Analysis of long-term water balance of the Yellow River basin
-Mechanisms of the drying-up-

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1. Introduction

In recent years, the river discharge in the lower reach of the Yellow River basin had decreased rapidly due to dry climate condition and heavy water demands. The river discharges observed at Huayuankou of the 1990s decreased almost half of the 1960s, and observed discharge at Lijin of the 1990s decreased less than one third of 1960s. Accordingly, the drying-up in the lower reach of the Yellow River basin occurred since 1972. The main factors to induce water shortage in the lower reach of the Yellow River basin are recognized as the increase in water consumption within the lower reach and decrease of river water supplied from its upstream. However, the contributions of these two factors had not been clarified quantitatively in the previous studies. Thus, in the present study, we attempted to clarify the mechanism of the drying-up of the Yellow River basin by long-term water balance analysis and several hydrological model simulations.

2. Data and Method

For the long-term analysis, we used 41 years (1960-2000) of daily observation data from 128 meteorological stations and interpolated them into $0.1° \times 0.1°$ degree grid scales as the input parameters for the semi-distributed hydrological model. Then, to predict the evapotranspiration loss from various land use types, we applied a high resolution satellite remote sensing data as another input parameters. The remote sensing data includes the elevation, land surface classification map, and normalized difference vegetation index (NDVI) data sets, which were also converted into $0.1° \times 0.1°$ degree grid scales. The hydrological model used in this study is based on the soil-vegetation-atmosphere transfer (SVAT) and hydrological cycle (HYCY) model, which is composed of the following three sub-models: a one dimensional heat balance model on the land surface, a runoff formation model and a river-routing network model. To understand the heat and water balances more precisely, the original model was modified as follows. First, the land surface was classified into five land-use types (bare, grassland, forest, irrigation area, and water surface). Then, potential evaporation was calculated using the heat balance models. The evapotranspiration without soil water deficit from each vegetation surfaces was calculated from the potential evaporation using functions of the leaf area index (LAI). The LAI of each vegetation type was derived from monthly NDVI data set. Thus, seasonal and spatial variations of vegetation were considered in this model. Finally, actual evapotranspiration was estimated by regulating the evapotranspiration using functions of soil moisture content. However, this hydrological model could not predict long-term water balance of the Yellow River basin as it includes a lot of anthropogenic factors such as irrigation water intake, large reservoir operation, and human-induced land-use changes. Thus, in the present study, we considered these artificial factors in our model by applying simple sub-models for irrigation water intake, reservoir operation and land-use change. The details of model structure and parameters used in this study are summarized in Sato *et al.* (2007b).

3. Results and discussion

3.1. Performance of model simulation

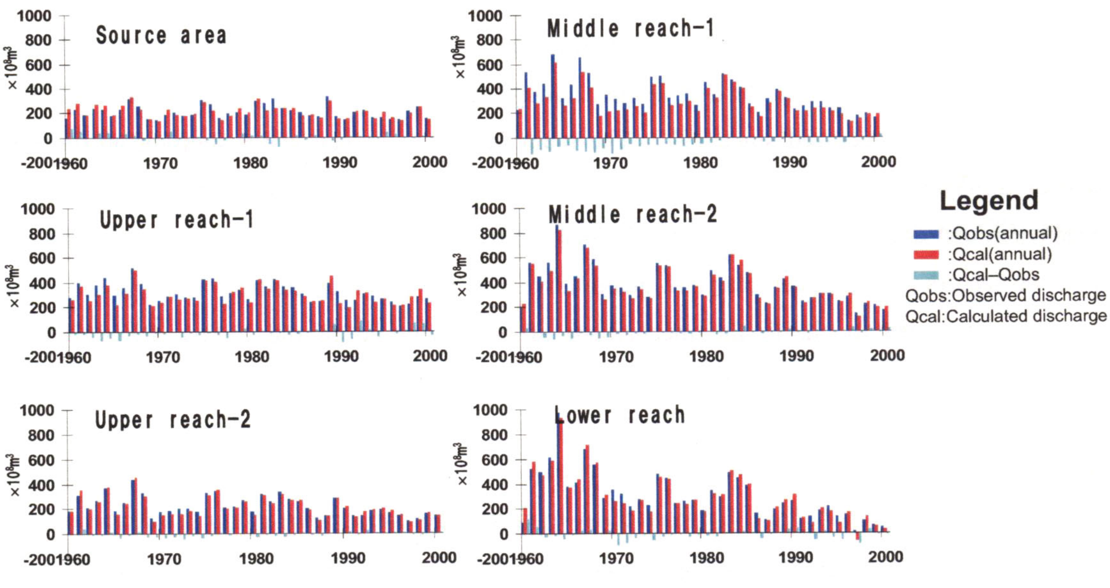


Figure 1 Performance of model simulation

The performances of the hydrological model applied in this study are shown in Figure 1. These figures indicate that the annual discharges from source area to lower reach during the past 40 years (1960 to 2000) estimated by the model (red bars) and observed results (blue bars). In this study, the Yellow River basin was divided into the following six sub-basins: (1) Source area (upstream of Tangnaihai), (2) Upper reach-1 (Tangnaihai to Lanzhou), (3) Upper reach-2 (Lanzhou to Toudaoguai), (4) Middle reach-1 (Toudaoguai to Sanmenxia), (5) Middle reach-2 (Sanmenxia to Huayuankou), and (6) Lower reach (downstream of Huayuankou). Although, we did not consider the influence of long-term land-use change in this model simulation, the observed discharges were reasonably captured by the model except for the Middle reach-1. Therefore, the influence of land-use change on long-term water balance of the Yellow River basin will not be so severe. During the past several decades, natural vegetations on the Loess Plateau located in the middle reaches have been severely destroyed due to human activities. Thus, the soil and water conservation measures (massive vegetation recovery and land surface engineering) become effective since 1970s. And then, the water balance in the middle reach of the Yellow River basin had clearly changed since 1980s. However, the long-term changes of NDVI did not change significantly since 1980s. Therefore, we assumed that the land-use (vegetation) condition in the Loess Plateau had changed drastically until the 1980s. Thus, the underestimation of river discharge from the 1960s to 1970s in the middle reach of the Yellow River basin (Figure 1) was assumed to be overestimation of the evapotranspiration by the model. Then, to reduce the evapotranspiration from the Middle reach-1, we modified (reduced) the model parameter of vegetation cover ratio (VCR). The details of modification procedures of VCR are described in Sato *et al*. (2007a). After that, the estimation error decreased significantly (Figure 2). Therefore, we found that it is necessary to consider the influence of land-use change for estimating long-term water balance in the middle reach of the Yellow River basin.

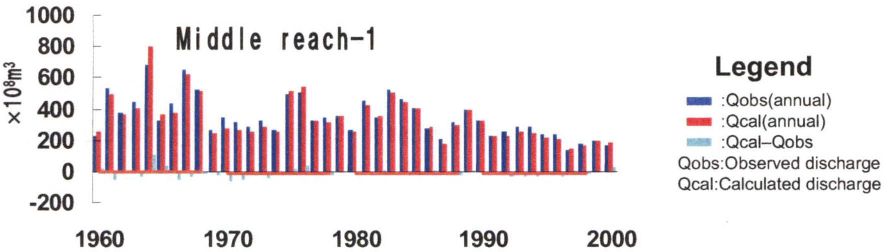


Figure 2 The results of modified model considering the land-use change in the middle reach of the Yellow River basin

3.2. Hydrological impact of soil and water conservation in the Loess Plateau

The massive land-use changes in the middle reach of the Yellow River basin also include "Land terracing", "Afforestation (tree and grass planting)", and "Silt-control" (check dam building) in the Loess Plateau. These land surface engineering will increase the amount of rainfall infiltration by reducing surface overland flow. Thus, to clarify the influence of the land-use change (soil and water conservation) more precisely, we considered the influence of the rainfall infiltration (soil permeability) as well as vegetation changes.

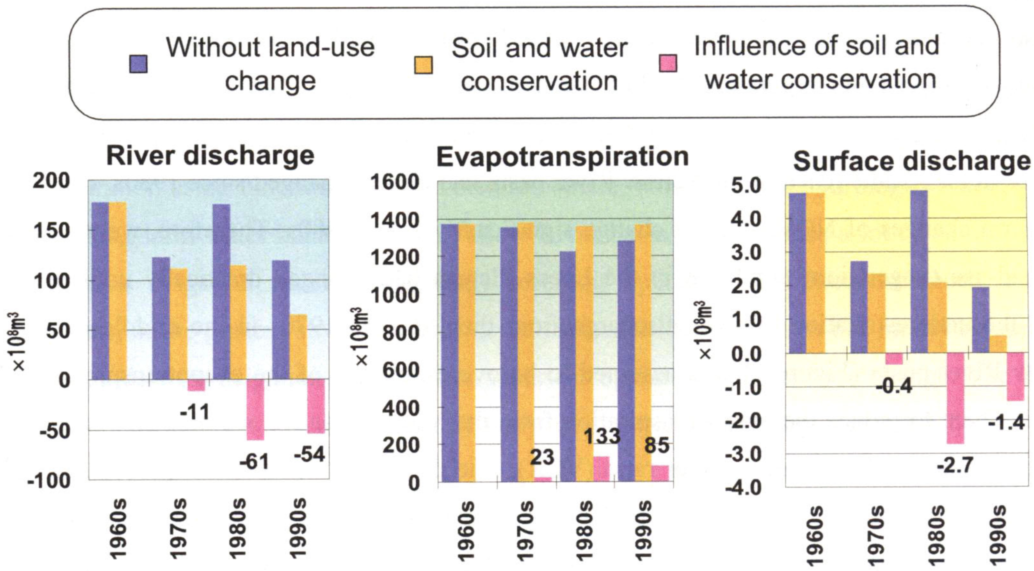
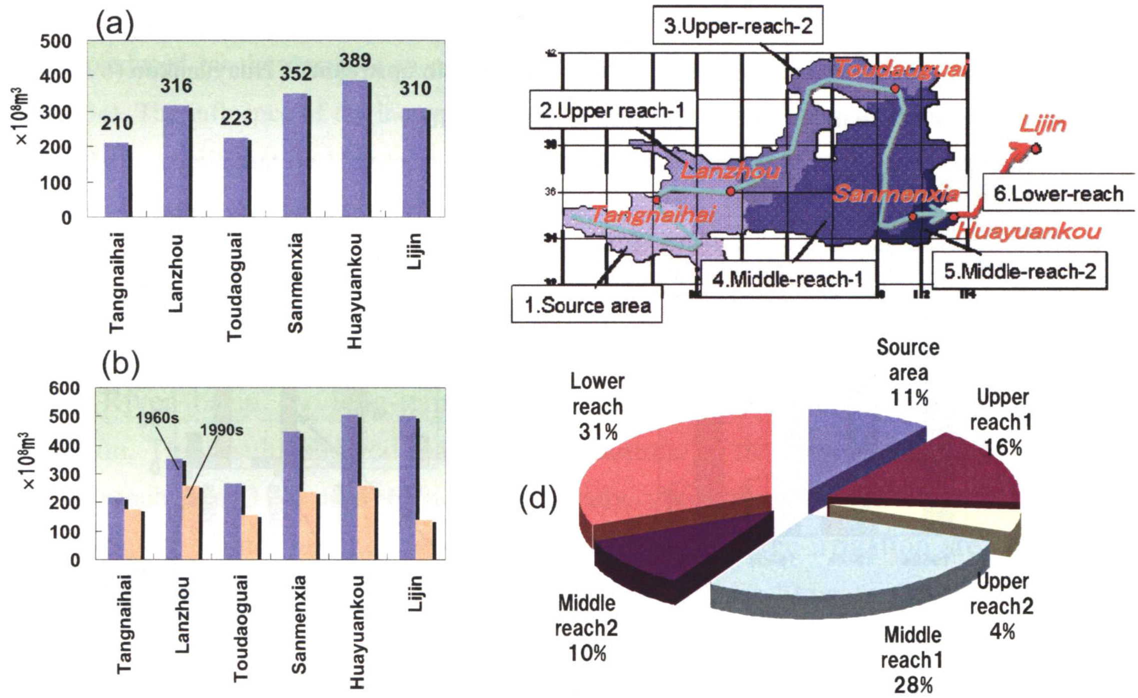


Figure 3 The influence of soil and water conservation in the Loess Plateau simulated by the model

Figure 3 indicates the influence of soil and water conservation on long-term water balance in the middle reach of the Yellow River basin. In the present study, we tried to compare the change of river discharge, evapotranspiration and surface (overland) flows due to soil and water conservation by the model simulation (Sato *et al.*, 2007a). According to these results, we can find that the model used in this study can simulate hydrological impact of soil and water conservation quantitatively as follows: The soil and water conservation will decrease the river discharge about 10-50%, and increase the evapotranspiration about 2-13%, and on the other hand, decrease the surface overland flow about 14-74%. These results suggested that the soil and water conservation will decrease not only soil erosions by decreasing surface (overland) flow, but also will decrease available water resources in the middle reach of the Yellow River basin by increasing evapotranspiration loss with the vegetation recovery.

3.3. Analysis of long-term water balance of the Yellow River basin



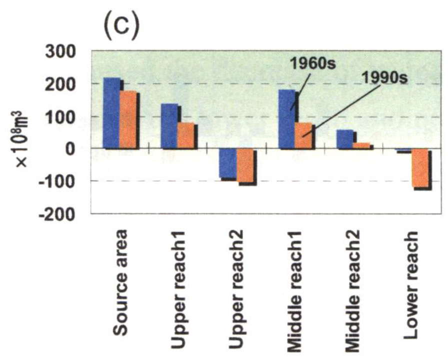


Figure 4 Analysis of long-term water balance of the Yellow River basin

(a) Annual discharge observed at each hydrological station (average of 1960 to 2000); (b) Change of discharge between the 1960s and 1990s; (c) Change of discharge from each sub-basin; (d) Amount of water decrease in each sub-basin

Figure 4a shows annual river discharge observed at each major hydrological station located in the main stream of the Yellow River. From this figure, we can find that there are two sinks in observed river discharge at Toudaoguai and Lijin. It is probably because large amounts of water intake from river channel to the large irrigation areas located in these relatively dry regions. According to the Figure 4b, we can notice that all the hydrological station's discharges had decreased, and consequently, the discharge near the river mouth (observed discharge at Lijin) had decreased almost 36 billion m^3 during the past 40 years. Figure 4c also indicates that there are 'source' and 'sink' in the Yellow River basin. From this figure, we can find that most of river water supplied from source area and middle reach-1. However, the amount of water supplied from middle reach had decreased drastically during the past 40 years. On the other hand, in spite of the amount of water consumption in the upper reach-2 had not changed so much, the rapid increase in water consumption had occurred in the lower reach (Figure 4c). Finally, from the result of figure 4d, we can see that the water shortage in the lower reach of the Yellow River basin (decrease of observed river discharge at Lijin: 36 billion m^3) was induced by the following two factors: (1) increase in water consumption within the lower reaches (31%) and (2) decrease in water supply from upstream of Huayuankou (69%).

3.4. Mechanisms of the drying up of the Yellow River basin

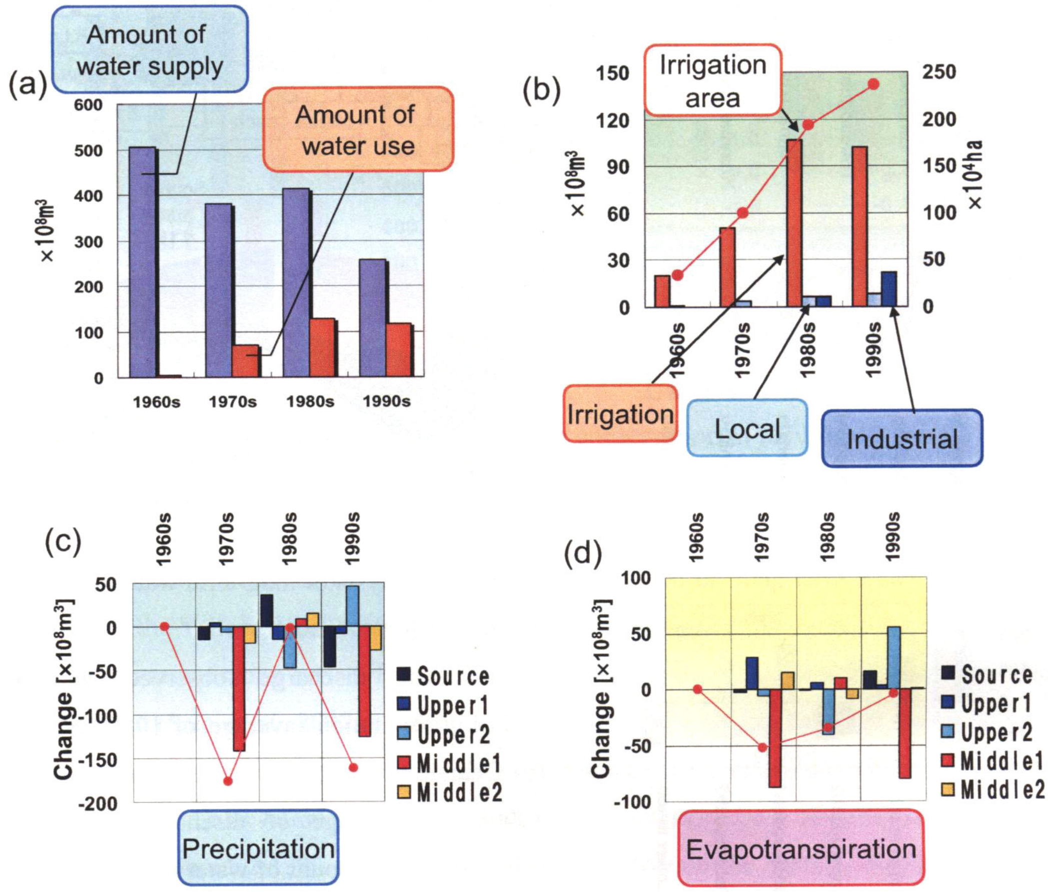


Figure 5 Mechanisms of the drying-up of the Yellow River basin

(a) Decadal change of water supply for the lower reach and water use within the lower reach; (b) Decadal change of irrigation area, irrigation water use, local water use and industrial water use within the lower reach; (c) Decadal change of precipitation from source area to middle reach-2; (d) Decadal change of evapotranspiration from source area to middle reach-2

According to the decadal analysis of the water use within the lower reach and the water supply to the lower reach, we can find that the water use within lower reach increased between the 1960s to the 1980s and water supply to the lower reach decreased in the 1970s and the 1990s (Figure 5a). The major reason of the increase in water use within the lower reach can be due to the increase in irrigation water use with the increase of irrigation areas from the 1960s to the 1980s (Figure 5b). However, despite of the increase in irrigation area from the 1980s to 1990s, the amount of irrigation water use did not change. This is probably because the influence of climate conditions (i.e. decrease in sunshine duration) will decrease the amount of potential evaporation or the efficiency of water use might improved in the lower reach after the 1980s. The decrease in water supply to the lower reach must be induced by the decrease in precipitation in the middle reach-2 in the 1970s and 1980s (Figure 5c). The influence of the increase in evapotranspiration with the increase of air temperature will not be so significant on long-term water balance of the Yellow River basin compared with the influence of the precipitation change (Figure 5d).

4. Conclusion

In the present study, we attempted to clarify the mechanisms of the drying-up of the Yellow River basin by long-term water balance analysis and hydrological model simulation. The results showed that the contributions of the lower reach and upper and middle reach are 31% and 69%, respectively. According to the results of model simulation, we found that the water consumption in the large irrigation area located in the upper reach did not change significantly during the past 40 years. On the other hand, the water consumption in the irrigation area located around the lower reach had increased significantly during the period from 1960s to 1980s. Furthermore, it was found that the rapid decreases in precipitation in the middle reach-2 in the 1970s and the 1990s caused the decrease of water supply to the lower reach. Compared with irrigation water use in the lower reach and precipitation change in the middle reach, the impact of rise in temperature and vegetation change on long-term water balance were found to be negligible. These results will contribute to the integrated water resources management in the Yellow River basin, such as the more adequate water allocation or soil and water conservation.

REFERENCES

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Sato *et al.* (2007b): Analysis of long-term water balance in the source area of the Yellow River basin. *Hydrological Processes*, DOI: 10.1002/hyp.6730