Journal of Hydroscience and Hydraulic Engineering
Vol. 29, No.1 May, 2011, 69-80

ON THE IMPORTANCE OF INCLUDING VEGETATION DYNAMICS IN HYDROLOGICAL SIMULATION

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SYNOPSIS

Vegetation exerts effects on runoff via features such as interception, stomatal behavior and transpiration, and rooting strategy. Therefore, it is essential to consider the dynamic role of vegetation e.g. physiological processes, phenological processes, and vegetation changes in runoff simulation. However, the parameterization of vegetation as a dynamic component is insufficient in stand-alone hydrological models. This paper evaluates and improves the hydrological performance of Lund-Postdam-Jena model (LPJ), a prominent dynamic global vegetation model considering transient structural changes in major vegetation types. Applications to four basins located in different climatic zones show that the modified LPJ simulated runoff and vegetation well. Additionally, to evaluate effects of vegetation on runoff and show the potential advantages of LPJ over stand-alone hydrological models, as an example, the model was run under a scenario of changing atmospheric CO_2 content alone and the results showed that runoff increased in humid basins while decreased in arid basins.

INTRODUCTION

Vegetation plays an active role in the hydrological cycle. The composition and the distribution of vegetation are of fundamental importance for evapotranspiration and runoff generation. Plants exert considerable effects on runoff via features such as albedo and interception, stomatal behaviour and transpiration, rooting strategy, leaf area and phenology (1). In turn, water availability is a key determinant for the distribution and productivity of vegetation. Therefore, there is a need to model dynamic interactions and feedbacks between vegetation and the water cycle.

The effects of vegetation's role in the hydrological cycle have long been a concern. Methodologies used for evaluating the effects of vegetation on runoff generation fall within two categories: the paired catchment methods and the time trend analysis technique (2), and process based analyses (3). The principal disadvantage of these methods is that without knowledge of the processes taking place in the catchments results are not flexible enough to be applied to other catchments directly for prediction. Some researchers have tried to consider vegetation effects on hydrological processes in terms of runoff and evapotranspiration by using hydrological models. Examples include those of Tague et al. (4), Oudin et al. (5), and Donohue et al. (6). These researches describe in detail hydrological processes such as runoff and routing while an insufficient parameterization of vegetation composition and distribution. Therefore, important biosphere-hydrosphere interactions can not be well considered by such stand-alone hydrological models. For example, they cannot sufficiently capture the hydrological effects resulting from changes in vegetation. Therefore, a realistic assessment of the effect of vegetation change on hydrological processes needs models that mechanistically link vegetation dynamics and hydrological process. Among candidate models to meet this requirement are land surface schemes used in climate models, but they also do not simulate transient changes in vegetation structure and distribution (1). Alternative candidates are dynamic global vegetation models (DGVMs), which are able to simulate transient structural changes in major vegetation types in response to variations in climate, water availability, and atmospheric CO_2 content. Few researches (1), (7), (8) have been done with a view of evaluating the hydrological performance of DGVMs and these researches focus on annual/monthly runoff and evapotranspiration calculation at global, regional, and large river basins. Under the changing climate conditions, understanding the vegetation dynamics and effects of vegetation on runoff at a daily step for basin scale is important for practical flood controlling and water management. However, few researches have discussed this topic.

The present study evaluates hydrological performance of a leading DGVM, the Lund-Potsdam-Jena model (8) (hereafter LPJ). The scope is to evaluate the hydrological performance of LPJ, identify limitations in runoff simulation by LPJ and improve its performance, and explore potential advantages of LPJ over stand-alone hydrological models. Therefore, simulations have been made for the period 1901-1998 for four basins located in the Asian Pacific region ranging from humid to arid zones where 9-year hydrological observation data is available for validation. Furthermore, vegetation type and composition produced by the DGVM were validated against remotely sensed data. To provide an idea to what extent vegetation affects runoff at basin scale and show the potential advantages of DGVM over stand-alone hydrological models, as an example, the model was run under a scenario of changing atmospheric CO_2 content alone.

METHODOLOGY

The Lund-Potsdam-Jena model

Lund-Potsdam-Jena (LPJ) is a coupled non-equilibrium biogeography-biogeochemistry model, which combines process-based representations of terrestrial vegetation dynamics and land-atmosphere carbon and water exchanges in a modular framework. For a detailed description of the model see Sitch et al. (8). LPJ explicitly considers key ecosystem processes such as vegetation growth, mortality, carbon allocation, and resource competition, although their representation is of intermediate complexity to allow for global applications. To account for the variety of structure and functioning among plants, 10 plant functional types (PFTs) are distinguished. The presence and fractional coverage of PFTs is determined annually according to individual bioclimatic, physiological, morphological, and fire-resistance features. The structure and distribution of the PFTs is decisive for the simulated site water balance, since evapotranspiration, soil water content, and runoff generation are modulated by PFT-specific attributes such as interception storage capacity, seasonal phenology, rooting depth, and photosynthetic activity. A brief introduction of water balance computations in LPJ (see Fig.1) is given in the following sections.

(1) Actual evapotranspiration

The actual evapotranspiration (AET) is calculated at a daily time step as the minimum of a supply function (S) and a non-water-stressed evapotranspiration rate (D) (9):

$$AET = \min\{S, D\} \quad (1)$$

D is calculated as a function of potential canopy conductance (g_p) following Monteith (10):

$$D = E_q \alpha_m \left[1 - \exp\left(-g_p / g_m\right)\right] \quad (2)$$

where E_q is the daily total equilibrium evaportanspiration calculated from latitude, temperature and sunshine hours data. g_p is calculated according to photosynthesis, which is calculated as a function of leaf area index (LAI), temperature, atmospheric CO_2 concentration, day length, and canopy conductance. The parameters α_m and g_m are empirical parameters with $\alpha_m = 1.4$ (dimensionless) and $g_m = 5$ mm/s following Monteith (10). D gives the evapotranspiration rate which the vegetation achieves when the supply of moisture from the soil is not limiting. S ($= E_{max} w_r$) is determined by the maximum transpiration rate that can be sustained under well-watered conditions (E_{max}) and declines linearly with relative soil moisture (w_r).

(2) Runoff generation

A simple bucket model (see Fig.1) is used for runoff generation and no routing method is used in LPJ. The soil layer is treated as a simple bucket consisting of two layers with a fixed thickness (upper 0.5m; lower 1.0m). Water content of both soil layers is updated daily, taking account of evapotranspiration, percolation and runoff. Since soil moisture spatial variability is not considered, runoff will not be generated until the soil is saturated across the basin, which is not the case for many basins. Therefore, runoff generation mechanism is modified by using HYMOD (HYdrological MODel) runoff generation and routing scheme (see Fig.2) (11). Hereafter, the modified LPJ is referred to as LPJH (Combination of LPJ with HYMOD) in the following sections. The HYMOD model assumes that the soil moisture storage capacity, c , varies across the catchment and, therefore, that the proportion of the catchment with saturated soils varies over time step t . The spatial variability of soil moisture capacity is described by the following distribution function:

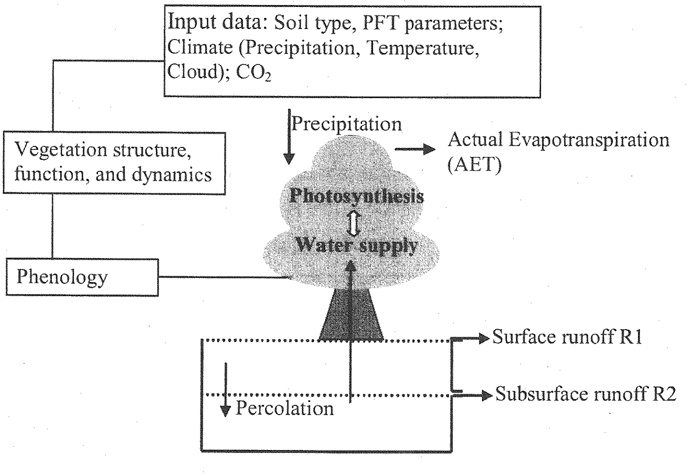

Fig. 1 Schematic representations of the water balance computed for each grid cell by the dynamic global vegetation model LPJ.

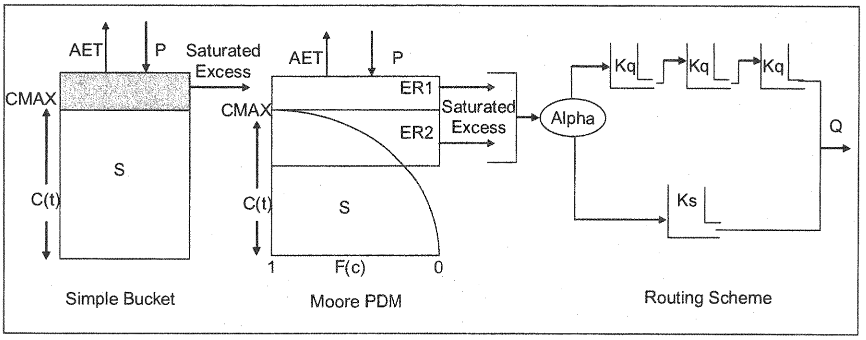

Fig. 2 The schematic structure of the HYMOD model. Effective rainfall ($ER1$ and $ER2$) is produced depending on the current catchment moisture state described by the storage capacity distribution function $F(c)$. The parameter C_{max} describes the maximum storage capacity in the catchment. The effective rainfall is distributed with respect to parameter Alpha and either routed through three linear reservoirs with residence time Kq in series, or a single reservoir with residence time Ks. Variable Q is the resulting streamflow. the remaining variables are the precipitation input P, the soil moisture storage S, and the actual evapotranspiration AET.

$$F(c) = 1 - (1 - c(t)/C_{max})^{B_{exp}}; \quad 0 \le c(t) \le C_{max} \tag{3}$$

where C_{max} is the maximum storage capacity and B_{exp} is the degree of spatial variability of soil moisture capacity.

Dataset

(1) Study area

Four basins located in Philippines, Japan, China, and Australia were selected as areas to be studied. The hydrological data of these basins was obtained under the collaboration with University of Yamanashi COE Virtual Academy (VA), Pristine Basin data, and Asian Pacific FRIEND. The main selection criteria were accessible hydrological data of good quality, long period, and the studied basins representing a variety of climate and vegetation conditions. The Angat basin of Philippines is humid throughout the whole year in the eastern part and is dry from January to April in the western part. A major portion of this basin is covered with tropical forests. The Haji basin in Japan has a temperate climate with the broadleaved summergreen and needleleaved evergreen trees being the major vegetation type. The Hushan basin in China is located in a monsoon climate area and its rainfall varies greatly with different seasons. Temperate needleleaved evergreen trees, temperate broadleaved evergreen and summergreen trees dominate this basin. The climate of Todd River in Australia is typically arid continental with large daily temperature variations. Rainfall may occur at any time of the year and is often due to thunderstorm activity caused by convective processes. The vegetation cover of this basin is highly dependant on the amount of rainfall seasonally and annually, but is generally sparse. Vegetation in the catchment area ranges from grasses to low shrublands and woodlands. The maximum value of a normalized difference of the vegetation index (NDVI) is used to represent roughly the vegetation condition within a basin. Basic characteristics and the data period used in this study are listed in Table 1.

(2) Model input and output

The LPJ and LPJH models were run for the period 1901-1998, preceded by a 1000-year spin-up period to reach an initial equilibrium with respect to carbon pools and vegetation cover from bare ground. The models were driven by grid (0.5° resolution) monthly precipitation, air temperature, and cloud cover from CRU TS 2.1 (12), and by texture for

Table 1 List of basin characteristics and data period for validation.

River system	Country	**Data period**	Area (km^2)	Annual rainfall(mm)	Aridity index*	Max. NDVI
Angat	Philippines	**1987-1995**	781	3150	0.60	0.729
Haji	Japan	**1990-1998**	305	1800	0.61	0.809
Hushan	China	**1990-1998**	6374	2150	0.79	0.772
Todd	Australia	**1990-1998**	445	260	5.51	0.474

Aridity index* = (mean annual potential evaporation)/(mean annual precipitation)

nine soil types provided by Food and Agriculture Organization (13). Non-gridded model inputs include annual CO_2 concentrations (one global value) provided by the Carbon Cycle Model Linkage Project. Furthermore, various parameters are assigned to the different PFTs following Sitch et al. (8). The parameters obtained from the optimized scheme developed by Li et al. (14) are forced to the LPJH model. Additionally, the LPJ and LPJH models were driven by in-situ observed daily precipitation at the four basins for the periods listed in Table 1, the other input data keeping the same with the aforementioned run.

The output of the LPJ and LPJH models includes hydrological processes such as evapotranspiration and runoff at different time scales, vegetation characteristics such as LAI and fraction plant cover (FPC), as well as net primary production (NPP) and net ecosystem productivity (NEP) at annual scale.

(3) Data for validation

Simulated runoff was compared with in-site observed data for the four basins at monthly and daily scales in terms of flow duration curves for the various periods listed in Table 1. It was also compared with runoff calculated from stand-alone hydrological model—the HYMOD model. Simulated FPC was compared with observed data from Japan Integrated Biodiversity Information System (J-IBIS) for the Haji basin in Japan, and from Global Land Cover Characterization (GLCC) with International Geosphere Biosphere Programme (IGBP) classification for the other three basins. Simulated LAI was compared with the NDVI derived from the Advanced Very High Resolution Radiometer (AVHRR) (15). LAI is an important surface biophysical parameter as a measure of vegetation cover and vegetation productivity; NDVI is an alternative measure of vegetation amount and conditions. Numerous studies have examined the relationship between the NDVI and LAI.

CO_2 scenario experiment

To explore the effects of vegetation on runoff at the basin scale under the changing climate conditions, and to show the potential advantages of LPJH over stand-alone hydrological models, the LPJH model was run under a scenario of changing atmospheric CO_2 content alone. Only the atmospheric CO_2 content for the historical period 1901-1998 including the spin-up was replaced by the B2 reference scenario for the period 2001-2098 calculated from ISAM (Integrated Science Assessment Model) model. As the values of CO_2 concentration were increased, plants increased their water use efficiency by transpiring less water per unit of carbon fixed (16). Furthermore, vegetation is expected to be more productive, which may counteract the water savings due to decreased transpiration. In turn, the changes in transpiration rate, vegetation structure and production should give feed back to soil water content and runoff generation. For example, soil water content will increase resulting from decreased transpiration, and consequently evaporation from the soil will increase. Since LPJH computes the dynamic relations among these processes, the net effect of increased atmospheric CO_2 concentration and of associated transient vegetation changes on the water balance can be quantified.

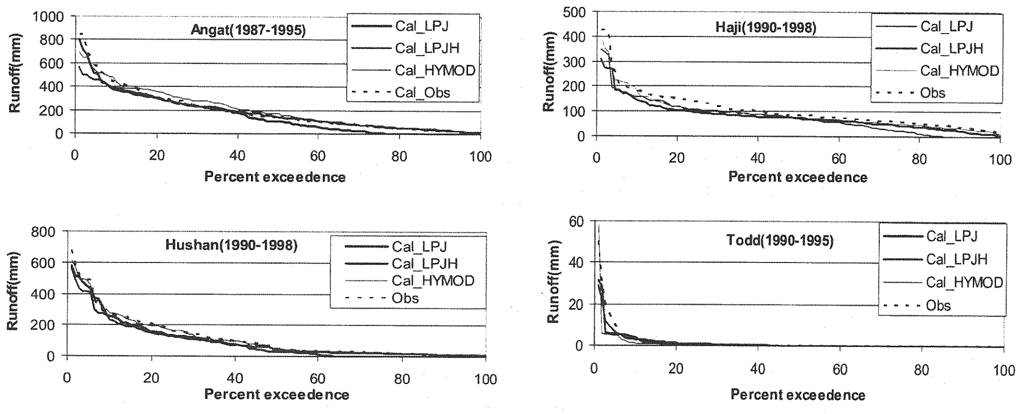

Fig.3 Observed and simulated monthly flow duration curves by the LPJ, LPJH and HYMOD models at the four basins.

Table 2 Relative error for simulated runoff, where Relative error = (Calculated Runoff – Observed runoff)/Observed runoff) for the simulated nine years at the four basins.

Relative error	LPJ(%)	LPJH(%)	HYMOD(%)
Angat	-16.03	-6.73	6.09
Haji	-25.89	-23.58	-11.96
Hushan	-20.03	-17.98	-1.90
Todd	-18.52	-11.21	-29.57

RESULTS AND DISCUSSION

Model validation

The LPJ and LPJH models are validated in terms of monthly and daily runoff, average LAI, and vegetation type and composition for the periods (Table 1) where in-site observed precipitation and runoff data are available at the four basins. The simulated runoff by LPJ and LPJH models is also compared with the simulated runoff by the stand-alone hydrological model-HYMOD. This comparison may help to identify the advantages and disadvantages of DGVMs in simulating runoff over stand-alone hydrological models.

Compared with the monthly runoff simulated by the LPJ model, the monthly runoff simulated by LPJH agrees much better with observed runoff for the four basins, especially in the low flow period (Fig.3 and Table 2). This is attributable to the runoff generation mechanisms adopted in different models. All of the models underestimate runoff in the high flow period for all the study basins as well as the middle flow period except the HYMOD model for Angat basin in the Philippines. One possible reason for the underestimation of runoff is that LPJ and LPJH consider only natural vegetation. Thereby simulated runoff should be low in regions where the model diagnoses a dominance of woody PFTs, although some parts of the land has converted into management land such as agricultural land and urban area. For the Todd River basin in Australia, the LPJH model performs better than both the LPJ model and the HYMOD model. This is probably due to the high variability of vegetation in this basin. However, the HYMOD model cannot capture this variability of vegetation and the LPJ model cannot simulate the spatial soil moisture

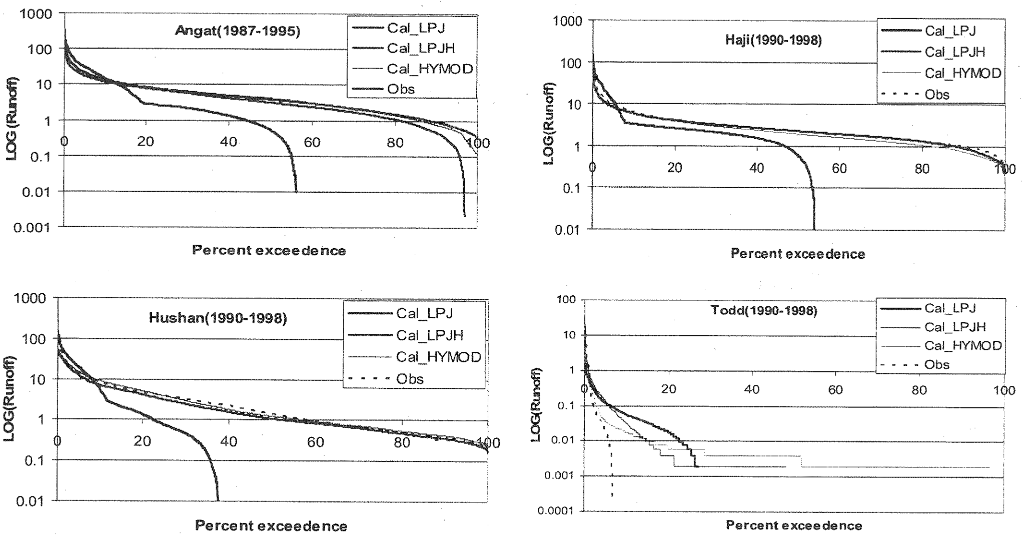

Fig.4 Observed and simulated monthly flow duration curves by the LPJ, LPJH and HYMOD models for the four basins at daily scale.

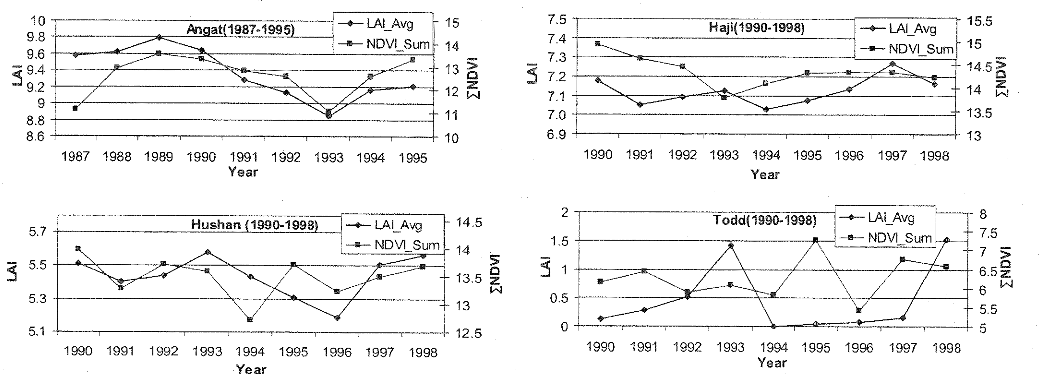

Fig.5 Trend comparison between $\sum NDVI$ values and LAI calculated by LPJH for various periods at the four basins.

variability properly. Likewise, the LPJH model underestimates runoff in the high flow period at the daily scale. The LPJH model has an absolute advantage over the LPJ model and the simulated runoff by LPJH lie well with the HYMOD performance at the daily scale (see Fig.4). Since the Todd River in Australia is a very arid basin, all of the models performed poorly in simulating daily runoff.

According to Equations (1) and (2), the potential canopy conductance (g_p) is a key factor in deciding the *AET*. As g_p is calculated as a function of LAI and other factors, PFTs dependant LAI is a key variable to decide the *AET*. The non-water-stressed evapotranspiration rate (D) will be large when LAI become large. Subsequently the *AET* will change according to the minimum value of D and water supply. The runoff consequently is expected to change due to the *AET* change. The Annual LAI computed by LPJH is compared with annual maximum and accumulated values ($\sum NDVI$) of basin-averaged NDVI calculated from semi-monthly data. As discussed in Box et al. (17), $\sum NDVI$

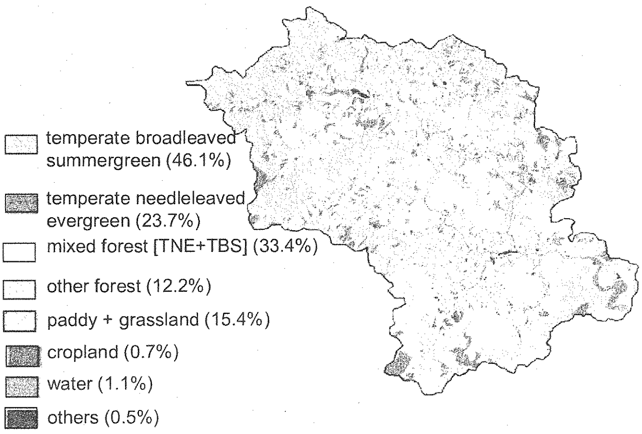

Fig.6 The dominant plant types derived from the Japan Integrated Biodiversity Information System for the Haji basin.

has high correlation with biomass and can be used as an indicator for detecting inter-annual variability of vegetation activities. Here only the $\sum NDVI$ trend is shown with LAI trend in Fig.5. This figure indicates that the LAI trend calculated by LPJH agrees with $\sum NDVI$ trend for Angat basin in the validation years and for Haji basin in most of the validation years. The LAI trend calculated by LPJH does not correspond so well with $\sum NDVI$ for Hushan basin, whereas correspond with maximum values of NDVI well. The LAI trend does not agree with NDVI trend in Todd River, which can probably attributed to the fact that LPJH does not consider shrub type plant functional types which are important in arid or semi-arid regions. Maximum values of NDVI indicates greening trend clearer while $\sum NDVI$ is more reliable for estimating biomass through the year. This trend correspondence demonstrates that LPJH can simulate vegetation biomass reasonably in humid basins.

Validation of simulated FPC is mainly performed in Haji river basin where detailed digital vegetation map (J-IBIS data) is available. The dominant plant types in the Haji basin derived from J-IBIS data are temperate broadleaved summergreen tree (referred to as TBS) and temperate needleleaved evergreen tree (referred to as TNE), with fractions being 29.4%, 7.0% respectively (see Fig. 6). If we assume that one half of the mixed forest (dominating 33.4%) is TBS and the other half is TNE, then the TBS and TNE dominate 46.1% and 23.7% respectively. The LPJH model provides the dominant plant functional types of TBS (52.8%) and TNE (42.2%), which corresponds mostly to J-IBIS data. For the other three study basins, the GLCC data with IGBP classification is used as a reference for validation of simulated FPC (Table 3 and Table 4). Since the classification schemes are different between IGBP and LPJH, it is difficult to validate simulated FPC quantitatively. However, major types of vegetation produced by LPJH are reasonable. For example, Cropland/Natural vegetation mosaic (Lands with a mosaic of croplands, forests, shrublands, and grasslands in which no one component comprises more than 60% of the landscape.) are dominant (57.56%) for the Hushan basin derived from IGBP data. However, there is no corresponding PFTs in LPJH. Besides this dominant type, mixed forests are major (18.07%) for the Hushan basin derived from IGBP data. Three different PFTs (TNE, TBS, and temperate broadleaved evergreen tree (TBE), with each type taking about 30% of the basin area) are produced by LPJH. The area with mixed forests in IGBP data would be composed of several different types of trees such as TNE, TBS and TBE. As some parts of the land have been converted into management land such as cropland, it is considered that LPJH can produce major types of vegetation reasonably.

Table 3 Vegetation type and structure for the three basins derived from GLCC data with IGBP classification.

River System	IGBP code	Class name	Percent (%)
Todd River			
	7	Open shrublands	99.67
	13	Urban and built-up	0.33
Angat			
	2	Evergreen broadleaf forest	0.16
	12	Croplands	4.08
	14	Cropland/Natural vegetation mosaic	91.38
	17	Water bodies	4.39
Hushan			
	4	Deciduous broadleaf forest	3.83
	5	Mixed forest	18.07
	6	Closed Shrublands	0.12
	8	Woody Savannas	2.27
	12	Croplands	18.04
	14	Cropland/Natural vegetation mosaic	57.56
	17	Water bodies	0.12

Table 4 Vegetation type and structure for the three basins calculated by the LPJH model.

River system	Plant functional type (PFT)	Fraction plant cover (FPC)
Todd River		
	Temperate broadleaved summergreen tree	0-0.135
	C3 perennial grass	0-0.815
Angat		
	Tropical broadleaved evergreen tree	0.68
	Tropical broadleaved raingreen tree	0.27
	C4 perennial grass	0.05
Hushan		
	Temperate needleleaved evergreen tree	0.31
	Temperate broadleaved evergreen tree	0.33
	Temperate broadleaved summergreen tree	0.31
	C3 perennial grass	0.05

Results of CO_2 simulation experiment

Fig. 7 shows the changes in daily runoff caused by an increase in CO_2 content for the various periods at the four basins. Runoff increases by 11.9%, 11.8%, and 21.8% under this scenario in the Angat, Haji and Hushan basins respectively. In contrast, it decreases by 48.6% in the Todd River. These changes in runoff generation are mainly related to concurrent changes in transpiration. As a consequence of elevated CO_2, carbon assimilation rate increases

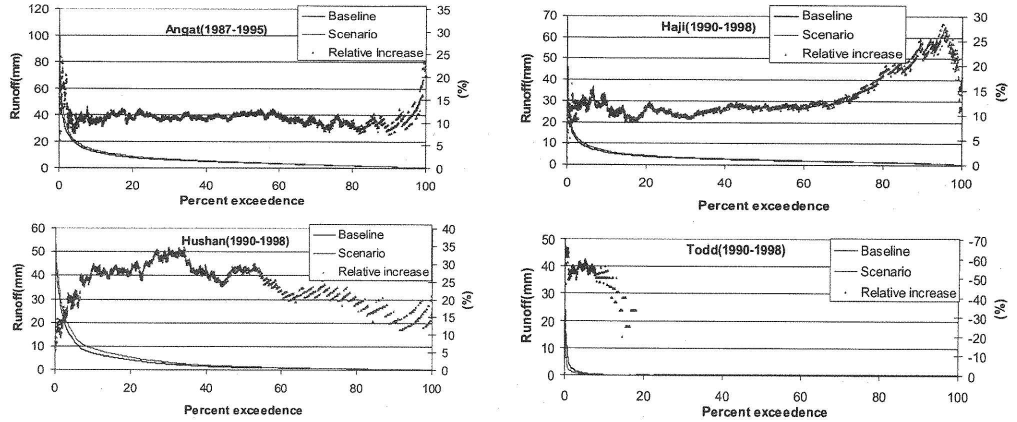

Fig.7 Change in daily runoff caused by increased atmospheric in CO_2 content for the various periods at the four basins. Y-axis on the right-hand side represents changes in daily runoff (%).

and water loss through the stomata decreases. This effect is most pervasive in non-water limited environments, whereas in drier basins water stress restricts transpiration irrespective of ambient CO_2 concentration (Eq.(1)). The lower transpiration results in increased evaporation, as there is more water stored in the soil column. The runoff increase in the three basins located in humid regions suggests that reduced transpiration cannot be compensated for by soil evaporation. The significant runoff decreases in the Todd River basin can be attributed to increased transpiration resulting from changing vegetation composition. Fig.7 indicates that changes in runoff are greater for peak flow at the Angat, Haji and Todd River basin and greater for middle flow at the Hushan basin. The great changes for low flow at Angat and Haji basin is probably due to the fact that the low flow value itself is very small, thereby the relative increase may become high easily.

CONCLUSIONS

The simulation of dynamic interactions between vegetation and water plays an important role in making realistic assessments of the water cycle. DGVMs are well suited tools for such biosphere-hydrosphere interrelations. The hydrological performance of a leading DGVM-LPJ is evaluated and improved by changing the runoff generation mechanism with the stand-alone hydrological model-HYMOD. The hydrological performance of LPJH is largely similar to that of stand-alone hydrological models at the basin scale. Moreover, the model produces reasonable vegetation type and composition in the humid basins while less reliable results in the arid basin. More basins having a wide variety of climate conditions should be included in order to evaluate the hydrological performance of LPJH comprehensively. Furthermore, the LPJH only produces natural vegetation type, which makes runoff generation unreliable. Interception loss from the canopy is also an important part of *AET*. Comprehensive researches on *AET* are needed to include all parts of evaporation. The CO_2 simulation experiment demonstrates that the LPJH model has the capacity to explore possible vegetation-driven changes such as runoff under the changing climate conditions at the basin scale. Similarly, reverse effects of changing hydrological conditions on vegetation can also be investigated, which is not considered in the present LPJH model.

In summary, the capacity of LPJH to simulate hydrological processes makes it a useful tool for examining impact of vegetation on runoff at basin scales. The potential advantage of LPJH over stand-alone hydrological models was clearly demonstrated by the CO_2 simulation experiment. It is shown that including vegetation dynamics is very important for realistic hydrological simulation, especially under changing climatic conditions.

ACKNOWLEDGMENTS

The authors express special thanks to MEXT and GCOE program at University of Yamanashi for supporting this study. We acknowledge the research group of the Potsdam Institute for Climate Impact Research for providing code of LPJ-DGVM, Climatic Research Unit in University of East Anglia for providing gridded climate data, and International Center for Water Hazard and Risk Management (ICHARM) for providing hydrological data.

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(Received Aug, 01, 2010 ; revised Mar, 28, 2011)