The hydrological impact zone in the lower reaches of the Yellow River: a new concept for water resources issues

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Abstract The lower reaches of the Yellow River have been affected by water shortages since the 1990s. We suggest that water balance and resources in the lower reaches should be considered from the standpoint of water diversion. In this paper, we define a new concept of an "impact zone" to replace that of "basin" for discussion of water resources issues. The objective of this study was to identify the spatial and temporal change in water use in the lower reaches over the last 50 years, and to evaluate the impact zone of the Yellow River.

Key words impact zone; lower reach; water diversion; water use; Yellow River

INTRODUCTION

The lower reaches of the Yellow River are defined as the zone from Huayuankou to Lijin, with an administration area of about 4.43×10^4 km² and population of about 2.5×10^7 (Ruan, 1997) (Fig. 1). This is an important agricultural region, with an irrigated area of about 1.93×10^4 km² (in 1990) using water diverted from the Yellow River (Xi, 1999; CDCID, 2002), and it accounts for about one-third of the total irrigation area of the whole basin. Since much of the river sediment precipitates in the lower reaches, and thus raises the river bed, the Yellow River flows at a higher level than its riparian zone; i.e. the river is suspended and subject to water loss in its lower reaches. Thus, water from the river flows outside the basin and is used not only in the Yellow River basin, but also in the Haihai (North China Plain) and Huihe rivers, which are traditionally defined as separate basins.

Water shortage is serious in the lower reaches as inflow at Huayuankou station has recently decreased and high demand exists for domestic, industrial, and agricultural water, especially in the North China Plain. In the case of an emergency, the Yellow River has even been diverted to supply water for Tianjin City, which is 400 km from the boundary of the Yellow River basin. The main channel of the Yellow River has dried up several times since 1972. Rational water allocation and use is an important issue in the management of the whole basin, and interacts with environmental problems, such as flooding control, coastal sediment, and erosion. The main objectives of this study were to examine the spatial and temporal water-use changes in the lower reaches over the last 50 years and determine their causes, and to identify the "impact zone" of the Yellow River.



Fig. 1 Schematic map of the Yellow River basin and irrigated area, and location of the lower reach. The map of the irrigated area was modified after Xi (1999) and the YRCC (2002).

DEFINITION OF THE "IMPACT ZONE"

In the past, the hydrological community has considered water balances in relationship to the river "basin." This is appropriate when the hydrological cycle is closed and the water budget can be handled without considering any inflow or outflow from adjacent basins. However, there is often a quite different situation in the lower reaches of a basin. A water flow can occur through the geomorphological boundary between adjacent basins, in particular where a river is subject to losses. Also, water transport from the basin, such as the extraction of irrigation water from the river, may produce transboundary flows from one basin to another. Another related situation involves submarine groundwater discharge (SGD), which has recently been recognized as an important pathway for water and dissolved material near the coastal zone (Taniguchi *et al.*, 2000). We believe that a replacement for the basin concept is needed when water resources issues in the lower reaches are discussed.

The term "basin" as used in hydrology is defined as "a geographic area drained by a river and its tributaries; it consists of a drainage system that may be comprised of streams, wetlands, and often natural or artificial lakes" (Dash, 2003). The words "catchment" and "watershed" are also used instead of "basin", but the concept behind those terms is always a natural, hydrologically-closed area. In contrast, we will define the "impact zone" to be "the area affected by the river water, groundwater, or other water without being limited to the geomorophological or hydrological basin boundaries". For example, a river losing water to groundwater illustrates the "impact zone" concept.

The terms "capture zone" and "release zone" (Nield & Chen, 1994; Townly & Turner, 1995; Taniguchi *et al.*, 1999; Taniguchi, 2000) are used to describe interact-

tions between surface water and groundwater; however, their use is restricted to natural (not human-induced) water transport. In this study, the impact zone is defined not only for natural flows, but also human-induced flows such as irrigation (Chen *et al.*, 2004a) in the lower reaches of the Yellow River.

METHODS

We used two methods to identify the impact zone of the Yellow River. The first was the water balance method used to evaluate the diversion of water in the lower reaches of the river. The second was the direct measurement of the hydraulic potential of the groundwater connected to the Yellow River, which indicated the physical impact zone where river water is being lost to groundwater in the lower reaches.

In the water balance method, river discharge rates at two stations were used. Water use (W_{use}) was estimated based on the difference of the monthly discharge at Huayuankou and Lijin stations (Fig. 1): $W_{use} = FL_H - FL_L$, where FL_H and FL_L are the discharges at Huayuankou and Lijin, respectively. Annual water use was calculated by summarizing the monthly data.

Although it is basically a suspended river in the lower reaches and the flow decreases along the main channel, there are three tributaries flowing into the Yellow River, the Tianran Wenyan Canal, the Jindi River, and the Dawen River. The annual average discharge for these three tributaries is about 2.1×10^9 m³ (Liu & Chen, 2001). River discharge is controlled by gates on the tributaries and there is no inflow to the Yellow River in the dry season. There are four gauging stations between Huayuankou and Lijin, Gaocun, Sunkou, Aishan, and Luokou, which were used to calculate the inflows in the lower reaches. W_{use} was thus adjusted by adding the inflow: $W_{use'} = FL_H - FL_L + Inflow$. The proposed impact zone in the lower reaches of the Yellow River was defined by considering both water diversion and water discharge from the irrigated area.

The second method was to identify the physical impact zone using the relationship between river water and groundwater. CTD (conductivity-temperature-depth) sensors (DIK 603A; Daiki Co., Ltd, Japan) were installed in 10 boreholes to continuously measure the groundwater level, temperature, and conductivity. Measurements were made every 10 min from September 2003 to May 2005. In this paper, we use the "impact zone" which has the maximum area with the effects of the natural flows and human-induced flows.

RESULTS

The monthly average discharge at the Huayuankou and Lijin stations from 1950 to 2001 is shown in Fig. 2(a), and the difference between the two stations is equivalent to the average monthly water diversion in the lower reaches. Water diverted (i.e. water use = $W_{use'}$) between the two locations, as well as the ratio of water diverted to river discharge at Huayuankou, is shown for every decade in Fig. 2(b). The result shows that the annual average discharge at Huayuankou decreased from 4.51×10^{10} m³ in the



Fig. 2 (a) Annual discharge at Huayuankou and Lijin during 1950–2002, and (b) decadal average discharge at Huayuankou, the water diverted in the lower reach, and the ratio of water diversion to the discharge at Huayuankou.

period 1951–1980, to 3.29×10^{10} m³ in the period 1981–2000, while that at Lijin decreased from 4.21×10^{10} m³ to 2.06×10^{10} m³ over the same period; i.e. water used in the lower reaches increased by about 9.2×10^9 m³ in the latter 20 years, compared to the period 1950–1980 (Fig. 2). Too much water was diverted for irrigation during 1959–1961 ("the Great Leap forward"), and salinization occurred because the discharge canal was not well constructed. As a result, the newly developed irrigation area was abandoned, except for the Renmin Shengli Canal with an irrigation area of 1.62 x 10^4 ha, and water use decreased sharply in 1962. Water diversion then resumed in the lower reaches; diversion increased noticeably from 1971 to 1980 and has maintained a relatively stable level since the 1980s.

Daily changes in river discharge from September 2003 to May 2005 at Lijin, and changes in groundwater hydraulic potential in 10 boreholes are shown in Fig. 3. As shown in Fig. 3, the groundwater level corresponding to the river discharge also changed, but with a time lag. The changes in the groundwater level south of the Yellow River were larger than those to the north, and the change in groundwater level due to the change in river discharge was larger, with decreasing distance of the borehole to the river.



Fig. 3 (a) Locations of the observation wells in the Yellow River delta; (b) daily river discharge at Lijin, and changes in groundwater levels in the (c) south line (N10, W35, N8, and N9) and the (d) north line (N1–N5).



Fig. 4 Time lag coefficient between river discharge and groundwater level at: (a) the north line, and (b) south line and relationships between distance from the Yellow River and (c) correlation coefficient, and (d) time delay of discharge–groundwater level changes.

DISCUSSION

The amount of water allocated to Henan, Shandong, Hebei, and Tianjin was about 1.45 $\times 10^{10}$ m³, as indicated by the line in Fig. 4. Since some areas in Shandong and Henan Province are outside the reach between Huayuankou and Lijin, the actual amount allocated for this reach was only 1.38×10^{10} m³, as indicated by the dashed line. Although discharge at Huayuankou decreased after the 1960s (Fig. 2), water diversion in the reach increased for the irrigation of newly developed land and the emergency water supply for Tianjin (Chen *et al.*, 2004b). Water diversion for Qingdao City started in 1989 with an annual amount of about 2×10^8 m³. The ratio of water diversion to discharge at Huayuankou has increased continuously since the 1960s, and more than half the water in the lower reach has been diverted in the 1990s, although the discharge was only about half of that in the 1950s and 1960s (Fig. 2(b)). This is considered to be the main reason for the drying up of the main channel.

To evaluate the hydraulics of the Yellow River impact zone based on its effects on groundwater, correlation analyses were made between the river discharge (Fig. 3(b)) and groundwater levels at 10 boreholes (Fig. 3(c),(d)). The groundwater level data was shifted every day, then regression analyses were made to obtain the correlation coefficients with the different time lags. The correlation coefficients between the river discharge and groundwater level are shown in Fig. 4 for the northern and southern area of the delta. The highest coefficients were found after a period of 2 months for the northern area (Fig. 4(a)), and within 1 month for the southern area (Fig. 4(b)).

The spatial distribution of the correlation coefficients between river discharge and groundwater level may indicate the hydraulic effects of the Yellow River impact zone on the groundwater. The relationship between distance from the river and the correlation coefficient is shown in Fig. 4(c). The correlation coefficient is more than 0.4 even 45 km from the Yellow River in the northern area of the delta; however, it decreases dramatically to 0.18 in the southern area, which adjoins the Bohai Sea. The groundwater is connected to seawater next to the coastal zone, and therefore, the correlation between river water and groundwater was weaker. However, the hydraulic connection between river water and groundwater was observed over 45 km from the Yellow River because of water loss to the groundwater.

As shown in Fig. 4(a) and (b), the maximum correlation between borehole levels and river discharge occurs with a time lag. The relationship between distance from the river and time lag is given in Fig. 4(d). The lag increases with distance from the river for both the north and south areas of the delta. This result shows that all groundwater in the delta is connected to the Yellow River. Therefore, the impact zone of the Yellow River comprises the entire delta.

CONCLUSIONS

In this paper, we presented the new concept of an "impact zone" to replace that of "basin" in relation to water resources issues. Yellow River water is connected to the groundwater hydraulically over the whole delta, and therefore, the impact zone of the river comprises the entire river delta. The impact zone includes not only natural water

transfer but also human-induced water movement such as irrigation in the lower reaches of the river. Water diversion from the river may be a major contributor to the recent water shortage in the lower reaches. We propose that the impact zone concept be used for water resources issues, particularly over the lower reaches of the basin.

Acknowledgements The authors acknowledge financial assistance from the MEXT (Japan) Fund for the Human–Nature–Earth Revolution Research Project in "Prediction Mission in Water Cycle Change–Development of Water Resource Prediction Model–Surface Water Research Program in the Yellow River". We also acknowledge the contribution of Tomotoshi Ishitobi who helped in drafting the figures. This study was also supported by the Scientific Research Foundation for the Returned Overseas Chinese Scholars and the "985 Project" of GIS and remote sensing for geosciences from the Ministry of Education of PR China.

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