Hydrological impacts of the land-use change in the middle reaches of the Yellow River basin

Yoshinobu SATO[1], XieyaoMA[2], Masayuki MATSUOKA[3], Jianqing XU[2] & Yoshihiro FUKUSHIMA[1]

[1] Research Institute for Humanity and Nature (RIHN)
[2] Frontier Research Center for Global Change (FRCGC)
[3] Department of Forest Science, Kochi University

Abstract

To clarify the influences of climate and land-use change on river discharge, the long-term (1960-2000) water balance of the middle reaches of the Yellow River basin was analyzed using a hydrological model. To estimate evapotranspiration from various land-use types, a high resolution land surface classification map in 2000 was used. When we applied the same land-use parameter of 2000 during the past 40 years, the model underestimated the river discharge. Then we modified the parameter to decrease evapotranspiration by reducing the vegetation cover ratio (VCR). After that the observed discharge was reasonably captured by the model. However, in spite of vegetation recovery, the amount evapotranspiration were decreased. It implies that the soil water deficit with the rapid decrease of precipitation in the middle reaches might regulate the evapotranspiration. Consequently, we confirmed that the massive land-use change and rapid decrease of available water resources in the Loess Plateau will induce the water shortage in the middle reaches of the Yellow River basin.

Key words climate change; land-use change; middle reaches of the Yellow River basin; water balance

INTRODUCTION

In recent years, water-related problems such as droughts, flooding, or water pollutions have affected most large rivers in China. In particular, water shortages are becoming more and more serious in the northern China because of dry climate conditions and heavy water demands. The Yellow River is the second largest river in China and is the most important river for agriculture, water resources managements, and socio-economical development. However, the river discharges in the lower reaches of the basin have been decreasing continuously. The riverbed of the lower reaches is higher than the surrounding area due to the sediment depositions. Therefore, almost all the surface water in the lower reaches is supplied from the upper and middle reaches. Thus, it is important to predict the water balances in the upper and middle reaches for managing the limited water resources of the lower reaches more effectively. To clarify the long-term water balances within the Yellow River basin, a hydrological model can be used. However, it is difficult to apply existing hydrological models directly to the Yellow River basin because the basin includes various artificial factors induced by human activities (i.e., irrigation water intake, reservoir operations, and human-induced land-use changes). Thus, we developed a new hydrological model applicable to the Yellow River basin using long-term (1960–2000) meteorological dataset and high-resolution land surface classification map. In the previous study, we confirmed that our model can predict the amount of annual water intake for irrigation reasonably and the effect of the large reservoir operation on river runoff in the upper reaches satisfactory. Therefore, in the present study, we applied the model to the middle reaches and analyzed the hydrological impact of long-term land-use changes.

STUDY AREA

In the present study, we focused on the middle reaches of the Yellow River basin located between Toudaoguai and Sanmenxia hydrological station. The catchment area is 306,780 km^2, which occupies about 40.8% of the Yellow River basin (752,443 km^2). Most of this region is located within the Loess Plateau.

MODEL STRUCTURE

Figure 1 shows the basic structure of our hydrological model. The model is based on SVAT-HYCY model developed by Ma and Fukushima (2002). The model consists of three sub models: (1) heat-balance model, (2) runoff formation model and (3) river routine network model. The input parameters of the model are routine meteorological data and remote sensing data. Both of them were interpolated into 0.1° × 0.1° grid scales. The remote sensing data includes elevation, land-use type, NDVI, and LAI dataset. The land-use type was classified into five categories (Type1: Bare land, Type2: Grassland & Crop field, Type3: Forest area, Type4: Irrigated area, and Type5: Water body) using a high-resolution land-use map over the Yellow River domain in 2000 developed by Matsuoka *et al.* (2005).

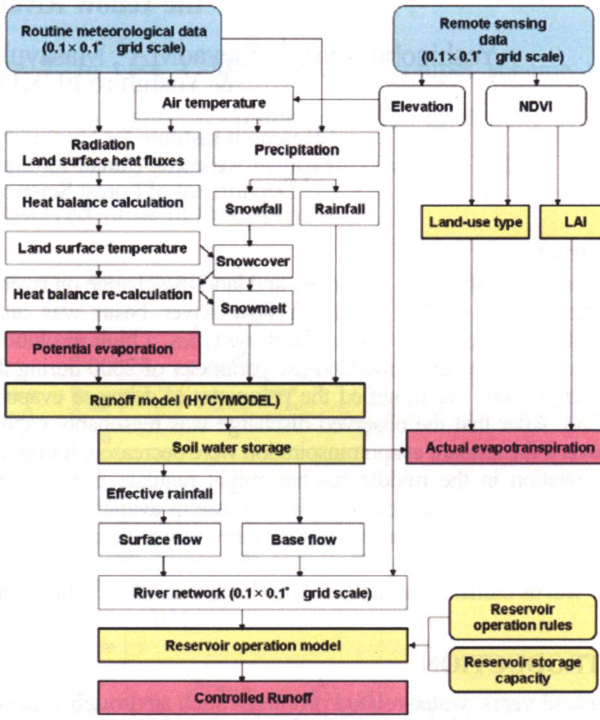

Figure 1 Simplified flow chart of the model.

Following three artificial factors were considered in this model: (1) reservoir operation, (2) irrigation and (3) land-use change. At first, to estimate the outflow from the reservoir, a simple reservoir operation model was applied. The model can simulate the influences of reservoir operation by using the following three parameters: (1) inflow to the reservoir, (2) water storage in the reservoir and (3) reservoir operation rules. Then, the discharge from the irrigation area during irrigation period (Qirr) was estimated as follows: Qirr = Precipitation (P) – Potential evaporation (Ep). The water deficit of Qirr was supplied from the nearest river channel. The discharge from non-irrigated period was calculated as same as bare land. The irrigation period (DOY: 90–300) was determined from seasonal change of LAI. The LAI in the vegetated areas were derived from NDVI created from NOAA-AVHRR images in 2000 using the formulas of Biftu and Gan (2000). Finally, to clarify the influences of the long-term land-use change, the index of vegetation cover ratio (VCR) based on total vegetation area of 2000 was introduced.

To estimate the actual evapotranspiration more precisely, we applied the following procedures. At first, we estimated the potential evaporation (Ep) following the definitions of Xu *et al.* (2005). Then, the evapotranspiration from each vegetated surface (Evt) without soil water deficit were estimated by the formula of Kondo (1998).

$$Evt/Ep = 0.45 + 0.4\,\{1 - \exp(-1.5 \cdot LAI)\} \quad (1)$$

Finally, the actual evapotranspiration Ea was estimated by the following equations:

$$Ea = Evt \qquad (St \geq Smax) \quad (2)$$

$$Ea = (St/Smax) \cdot Evt \qquad (Smin < St < Smax) \quad (3)$$

$$Ea = 0 \qquad (St \leq Smin) \quad (4)$$

$$Smax = \{D50 + (Dsig \times 3)\} \times 0.5 \quad (5)$$

where St is the total soil water content derived from Su + Sb in the HYCYMODEL (Fukushima, 1988). D50 is the effective soil depth (600 mm) and Dsig is its standard deviation (100 mm). Smax (450 mm) and Smin (100 mm) are parameters to regulate Ea. These four parameters were determined empirically. Other parameters were set as same as the original SVAT-HYCY model.

RESULTS AND DISCUSSION

Performance of model simulation

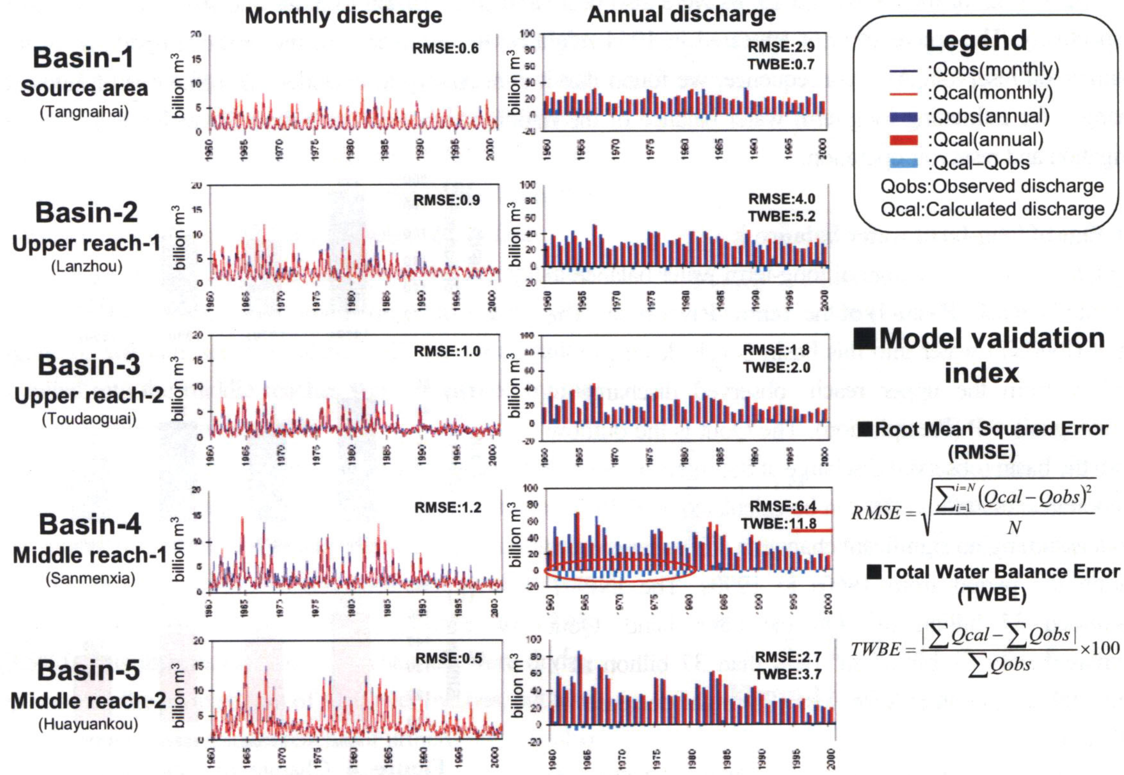

Figure 2 Performance of model simulation.

The performances of our hydrological model from Basin-1(source area) to Basin-5 (middle reach-2) from 1960 to 2000 are shown in Figure 2. In the present study, the root mean squared error (RMSE) and total water balance error (TWBE) were used for model validation index. According to these results, we can see that our model agreed well with the observed discharge during the past 40 years. However, some underestimated discharge was found in the 1960s and 1970s in the Basin-4 (middle reach-2). Then, to improve this underestimation, we analyzed the hydrological impact of land-use change in the middle reaches of the Yellow River basin in detail.

Hydrological impact of land use change

In the initial simulation (SIM-1), we applied a constant VCR (=100%) to all the study periods. However, the estimated discharge underestimated the observed discharge during the period from 1960s to 1970s. In other words, our initial model overestimated the actual

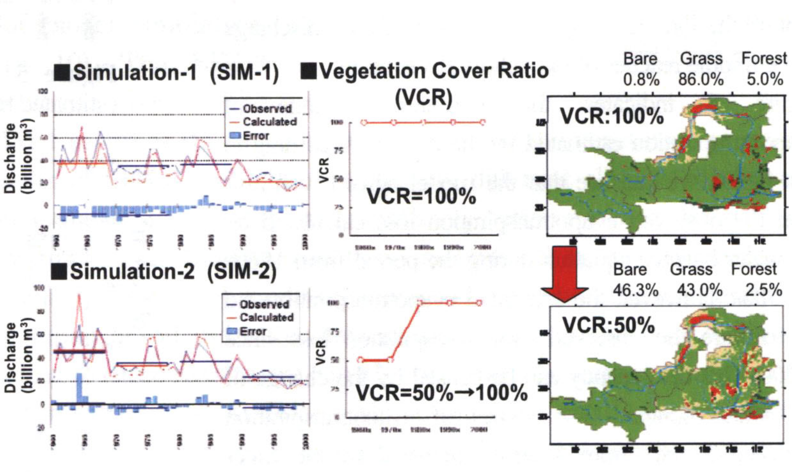

Figure 3 Hydrological impact of land use change

evapotranspiration. Thus, to reduce the evapotranspiration, we modified the value of VCR until 50% in the second simulation (SIM-2). After that the observed discharges were reasonably captured by the model (Figure 3). The TWBE of the 1960s and 1970s were also decreased from 15.4% to 3.4% and from 20.8% to 7.0% respectively. The emergent error appeared in 1964 might be the influences of the artificial operation of the Sanmenxia reservoir. As a consequence, we found that it is necessary to consider the influences of land-use changes for estimating long-term water balance of the middle reaches of the Yellow River basin as well as irrigation and reservoir operation.

Change of long-term water balance

Figure 4 shows the change of long-term water balance in the middle reach (Basin-4) of the Yellow River basin. The input (INPUT) water into this basin is calculated as Qin (inflow from the upper reach: observed discharge at Toudaoguai) + P (Precipitation). The Qout is the outflow from the basin (observed discharge at Sanmenxia). So, the evapotranspiration loss (E) can be calculated as INPUT – Qout assuming no significant change in soil water content during the period from 1960s to 1990s. The INPUT decreased 37 billion m^3. On the other hand, Qout decreased only 21 billion m^3 (less than 37 billion m^3). Thus, the evapotranspiration loss (E) might decrease 16 billion m^3.

The rapid decrease of Qout from 1960s to 1970s (-9 billion m^3) and from 1980s to 1990s (-13 billion m^3) can be explained by the decrease of INPUT (-18 billion m^3 and -21 billion m^3 respectively). The ratio of Qout/INPUT was decreasing from 23.1% (1960s) to 15.2% (1990s). This implies the ratio of evapotranspiration/INPUT was increasing with the decrease of INPUT.

Figure 5 indicates the long-term change of river discharge estimated by the model. By comparing this figure with figure 4(b), we can see that our model can reasonably capture the long-term change of observed river discharge in the middle reaches of the Yellow River basin.

Figure 6 indicates the long-term change of evapotranspiration estimated by the model. According to this figure, we can see that the model agreed well also with the observed evapotranspiration loss calculated by the water balance equation during the period from 1960s to 1980s. However, the estimated evapotranspiration did not capture the observed evapotranspiration loss since 1980s. This discrepancy can be caused by the change of soil water content. The values of evapotranspiration indicated in the figure 4 were calculated by the water balance equation assuming soil water content is constant.

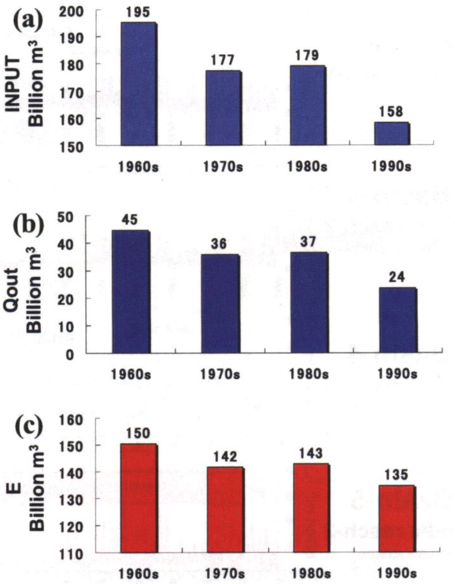

Figure 4 Change of long-term water balance in the middle reach of the Yellow River basin.

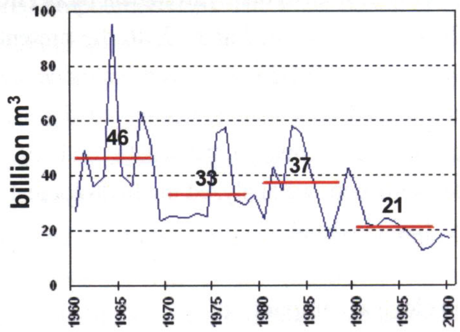

Figure 5 Change of river discharge estimated by the model (SIM-2).

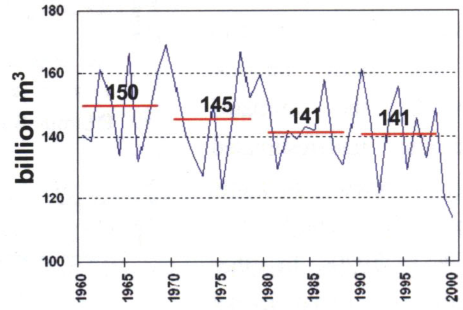

Figure 6 Change of evapotranspiration estimated by the model (SIM-2).

On the other hand, the values of estimated evapotranspiration in the figure 6 were considering the change of soil water content. Figure 7 shows the long-term change of soil water content estimated by the model. From this figure, we can see that the soil water content was decreasing continuously. These results suggest that the discrepancy between figure 4(c) and figure 6 in 1990s can be explained by the regulation of the estimated evapotranspiration by the soil water deficit.

Figure 8 shows the long-term change of the precipitation in the middle reaches. By comparing this figure with figure 6, we can see that almost all the precipitation supplied into the middle reaches were consumed by the evapotranspiration in the 1990s.

Consequently, the discharge from the tributaries (Qtrb) in the middle reaches of the Yellow River basin estimated by the model had been decreasing significantly during the past 40 years (Figure 9). The discharge ratio (Qtrb/P) was also decreased rapidly from 1960s (11.8%) to 1990s (3.5%). This implies that the river channels were drying up not only the main stream of the lower reaches, but also the tributaries in the middle reaches. Furthermore, it is also suggesting that the amount of available water resources in the middle reaches of the Yellow River basin was almost exhausted in recent years. Therefore, immediate attention and action including integrated water resources management should be encouraged in this area.

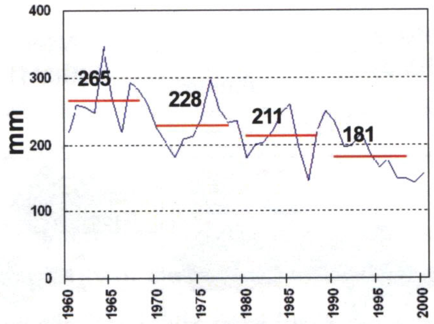

Figure 7 Change of soil water content estimated by the model (SIM-2).

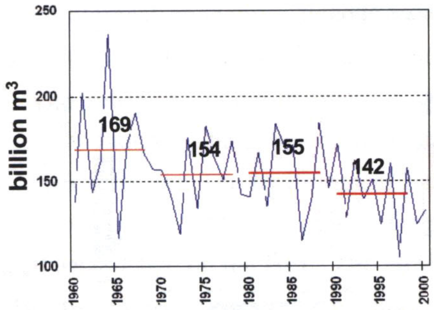

Figure 8 Change of precipitation

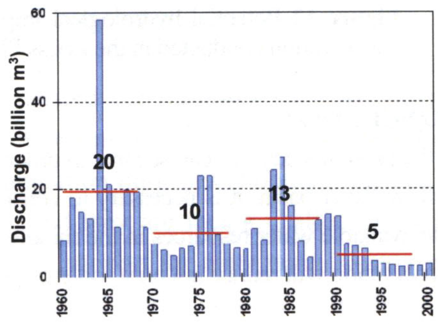

Figure 9 Discharge from tributaries in the middle reaches of the Yellow River basin estimated by the model (SIM-2).

Hydrological impact of soil and water conservation in the Loess Plateau

Finally, in order to evaluate the impact of soil and water conservation in the Loess Plateau, we conducted the two types of model simulation: SIM-3 and SIM-1 (Figure 10). The SIM-3 assumes the land-use condition before the vegetation recovery. And, SIM-1 assumes the land-use condition after the vegetation recovery. Then, we compared the results of SIM-3 and SIM-1 under the different climate conditions. Figure 11(a) shows that the change of evapotranspiration with vegetation recovery. We can see that the increase of evapotranspiration in the wet condition was larger than the dry condition. And, the decrease of river discharge in the wet condition was also larger than the dry condition (Figure 11(b)). Therefore, the impact of soil and water conservation can be changed with climate conditions (Figure 12). According to these results, we can also find that the impact of vegetation change will become larger in the wet climate conditions. Moreover, these results suggest that if the precipitations increase after the dry condition does not mean that it increase the amount of river discharge directly, because at first, the evapotranspiration will increase significantly.

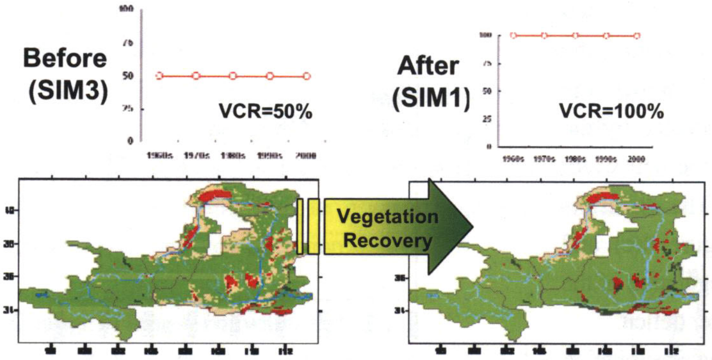

Figure 10 Comparisons of the estimated vegetation coverage between before (SIM-3) and after (SIM-1) the soil and water conservation.

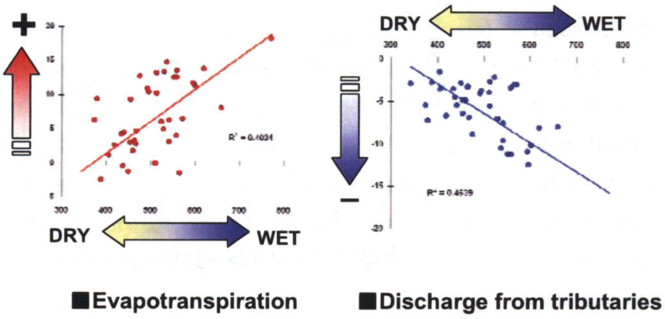

Figure 12 Potential hydrological impact of soil and water conservation conducted in the Loess Plateau.

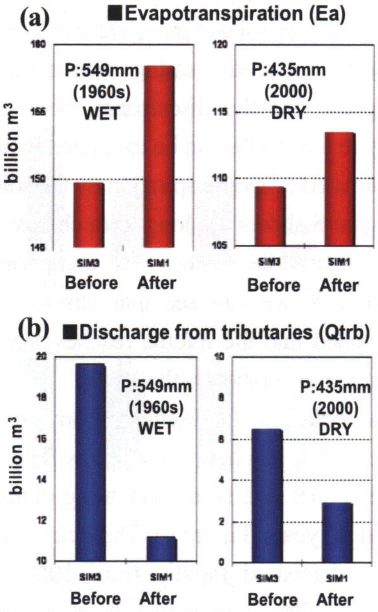

Figure 11
Change of evapotranspiration and discharge from tributaries with the vegetation recovery.

CONCLUSION

In the present study, we can see that in order to understand long-term water balance in the middle reaches of the Yellow River basin, it is necessary to consider the influences of the long-term land-use (vegetation) changes. The available water resources in the middle reaches were almost exhausted in recent years. The soil and water conservation will reduce not only soil erosion, but also river discharge with the climate (wet/dry) conditions.

REFERENCES

Biftu, G. & Gan, T. (2000) Assessment of evapotranspiration models applied to a watershed of Canadian prairies with mixed land-uses. *Hydrol. Processes* **14**, 1305-1325.

Fukushima, Y. (1988) A model of river flow forecasting for small forested mountain catchment. *Hydrol. Processes* **2**, 167-185.

Kondo, J. (1998) Dependence of evapotranspiration on the precipitation amount and leaf area index for various vegetated surfaces. *J. Japan Soc. Hydrol. & Water Resour.* **11**(4), 346-359 (in Japanese).

Ma X, Fukushima Y. 2002. Numerical model of river flow formation from small to large scale river basins. In *Mathematical Models of Large Watershed Hydrology*, Sigh VP, Frevert DK (eds). Water Resources Publications: Highlands Ranch, CO; 433–470.

Matsuoka, M., Hayasaka, Y., Fukushima, Y. & Honda, Y. (2005) Land cover classification over the Yellow River domain using satellite data. *YRiS News Letter* **4**, 15-26.

Xu, J., Haginoya, S., Saito, K. & Motoya, K. (2005) Surface heat balance and pan evaporation trends in Eastern Asia in the period 1971–2000. *Hydrol. Processes* **19**, 2161-2186. doi:10.1002/hyp.5668.