DEVELOPMENT OF DISTRIBUTED CONCEPTUAL HYDROLOGICAL MODEL FOR FOREST WATERSHED IN NORTHERN THAILAND: A DOWNWARD APPROACH

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Abstract

This paper reports promising use of the downward approach in the construction of the distributed conceptual hydrological models for a forest watershed in Chiang Mai Province, northern Thailand, at monthly and daily time scales with 30-m spatial resolution. It was found that the built models have exhibited impressive capability in the simulation of actual runoff yield with R^2 and the Nash-Sutcliffe efficiency index (E) of 0.94 and 0.88 (for the optimal monthly model), and 0.96 and 0.94 (for the optimal daily model), respectively. The applied water balance system with three main hydrological processes; surface runoff, subsurface runoff, and evapotranspiration (ET), was proved to be sufficient in explaining general runoff characteristics of the area at both studied scales, especially during strong monsoon months from August to October. Obtained results from the monthly cases indicate that rainfall variation plays more important role than the soil depth heterogeneity in producing more realistic pattern of the runoff product and integration of subsurface runoff process was found vital in the development of successful model. In addition, sole use of the evaporation component of ET was found sufficient in building the successful monthly model but in case of the daily model, the transpiration part was also necessary.

Keywords: Hydrological model, Distributed model, Downward approach, Runoff

Introduction

Hydrological modelling is a well-established branch of science whose origin can be traced back to the 19^{th} century when the rational method was used to identify relationship of rainfall and its associated stream runoff data, empirically (Singh and Woolhiser, 2002). Typically, principal interest of the research is to understand dominant hydrological processes over a particular area to aid hydrological prediction and effective water resource management (Refsgaard, 1996; Praskievicz and Chang, 2009). Several recent studies are also focused on assessing impact of the environmental changes (e.g., climate or land use) on runoff yield of an area (Atkinson et al., 2002; Im et al., 2009; Chu et al., 2010). Through, plenty of the hydrological models are known at present, however, to find an appropriate one for the area of interest is still considered a challenged task for responsible hydrologists as main controlling mechanisms of the hydrological system often vary from place to place under scope of the spatial and temporal scales in use (Blöschl and Sivapalan, 1995; Sivakumar, 2004; 2008).

According to Klemes (1983), there are two fundamental approaches for the building of a hydrological model; the traditional upward (or bottom-up) approach and the alternative downward (or top-down) approach. In case of the standard upward approach, the model structure is usually developed based principally on prior perception of actual mechanisms that underlie the observed hydrological aspects of an area. This practice often leads to a fairly complicated structure of the resulted model if most concerned mechanisms are included just to make it appear to be most realistic. Moreover, its typical implication that what found to work well at lower (spatial or temporal) scale should appear so at broader scale is generally inapplicable (Sivapalan, 2003; Sivapalan et al., 2003). On the contrary, in case of the downward approach, it tries to minimize complexity of the model structure and maximize predictive capability through a process of the data-based hypothesis testing, in which, the first task is to establish a simplified water balance model believed to be able to explain known behavior of the studied hydrological system at broad scale (e.g., basin scale). More complexity is then added into this initial model as necessary for the investigation at finer scales, usually in forms of the new parameters or hydrological processes, to fulfill desire for its high predictive ability. This practice allows key hydrological elements of the examined area to be thoroughly identified at each used scale (Jothityangkoon et al., 2001; Sivapalan et al., 2003; Barthold et al. 2008; Lan-Anh and Willems, 2011).

The main objective of this reported work is to investigate capability of the downward approach in constructing the effective hydrological model called "distributed conceptual model for Chiang Mai" (DCM4CM) for the fertile forest watershed in the Chiang Mai Province, northern Thailand. The stated model was built for the use at two different temporal scales (monthly and daily levels) with considerably fine spatial resolution of 30 meters which has never been reported before. Its efficiency in the simulation of runoff data was assessed in terms of the coefficient of determination (R^2) and the Nash-Sutcliffe efficiency index (E) (see for relevant details in Krause et al., 2005). The great flooding incidence in 2005 was chosen as a case study and several GIS tools were applied in the process to complete the study.

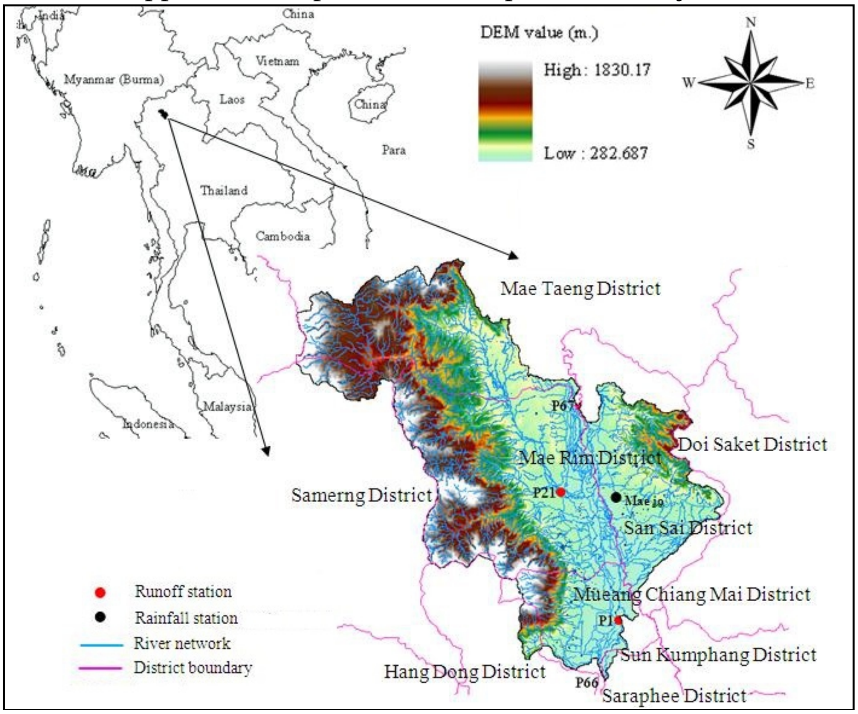

Figure 1: Map of the study area (part of the upper Ping River basin).

Study area

The studied catchment situates in central portion of the Chiang Mai Province; a formal administrative and economic center of northern Thailand, with approximate area of 1,121 km^2 (Figure 1). This area is a significant part of the upper Ping River basin, one of the major contributories of the famous Chao Phraya River of central Thailand. Dominant topography is a complex network of several high mountains on the western part and lowland flat plain on the middle and eastern part with elevation ranging from 278 m to 1,826 m above mean sea level (Figure 1). The classified satellite image in year 2005 (Landsat-5 TM data) indicates that majority of the LULC components was fertile forest (about 60%) which mostly located in the mountainous region. This is followed by orchard and paddy plantation fields (about 20%) situated mostly over the lowland close to major rivers, and the urban and built-up land (about 14%) mostly distributed in the developed area along the major rivers (Figure 2).

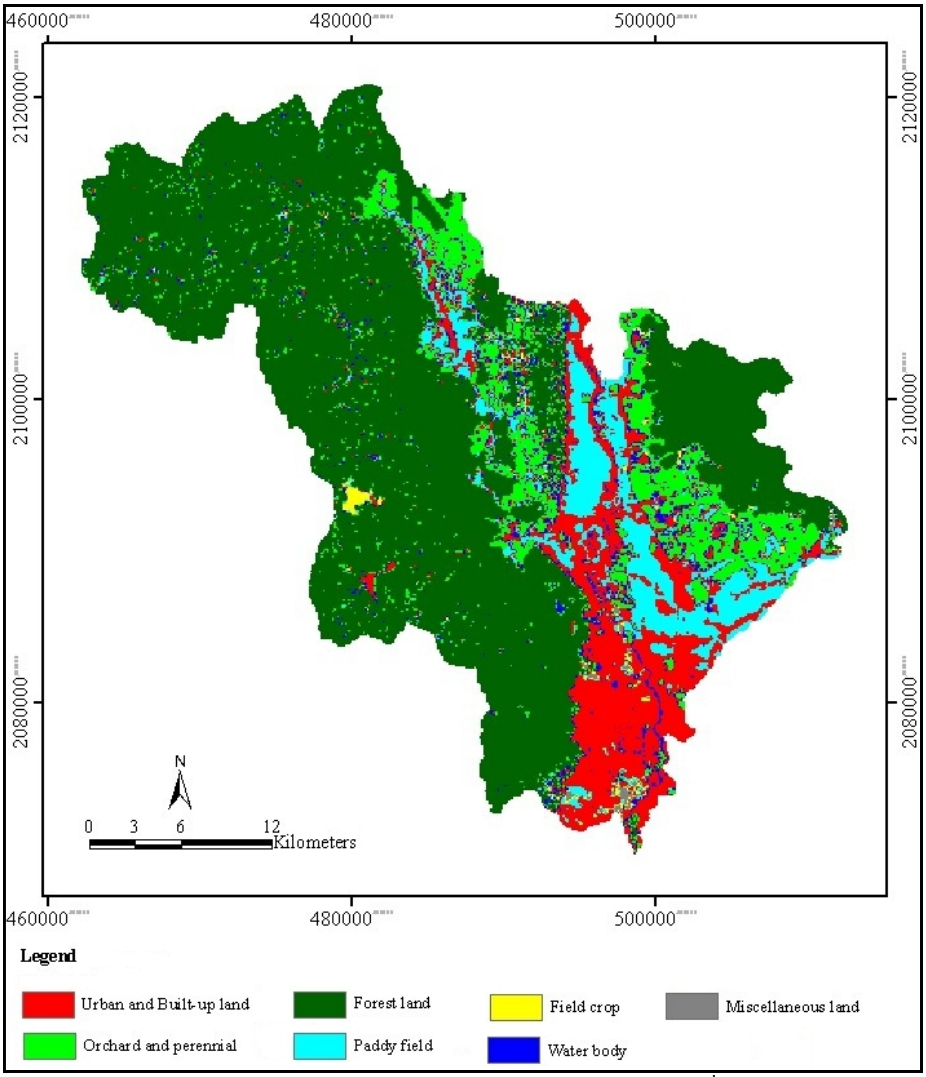

Figure 2: Classified land use/land cover (LULC) map on 11th March 2005.

Model Development Process

The downward approach was applied in the development of the stated model. To achieve this, first, the entire catchment was conceptually divided to constitute a rectangular grid network with cell size dimension 30x30 m^2 (to match with the standard Landsat-TM pixel size). Each referred grid was assumed to behave like an independent bucket that could store rainfall input up to a limit of its predefined capacities (field capacity and bucket capacity) before contributing the excessive water to its predetermined neighbor cell in forms of the surface and subsurface runoff. Amount of the excess runoff data (for a particular grid cell) over daily and monthly time scales was determined from the water balance analysis performed at grid scale in which the water loss to atmosphere by evapotranspiration (ET) process was also incorporated. The transferred water was assumed to be gradually accumulated downward along designated route until reaching lowland drainage channels like rivers and becomes the channel runoff that could be measured at the existing runoff gauging stations.

In addition, inflow of the stream water originated from the headwater basin further north of the study area (measured at the P67 inlet station) was also taken into account for the calculation of total stream runoff observed at the reference P1 station (Figure 1). If the runoff yield still failed to satisfy the accepting criteria; which are the coefficient of determination (R^2) > 0.8 and Nash-Sutcliffe efficiency (E) > 0.8, more complexity was then added to the initial model in forms of the new, or modified, parameters or given processes until such demands were met. The attained monthly model was subsequently used to establish a daily model that could simulate daily runoff data observed at the P1 station well (based on the same criteria for the monthly model). In this work, model structures were built and utilized through the ArcToolbox component of the ArcGIS software.

Detailed formulation of the models

In this study, the monthly model was evaluated for five study cases (called M1 to M5) with different assumptions of the input rainfall, soil depth and subsurface runoff factor as detailed below:

Case M1: Uniform rainfall/fixed soil depth (no sub-surface runoff);

Case M2: Variable rainfall/fixed soil depth (no sub-surface runoff);

Case M3: Uniform rainfall/variable soil depth (no sub-surface runoff);

Case M4: Variable rainfall/soil depth (no sub-surface runoff);

Case M5: Variable rainfall/soil depth (with sub-surface runoff).

Noted that, rainfall data measured at the Maejo University station (Figure 1) were employed in cases of the uniform rainfall scenario (Cases M1 and M3) and a fixed value of 3 m was applied in cases of the fixed soil depth (Cases M1 and M2). Also, the subsurface runoff was incorporated in Case M5 only.

First task of the process was to find the proper water balance equation for the area. As suggested in Jothityangkoon et al. (2001) along with results from the preliminary analysis, the water balance equations for a catchment unit area over a short time period were proposed as follows:

Cases M1-M4:
$$\frac{ds(t)}{dt} = p(t) - q_{se}(t) - e_b(t) \tag{1a}$$

Case M5:
$$\frac{ds(t)}{dt} = p(t) - q_{ss}(t) - q_{se}(t) - e_b(t) \tag{1b}$$

where $s(t)$ is the volume of the soil moisture storage at time t, $p(t)$ is the rainfall input rate, q_{ss} is the subsurface runoff rate, q_{se} is the saturation excess runoff rate (or the surface runoff rate), and e_b is the bare land evaporation rate. Note that the interception rate of 10% was also applied to the vegetation group (forest, orchard, perennial) based on relevant data reported in Tanaga et al. (2005) and Jothityangkoon and Hirunteeyakul (2009).

The information illustrated in Eqs. 1a and 1b indicates that, for each assumed bucket, the rainfall input accumulated over a short period of time shall be transformed into three main parts in cases M1-M4 and four main parts in case M5 (with different proportion at different places). These include the net soil moisture storage, the surface runoff, the subsurface runoff, and the evaporation to the atmosphere. The transpiration effect was neglected at this stage as it was primarily found that sole use of the evaporation term (for all land units) was sufficient to mimic of the observed runoff data of the area well (regarding to the accepting criteria) as illustrated in Figure 3.

The daily water balance model was subsequently built based on the structure of the optimal monthly model found in the previous step (Case M5) in which two different cases were investigated (called D1 and D2);

Case D1: As in Case M5 (without plant transpiration factor included);

Case D2: As in Case M5 (with plant transpiration factor included).

The corresponding water balance equations for each case are as follows;

Case D1:
$$\frac{ds(t)}{dt} = p(t) - q_{ss}(t) - q_{se}(t) - e_b(t) \tag{2a}$$

Case D2:
$$\frac{ds(t)}{dt} = p(t) - q_{ss}(t) - q_{se}(t) - e_b(t) - e_v(t) \tag{2b}$$

where e_v is the transpiration rate (for the vegetation group). The transpiration term was introduced as it was evidenced that sole use of the evaporation term for all land units, as done for the monthly model (Case D1), was unable to simulate actual runoff yield at this scale well (with R^2 = 0.63 and E = -0.06) for the runoff analysis in September 2005 as shown in Figure 4 and Table 1.

Table 1: Modeled results of the monthly (M1-M5) and daily (D1-D2) cases.

Monthly model	Yielded relationship	Validation R^2	Validation E	Daily model	Yielded relationship	Validation R^2	Validation E
M1	y = 1.462x - 27.86	0.74	- 0.12	D1	y = 1.262x - 0.427	0.63	-0.06
M2	y = 2.041x - 39.28	0.74	- 1.53	D2	y = 1.050x - 0.065	0.96	0.94
M3	y = 1.627x - 31.41	0.73	- 0.48				
M4	y = 2.015x - 38.86	0.74	- 1.46				
M5	y = 1.154x - 5.839	0.94	0.88				

Note: y ≡ simulated runoff (mm), x ≡ observed runoff (mm)

Results and Discussion

Summarizations of the yielded results from each examined case (M1-M5, D1-D2) are given in Figures 3, 4 and Table 1, respectively. From data in Table 1, it can be primarily concluded that the applied model for Cases M1 to M4 can simulate the actual monthly runoff data in 2005 well in terms of the R^2 (about 0.73-0.74) but those of the Nash-Sutcliffe efficiency index (E) are still not acceptable (much less than 0.8). The remarkable deficiency is the clearly underestimation of runoff yield in most months except in August and September which is substantially overestimated (especially in September). This discovery might be because without subsurface runoff included in the model structure, the runoff yield shall happen only when soil volume is fully saturated which is often met during the strong monsoon months of the area (August to October). This shall result in sharp increase and rapid decline of the runoff data during this time period. On the contrary, in dry months (e.g., November to April), the modeled runoff is notably low by the similar reason. In addition, variations of the rainfall and effective soil depth input (Case M4)

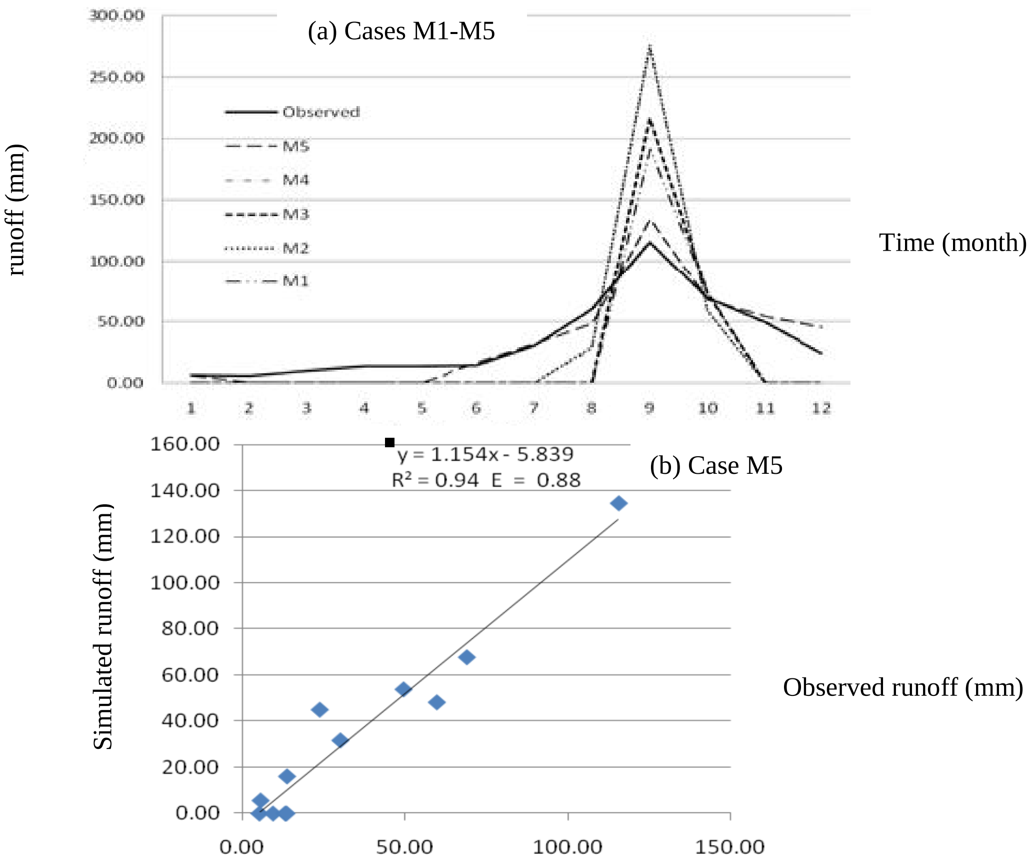

Figure 3: Comparison of the simulated and observed runoff data in 2005 at the gauging station P1 for (a) Cases M1-M5 and (b) Case M5.

seems to produce more realistic pattern of simulated runoff data than that of the uniform-value case (Case M1) especially during strong monsoon months. However, comparison of results obtained in Cases M2, M3 and that in Case M4 suggested that this difference was due mainly to the variation in rainfall data not the effective soil depth. This analysis also indicates that the runoff yield at peak values is highly sensitive to the variation of rainfall not the soil depth in the area.

The notable overestimation of the runoff yield during strong monsoon months stated earlier was eventually resolved by introducing the subsurface runoff factor (q_{ss}) in the model structure (case M5). This modification was proved vital as it contributed highly satisfied values of R^2 (at 0.94) and E (at 0.88) as shown in Figure 3(b). This success is resulted from the assumed role of the sub-surface runoff term directly because it can allow some runoff yield to happen while the soil volume is still not fully saturated. This mechanism shall act as a delayed mechanism for the accumulation of the modeled runoff outcome especially during the monsoon season, and generate a more realistic results in which gradual increase and receding pattern of the monthly runoff data is distinctly evidenced and resembled to the observed ones. Crucial role of this process was also recognized in Montanari et al. (2006). However, the underestimation of the observed runoff data by the model during dry summer season (February to May) was still pronounced and needed to be fixed in the further work (e.g., with deep groundwater parameter included).

The achieved results from both daily cases (D1-D2) are illustrated in Figure 4 and Table 1, respectively. Most apparent deficiency in Case D1 is the substantial overestimation of the runoff yield on dates having peak values of the runoff data under consideration (e.g., 11th and 20th September). And as these dates are likely to have most severe floods in central area of the city, the noticeably wrong simulation of the runoff data at station P1 in this case tends to greatly undermine reliability of the associated flood risk assessment for the known vulnerable areas on these dates also. This finding suggests that structure of the optimal monthly model (Case M5) is still insufficient for the direct use in the build-up of the daily-scale water balance model and needed to be modified. This proposition was fulfilled in Case D2 by incorporating the plant transpiration factor in the developed model structure as well as the evaporation that prevails in the examined monthly model. This modification led to a substantial improvement in working ability regarding to the resulted R^2 and E if compared to those in Case D1 (R^2 = 0.96 and E = 0.94) as seen in Figure 4(b). This is probably because, in 2005, the area was mostly occupied by the deep-rooted vegetation, e.g., forest and orchard/perennial, (about 75% as illustrated in Figure 2) which made the transpiration mechanism become critically crucial in the water balance process at daily scale. This mechanism shall perform as a runoff deduction function that works much better than the evaporation process in the area. This process would significantly reduce total amount of the modeled runoff output derived from the developed daily water balance model which makes the simulated data in general appear to conform well to the observed ones.

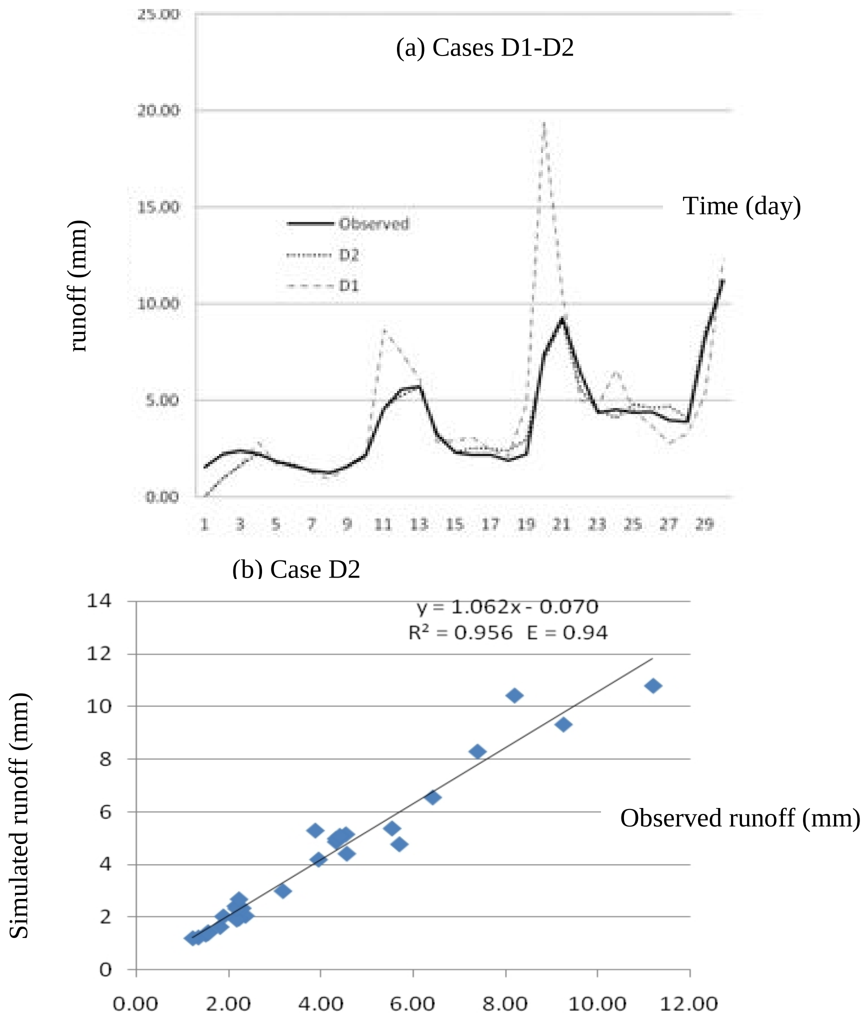

Figure 4: Comparison of the simulated and observed runoff data at gauging station P1 in September 2005 for (a) Cases D1-D2 and (b) Case D2.

Conclusion

This paper reports fruitful use of the downward approach to develop the distributed conceptual hydrological model called “DCM4CM” for forest watershed in the Chiang Mai Province, northern Thailand, at the monthly and daily time scales. It was found that the attained optimal models in both cases had shown an impressive capability in the simulation of actual runoff yield measured at the gauging station P1with the R^2 and the Nash-Sutcliffe efficiency index (E) of 0.94 and 0.88 (for the monthly model) and 0.96 and 0.94 (for the daily model), respectively. Obtained results from the monthly simulation in Cases M1-M4 indicate that incorporation of land heterogeneity, i.e. rainfall and effective soil depth, is essential but it still does not contribute obvious improvements in terms of the R^2 and E. It was also found that the modeled peak runoff is highly sensitive to the variation of rainfall but rather insensitive to variation of effective soil depth in the area. The subsurface runoff factor was found to be critical for making an effective monthly model without need for inclusion of plant transpiration factor (Case M5). This is on the contrary to what found in the preferred daily model (Case D2) in which role of the transpiration effect was very essential and could not be neglected.

Acknowledgements

Financial support by the Suranaree University of Technology and the Nakhon Ratchasima Ratjabat University is greatly appreciated. Kind support for data from all responsible agencies is also gratefully acknowledged.

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