Effects of landuse change on the hydrologic regime of the Mae Chaem river basin, NW Thailand

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Summary   Conflicts between upland shifting cultivation, upland commercial crops, and lowland irrigated agriculture cause water resource tension in the Mae Chaem watershed in Chiang Mai, Thailand. In this paper, we assess hydrologic regimes of the Mae Chaem River with landuse change. Three plausible future forest-to-crop expansion scenarios and a scenario of crop-to-forest reversal were developed based on the landcover transition from 1989 to 2000, with emphasis on influences of elevation bands and irrigation diversion. Basin hydrologic responses were simulated using the Distributed Hydrology Soil Vegetation Model (DHSVM). Meteorological data from six weather stations inside and adjacent to the Mae Chaem watershed during the period 1993–2000 were the climate inputs. Computed stream flow was compared to observed discharge at Ban Mae Mu gauge on Mae Mu river, Ban Mae Suk gauge on Mae Suk river, and at Kaeng Ob Luang, located downstream from the district town in Mae Chaem. With current assumptions, expansion of highland crop fields led to slightly higher regulated annual and wet-season water yields compared to similar expansion in the lowland–midland zone. Actual downstream water availability was sensitive to irrigation diversion. This modeling approach can be a useful tool for water allocation for small watersheds undergoing rapid commercialization, because it alerts land managers to the potential range of water supply in wet and dry seasons, and provides information on spatial distribution of basin hydrologic components.
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Introduction

Landscape and water resource management are major challenges for the socio-economic development of upland

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watersheds in Southeast Asia due to their association with downstream environmental impacts and water supply. During recent decades, concerns about the impacts of changing patterns of landuse associated with deforestation and agricultural transformation on water resources have created social and political tensions from local to national levels. Major concerns focus on consequences of landuse change for water supply and demand, for local and downstream hydrological hazards, and for biodiversity conservation. Ziegler et al. (2004) refer to studies by Sharma in 1992 and by Tuan in 1993, which conclude that shifting agriculture and deforestation in highlands of Vietnam result in watershed degradation such as soil and nutrient loss. In northern Thailand, the prevalent views are that logging, shifting cultivation by mountain ethnic minorities, and commercial agriculture in highland watersheds cause severe dry-season water supply shortages. Water demand is the other side of the equation, as it also places constraints on water availability. Dynamics of water use relate to landuse change, especially through expansion of lowland cultivation, irrigated upland fields, urban areas, and industrialization. Walker (2003) points out that public debate is mostly centered on consequences of highland activities on water supply, but there is little focus on increasing levels of stream water diversion by lowland dry-season irrigated agriculture. Controversy over the eight-dam hydropower cascade system on the Lancang river of the upper Mekong basin in China is an example at a wider, transboundary scale where potential effects on downstream river flows and sediment transport are an international issue for the five countries sharing the lower Mekong river.

In response, public policy decision-making processes are now seeking both economic and conservation goals. More informed decisions for watershed planning and water allocation must rely on the better understanding of highland basin hydrology and the relationship between landuse practices, flow generation processes, and associated water distribution and use. Furthermore, the ability to evaluate basin hydrology beyond just stream flow is crucial for determining spatially-explicit relationship between landscape structure, configuration of landuse change, and the hydrology across the landscape. Distributions of soil moisture across a basin impact agriculture, and provide the antecedent conditions for response to floods or droughts. Process-based distributed models of basin hydrology have the potential to assess these management objectives by quantifying and forecasting the dynamics of water availability with the landuse and climate change. But such models require considerable data, and are perceived to be not feasible for application in many cases. For example (Schreider et al., 2002; Croke et al., 2004) applied IHACRES, a metric-conceptual rainfall-runoff model for hydrologic simulation in gauged and ungauged subbasins in this region. But flow prediction at the Mae Chaem basin outlet was not done, due to sparse basin input data, and Croke et al. stated that this limitation makes use of a physically-based model inapplicable.

In this paper we utilize the Distributed Hydrology-Soil Vegetation Model (DHSVM) (Wigmosta et al., 1994), a spatially-explicit landscape/hydrology model to evaluate the seasonal patterns and the hydrologic components of the Mae Chaem River. As DHSVM is a fully-distributed model that recognizes the spatial heterogeneity of the watershed, we can evaluate the spatial variation of hydrologic attributes inside the basin, and adjust calculations based on the availability of data and level of complexity. Our focus is to assess effects of landuse conversion between forest and croplands on the basin hydrology and on water availability in terms of annual and seasonal water yields. Specifically, we assess the influence of elevation bands of agricultural fields (highlands versus lowlands) and irrigation diversion. Scenario analysis eliminates interpretation problems associated with direct comparison of stream flow in paired watershed analyses where basins have different underlying geological settings (Bruijnzeel, 2004). In the process of conducting these analyses, we will assess the applicability of this class of physical model for use as a water resource tool, in basins where data are relatively sparse. This can be compared and contrasted to the work performed by Croke et al. (2004), as mentioned in the preceding paragraph.

Mae Chaem basin: the study area

The Mae Chaem (Chaem River) watershed is located in the Chiang Mai province of northern Thailand (Fig. 1). It is a major upper tributary subbasin of the Ping River, which in turn, is the largest tributary of central Thailand's Chao Phraya River. The Mae Chaem subbasin is bounded by coordinates 18°06′−19°10′N and 98°04′−98°34′E, and includes a total area of 3853 km^2 above the Royal Irrigation Department (RID) river gauge station P.14. The climate of this mountainous basin is defined by large variations in seasonal and annual rainfall that are influenced by Pacific-born typhoons, superimposed on the south-west monsoon (Walker, 2002). The orographic effect induces an altitudinal increase of spatial rainfall distribution (Dairaku et al., 2000; Kuraji et al., 2001). The average annual temperature ranges from 20 to 34 °C and the rainy season is from May to October.

Sharp relief and forest vegetation (and relatively sparse data) characterize the Mae Chaem. The basin has a wide range of elevation, from 282 m.a.s.l. at its lowest point to 2565 m.a.s.l. at its highest peak, Doi Inthanon (Mount Inthanon). Altitude variation induces different climatic zones with distinctive types of natural landcover. Dominant vegetation includes dry dipterocarp and mixed deciduous forests below 1000 m.a.s.l., tropical mixed pine forest from 900 to 1500 m.a.s.l. alternating with hill evergreen forest that extends up to 2000 m.a.s.l., and tropical montane cloud forest above 2000 m.a.s.l. (Dairaku et al., 2000; Kuraji et al., 2001). Steep hillsides with slopes exceeding 25% are a common landscape element, resulting in rates of soil erosion that prevent advanced soil development. Thus, soils are relatively shallow and have limited water-holding capacity (Hansen, 2001). Dominant soil textures are sandy clay loam and clay loam.

The population of Mae Chaem is ethnically diverse and distributed among numerous small villages. The majority Karen and the Lua ethnic groups live primarily in mid-elevation zones between 600 and 1000 m.a.s.l., with some communities extending into higher elevations. Ethnic northern Thai (*khon muang*) villages are mostly clustered in lowland areas below 600 m.a.s.l., whereas Hmong and Lisu ethnic groups live mostly in highland villages located above 1000 m.a.s.l.
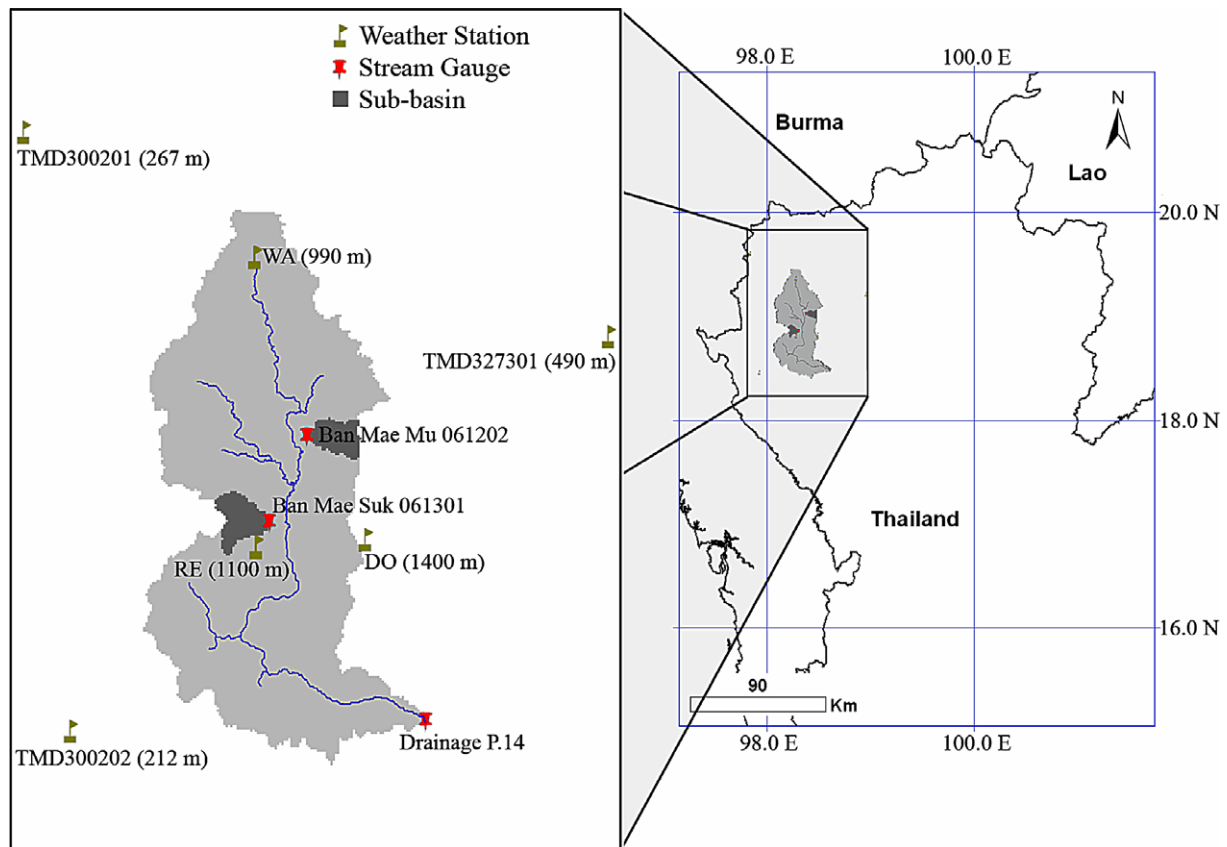
Figure 1 Location of Mae Chaem river watershed, stream gauges, and meteorological stations within and adjacent to the watershed.

Land use patterns in Mae Chaem have undergone substantial change during the past several decades. As recently as the 1960 s, the agriculture mosaic was comprised of highland (above 1000 m.a.s.l.) pioneer shifting cultivation that often included opium, mid-elevation (600—1000 m.a.s.l.) rotational forest fallow shifting cultivation with a decade long fallow period, and paddy and home garden-centered cultivation in the lowlands (Thomas et al., 2002; Walker, 2003). In the 1980 s, development projects and programs in Mae Chaem began building infrastructure and promoting commercial agriculture, under programs to reduce rural poverty and promote alternatives to opium cultivation and shifting agriculture. Results have included significant increases in production of highland cash crops such as cabbage and carrots, expansion of industrial field crops such as soybeans and maize up watershed slopes above lowland paddies into mid-elevation zones, expansion of irrigated paddy fields wherever terrain allows, and planting of fruit orchards in some areas of all altitude zones (Praneetvatakul et al., 2001; Pinthong et al., 2000; Thomas et al., 2002; Walker, 2003).

Development of geospatial landscape/hydrology model

DHSVM is utilized for stream flow forecasting and for addressing hydrologic effects of land management or of climate change, for small to moderate drainage areas (typically less than about 10,000 km^2), over which digital topographic data allows explicit representation of surface and subsurface flows. It simulates soil moisture, snow cover, runoff, and evapotranspiration on a sub-daily time scale. It accounts for topographic and vegetation effects on a pixel-by-pixel basis, with a typical resolution of 30—150 m. Snow accumulation and snow melt, where needed, are calculated by a two-layer energy-balance model. Evapotranspiration follows the Penman—Monteith equation. The multi-layer soil column in each pixel is a series of soil moisture reservoirs, and saturated subsurface flow exists in the deepest soil layer. Runoff generation is represented by saturation excess and infiltration excess mechanisms. Stream segment storage volume is computed using linear-reservoir routing.

The model has been applied to basins in the USA (Bowling et al., 2000; Bowling and Lettenmaier, 2001; Storck, 2000; VanShaar et al., 2002) and in British Columbia (Schnorbus and Alila, 2004), and Southeast Asia (Cuo et al., 2006).

Development of the geospatial model of the Mae Chaem basin

Topography and flow network
Topography for the Mae Chaem basin was acquired as a 30-m digital elevation model (DEM) constructed by the World Agroforestry Centre (ICRAF), Chiang Mai. This 30-m DEM was then aggregated to 150-m resolution (Fig. 2) using the average of all 30-m elevation data which were nested within
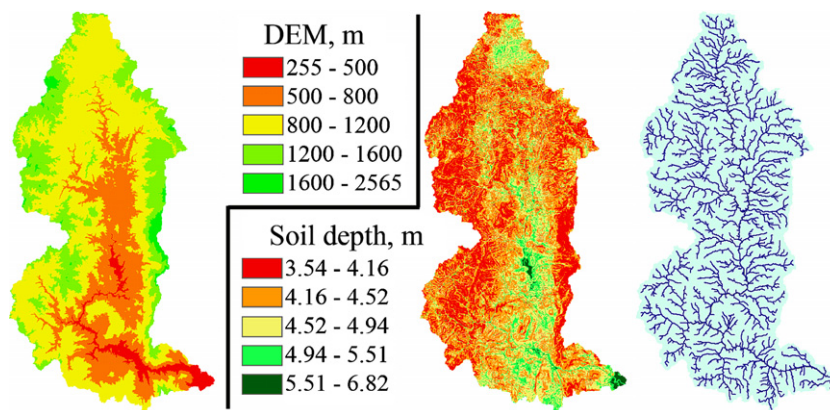
Figure 2 DEM, soil depth, and stream network grids (left to right) represented by the 150-m resolution.

the boundary of each 150-m cell. Flow direction, flow accumulation, and stream network were derived from the 150-m DEM. Soil depth was generated by DHSVM, based on the DEM, and was adjusted during model calibration.

Soil map and attributes

Soil data in Mae Chaem are very sparse and restricted to the lowlands (Land Development Department (LDD), Ministry of Agriculture and Cooperatives, Thailand). The majority of the area is mountainous and is classified only as 'slope complex' in the soil survey. Therefore, a soil map containing physical and chemical properties was constructed using Soil-Program software (Carter and Scholes, 1999), which derives 5-min resolution (about 10 km) soil data from the WISE ped-on-database (Batjes, 1995) developed by the International Soil Reference and Information Centre (ISRIC) and the FAO-UNESCO Digital Soil Map of the World (FAO, 1995). The soil map was re-sampled to 150-m resolution, with the number of soil types equal to the number of unique values of physical and chemical soil properties. Soil texture was assigned based on the percent sand and clay. Porosity and field capacity were estimated from the soil texture triangle hydraulic properties calculator (Saxton et al., 1986). Infiltration rates and an estimated range of soil depths were quantified using a local descriptive soil survey (Putivoranart, 1973).

Vegetation and land use: 1989, 2000, future

Two landcover datasets form the basis for the landcover change scenarios in the hydrology model. The original classification schemes of these data vary significantly, so scheme modifications were made to achieve similarity between landcover data.

The first dataset in the landcover time series is a historical 1989 dataset, acquired from the LDD. These data, subsequently referred to as Veg 1989, originated as polygons, which were converted to a 150-m raster grid representation using a nearest-neighbor assignment algorithm. Data were then generalized into 11 classes (Fig. 3) from its original 39. The second dataset represents landcover for the year 2000, referred to as current landcover or Veg 2000. This dataset, also from LDD, was prepared for the model using the same procedure as utilized for the 1989 data. However, since the original 47 class names in this dataset differed

from those in the 1989 data, class names were reconciled by performing a combinatorial analysis between the 1989 reclassified dataset and the 2000 original data. In this way we were able to establish a correlation between the 11 classes in 1989 and the 47 original classes in 2000. This type of spatial overlay analysis returns not only the frequency of all unique combinations of landcover types, but also a map product of the spatial commonalities. A plot was made to identify the frequency of occurrence between a 2000 value (1–47) and a 1989 value (1–11). Based on this plot, the 2000 vegetation values were re-assigned a value consistent with the frequency distribution of shared space with the 1989 dataset.

Veg 2000 is employed as the reference landuse case, and four future scenarios (Fig. 3) were created based on the transition from Veg 1989 to Veg 2000, with a focus on forest-to-crop conversion. The first scenario represents reversal of all croplands back to evergreen needleleaf forests in zones above 1000 m.a.s.l., and to deciduous broadleaf forests below 1000 m.a.s.l. Selected forest types were generally in accord with actual dominant vegetation in the respective elevation zones. The second scenario forecasts the doubling of cropland area in Veg 2000 by growing a buffer of new crop cells around all existing crop patches. This ultimately increased the cropland share of total basin area from 10.4% in 2000 to 19.9%. Finally, the third and fourth scenarios depict a doubling of cropland that is limited to either highland zones of the basin (above 1000 m.a.s.l.), or to lowland and midland basin zones (below 1000 m.a.s.l.). Growth of croplands limited to highland and to lowland—midland basin zones increased cropland shares of total basin area to 18.0% and 19.1%, respectively. In both cases, crops were expanded around existing patches in the selected elevation range, while crop cell areas outside the selection remained the same as in 2000.

Climate forcing and hydrology

The meteorological variables required by the DHSVM are precipitation, temperature, relative humidity, shortwave, and longwave radiation. To best represent climatic variation within the catchments, we used daily rainfall, and maximum and minimum air temperature records for the period of 1993—2000, which were obtained from five meteorologi-
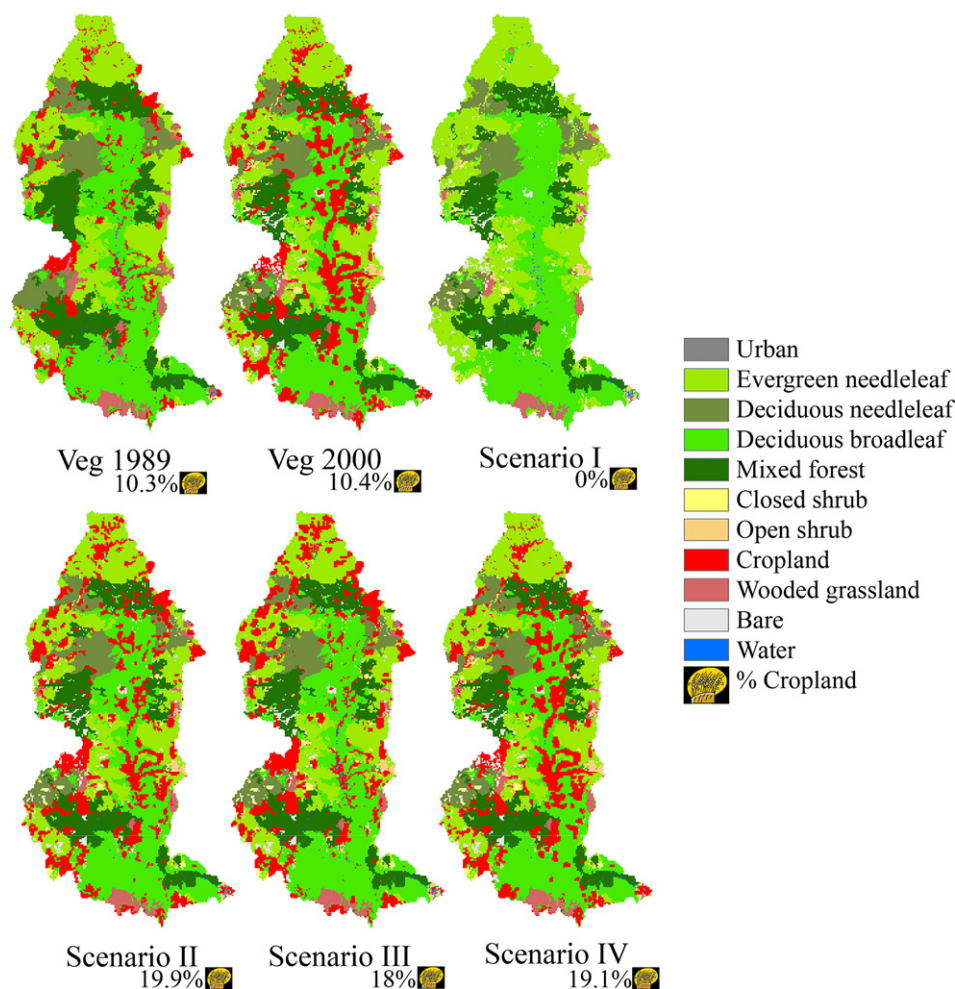
Figure 3 Mae Chaem landcover scenarios from top left to bottom right: (Veg 1989) re-processed 1989, (Veg 2000) re-processed 2000, (Scenario I) conversion from crops to forest, (Scenario II) double crop areas, (Scenario III) more upland crops, and (Scenario IV) more lowland—midland crops.

cal stations and one agro-meteorological station (Fig. 1). Doi Inthanon (DO) and Wat Chan (WA) stations are operated by the Royal Project Foundation, and their recorded values were obtained from both ICRAF and the Royal Project Foundation. The Research Station (RE) belongs to the Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment-Tropics (GAME-T), led by the University of Tokyo in Japan. Mae Jo Agromet (TMD327301), Mae Hong Son (TMD300201), and Mae Sariang (TMD300202) stations are managed by the Thai Meteorological Department (TMD). Data for these stations were acquired directly from the respective agencies. TMD300201 has two gaps in temperature data from September 24 to October 14, 1995 and February 19 to March 23, 1997 and were filled by linear interpolation of data from the nearest station. DO has a gap in rainfall data in 1998 and the daily rainfall from another GAME-T meteorological station located on Doi Inthanon at 2565 m was used instead. Wind speed was set to the model default value of 2 m/s for all stations except RE and TMD327301, where actual daily wind speed records are available, whose mean speeds were slightly lower. After disaggregated three-hourly data was generated, the 3-h

precipitation values in 1998—2000 were then replaced by observed records for all TMD stations.

The Mae Chaem hydrologic regime consists of high flow from May to October, contributing to 70% of the total flow. The base-flow is from November to April, and from 1989 to 2000 there is an average annual water yield of 270 mm (we consider the water year to begin in November of the year previous to the year cited). Due to the strong orographic effect on precipitation (Fig. 4), the surface runoff ratio could be between 12% and 25%, depending on selection of reference rainfall stations and the interpolation scheme. Walker (2002) provides thorough discussions on the long-term rainfall-discharge relationship in Mae Chaem.

The gauge at Kaeng Ob Luang (RID gauge P.14) represents the basin output, and is the primary record used here. 1993—1999 discharge records were acquired from GAME-T, and the estimated daily discharge in 2000 was computed from the stage height observation obtained from the RID Hydrology and Water Management Center for the Upper Northern Region. For local calibration and validation purposes, the 1993—2000 daily average stream flow measurements at the Ban Mae Mu gauge 061202 on the 70.6 km^2
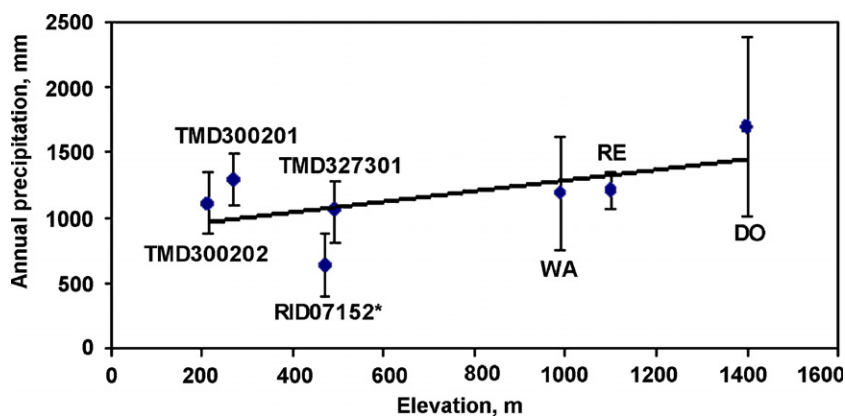
Figure 4 Orographic effects on average annual rainfall (1989—2000). *Rainfall from this station is used only for demonstration of orographic effect, but not in actual simulation.

Mae Mu river subcatchment and at the Ban Mae Suk gauge 061301 on the 86.5 km^2 Mae Suk river subcatchment (Fig. 1) were obtained from ICRAF.

Model setup and operations

Simulation conditions and parameter estimation

The spatial domain was partitioned into 150-m grid cells and the simulation was performed on a 3-h time step using the current landcover (Veg 2000) as the base case for calibration and validation. Disaggregated three-hourly temperature, radiation and relative humidity were generated from daily records using a diurnal interpolation scheme from the Variable Infiltration Capacity (VIC) model (Liang et al., 1994; Maurer et al., 2002). In this scheme, total daily rainfall was evenly distributed through sub-daily intervals. Climate data across the basin was computed from data of the six meteorological stations using a nearest-station interpolation. The soil profile was divided into three root zones, 0—30 cm, 30—60 cm, and 60—100 cm. Lateral subsurface flow was calculated using a topographic gradient. In the routing scheme, roads were not included, and stream classification was based on Strahler stream order and segment slope, derived from the DEM. A precipitation lapse rate of 0.0005 m/m was estimated from the rate of increase in average annual rainfall, as it corresponds with station elevation (Fig. 4), using data from 1989 to 2000. For the temperature lapse rate, we first calculated daily temperature using the mean of daily maximum and minimum temperatures at each station. The temperature lapse rate of −0.0053 °C/m was then approximated from the gradient of average daily temperature (1993—2000) with the elevation. Both precipitation and temperature lapse rates were assumed constant for the entire catchment. A rain LAI multiplier (leaf area index multiplier to determine interception capacity for rain) of 0.0005, a reference height of 40 m, and an aerodynamic roughness of bare ground of 0.02 m were set as constants. The initial spatial distribution of soil depth was created using ArcInfo (ESRI, Inc.) macrolanguage script as part of DHSVM pre-processing, based on the specified range of soil depths and the DEM. The soil depth was then adjusted during calibration. The initial vegetation parameters came from Global Land Data Assimilation Systems (GLDAS) by

NASA and were tuned to northern Thailand based on forest description by Gardner et al. (2000) and by parameters in the transpiration estimation of Tanaka et al. (2003). After the simulation, the approximate amount of irrigation diversion was subtracted from simulated stream flows before comparing to observed values.

To study the effects of landuse change, the same set of climate data and parameters were used for all vegetation scenarios, both with and without irrigation. When irrigation was considered, daily irrigation consumption was calculated, divided by the irrigation efficiency coefficient, and then subtracted from computed daily discharge to account for water diversion to irrigated area. Crops were divided into three categories based on their water demand: wet-season rice, dry-season rice, and cash crops (Table 1). Irrigated areas were approximated from the number of pixels of each crop type in the original 1989 and 2000 landcover data sets. Percentages of total irrigated areas in the basin in 1989 and 2000 were used to project a range of potential irrigated areas in the future scenarios. The following assumptions were made in calculating irrigation diversion: first, only 1/8 of the area designated as swidden cultivation in the original classification scheme was used for irrigated cropping. Second, for general field-crop classes, half of the area was wet-season rice and the other half was cash-crop; the composition of incremental cropland in future scenarios was divided in the same manner. Irrigation efficiency coefficients were based on the estimation by the Royal Irrigation Department and the values were 0.6 and 0.85 for wet and dry seasons respectively. The diverted water in the amount equal to crop water demand was then added to simulated evapotranspiration to maintain the water balance. Table 2 summarizes all simulation conditions.

Calibration and testing procedures

Model calibration was done by optimizing the model simulation of daily discharges at the basin outlet (P.14), Ban Mae Mu and Ban Mae Suk. The main focus was on the result at the basin outlet. Three methods of quantitative assessment for the goodness of model fit are the relative efficiency E_{rel} (Krause et al., 2005) (1), the root mean square errors (RMSEs) of daily discharges (2) and bias.

Table 1 Monthly irrigation water demand (in mm) of northern agricultural crops, Schreider et al. (2002)

Crop type	Month											
	January	February	March	April	May	June	July	August	September	October	November	December
Wet season rice	0	0	0	0	250	300	350	150	50	50	0	0
Dry season rice	250	200	200	0	0	0	0	0	0	0	300	500
Cash crops	150	150	100	0	0	0	0	0	0	0	300	100

Table 2 Simulation scenarios to look at effects of landuse type and irrigation

Secondary factor	Primary factor: landuse[a] change					
	Veg 1989	Veg 2000	Scenario I	Scenario II	Scenario III	Scenario IV
Irrigated areas (%)						
0	X	X	X	X	X	X
23[b]	X			X	X	
35[c]		X		X		X

[a] Veg 1989: re-processed 1989; Veg 2000: re-processed 2000; Scenario I: conversion from crops to forest; Scenario II: double crop areas; Scenario III: more upland crops; Scenario IV: more lowland crops.
[b] Approximate maximum percentage of croplands being irrigated based on Veg 1989.
[c] Approximate maximum percentage of croplands being irrigated based on Veg 2000.

$$E_{rel} = 1 - \frac{\sum_{i=1}^{N}\left(\frac{Q_i - Q_i'}{Q_i}\right)^2}{\sum_{i=1}^{N}\left(\frac{Q_i - \bar{Q}}{\bar{Q}}\right)^2} \quad (1)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Q_i' - Q_i)^2} \quad (2)$$

where Q_i is observed discharge at time step i, Q_i' is the simulated discharge at time step i after subtracting irrigation diversion, $\bar{Q}$ is the mean observed discharge, and N is the total number of time steps.

E_{rel}, a modified form of the model efficiency E (Nash and Sutcliffe, 1970), measures the goodness of model fit by comparing both the volume and shape of the discharge profile. The difference between simulated and observed values was quantified based on relative deviations instead of absolute values. The rationale for using E_{rel} is because E calculates the differences between the two time series as squared values. Consequently, an over- or under-estimation of higher values in the time series has greater influence than that of lower values (Krause et al., 2005). E_{rel} enhances the lower absolute differences during the low flow period since they are substantial when considered relatively. Thus, E_{rel} is more sensitive to systematic over- or under-prediction in the dry season. Since E_{rel} focuses on the reproduction of hydrograph dynamics, RMSE is also reported for quantifying the volume errors, and bias is the percent error in total stream discharge.

The climate data from March 1993 to February 1994 was used for model start-up. The calibration period was from March 1994 to March 1996 and the validation was from April 1996 to October 2000.

The key parameters for model calibration were first identified and then the optimization was done based on trial and error; one parameter was adjusted at a time. Whitaker et al. (2003); Cuo et al. (2006) took a similar calibration approach in their DHSVM applications. The objective is to obtain E_{rel} closest to unity and to minimize RMSE and bias. Negative E_{rel} indicates that the mean value of observed data is a better predictor than the model.

The model was sensitive to total soil depth, soil lateral hydraulic conductivity, and exponent decrease in lateral hydraulic conductivity with depth, and these are chosen as calibration parameters. Among three parameters, soil depth is the parameter that we have the least information on and is important in influencing the basin moisture storage size; therefore, it is the first calibration parameter. Soil lateral hydraulic conductivity influences the rate of subsurface flow, the water table depth, and the relative importance of subsurface runoff to the overland flow (Whitaker et al., 2003). The adjustment of soil lateral hydraulic conductivity was constrained to be within an order of magnitude of the initial known value obtained from SoilProgram. After calibration, the value of soil hydraulic conductivity was comparable to literature value and to those used in Cuo et al. (2006) on a small subbasin nearby. For the exponent decrease, the choice is confined to the range used in Cuo et al. (2006).

In addition to calibrating the discharge, we also checked the estimated annual evapotranspiration with literature values to make sure the parameter set yielded reasonable results. Final calibration parameters are listed in Tables 3 and 4.

Calibration results and assessment

During the calibration period, the stream flow at main basin outlet P.14 was reproduced reasonably well, though the performance at the two much smaller subbasins (Mae Mu and Mae Suk) was not as consistent (Table 5).

For P.14 the model captured the onset of the storm season, and the peak flows well (Fig. 5a).The overall efficiency

Table 3 DHSVM vegetation parameters

Parameter	Overstory (Class 2–5, 9)[a]	Understory (Class 1–9)
Fractional trunk space height	0.4–0.5	N/A
Height (m)	20–30	0.2–5
Aerodynamic attenuation coefficient	0.3–2	N/A
Radiation attenuation coefficient	0.1–0.2	N/A
Maximum stomatal resistance (s/m)	4000–5000	600–4000
Minimum stomatal resistance (s/m)	200–400	120–175
Vapor pressure deficit threshold (Pa)	4000–5000	4000–5000
LAI	1–8.2 (broadleaf) 3.5–8.8 (needleleaf)	1–5.5
Albedo	0.2	0.2
Root fraction in layer 1, 2, and 3	0.2, 0.4, 0.4	0.4, 0.6, 0.0

[a] Class 1: urban; 2: evergreen needleleaf; 3: deciduous needleleaf; 4: deciduous broadleaf; 5: mixed forest; 6: closed shrub; 7: open shrub; 8: cropland; 9: wooded grassland; 10: bare; 11: water.

Table 4 Final DHSVM soil parameters

Parameter	Soil layer	Soil class	
		1	2
Texture		Sandy clay loam	Sandy clay loam
Lateral soil hydraulic conductivity (m/s)		3.12×10^{-5}	5.1×10^{-5}
Exponent decrease rate of lateral saturated hydraulic conductivity		0.5	0.5
Porosity (m^3/m^3)	1	0.5	0.50
	2	0.5	0.51
	3	0.5	0.51
Vertical saturated hydraulic conductivity ($\times 10^{-5}$ m/s)	1	36.0	4.52
	2	15.6	2.55
	3	15.6	2.55
Pore size distribution index	1	0.12	0.12
	2	0.12	0.12
	3	0.12	0.12
Air bubbling pressure (m)	1	0.29	0.29
	2	0.29	0.29
	3	0.29	0.29
Field capacity (m^3/m^3)	1	0.26	0.27
	2	0.30	0.30
	3	0.30	0.30
Wilting point (m^3/m^3)	1	0.15	0.15
	2	0.18	0.18
	3	0.18	0.18
Maximum infiltration rate (m/s)		1.0×10^{-5}	1.0×10^{-5}

of 0.79 indicated reasonable model performance, even though the model systematically under predicted the dry-season flow by a little over 20% (Fig. 7a). The mean observed flow for the whole calibration period, 43.4 m³/s, was underestimated by 9% with a RMSE of 75% (Table 5).

During the validation period, the model efficiency was 0.74, close to the results of the calibration period. The model captured the right timing and magnitude for peaks (Fig. 6a). The prediction of annual flow matched very well with the observed values (Fig. 7a) with a 2% overall bias in stream flow and RMSE of 23.6 m³/s. This, like the calibra-

tion results, was 75% of the measured mean (31.3 m³/s). The validation period also consistently underestimated dry-season flow by nearly 20%.

For the Mae Mu and Mae Suk subbasins, the timing and magnitude of the modeled stream flow peaks had a higher variance than the actual observations (Fig. 5b and c, Fig. 6b and c), contributing to a relatively poor performing model. The efficiencies during the calibration period were relatively low, but slightly better than in the validation period, which had negative values for overall model efficiency (Table 5). Through out the simulation for the Mae Mu, the

Table 5 Model calibration performance for the main basin outlet: P 14, Mae Mu subcatchment, and Mae Suk subcatchment

Year	Gauge location								
	Basin outlet (P. 14)			Ban Mae Mu			Ban Mae Suk		
	E_{rel}	Bias (%)	RMSE (m³/s)	E_{rel}	Bias (%)	RMSE (m³/s)	E_{rel}	Bias (%)	RMSE (m³/s)
Calibration − overall	0.79	−9	32.7	0.15	7	1.2	0.43	−50	1.5
Wet season 1994	0.69	4	41.8	−0.86	32	1.4	0.14	−58	2.1
Dry season 1995	−0.07	−25	7.4	0.42	−29	0.2	−0.24	−56	0.5
Wet season 1995	0.63	−14	49.1	−0.56	27	1.8	−0.94	−48	2.0
Dry season 1996	0.16	−21	15.4	−1.83	−33	0.6	−2.52	−11	0.7
Validation − overall	0.74	2	23.6	−0.92	24	1.1	−2.22	−5	1.3
Wet season 1996	0.49	10	37.5	−1.95	42	1.5	−0.28	−21	1.4
Dry season 1997	0.33	−8	10.4	−0.16	−20	0.4	−6.15	−8	0.6
Wet season 1997	0.60	−9	20.0	−2.82	29	1.1	0.71	−47	2.1
Dry season 1998	0.63	−28	7.6	0.39	−37	0.2	0.72	−32	0.3
Wet season 1998	0.68	21	20.1	−0.02	−8	0.7	−19.44	17	1.1
Dry season 1999	0.14	−10	4.5	−0.87	−24	0.2	−2.48	26	0.2
Wet season 1999	0.42	7	29.5	−15.98	92	2.2	−1.87	−5	1.5
Dry season 2000	0.82	−22	19.6	0.64	−29	0.7	−0.23	−4	0.4
Wet season 2000	0.37	16	36.8	−7.76	65	1.5	−22.49	73	2.0

modeled dry-season flow consistently under-predicted measured flow by 28% (Fig. 7b, Table 5). The modeled wet-season flow overestimated measured flow by varying amounts, with worst performance in the wet seasons of 1999 and 2000, with 92% and 65% bias respectively.

During the calibration period for the Mae Suk, the annual and seasonal flows were underestimated (Table 5), the overall bias was −50% and RMSE was in the same magnitude as the measured mean (1.5 m³/s).

During the validation period, the overall bias of 5% was relatively small. However both annual and seasonal flows did not seem to correlate with the observation (Fig. 7c). The wet-season flow in 2000 was highly overestimated with a 73% bias, and the simulation yielded several peak flows during the beginning of the wet season while the actual peak flows occurred late in September and October.

While it is possible to fine tune the results of the two subbasins by adjusting soil depth or soil hydraulic properties, there is not enough information to justify the adjustment. With the sparse input data, the guiding rationale is that it is more important to capture the discharge dynamics of the whole basin rather than at the smaller catchments.

Model performance and sources of errors

Overall, the model at P.14 performed within published ranges (comparable to Nash and Sutcliffe model efficiency −0.76 to 0.5, Cuo et al., 2006, 0.57—0.87; Beckers and Alila, 2004). That there was greater divergence for the Mae Mu and Mae Suk subbasins is not surprising, given their small size relative to the overall scale of the basin and data available. The divergence of estimated stream flow from the observed could have been due to:

(1) Uncertainty in estimated rainfall distribution within the basin. The shapes of observed wet-season stream flow peaks for the subcatchments are different than that at the main basin outlet, especially in the wet season of 1999 and 2000. Those observed peaks also do not match with basin-wide rainfall (Fig. 6), indicating that local rainfall events differ from basin-wide events. Rainfall could be overestimated in the higher elevation zone of the two subcatchments. Therefore, rainfall measurement and appropriate basin-wide meteorological data interpolation from weather station records are critical for model performance, especially when the basin has a large elevation range.

(2) Water regulation from irrigation. Two aspects regarding irrigation are the percent of croplands being irrigated and the uncertainty in the timing and frequency of irrigation diversion. In the Mae Suk especially, 17% of the subcatchment is crop area. These crop areas are mainly paddy fields near the streams, field crops, and shifting cultivation. The percentage of crop areas in the Mae Suk is 70% higher than that of the whole Mae Chaem basin (10.4%), and the fraction of calculated irrigation diversion accounts for 10—60% of the mean observed flows whereas the estimated irrigation diversion from the main stream flow only accounts for 4—30% of the observed values. Therefore, the channel prediction at Mae Suk is more sensitive to the subtraction of irrigation water than at the main basin outlet (P.14).

(3) Dynamics of crop conversion. The simulation from 1994 to 2000 was performed on a static landcover using Veg 2000 dataset. However, the landcover gradually changes over time, as observed in the original landcover classifications from 1989 and 2000. This shows a cropland area net increase of about 1%. Even though the total increase in the crop area is small, the location of land conversion between crop type subgroups is not represented in the model.

(4) Estimated sub-daily climate data. Sub-daily data was interpolated from daily data. This, compounded by the need to estimate missing temperature values for TMD300201 and DO rainfall data, is another source of uncertainty.
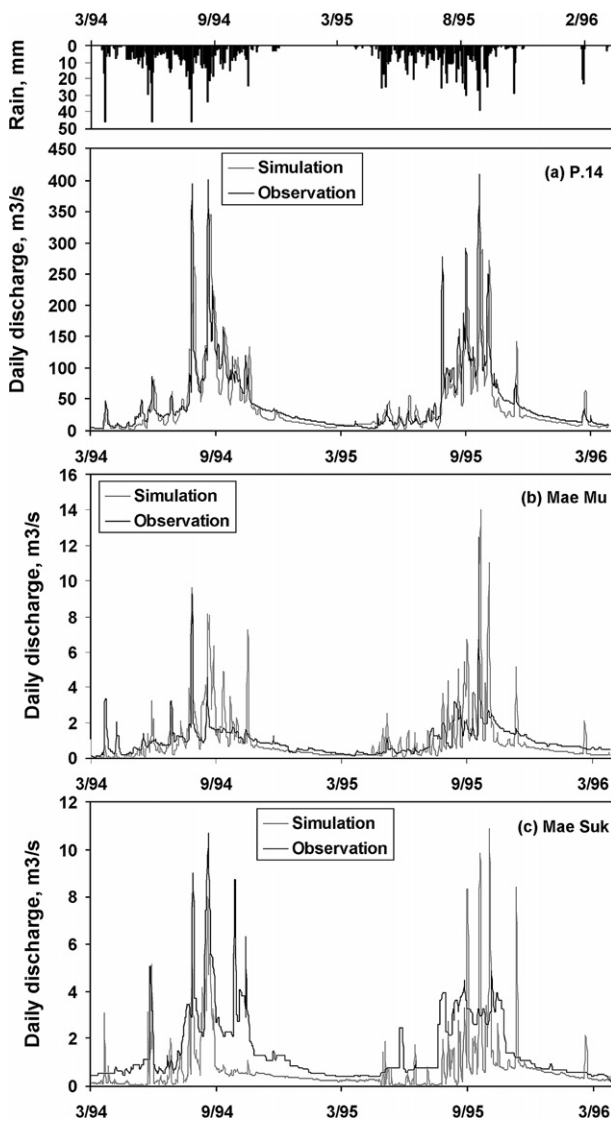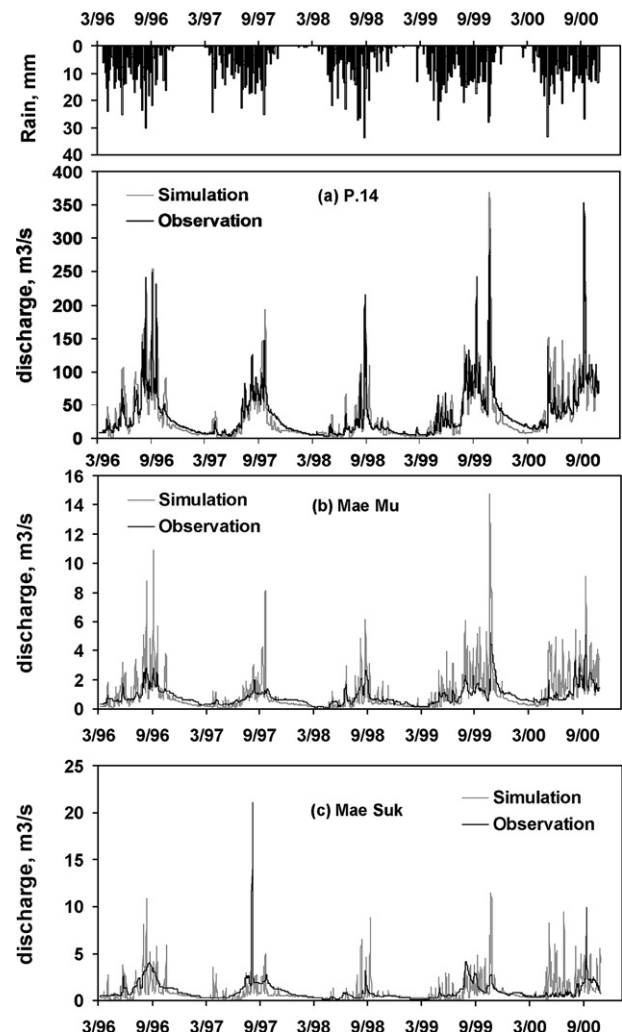
Figure 5 Observed and predicted hydrographs simulated using Veg 2000 during calibration period for (a) basin outlet: P.14, (b) Mae Mu subcatchment, and (c) Mae Suk subcatchment.

(5) Preferential flow not represented. The prediction performance also depends on the representation of subsurface and surface flows in the model. The version of DHSVM used in this work does not account for the preferential flow. Cuo et al. (2006) discussed the work by Beckers and Alila (2004) which explained the tradeoffs for model accuracy between peak flows versus base flows when the preferential flow was not represented.

Hydrologic flow paths: current conditions and scenarios

We evaluated the hydrologic response at the main basin outlet to the current landcover and to the effect of forest-to-crop conversion. The evaluation was in terms of the water yields and spatial variation of soil moisture and evapotranspiration inside the basin.

Figure 6 Observed and predicted hydrographs simulated using Veg 2000 during validation period for (a) basin outlet: P.14, (b) Mae Mu subcatchment, and (c) Mae Suk subcatchment.

Hydrologic dynamics under current conditions

The Mae Chaem river observed runoff ratio is approximately 19% of total rainfall, and 70% of the discharge appears as the wet-season flow (Table 6). Predicted annual yields from DHSVM, accounting for irrigation, were about the same as observed values. The runoff ratio was consistent with the 15—25% runoff ratio published in Alford's study of annual runoff in mountainous regions of northern Thailand (1992). However, in our simulation the high flow was overestimated by 9% and the low flow was underestimated by nearly 20%. The magnitude of forecasted flow was sensitive to the estimated irrigation consumption, as discussed earlier in section ''Model performance and sources of errors''.

The simulated average annual evapotranspiration was 1016 mm, corresponding to 74% of basin-wide estimated precipitation. Evapotranspiration was highest in the period from May to August and reached minimum values in January and February. The seasonal trend is positively correlated with rainfall seasonality.

The spatial distribution of soil moisture and evapotranspiration was demonstrated in Fig. 8. Direct observation indi-
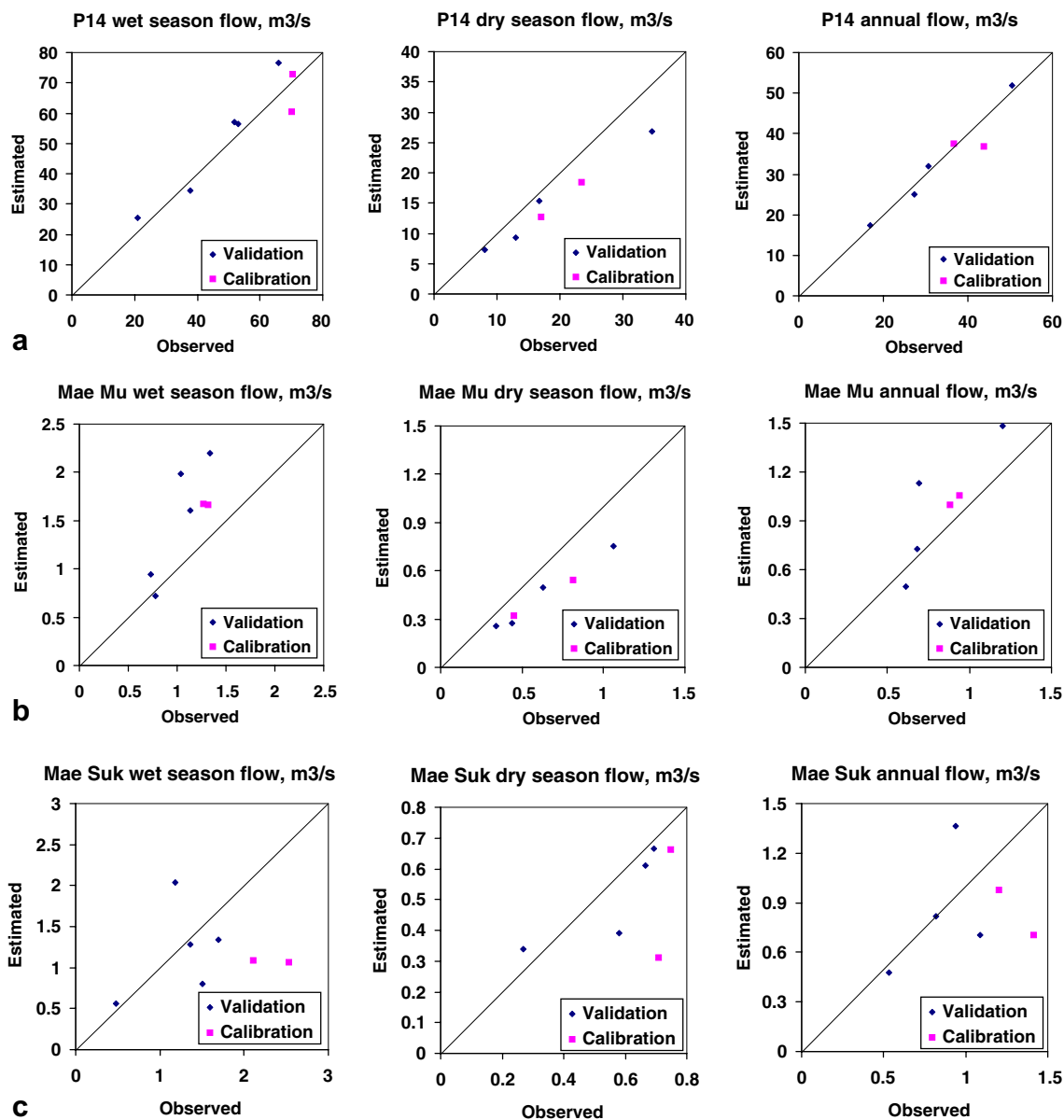
Figure 7 Comparison between observed and estimated annual, wet-season, and dry-season discharges for (a) basin outlet: P.14, (b) Mae Mu subcatchment, and (c) Mae Suk subcatchment.

cates that soil moisture dynamics may follow spatial variation of rainfall across the basin. To analyze if spatial relationships exist, basin elevation data was categorized into five zones, and zonal means of simulated soil moisture and evapotranspiration were computed. Results showed that soil moisture was relatively high near the main channel and on the ridges and decreased towards midlands at 800–1200 m (Fig. 9). The exception was the soil moisture in the second layer on a dry day (March 9, 1999), which had decreasing soil moisture with increasing elevation. There was no clear correlation between evapotranspiration and elevation zone.

Simulation results were sensitive to soil depths and soil lateral conductivity, indicating that the saturation excess overland flow could be an important mechanism for runoff production. The saturation excess area is expected to occur near the stream channel, with the size of the runoff source areas varying seasonally and during individual storm events. To evaluate the importance of saturation excess runoff, we analyzed the spatial distribution of depth to the water table during both wet and dry periods (Fig. 8). During a selected dry period (March 9, 1999), the water table depth intersected the surface (depth to water table < 0.01 m) primarily around the main and tributary channels. On the selected wet days October 30 and December 9, 1999, the saturation excess overland flow is evident on a larger portion of the basin, including wider areas around the main stem, near the basin outlet, and along the ridges, consistent with the higher precipitation. The occurrence of saturation excess overland flow on October 30, 1999 along the ridges is highly unusual. If this occurrence is valid, the flow was probably due to high antecedent moisture conditions caused by sev-

Table 6 Potential ranges[a] of basin hydrology simulated on different landcover scenarios, with and without irrigation based on water year (November—October)

Landcover scenarios		Average hydrologic components (hydrologic year 1997—2000)				
		Annual yield, mm (m^3/s)	High flow (m^3/s)	Low flow (m^3/s)	Annual evapotranspiration (mm)	Runoff ratio[b]
Observed		257 (31.3)	45.8	18.1	750[c], 1230[d]	0.19
Veg 2000	Irrigated	259 (31.6)	50.0	14.7	1016	0.19
	Unregulated	294 (35.8)	54.1	19.1	981	0.21
Scenario I	Unregulated	286 (34.9)	53.1	18.3	988	0.21
Scenario II	Irrigated	237 (29.0)	47.0	12.3	1042	0.17
	Unregulated	300 (36.6)	54.8	19.8	975	0.22
Scenario III	Irrigated	256 (31.2)	49.6	14.2	1020	0.19
	Unregulated	301 (36.8)	55.1	19.8	973	0.22
Scenario IV	Irrigated	235 (28.6)	46.5	12.1	1045	0.17
	Unregulated	297 (36.2)	54.3	19.6	978	0.22

[a] Based on percentage of irrigated croplands in Table 2. Veg 2000: re-processed 2000; Scenario I: conversion from crops to forest; Scenario II: double crop areas; Scenario III: more upland crops; Scenario IV: more lowland crops.
[b] Based on the average 1997—2000 simulated basin-wide rainfall of 1376 mm.
[c] Hill evergreen forest in Chiang Mai (Tangtham, 1999).
[d] Typical mountainous watershed, excluding cloud forests (Tangtham, 1999).

eral preceding storm events. To determine the runoff mechanism more precisely, field observation should be made. In the absence of such additional observations, this occurrence should be treated as erroneous.

Effects of landuse change on hydrologic responses

One of the most important concerns regarding forest-to-crop landuse change relates to water availability during the dry season. If we compare the simulated unregulated flows for future scenarios with respect to the referenced Veg 2000, cropland expansion elevated the dry-season flow by about 4%, and slightly elevated the annual and wet-season flows (Table 6). The opposite trend was true when croplands were converted to forests as in Scenario I. The unregulated water yields among Scenarios II, III and IV were about the same although highland crop expansion (Scenario III) yielded slightly higher annual and wet-season flows compared to lowland—midland crop expansion (Scenario IV).

The next step was to consider the effect of irrigation. Under the current set of model parameters, we demonstrated that increased croplands throughout the basin (Scenario II) caused a reduction in the regulated annual (−9%), wet-season (−6%), dry-season flows (−16%), and increase in evapotranspiration (+3%), compared to the simulation using Veg 2000 (Table 6). Scenario III resulted in about the same regulated annual and seasonal water yields as Veg 2000. When compared to Scenario IV, Scenario III yielded higher regulated annual (+8.6%), wet-season (+6%), and dry-season (+16%) flows. Simulations using Scenario II and IV produced about the same water yields.

The magnitude of differences in stream flow behavior among scenarios depends on the approximation of irrigation diversion. Thus, the unregulated water yields provided a

reference for potential ranges of stream flows. We also compared the regulated to estimated unregulated flows. Low-season flow was a volatile component and available yields at the basin outlet varied from 77% of unregulated flow under Veg 2000, to 74% under Scenario III, and to 62% on Scenarios II and IV. Wet-season discharge was less sensitive and the flow remaining after diversion was about 90% of unregulated flow in each case. Evapotranspiration was 4% higher than the non-irrigated case for Veg 2000, and about 5—7% higher for Scenarios II—IV.

Discussion and conclusions

Landuse change in Mae Chaem has largely featured agricultural transformations in different altitude zones. Highland pioneer shifting cultivation has been replaced by expanded permanent fields producing commercial horticultural crops, often with seasonal sprinkler irrigation. While some midland rotational forest fallow shifting cultivation systems remain, others have been replaced by rainfed permanent plots producing subsistence and commercial field crops. Irrigated paddy has expanded where terrain allows, and lowland agriculture has increased dry-season water use for irrigated rice, cash crops and fruit orchards.

Objective 1. Basin hydrologic regime. The DHSVM hydrology model was used as a tool for analyzing impacts of forest-to-crop conversion, and *vice versa*, on basin hydrology and water availability at the basin outlet. As would be expected in such a steep basin, topography is the primary factor controlling climatic, vegetation, and, consequently, spatial variation of Mae Chaem's hydrologic components. Saturated overland flow was the predominant flow path for water into streams. That said, this work assumed agricultural practices do not cause significant soil compaction, which would lower
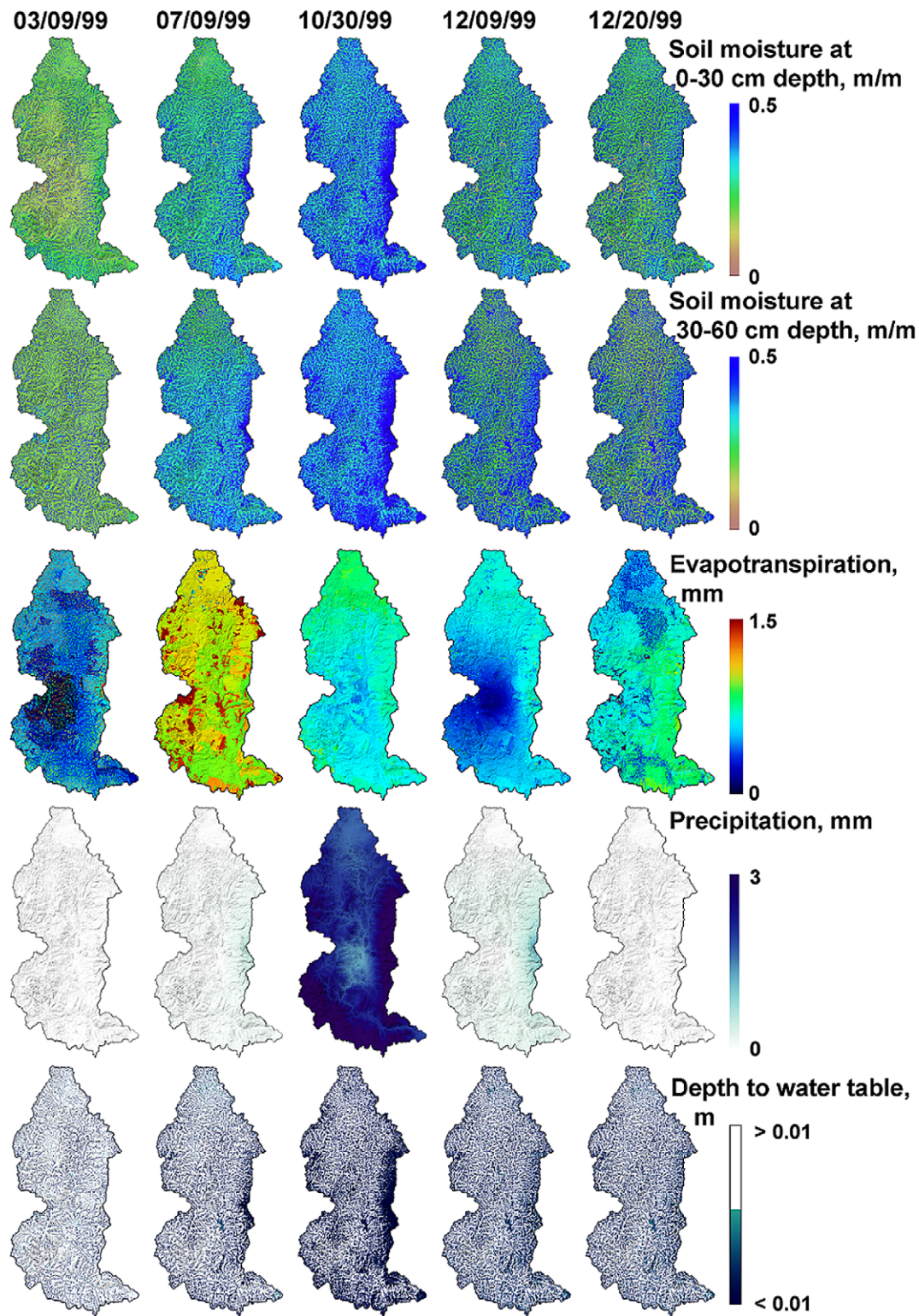
Figure 8   Illustration of the underlying dynamics changes in hydrographs, with soil moisture in the root zones at 0–30 cm, 30–60 cm, evapotranspiration, precipitation, and depth to water table (top to bottom). Values are at time = 0:00–3:00 and simulated on Veg 2000.

infiltration rate and vertical hydraulic conductivity and would induce Horton overland flow. Additional study on the extent and effects of soil compaction may increase the accuracy of the simulation. Irrigation diversion is the most direct influence on discharge magnitude, and it causes vegetation scenario water yields ranges to significantly vary. Discharge magnitude is sensitive to assumptions on the percentage of area irrigated, crop types, and crop water needs.
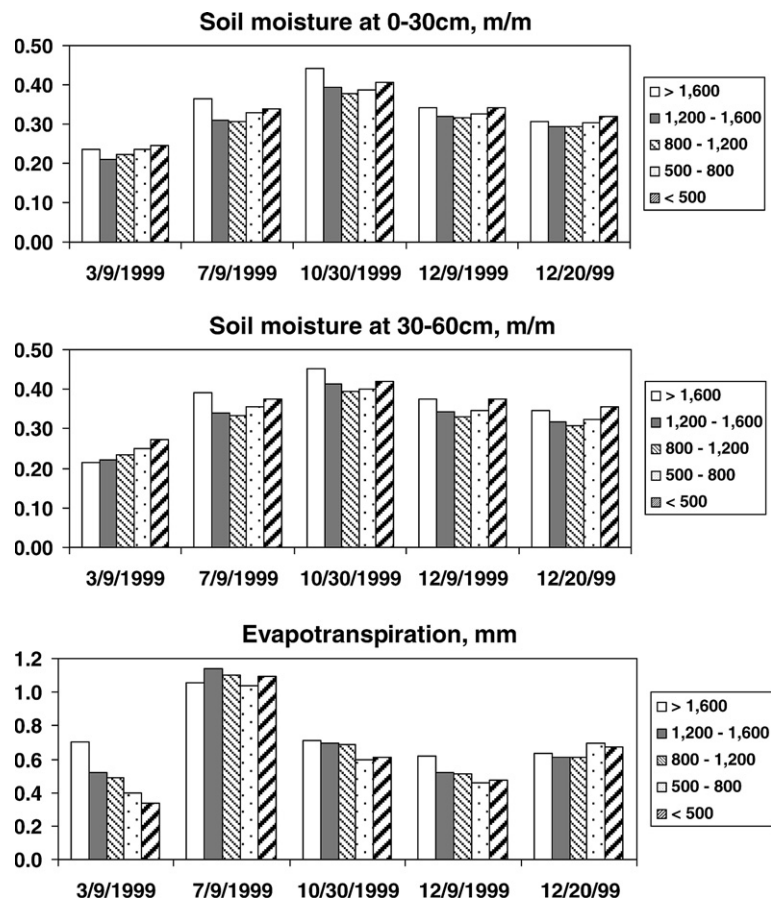
Figure 9 Temporal dynamics of evapotranspiration and soil moisture at 0—30 cm and 30—60 cm root depth and their correlations with elevation zone, simulated using Veg 2000.

The basin hydrology is sensitive to changes in landcover attributes, with a general pattern of increasing unregulated runoff with migration from trees to crops due to decreasing evapotranspiration. Rainfed upland agriculture, especially in the midland zone, does not appear to result in lower water availabilities downstream. This is in agreement with the conclusion from Walker (2002) that while the forest clearing to agriculture may alter the stream flow pattern, it does not necessarily cause a decline in the dry-season water supply. The net effect depends on whether the benefit of reduced evapotranspiration outweighs the cost of reduced infiltration. Under current irrigation schemes, highland crop expansion (>1000 m.a.s.l.) may lead to slightly higher seasonal and annual yields than lowland—midland crop expansion.

Objective 2. Assessment of the utility of a distributed, physically-based model as a management tool. The utility of a spatially-explicit, process-based analytical modeling environment is demonstrated by its ability to reproduce hydrographs across a range of conditions, in a basin where data are relatively sparse. Though the model performance at the two subbasins is lower, the simulation results at the main basin outlet show that the efficacy of the model as an intelligent data-interpolation engine is clear. That the model does as well as it does basin-wide implies that the constituent dynamics are relatively well-understood over a large and complex watershed and some confidence can be placed in the quantitative implications of the scenarios. This modeling approach can be useful in assessing the influence of spatial configuration or fragmentation of landcovers.

Acknowledgements

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