Development of a hydrological model for predicting the effects of land use changes at Yasu River basin

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Abstract This study proposes a hydrological model for Yasu river basin. The model is developed using the object-oriented approach defining physical structures and processes by objects, which are linked with specific rules, to simulate river flow at catchment's level. The digital elevation model is used to define the connection of flow routing objects. A land surface parameterization scheme, proposed by Noilhan and Planton (1989), is used for calculation of Evapotranspiration at grid scale, to provide net rainfall input to the runoff routing model. Test results from similar climatic conditions in China shows that the scheme can be applied with dependable results for this purpose. In the test simulation conducted to verify the applicability of the scheme, the net radiation was quite well reproduced to match the magnitude and patterns of daily variations. A combination of low value (0.4) of solar foliage-shielding factor, and assumption of saturated soil conditions throughout the simulation, was found to be sufficient for reproducing the observed fluxes in paddy field conditions. This was possible even without modifying the structure of the scheme. Estimated surface temperature was found to be at least 6^0 to 7^0C higher than observed values. The estimated sensible heat did not fit well to the observed data. The deviation however, did not seem to affect significantly the rest of other fluxes as the sensible heat constituted only a small fraction of the net radiation, ranging from -40 to 40 w/m^{2,} which is considered to be within the range of measurement errors in this experiment.

Keywords Yasu river basin, distributed hydrological model land surface parameterization

INTRODUCTION

The Yasu River basin has a catchment area of about 400 sq. km. The basin is located at the headwaters of Lake Biwa in Shiga prefecture, Honshu Island, Japan. The rainfall tends to occur in summer from July to September and annual precipitation is about 1600mm. The lower part of the basin is very flat and consists of paddy fields and urban settlements while the upper part has a hilly terrain and is covered by forests. Several townships are located within the basin with a total population of 220,000. Water resources of the basin are generally used for industrial, irrigation, domestic supply and recreation. Surface as well as groundwater resources are extensively developed to cater for these needs. There are 2 dams, 2 major weirs (diversion points) and several irrigation canals for supplying water to paddy fields. There is a concern for proper management of water resources of this basin in order to satisfy optimally conflicting demands between water use for meeting daily demands and water required to maintain the environmental quality of the river. This involves modeling studies to establish among others the sensitivity of water resources to environmental and climatic factors for future planning and operational for purposes.

STUDY APPROACH

The current work employs mathematical modelling for quantification of the runoff distribution in the basin over space and time. The underlying assumption is recent and historical river flow variation patterns can be explained by observed changes in both the forcing climatic and land use data. It is also known that the rivers in the basin have been extensively taped for irrigation and water supply. With this fact inn mind one of the objectives in this study is to include the spatial information data on water use and study their effects downstream. Statistical analyses are able to show changes in the climatic data but to interpret the effect of such changes to a river flow a model is required. In this particular study a distributed rainfall runoff model for a study basin is proposed at 500x500m spatial resolution. The net rainfall input to this model is obtained by vertical moisture balance at same spatial resolution using a land surface parameterization scheme with spatial data generated from observed ground stations in or near the basin. The horizontal movement of water is defined by digital elevation model of the basin using the 8D steepest flow direction algorithm. Through the object oriented programming approach, grid cells are considered as objects, which can be connected horizontally or vertically with other objects, data files or output files. This approach makes it easier to include any objects within the model to represent physical structures or conditions, which affect the river flow, thus including their effect on the simulated flow. In this particular work such objects are expected to represent structures such diversion points, reservoirs or physical processes such as overland flow or evaporation. Layers of objects forms different levels of water balance in the vertical direction while horizontal position or connection are determined by geographical data to include processes or structures affecting the horizontal movement of water. A conceptual model of a basin using this approach is shown in Figure 1 below.

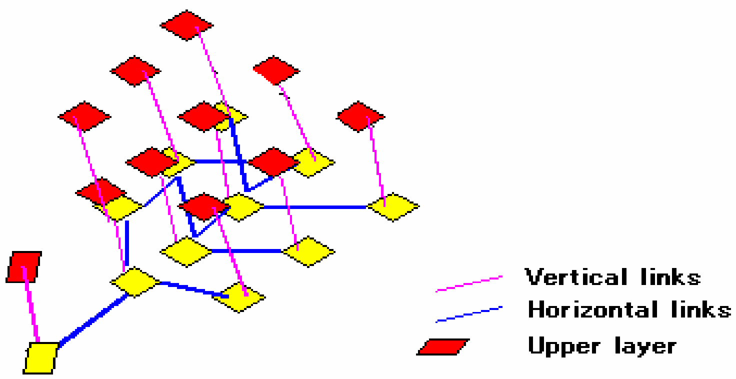

Figure 1: Schematic diagram of the cell distributed model in 3D

MODEL CONSTRUCTION

The object-oriented approach is employed in this study as an efficient way of interrelating the various physical process and objects interacting with water movement horizontally and vertically in the study basin. In the current study the model is divided into two main parts to deal with the vertical and horizontal processes. The vertical process objects are defined to link data and functions for calculation of energy and moisture balance at grid scale. In the present formulation each grid cell is treated as such object. The ohymos library functions Takasao *et al.* (1996), Ichikawa *et al.* (2000) is applied to input data to the object and send results to other objects or output files. A typical vertical grid object using the proposed land surface scheme consist of eight (8) data ports for sending in data and ten (10) send data ports for sending out the calculated variables. The input data consist of air temperature, solar radiation, long wave radiation, specific humidity, vapor pressure, wind speed, as well as albedo and leaf area index. The send ports sends out the evaporation at Canopy level, ground level and evapotranspiration. Other results sent out are surface and deep ground temperature, soil moisture and the net grid rainfall.

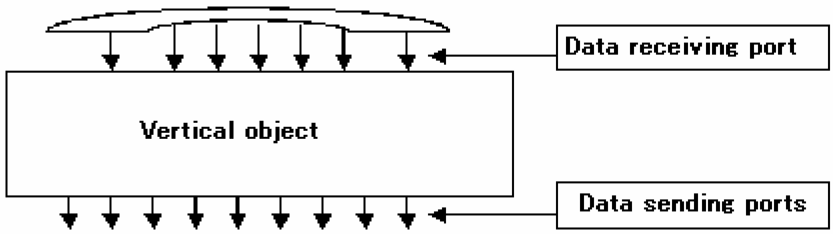

Figure 3: Typical vertical object

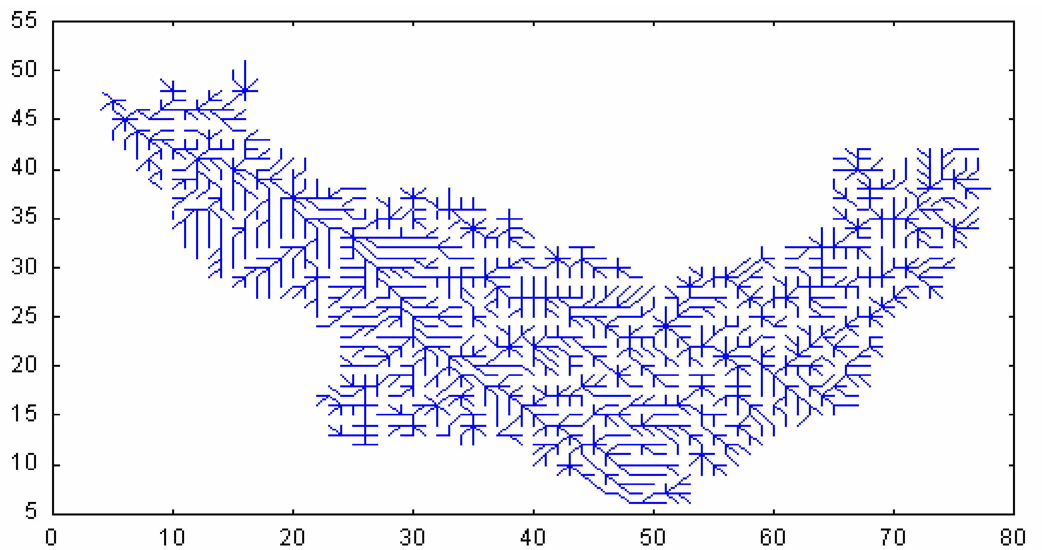

Figure 4: Yasu River Basin 500m resolution flowmap derived from 50m DEM

The horizontal movement of water over the land is defined by the steepest direction method using the DEM data. At each grid level excess rainfall generated by the vertical objects is sent to the input ports of horizontal objects for flow routing. In the current stage the horizontal objects uses the lumped kinematic wave model Shiiba et al. (1996) to route the flow to outlet of the grid where the send port sends it to a downstream object. To effect an automatic connection of objects horizontally the flow map at the same resolution as grid cells is stored in a file, which is referred during model construction while executing the model. The flow network stored in this form can be considered, as channels and information about physical structures can be included in the network at their exact geographical locations. In this study a 50m DEM data of Japan is used to create a flow network at 500m resolution utilized in this model as shown in figure 4.

PHYSICAL PROCESSES

In order to study water movement realistically the model have to simulate the physical processes involved in the local water cycle. Of major concern here are biophysical properties of the basin, which govern exchange of moisture between land and atmosphere. When these processes are properly represented in the model it enables river flow studies involving the dynamics of vegetal cover to be conducted which is one of the main objective of this study. In the current approach the physical processes involved in generating the net rainfall that is the main input to the rainfall runoff model are modeled at each grid using a scheme proposed by Noilhan and Planton (1989). The scheme models the radiation balance at the ground surface and vertical moisture movement at each grid depending on the climatic input data soil types and land use as defined by leaf area index and albedo. A schematic diagram of this model is shown in Figure 2 followed by a brief discussion of the main components. For full discussion of this scheme a reference is made to the works Noilhan and Planton (1989) and Sealers and Mintz (1986) among others.

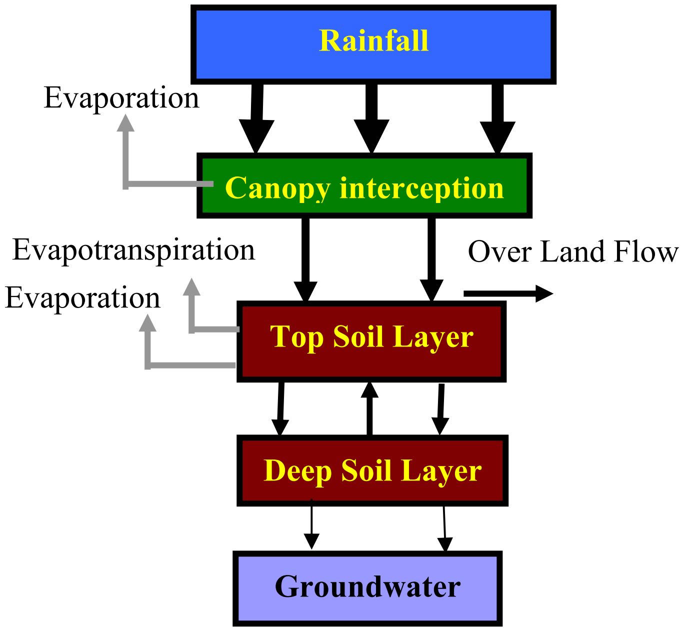

Figure 2 Vertical Model Structure

The governing equations for energy and moisture movement in vertical direction applied for each grid are given at canopy level, ground level and deep soil level. Soil heat is described by temperature at the surface and deep soil layer by equations 1 and 2 below as

$$\frac{\partial T_s}{\partial t} = C_T G - \frac{2\pi}{\tau}(T_s - T_2) \qquad (1)$$

$$\frac{\partial T_2}{\partial t} = \frac{1}{\tau}(T_s - T_2) \qquad (2)$$

Where T_s is surface layer soil temperature [K], T_2 is the mean daily soil temperature [K] of deep soil layer over period τ obtained by force restore method Bhumralcar (1975) and Blackdar (1976).
In Equation 3 G is the heat storage rate in the soil vegetation medium, which is equal to the sum of all the atmospheric energy fluxes at the surface.

$$G = R_n - H - LE \qquad (3)$$

where R_n is the net radiation at the surface, H and LE the sensible and latent heat fluxes from the atmosphere.
The coefficient C_t in equation 4 is expressed as

$$C_T = 1 \Big/ \left(\frac{1 - veg}{C_G} + \frac{veg}{C_v} \right) \tag{4}$$

where

$$C_G = C_{G_{sat}} \left(\frac{W_{sat}}{W_2} \right)^{b/2\log 10} \tag{5}$$

To complete the definitions the values of b and C_{Gsat} are referred to clap and Honberger (1978).
The moisture movement is modeled at canopy top soil and deep soil layers. The soil moisture at top layer (W_g) and in the deep (W_2) layer are given by

$$\frac{\partial w_g}{\partial t} = \frac{C_1}{\rho_w d_1}(P_g - E_g) - \frac{C_2}{\tau}(w_g - w_{geq}),$$
$$0 \le w_g \le w_{sat} \tag{6}$$

And

$$\frac{\partial w_2}{\partial t} = \frac{1}{\rho_w d_2}(P_g - E_g - E_{tr}), 0 \le w_2 \le w_{sat} \tag{7}$$

Where P_g is the flux of liquid water reaching soil surface, E_g the evaporation at the soil surface, E_{tr} the transpiration rate, ρ_w the density of liquid water and d_1 an arbitrary normalization depth of ten centimeters. The two coefficients C_1 and C_2 and the surface volumetric moisture W_{geq} when gravity balances the capillarity forces have been calibrated for different soil moistures as discussed in Noilhan and Planton (1989). The equation governing intercepted water at the canopy level is stated as

$$\frac{\partial w_r}{\partial t} = vegP - (E_v - E_{tr}) - R_r \tag{8}$$

where P is the precipitation rate at the top of the vegetation, E_v the evaporation from vegetation including the transpiration E_{tr} and direct evaporation E_r when positive, and dew flux when negative (in this case $E_{tr} = 0$), R_r is the runoff of the interception reservoir. This runoff occurs when W_r exceeds a maximum value W_{rmax} depending on the density of the canopy. W_{rmax} is calculated according to Dickinson (1984) as

$$W_{r\max} = 0.2 vegLAI[mm] \tag{9}$$

For calculation purposes Equations 1 and 2 and 6 to 8 can be written in the following compact form

$$\begin{cases} \dfrac{\partial T_t}{\partial t} = f_1(T_s, T_2, W_2, W_g, W_r; t) \\ \dfrac{\partial T_2}{\partial t} = f_2(T_s, T_2; t) \\ \dfrac{\partial w_g}{\partial t} = f_3(T_s, W_g, W_2; t) \\ \dfrac{\partial w_2}{\partial t} = f_4(T_s, W_g, W_2, W_r; t) \\ \dfrac{\partial w_r}{\partial t} = f_5(T_s, w_r; t) \end{cases} \quad (10)$$

Where f_1 to f_5 are functions representing the right-hand side of the original equations 1-2 and 6-8 above. A five step Runge Kutta method William et al. (1995) was utilized to obtain a simultaneous solution of the system of equations (10) above for T_s, T_2, W_2, W_g and W_r while imposing the necessary conditions for moisture and energy balance. As cited earlier the scheme even though taking into consideration all important runoff generation factors such as soil types, vegetation cover soil moisture yet it has remained simple enough to be applied with easy to a local area using operational meteorological data. The real challenge however is specification of the initial conditions for moisture and temperature, which are important to arrive at correct results.

The Yasu River basin

The Yasu river basin is in Shiga prefecture Japan. The basin is approximately 400 square kilometers. The mean annual rainfall is estimated at 1600 mm and the main land use categories are forests (60%), paddy fields (20%) and urban area (9%). The urban area percentage is expected to increase in the near future due urban rural migration caused by people looking for cleaner countryside environment for a home away from overcrowded noisy urban areas of Osaka and Kyoto cities.

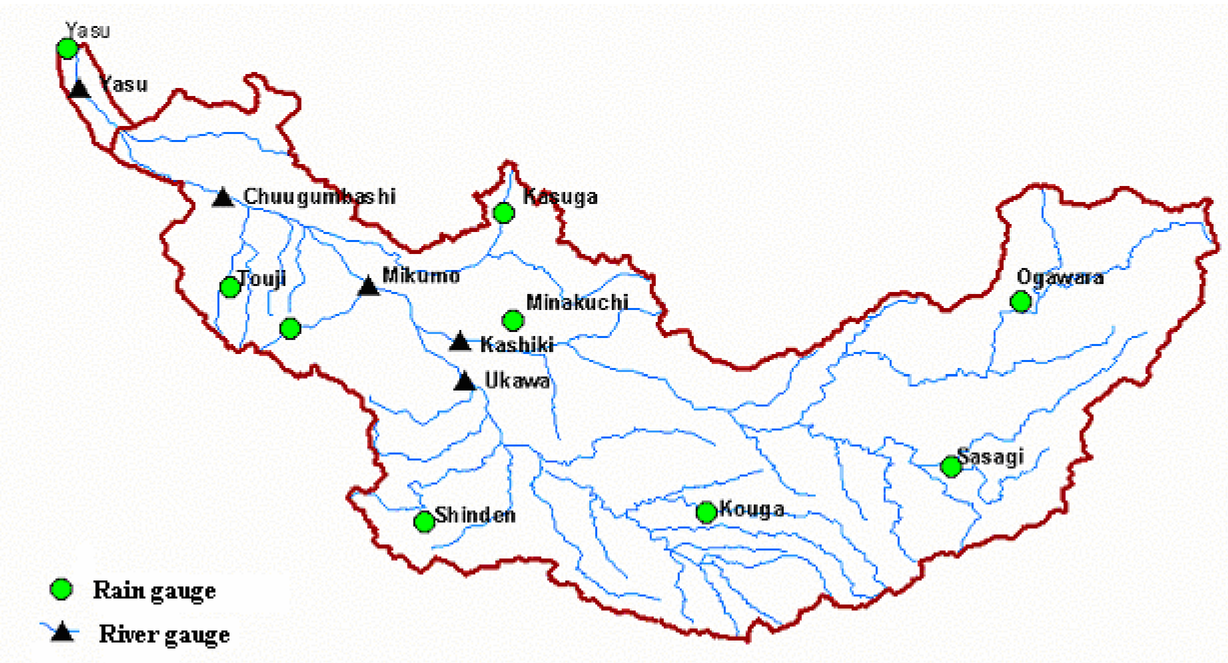

Figure 5: Locations of river gauging stations and rainfall stations in the Yasu river basin

The upper reaches of the river have 3 dams namely Taniguchi, Yasugawa and Ohara for regulating flows in the river during floods. The river gauges are installed at Ukawa, Kashiki, Chuugumbashi, Mikumo and Yasu and there are rain gauges at seven location fairly distributed over the basin as shown in Figure 5 above. Data available at these stations are summarized in Tables 1 and 2 below.

Table 1 Available River flow data in Yasu river basin

Station	Available water level (hourly data)	Available Water level (daily data)
Yasu	1975-2001	1975-2001
Chuugumbashi	1978-2000	1978-2000
Kasiki		1978-2000
Mikumo	1975-1998	1975-1998
Ukawa		1978-1998

The Yasu river gauge is the main focus of river flow study and a point for comparing model simulation and observed data. The station is located in the lower reaches of the river and the effect of changes upstream can thus be studied. The river flow at this station is also highly regulated by upstream headwater works and dams requiring necessarily inclusion of such effects in the model in order to compare the observed and estimated hydrographs. Rainfall records are better and extend a larger time period than river flow data as shown in Table 2.

Table 2 Available Rainfall data in Yasu river basin

Station	Location	Available continuous hourly data
Yasu (R27)	136°00'22" 35°04'10"	1969-1996
Kouga (R24)	136°14'17" 34°54'03"	1969-1996
Minakuti (R19)	136°10'07" 34°50'13"	1969-1996
Sasagi (R22)	136°19'40" 34°55'03."	1969-1996
Kasiga	136°09'53" 35°00'35"	1969-1996
Kumoi	136°05'14" 34°58'04"	1969-1996
Ogawara	136°21'10" 34°58'39"	1971-1996
Shinden	136°08'11" 34°53'50"	1970-1996
Touji	136°03'56" 34°58'57"	1969-1996

Meteorological data is available only at special observatories managed by the Japan meteorological agency. The nearest station is at Hikone observatory where input data required for evapotranspiration has been obtained. This data includes the sunshine hours, vapor pressure and air temperature, which is used to calculate the long and short wave radiation input to the model. At least the records consist of 12 years of data dating back to 1989 from 2000.

Test simulations and discussions

Before using the model for studying the land use and climate changes it is required to test the various components of the model to verify their ability to model the natural behavior. This not only involves the check of the accuracy of calculations but more importantly the performance of the model in the same climatic and environmental factors specific to a given basin. Since in this approach the model is deterministic longterm term records are not necessary for calibration and verification as for a black box approach. However the tuning of parameters to obtain desirable results under assumptions of various initial conditions are necessary. In the first part of this study the vertical process component utilizing the Noilhan and Planton scheme was tested for paddy field conditions using Game/Hubex-IOP data Tanaka et al. (1998) obtained from test sites in China. The data was collected during the summer season of 1998. During this experiment full set of flux data was obtained including radiation data and climatic variables required as input to the land surface scheme. The experiment also collected data for temperature at ground surface and deep soil level thus providing a basis for comparing the results of the model with observation data at site. A total of 17 days of hourly data was used in this study for simulation of surface energy balance and compare with the observation data to check the applicability of the scheme under paddy field conditions. Figure 6a to 6d presents the results of this simulation. In this simulation hourly net, latent, sensible and ground heat flux outputs from the model are made and compared to observed values. Soil parameters obtained from literature were used and vegetation parameters including solar foliage shielding factor (*veg*) were chosen to yield the best representation of the observed fluxes. The net radiation (Figure 6a) was found to be the easiest to reproduce since it has the minimum dependence on soil and vegetation parameters. The pattern and magnitude of the estimated flux agrees quite well with the observations. The latent heat estimates (Figure 6b) could not be reproduced reasonably well except for a proper estimate of the solar foliage-shielding factor (*veg*). In this case a value as low as 0.4 was found to be the most suitable for reproducing the observed fluxes in the paddy field site. A combination of this low value of foliage shielding factor and saturation conditions in the soil layers throughout the simulation period enabled the scheme to give good estimates of net radiation, latent and ground heat fluxes comparable to results of studies in sites with different land cover such as cropland and forests. It was thought earlier that this scheme might need some modifications like those reported by Woskin *et al.* (2001) for Sib model to reproduce observed fluxes in paddy field conditions. However the results of this study does not indicate the need for such modifications. The fact that a low foliage shielding factor gives good results in paddy field environment follows from the fact that more evaporation is expected from the water covered ground in the paddy field than from transpiration. Estimated surface temperature was found to be at least 6^0C to 7^0C too higher than observed values and highly dependent on the initially specified temperature. This however was found to be necessary to maintain a good partition of the net radiation at the surface into latent sensible and ground heat flux. The diurnal variation pattern and magnitude of sensible heat flux (Figure 6c) deviated much from the observations. The deviation however does not seem to affect the rest of fluxes as it constituted only a small fraction of the net radiation ranging from -40 to 40 w/m^2. This range is considered to be within the range of measurement errors. The ground heat flux (Figure 6d) was also found to match well with the observations. Since this scheme can easily utilize operational meteorological data it is recommended for incorporating into distributed hydrological model to provide a better-estimated input.

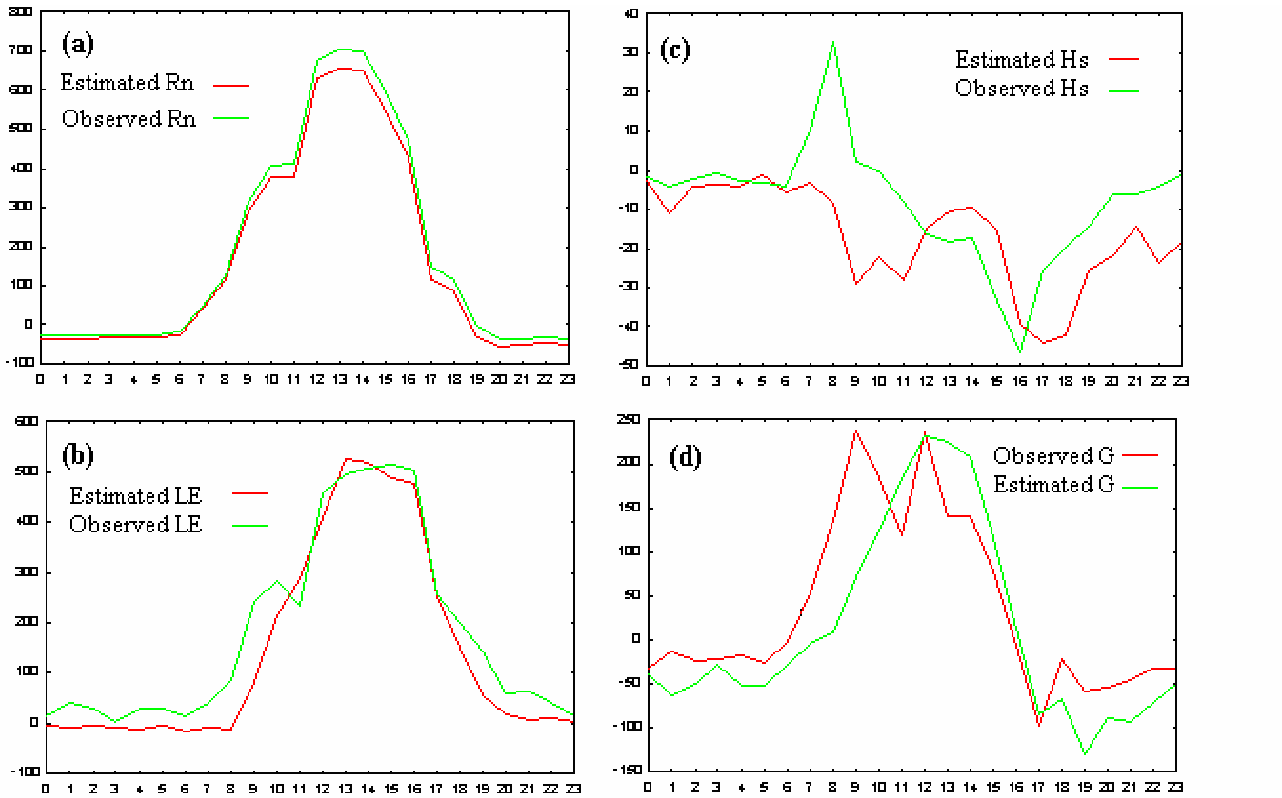

Figure 6: Diurnal variations of simulated and observed surface fluxes for paddy field conditions W/m2

CONCLUSIONS AND FURTHER WORKS

This study has developed a hydrological model for Yasu River basin using the object-oriented approach that defines physical structures and processes by objects, which are linked with specific rules to simulate flow at catchment's level. The digital elevation model has been used to define the connection of flow routing objects. The Noilhan and Planton land surface parameterization proposed for calculation of evapotranspiration at grid-cell size in order to generate the net rainfall input to the runoff routing model has been tested using data from similar climatic condition. Test results shows that the scheme can be applied with dependable results for this purpose.

Specifically the results of this study indicate that

- The land parameterization scheme of the Noilhan and Planton (1989) can used be in swampy areas or paddy fields without necessarily having to modify the structure of the scheme making it more complex provided the right conditions are specified during simulation.
- In order to estimate properly the evaporation losses from paddy field, a low value of solar foliage shielding factor *veg* have to be specified despite the fact that paddy crop seems to cover the whole ground suggesting a high value for this parameter.
- The representation of the basin's physical processes and structures as objects interacting with each other in the simulation process is suggested as the best way of including man made effects such as dams and diversions to hydrological models.

The next work in this study is to apply the proposed parameterization scheme to the whole of Yasu basin and use the calculated net rainfall to simulate river discharge. It is expected that a continuous simulation with real land use data as represented by leaf area Index and albedo in the Noilhan and Planton scheme used evapotranspiration calculations will give clue to the effect of land use changes on the river flow.

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