Impacts of human activities on the hydrological regime and ecosystems in an arid area of northwest China

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Abstract This paper focuses on the impacts of human activities on the hydrological system in relation to ecological environment in the arid area of northwest China. The eco-environmental problems mainly associated with agricultural ecosystems are discussed in detail dealing particularly with the development of surface water resources which has caused an extensive decline of the groundwater table. This has resulted in serious deterioration of the ecological environment, including the deterioration of water quality, depletion of springs and lakes, decay of vegetation and the extension of desertification; while in irrigated areas the extension of soil salinization has resulted from the rising groundwater table. A conceptual model is developed to show the complex relationships between the hydrological system and eco-environmental system under human influences.

INTRODUCTION

Quaternary inland basins are well-developed in northwest China, consisting mainly of the Hexi Corridor, Zhungeer, Talimu and Chaitamu, better known as the Gobi Desert area. All the streams draining the mountain area flow into the piedmont plain and usually pass through two or three basins. Groundwater emerges on the frontal part of the alluvial fans in the form of spring clusters, and flows into the green land, the so-called "Oasis", the main cultivated area in the basin. However, the present hydrological situation is already strongly affected by human activities, resulting in serious deterioration of the ecological environment. This is one of the most important problems urgently to be studied for the sustainable water development of the vast arid region of northwest China.

ANALYSIS OF THE HYDROLOGICAL SYSTEM

All the basins belong to the Quaternary fault-depression, inherited from Meso-Cenozoic basins. They have an accumulation of enormously thick unconsolidated gravel and other terrestrial sediments. Within the basin, precipitation is only 50-200 mm, while strong potential evaporation reaches 2000-3000 mm. The wide piedmont plain can be divided into three distinct zones based on either geological or hydrological aspects. They are the zone of the Gobi plain (zone of infiltration), the zone of green land "Oasis" (zone of spring clusters), and the zone of saline soil (zone of evaporation), a transition zone to the desert area (Chen, 1990).
All the streams that originate from the rainfall and melting snows in high mountains form a large volume of runoff flowing into the piedmont plain and usually passing through two or three basins separated by rock gorges, such as the Wuwei basin and Minqin basin of the Shiyanghe drainage system. Finally, flows enter the inland lake or are dissipated in the desert. In short, the complete hydrological system of a typical completely closed inland drainage usually involves two or three connected sub-systems, within which surface water and groundwater closely interact (Chen, 1994).

The interaction of surface water and groundwater in different zones is actually very complex, but the predominant features of the hydrological system in arid area (Chen, 1990) can be summarized as follows:

(a) The total inflow to the basin is more or less nearly equivalent to the total amount of water resources in the entire region. For example, the major components of total water resources in Hexi Corridor (Table 1) shows that the surface runoff from the mountain area comprises 93.22% of the total resources.

(b) In regard to groundwater resources, the recharge of the surface water in Hexi Corridor, including both stream infiltration and canal seepage loss, comprised more than 90% of the total recharge; while for discharge, the outflows of spring clusters and the groundwater evaporation are most dominant, reaching 44.5% and 40.7% of the total amount (Table 2) respectively. According to recent data, the exploitation of groundwater is increasing rapidly and also becoming one of the important factors of the total discharge.

(c) In consideration of the infiltration of surface water, particularly the infiltration of irrigation water and the re-use of the so-called return flow, the maximum water yield is much larger than the natural water resources (Table 1). Statistically speaking, the total permissible yield reaches $104.88 \times 10^8$ m$^3$ year$^{-1}$ (Table 3), while the average rate of water re-use is about 40% (Fan, 1990).

(d) From the viewpoint of a complete hydrological system, the upper basin usually plays a leading role in the whole system, in which the piedmont plain shows a distinct zonal distribution particularly with a very wide green land — the main culti-

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**Table 1** The major components of total water resources ($10^8$ m$^3$ year$^{-1}$).

<table>
<thead>
<tr>
<th>Surface runoff</th>
<th>Subsurface runoff</th>
<th>Precipitation infiltration</th>
<th>Total water resource</th>
</tr>
</thead>
<tbody>
<tr>
<td>67.30</td>
<td>2.52</td>
<td>2.42</td>
<td>72.24</td>
</tr>
<tr>
<td>93.22%</td>
<td>3.50%</td>
<td>3.28%</td>
<td>100%</td>
</tr>
</tbody>
</table>

**Table 2** Main elements of ground water balance (1977).

<table>
<thead>
<tr>
<th>Recharge ($\times 10^8$ m$^3$ year$^{-1}$)</th>
<th>%</th>
<th>Discharge</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface runoff</td>
<td></td>
<td>Springs</td>
<td>25.95</td>
</tr>
<tr>
<td>South basin</td>
<td>42.12</td>
<td>77.2</td>
<td>Evaporation</td>
</tr>
<tr>
<td>North basin</td>
<td>7.46</td>
<td>13.7</td>
<td>Withdrawal</td>
</tr>
<tr>
<td>Subsurface runoff</td>
<td>2.52</td>
<td>4.6</td>
<td>Others</td>
</tr>
<tr>
<td>Precipitation</td>
<td>2.42</td>
<td>4.5</td>
<td>Total</td>
</tr>
<tr>
<td>Total</td>
<td>54.52</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>
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Table 3 Statistics on the total permissible yield ($10^8$ m$^3$ year$^{-1}$).

<table>
<thead>
<tr>
<th>Drainage system</th>
<th>Shiyanghe</th>
<th>Heihe</th>
<th>Shulehe</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum water yield</td>
<td>23.74</td>
<td>57.66</td>
<td>23.48</td>
<td>104.88</td>
</tr>
<tr>
<td>Rate of water re-use (%)</td>
<td>39.70</td>
<td>42.60</td>
<td>34.50</td>
<td>40.00</td>
</tr>
</tbody>
</table>

vated area, while along the lower reaches of the river, relatively little water emerges from springs and the zone of saline soil is much wider and the shallow groundwater level results in very high evaporation (Chen, 1994). The amount of water resources in the lower basin is the surplus of the upper basin, that means the surplus of the total losses of the upper basin.

(e) In general, the characteristics of a hydrological system (consisting of two basins) can be expressed by the following simplified equations:

(i) Total water resources ($W_t$):

$$W_t \approx S \ (\text{surface runoff in mountain area})$$
$$\approx W_{t1} \ (\text{upper basin}) + W_{t2} \ (\text{lower basin})$$
$$\approx S_1 \ (\text{upper basin}) + S_2 \ (\text{lower basin})$$

where $S_1$ = total consumption of $S$ in upper basin; and $S_2$ = surplus of $S$ from upper basin.

(ii) Groundwater resources ($G$):

$$G \approx I \ (\text{surface water infiltration})$$
$$\approx I_1 \ (\text{upper basin}) + I_2 \ (\text{lower basin})$$

where $I$ includes infiltration of streams ($I_a$), canals ($I_b$) and return flow ($I_c$).

(iii) Simplified groundwater balance equations (Chen, 1994):

upper basin: $(I_{1a} + I_{1b} + I_{1c}) - (S_p + Z + E) = \pm W$

lower basin: $(I_{2a} + I_{2b} + I_{2c}) - (Z + E + L) = \pm W$

where $S_p$ = overflowing spring, $Z$ = groundwater evaporation, $E$ = extraction, $L$ = discharge into lake, and $W$ = variation of groundwater storage.

(iv) Simplified water balance equation:

$$W_t \approx S_o + I \approx S_o + (S_p + Gr) \approx SI + SpI + E + Zs + Zg + L$$

where $S_o$ = surface water excluding infiltration; $SI$ = irrigation expenses of surface water; $Gr$ = groundwater runoff; $SpI$ = irrigation expenses of overflowing springs; $E$ = groundwater extraction; $Zs$ = surface water evaporation; $Zg$ = groundwater evaporation; $L$ = inflow of the terminal lake including the discharge of both surface water and groundwater.
ECOLOGICAL EFFECTS DUE TO WATER DEVELOPMENTS

Depletion of spring outflows

During the past 30 years, many reservoirs and irrigation channels have been built for the development of water resources. These developments have resulted in the reduction of groundwater recharge which has caused the serious decline of groundwater levels and the depletion of spring outflows. The example of Hexi Corridor (Table 4) shows clearly that the range of decline in water tables or the reduction of spring outflows are exactly proportional to the increasing rate of surface water utilization. Similar conditions can be found in Zhungeer basin of Xinjiang Autonomous Region, where the groundwater tables of the Urumqi River basin and Manas River basin have widely and continuously declined with an amplitude of 11.8 m and 6.0 m respectively, while the spring outflows reduced from 2.06 to 0.61 and 4.30 to 2.70 (unit $10^8 \text{ m}^3 \text{ year}^{-1}$) respectively, due to decreasing groundwater recharge (Fan, 1990).

The ecological effects due to the depletion of spring outflow, mainly involve: (a) a lot of streams originating from overflowing springs dry up, such as in the vicinity of Wuwei city where more than 230 streams (about 80% of the total streams) have disappeared; (b) the overflowing zone has retreated about 2-5 km, swamps or small lakes mostly dried up, and many villages have lost their drinking water sources; (c) spring irrigation of fields has been abandoned and replaced by well irrigation; (d) the rate of re-use has decreased from 70% to 40%; (e) reservoirs and other water works have suffered great evaporation losses (Chen, 1987).

Regulation of irrigation system due to allocational change of water resources

As mentioned above, the original spring irrigation of fields is now mostly replaced by well irrigation due to the depletion of the overflowing springs. For example, in the 1960s the spring irrigation area in Wuwei region was about $2 \times 10^4$ ha, whilst the well irrigation area was only 680 ha. In the 1980s, the well irrigation area had increased to $2.02 \times 10^4$ ha, while the spring irrigation area decreased to $0.24 \times 10^4$ ha i.e. about an 88.37% reduction (Chen, 1987). The over-exploitation of groundwater hastened the decline of the groundwater table.

On the other hand, the high consumption of water resources in the upper basin,

<table>
<thead>
<tr>
<th>Drainage system</th>
<th>Range (m)</th>
<th>Rate (m year$^{-1}$)</th>
<th>Amount of reduction ($10^8 \text{ m}^3 \text{ year}^{-1}$)</th>
<th>Rate of reduction (%)</th>
<th>Rate of surface water utilization (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shiyanghe</td>
<td>6-20</td>
<td>0.3-0.9</td>
<td>5.06</td>
<td>60</td>
<td>79</td>
</tr>
<tr>
<td>Heihe</td>
<td>1-4</td>
<td>0.1-0.4</td>
<td>2.94</td>
<td>16</td>
<td>69</td>
</tr>
<tr>
<td>Shulehe</td>
<td>1-6</td>
<td>0.1-0.4</td>
<td>2.14</td>
<td>38</td>
<td>53</td>
</tr>
</tbody>
</table>
especially expanding the new irrigation area in the upper part of the piedmont plain, has caused a rapid decrease in flow to the lower basin. For example (Chen, 1987), the inflow of Minqin basin (lower basin of Shiyanghe drainage) decreased from $5.73 \times 10^8$ m$^3$ year$^{-1}$ in the 1950s to $3.22 \times 10^8$ m$^3$ year$^{-1}$ in the 1970s. In contrast, the well irrigation area increased from $0.64 \times 10^4$ ha in 1965 to $4.29 \times 10^4$ ha in 1979 (Table 5). The exploitation of groundwater and the reduction of surface water infiltration will continue to cause the progressive drawdown of the regional groundwater table.

<table>
<thead>
<tr>
<th>Years</th>
<th>1950s</th>
<th>1960s</th>
<th>1980s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflow (10$^8$ m$^3$ year$^{-1}$)</td>
<td>5.73</td>
<td>4.45</td>
<td>2.25</td>
</tr>
<tr>
<td>Well irrigation area (10$^4$ ha)</td>
<td>0.64-0.95</td>
<td>3.44-4.29</td>
<td></td>
</tr>
</tbody>
</table>

Deterioration of water quality

The sharp decrease of the inflow to Minqin basin means not only that the streamflow is reduced but also groundwater recharge is decreased. On the other side, the strong evaporation of both surface water and groundwater has caused a rapid deterioration of water quality. Nowadays, salty water of the carbonate-sulphate type, with a concentration of 1-3 g l$^{-1}$, is extensively distributed; fairly salty water of the sulphate-chloride type, with concentrations of 3-10 g l$^{-1}$, occurs mainly in the northern part of the lake region. More than 50% of wells show increasing salt concentrations, and the others are more or less stable. It is estimated that the salt concentration in well water has increased by about 0.1 to 0.2 g l$^{-1}$ per year in the irrigation area. A typical example is an observatory borehole (M-94) which shows the concentration of salts in groundwater increased from 1.421 g l$^{-1}$ (1978) to 2.092 g l$^{-1}$ (1980). The graph in Fig. 1 shows the variation of the different ions, in which the HCO$_3^-$ stays at a low level whilst the SO$_4^{2-}$ and Na$^+$ have risen rather rapidly (Liu, 1992). In addition, the concentration of fluoride anion in the groundwater has also obviously increased.

Qualitative changes in the surface water are particularly displayed in the chemical changes of the lake water. For example, the famous inland lake East Juyanhai is the terminus of Heihe River. During the past 50 years, the lake has become smaller and smaller, while the concentration of the lake water has increased progressively (Table 6) because of the rapid reduction of the inflow i.e. the reduction of surface runoff in lower reach of the river (Liu, 1992).

Extension of salinization and desertification

Soil salinization and desertification are mostly manmade disasters in arid areas caused by irrational development of water resources. Construction of reservoirs in the upper reaches, diversion of water from reservoirs into low land on lower reaches, and flood irrigation result in rising groundwater levels and soil salinization over vast areas. According to statistics, the area of secondary soil salinization in inland basins in north-
west China reaches $1.13 \times 10^6$ ha, among them $9.53 \times 10^4$ ha in Hexi Corridor, constituting $1/8$ of the cultivated area; in Minqin basin the area of salinization increased from $1.73 \times 10^4$ ha in the 1950s to $2.53 \times 10^4$ ha at present, constituting 64% of the cultivated area. The cultivated area in Xinjiang is $3.15 \times 10^6$ ha, including more than $1/3$ with salinization to various degrees. The area of land recently brought under cultivation and abandoned due to salinization is $(6.67-10) \times 10^5$ ha. In some regions the area of cultivation is approximately equal to the area of abandonment in many years, resulting in enormous economic losses (Lin, 1992). In fact, groundwater is generally distributed on low plains; where the water table is shallow, well irrigation is appropriate. If well irrigation is predominant and combined with well drainage as well as with canal irrigation, to integrate management of surface water and groundwater, then soil salinization will no longer be inevitable, and a great quantity of water resources could be economized.

As mentioned above, a great quantity of water resources are depleted by various hydraulic structures on the upper reaches, so that the flow in the lower reaches of many rivers has decreased seriously and even disappeared, resulting in the decline of groundwater levels, deterioration of water quality, degeneration of pasture, and withering of vegetation. Lakes at the terminus of many rivers have become depleted and even dry up.

Table 6 Variation of the dimension and water quality of the lake Juyanhai.

<table>
<thead>
<tr>
<th>Year</th>
<th>Dimension of the lake (km²)</th>
<th>Average concentration (g l⁻¹)</th>
<th>Chemical composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1940s</td>
<td>&gt; 120</td>
<td>&lt;1</td>
<td>HCO⁻ -SO₄²⁻ -Na⁺ -Ca²⁺</td>
</tr>
<tr>
<td>1950s</td>
<td>75</td>
<td>1-2</td>
<td>SO₄²⁻ -HCO₃⁻ -Na⁺ -Ca²⁺</td>
</tr>
<tr>
<td>1960s</td>
<td>35 (1966)</td>
<td>2.3 (1960)</td>
<td>SO₄²⁻ -Cl⁻ -Na⁺ -Mg²⁺</td>
</tr>
<tr>
<td>1970s</td>
<td>23 (1980)</td>
<td>7.4 (1979)</td>
<td>SO₄²⁻ -Cl⁻ -Na⁺ -Mg²⁺</td>
</tr>
<tr>
<td>1980s</td>
<td>43 (1982)</td>
<td>9.7-34.5</td>
<td>SO₄²⁻ -Cl⁻ -Na⁺ -Mg²⁺</td>
</tr>
</tbody>
</table>
Land desertification can become a major problem. For example, the famous Luobupo lake on the lower reaches of the Kongque River at the southeast edge of the Talimu basin had an area of 1900 km\(^2\) in 1943, decreased to 530 km\(^2\) in 1962 and is dry at present. The Manas lake at the terminus of the Manas River in Zhungeer basin had an area of 550 km\(^2\) in 1968 and is also dry at present. The area of the Aibi lake in the west part of the Zhungeer basin decreased from 1070 km\(^2\) in 1958 to 570 km\(^2\) at present. Most of the above examples have been replaced by desert. Talimu River, the biggest river in Xinjiang, had an annual flow \(49.8 \times 10^8\) m\(^3\). For the last 20 years, a great quantity of water has been diverted into the fields along the upper reaches so that the surplus of annual flow on middle reaches is only \(9.5 \times 10^8\) m\(^3\), i.e. decreased by 81%; the lower reaches of the river dried up, the groundwater level decreased by 8 m, and the salt content in groundwater increased dramatically. The forest of diversiform-leaved poplar and red willow withered; more than \(2 \times 10^9\) ha of grassland disappeared, and more than \(6.67 \times 10^3\) ha of cultivated land was abandoned and was followed by desertification. A great part of the previous "green corridor", with a length of 300 km, was reduced to wilderness. According to statistics, over the last 30 years the area of desert in Xinjiang has increased by \(3.4 \times 10^4\) km\(^2\), resulting in a loss of \(3.4 \times 10^6\) ha of agricultural land and grassland.

The complicated relationships between the hydrological systems and ecosystems are summarized in Fig. 2, which presents a conceptional model to show the interactions between surface water and groundwater in different geomorphological zones along a river. Artificial influences have changed the allocation of water as well as the irrigation systems. It indicates that the development of surface water has caused extensive desertification in the lower reaches of the rivers causing heavy losses in agricultural production.

CONCLUSION

According to the hydrological review above, a new policy for water development in arid areas must be established. The original strategy was to build more water works to increase the use of surface water, irrespective of any negative ecological effects. Attention should be directed to developing groundwater including the use of overflowing springs, and the construction of reservoirs in the upper reaches should be limited. The great thickness of the gravel beds in the Gobi plain should be used as a natural underground reservoir, having a great storage capacity and absolutely no evaporation. The underground flow can be transferred naturally into the green land without any artificial water works, which has obvious benefits over surface reservoirs and artificial canals.

A rational irrigation system needs to adopt different approaches in different geomorphic zones. In the Gobi plain where occasionally there is a thin layer of soils; a certain quantity of surface water to extend the irrigated area is certainly necessary, but water consumption should be strictly controlled. In green land, the priority is to make full use of the overflowing springs and to protect the spring irrigation system. In the lower part of the green land, the use of spring irrigation combined with well irrigation is reasonable. In low land along lower reaches, attention must be given to avoiding "over-irrigation" which usually causes a wide extension of salinization due to the rising groundwater table. The preferred approach is to use well irrigation as the major water
Drainage system | upper reach (upper basin) | lower reach (lower basin) |
--- | --- | --- |
Geomorphologicalzonation | mountain area | Gobi plain | green land (oasis) | low land (saline plain) |
Hydrologic system (in natural condition) | | | | |
Changes of hydrologic systems (under man-made influences) | | | | |
Changes of building water allocation | reduction of inflow | reduction of stream flow | over-exploitation of groundwater | stream flow exhausted |
Changes of irrigation system | development of new irrigated field | fully irrigated field by canal system | development of new irrigated field | stream flow irrigation replaced by well-irrigation |
Effect of ecosystem | strong evaporation of reservoir | building of new basin | building of new basin | extensive decline of lake water table, deterioration of water quality, strong evaporation of soil salinization |

Fig. 2 Relationships between the hydrological systems and ecosystems in an arid area. 

\[
P = \text{precipitation; } M = \text{meltwater; } G = \text{fissure water; } S_t = \text{total inflow; } S_1-S_8 = \text{streamflow (including canals); } G_2-G_7 = \text{groundwater flow; } R = \text{reservoir; } I = \text{infiltrations of: streamflow (a), canals (b) and return flow (c); } S_o = \text{overflowing springs; } IR = \text{irrigated waters; } E = \text{exploitation of groundwater; } Z = \text{evaporation; } L = \text{discharge into lake; } \rightarrow = \text{direction of water flow; } \Rightarrow = \text{direction of main water flow; } \uparrow = \text{evaporation or extraction.} \]

Source combined with well discharges, using canal irrigation only to supplement supplies.

Optimal water distribution between upper and lower basins is another important problem. The main principle is to guarantee that the inflow to the lower basin can satisfy the water requirements without any harmful side effects to the environment. However, in the arid area of northwest China, many reservoirs have already been built and the negative ecological effects are clearly apparent. Remedial measures include not only change of the irrigation system but also to provide artificial groundwater recharge in the Gobi plain to protect the original spring irrigation system. In conclusion, the design of a complete and scientific management plan for the optimal allocation of water resources and the integrated development of surface water and groundwater is most important. The trend is towards environmental management of watersheds as the main approach in water management strategy.
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