng JD, Lin LL & Lu HS. 2002. Influence of forests on water flows from headwater watersheds in Taiwan. *Forest Ecology and Management* 165: 11–28.

Clapp RB & Hornberger GM. 1978. Empirical equations for some soil hydraulic properties. *Water Resources Research* 14: 601–604.

Clemente RS. 1991. A water study of water supply from a small agricultural watershed for lowland rice production at Ilo-ilo, Philippines. Master of Engineering thesis, Asian Institute of Technology, Bangkok.

Combalicer E, Im S, Lee S, Ahn S & Kim DY. 2008. Modeling water balance for the small-forested watershed in Korea. *Korean Society of Civil Engineering (KSCE) Journal of Civil Engineering* 12: 339–348.

Cruz RVO. 1982. Hydrometereological characteristics of selected upland cropping systems in Mt. Makiling. MSc Thesis, University of the Philippines Los Banos, College.

Early AC, Clemente RS, Collado CU, Sipin MYL & Cablayan DM. 1980. Water balance and cropping performance of a small rice producing watershed in the Philippines. Paper presented at the seminar held at the Department of Irrigation Water Management, Los Banos.

Federer CA. 2002. BROOK 90: A simulation model for evaporation, soil water, and streamflow. http://home.maine.rr.com/stfederer/b90doc.html. (Accessed 30 August 2007)

Federer CA, Vörösmarty C & Fekete B. 1996. Intercomparison of methods for calculating potential evaporation in regional and global water balance models. *Water Resources Research* 32: 15–21.

Federer CA, Vörösmarty C & Fekete B. 2003. Sensitivity of annual evaporation to soil and root properties in two models of contrasting complexity. *Journal Hydrometeorology* 4: 1276–1290.

Feng CC. 2000. Open hydrologic model for facilitating GIS and hydrologic model interoperability. *4th International Conference on Integrating GIS and Environmental Modeling (GIS/EM4): Problems, Prospects and Research Needs.* 2–8 September 2000, Banff. http://www.colorado.edu/research/cires/banff/pubpapers/6/. (Accessed 8 October 2008)

Galvez JA. 1976. Evaulation of the water resources of the Central Luzon Basin, Philippines. PhD thesis, University of Arizona, Tucson.

Han SR. 2009. Carbon storage and flux in aboveground vegetation and soil of secondary natural forest stand and mahogany (*Swietenia macrophylla* King) plantation in Mt. Makiling, Philippines. MSc thesis, Seoul National University, Seoul.

Harris PP, Huntingford C, Cox PM, Gash JHC & Malhi Y. 2004. Effect of soil moisture on canopy conductance of Amazonian rainforest. *Agricultural and Forest Meteorology* 122: 215–227.

Ito A & Oikawa T. 2002. A simulation model of the carbon cycle in land ecosystems (Sim-CYCLE): a description based on dry-matter production theory and plot-scale validation. *Ecological Modelling* 151: 147–179.

Jost GT, Heuvelink GBM & Papritz A. 2005. Analysing the space–time distribution of soil water storage of a forest ecosystem using spatio–temporal kriging. *Geoderma* 128: 258–273.

Klinge R, Schmidt J & Fölster H. 2001. Simulation of water drainage of a rain forest and forest conversion plots using a soil water model. *Journal of Hydrology* 246: 82–95.

Kuraji K. 1996. Hydrological characteristics of moist tropical forests. *Bulletin of Tokyo University Forests* 95: 93–208.

Lasco RD, Guillermo IQ, Cruz RV, Bantanyan NC & Pulhin FB. 2004. Carbon stocks assessment of a secondary forest in Mount Makiling Forest Reserve, Philippines. *Journal of Tropical Forest Science* 16: 35–45.

Lee YK. 2006. Ecosystem structure and functions in relation to restoration of degraded tropical forests in the La Mesa watershed and Mt. Makiling, Philippines. PhD thesis, Seoul National University, Seoul.

Luo T, Neilson RP, Tian H, Vörösmarty CJ, Zhu H & Liu S. 2002. A model for seasonality and distribution of leaf area index of forests and its application to China. *Journal of Vegetation Science* 13: 817–830.

Lu SY & Tang KJ. 1995. Study on rainfall interception characteristics of natural hardwood forest in central Taiwan. *Bulletin of Taiwan Forest Research Institute* 10: 447–457.

Maidment DR. 1993. GIS and hydrologic modeling, in environmental modeling with GIS. Pp. 147–167 in Goodchild MF, Parks BO & Steyaert LT (Eds.) *Environmental Modeling with GIS.* Oxford University Press, New York.

Mun CY. 1987. Rainfall and streamflow analysis of a large tropical rainforest watershed. MSc thesis, University of the Philippines Los Banos, College.

Oh SN. 1999. A bio-climatic assessment on urban area at Seoul based on observations and numerical simulations. http://klter.kookmin.ac.kr/EVENTS/Conference00/html/osungnam.htm. (Accessed 3 October 2007)

Pasa AE. 1997. Effects of rainfall and watershed characteristics on the water yield of Molawin watershed. MSc thesis, University of the Philippines Los Banos, College.

Pierce LL *et al.* 1993. Ecological changes in Murray–Darling Basin III. A simulation of regional hydrological changes. *Journal of Applied Ecology* 30: 283–294. (Cited by Pullen 2000)

Pudasaini BP. 1993. Land capability classification and land use suitability assessment in Mount Makiling Forest Reserve using geographical information system. MSc thesis, University of the Philippines Los Banos, College.

Saplaco SR. 1983. Microclimate profile of a man-made dipterocarp forest in Mt. Makiling. *The Philippine Lumberman* 24: 25–30.

Saplaco SR & Aquino M. 1991. *Hydrometeriological Characterization of Upland Ecosystems at Mt. Makiling*. Technical Report on Tropical Ecology and Development. University of the Philippines Los Banos, College.

Saterlund DR. 1972. *Wildland Watershed Management*. The Ronald Press Co, New York.

Saxton KE & Rawls WJ. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil Science Society American Journal* 70: 1569–1578.

Saxton KE, Rawls WJ, Romberger JS & Papendick RI. 1986. Estimating generalized soil water characteristics from texture. *Transactions of the American Society of Agricultural Engineers* 50: 1031–1035.

Scurlock JM, Asner P & Gower ST. 2001. Global leaf area index data from field measurements, 1932–2000.http://www.daac.ornl.gov. (Accessed 13 August 2007)

Shuttleworth WJ & Wallace JS. 1985. Evaporation from sparse crops—an energy combination theory. *Quarterly Journal Royal Meteorological Society* 111: 839–855.

Tanaka N *et al*. 2008. A review of evapotranspiration estimates from tropical forests in Thailand and adjacent regions. *Agricultural and Forest Meteorology* 148: 807–819.

Tingsanchali T, Arbhabhirama A, Nir D, Okamoto M & Selvalignam S. 1976. *Water Balance Study: Bicol River Basin*. Asian Institute of Technology, Bangkok.

Vallesteros AP. 2002. GIS-based determination of socio-economic variables affecting land-use change in Mt. Makiling Forest Reserve, Philippines. MS thesis, University of the Philippines Los Banos, College.

Vilhar U, Simoncic P, Kajfe-Bogataj L, Katzensteiner K & Diaci J. 2006. Influence of forest management practice on water balance of forests in the Dinaric Karst. Pp. 290–295 in *All About Karts and Water: Decision Making in a Sensitive Environment*. 11 October 2006, Vienna.

Wahren A, Schwärzel K, Feger KH, Münch A & Dittrich I. 2007. Identification and model based assessment of the potential water retention caused by land-use changes. *Advances in Geosciences* 11: 49–56.

Wang Q, Adiku S, Tenhunen J & Granier A. 2005. On the relationship of NDVI with leaf area index in a deciduous forest site. *Remote Sensing of Environment* 94: 244–255.

Wu K & Johnston CA. 2008. Hydrologic comparison between a forested and a wetland/lake dominated watershed using SWAT. *Hydrological Processes* 22: 1431–1442.