Characteristics of Green and Blue Water Flow of Hydrological Landscapes of Upper Heihe in Northwest China

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Abstract. Blue water and green water are of great importance for food production and maintenance of ecosystem. Blue/green water flow on landscape scale and its seasonal variation remains unclear. This study attempt to analyze characteristics of green and blue water flow on landscape scale. In this study, FLEX-Topo model was adopted. And upstream of Heihe River Basin (UHB) was selected as the study area, which was divided through topographic information into four landscapes, such as riparian area, grass hillslope, forest hillslope and bare soil/rock. Based on the analysis of the simulation during the period of 1979-2015, characteristics of green and blue water flow of the four landscapes was presented. The results showed that (1) FLEX-Topo proved to be an efficient approach for catchment hydrological process simulation as well as for green and blue water study; (2) Annual green water flow (GWF) of riparian area was 325.19 mm/a while its blue water flow (BWF) was 151.92 mm/a. GWF and BWF of grass hillslope was 270.50 mm/a and 199.91 mm/a, respectively; GWF of forest hillslope was 424.75 mm/a which is much greater than its BWF (42.11 mm/a); as for bare soil/rock, GWF (227.96 mm/a) was a litter smaller than BWF (295.32 mm/a). From the results, its can be concluded that: (1) on annual scale, majority of precipitation and water reserve in riparian area, grass hillslope, forest hillslope became green water flow, especially in forest hillslope. More than half of precipitation in bare soil/rock turn to blue water flow; (3) seasonal variation of both green water flow and green water flow of the four hydrological landscapes synchronized with precipitation.

1. Introduction

Water resources are essential for both human beings and the ecosystem (Oki and Kanae, 2006). Blue water is the water stored in the rivers, lakes, reservoirs, wetlands and aquifers. And green water, originated from precipitation, is the water stored in unsaturated soil and later used for evapotranspiration (Falkenmark, 1995). Though often ignored, green water, as a matter of fact, is of great importance for food production and maintenance of ecosystem (Oki and Kanae, 2006). Traditionally, water resources planning and management focus on blue water and pay little attention on green water (Falkenmark, 1995). Therefore, comprehensive assessment of both blue and green water spatially and temporally is a key for understanding of water resource, as well as better planning and management (Zhang et al., 2014). For researches in regard to the spatial distribution of green and blue water at a basin level, they usually either take the basin as a whole or break up the catchment into small interacting cells (Gao et al., 2014). The limitation of these research is that it fragmentizes the patterns that can be presented in a larger scale, such as landscape scale (Gao et al., 2014). Winter (2001) pointed out that some
commonalities are likely to arise if the study areas were viewed within the framework of hydrologic landscapes. In addition, seasonal variation of green/blue water is necessary to understand the temporal behaviors of water resources (Zhang et al., 2014). This study attempted to figure out the characteristics of green and blue water flow of hydrological landscapes, which took the UHB as the study area.

2. Materials and Method

2.1. Study Area
The study area is the Upper Heihe River basin (UHB) which is part of the second largest inland river in Northwest China (Fig. 1a). UHB originates from Qilian Mountain to the Yingluoxia with a length of 303 km and area of 10009 km². The elevation of the UHB ranges from approximately 1700 m to 5000 m. As the important source of water yield of the Heihe River Basin, UHB is essential for the integrated water management and thus has attracted more and more attentions.

There is one hydrological station and four meteorological stations in and around UHB (Fig. 1b). Thus, the entire UHB was discretized into four parts by the Thiessen polygon method. Precipitation and temperature was collected in each part and were adjusted through empirical relationships. The observed discharge data was obtained from the hydrological station (Yingluoxia station) to calibrate and validate the model. The input data were available from Cold and Arid Regions Science Data Center (http://westdc.westgis.ac.cn/).

2.2. Method
The hydrological model utilized in this study was FLEX-Topo model. UHB was devided into four hydrological landscapes, such as bare rock/soil, forest hillslope, grass hillslope, riparian area (Fig.1b) based on topographical information including HAND (Height Above the Nearest Drainage) (Nobre et
al., 2011), slope, elevation and aspect. The dominant mechanisms of the landscapes mentioned encompass deep percolation (DP)/Hortonian overland flow (HOF), storage excess subsurface flow (SSF) and saturation excess overland flow (SOF). Four structurally identical, parallel components, corresponding to the four landscapes, with various parameter sets were constructed in FLEX-Topo model. In each parallel component, different but mutually interrelated reservoirs (i.e. a snow reservoir ($S_w$), an interception reservoir ($S_i$), an unsaturated reservoir ($S_u$), a fast-response reservoir ($S_f$) and a slow-response reservoir ($S_s$)), lag functions and connection elements were designed with flexible modelling framework SUPERFLEX (Fenicia et al., 2011) to represent various components of the rainfall-runoff process. Overall, FLEX-Topo model consists of four structurally identical, parallel components, with totally 25 parameters. More details on the model structure and water balance equations are described by Gao et al (2014).

The objective function adopted was Nash-Sutcliffe efficiency coefficient (NSE), correlation coefficient (CC). Mathematical formulations of these indicators were shown in Table 1. Generally, a 20-year-period of 1959-1978 was used for model calibration while a 28-year-period of 1978-2015 was adopted for model validation. The first year of the calibration and validation periods was disregarded in the calculation in order to minimize the influence from the initial condition. Simulation of the validation period was adopted to analyze the characteristic of the green water flow (GWF) and blue water flow. GWF refers to actual evapotranspiration, and BWF is the sum of surface runoff, lateral flow and flux from shallow aquifers. Green water coefficient (GWC) is the ratio of GWF to sum of GWF and BWF.

Table 1. Mathematical formulation of the objective functions

| Criteria | Mathematical formulation | Range of values | Value of perfect agreement |
|----------|--------------------------|-----------------|---------------------------|
| NSE      | $\text{NSE} = 1 - \frac{\sum_{i=1}^{N}(O_i - S_i)^2}{\sum_{i=1}^{N}(O_i - O)^2}$ | $(-\infty, 1]$ | 1 |
| CC       | $\text{CC} = \frac{\sum_{i=1}^{N}(O_i - O)(S_i - S)}{\sqrt{\sum_{i=1}^{N}(O_i - O)^2} \sqrt{\sum_{i=1}^{N}(S_i - S)^2}}$ | $[0, 1]$ | 1 |

Note: $O_i$ is the observed discharge at time step i; $S_i$ the simulated discharge; $O$ the mean observed discharge over the entire simulation period of length N; $\gamma$ means the correlation coefficient; $\alpha$ means the relative variability; $\beta$ means the normalized bias.

3. Results and Discussion

3.1. Model Calibration and Validation

Figure 2 shows the hydrograph of calibration and validation period of Yingluoxia. The NSE and CC for model evaluation were 0.82 and 0.90 indicating that model performance was satisfactory.
Figure 2. Model performance of calibration and validation period at Yingluoxia hydrological stations

3.2. Green and Blue Water Flows of Each Landscape
Table 2 illustrated the precipitation, GWF and BWF in each landscape. In riparian area, annual GWF (325.19 mm/a) was more than twice of the BWF (151.92 mm/a), resulting in a relatively high GWC (0.68) (Figure.3), indicating more GWF than BWF in annual scale. As for seasonal variation of the three fluxes, their patterns were similar. Their maximum and minimum values respectively appeared in summer and winter. Precipitation surpassed the total water flow only in spring. Figure.3 showed that GWC was greater than 0.5 in all four seasons, indicating GWF exceeded BWF.

In grass hillslope, GWF and BWF was respectively 270.50 mm/a and 199.91 mm/a. The annual GWC was 0.58 (Figure.3), manifesting that the GWF also exceeded BWF in this landscape. Precipitation, GWF and BWF shared similar seasonal pattern, with maximum values in summer and minimum values in winter. The GWF was greater than BWF all year round, as shown in Fig.3 where the GWC in each season was larger than 0.5. The minimum GWC occurred in summer while the maximum in winter. The variation of GWC, whose range was from approximate 0.51 to 1.00, was relatively significant in this landscape shown in Figure.3.

In forest hillslope, The GWF (424.75 mm/a) much greater than the BWF (42.11 mm/a), leading to a considerably high annual GWC (0.91) (Figure.3). It demonstrated that evapotranspiration depleted most of the precipitation. As for seasonal variation, precipitation and the other two fluxes achieved their maximum in summer while minimum in winter. Precipitation was greater than the total water flow in spring and summer. GWF surpassed BWF in all seasons, as shown in Fig.3, and the GWC was
lowest in summer. The variation of GWC was fairly small in this landscape, whose range was from approximately 0.90 to 1.00, as shown in Figure. 3.

In bare soil/rock, the GWF (227.96 mm/a) was a litter smaller than BWF (295.32 mm/a) in bares soil/rock, resulting in a reltively low annual GWC (0.44) (Figure.3). Seasonal variation of GWF was similar to that of precipitation, with maximum value in summer and minimum value in winter. But BWF reached its minimum value in spring (Table 2) instead of winter, which was mainly because of the relitively small precipitation and the decreasing water reservers in the unsaturated reservoir and fast-response reservoir. GWF only exceeded BWF in autumn, where GWC was highest (0.51) (Figure.3). The lowest GWC (0.2) was generated in winter.

Table 2. Green/blue water flow in UHB and each hydrological landscapes(unit: mm/a)

| Landscape   | Type       | Winter | Spring | Summer | Autumn | Year |
|-------------|------------|--------|--------|--------|--------|------|
| UHB         | Precipitation | 5.27   | 73.55  | 311.45 | 81.36  | 471.62 |
|             | GWF        | 12.33  | 42.28  | 175.74 | 77.91  | 308.26 |
|             | BWF        | 15.39  | 17.97  | 89.47  | 40.80  | 163.62 |
| Riparian area | Precipitation | 5.05   | 69.92  | 300.75 | 75.48  | 451.20 |
|             | GWF        | 7.65   | 49.16  | 198.22 | 70.16  | 325.19 |
|             | BWF        | 0.00   | 15.27  | 116.97 | 19.69  | 151.93 |
| Grass hillslope | Precipitation | 5.40   | 73.16  | 310.16 | 81.47  | 470.20 |
|             | GWF        | 14.00  | 36.69  | 148.91 | 70.89  | 270.50 |
|             | BWF        | 0.02   | 22.93  | 145.02 | 31.95  | 199.91 |
| Forest hillslope | Precipitation | 4.89   | 74.24  | 303.39 | 84.10  | 466.62 |
|             | GWF        | 20.00  | 63.52  | 231.78 | 109.44 | 424.75 |
|             | BWF        | 0.01   | 5.80   | 28.51  | 7.80   | 42.11  |
| Bare soil/rock | Precipitation | 5.86   | 81.56  | 345.12 | 91.35  | 523.90 |
|             | GWF        | 12.05  | 16.89  | 121.72 | 77.30  | 227.96 |
|             | BWF        | 47.43  | 29.42  | 115.46 | 103.00 | 295.32 |

In general, GWF and BWF of the four hydrological landscapes all achieved their highest values in summer while the former fluxes reached the lowest values in winter. GWC in summer was greater than 0.5 (Figure 3), indicating GWF exceeded BWF. In addition, the riparian area, grass hillslope and forest hillslope shared some common ground. GWF was larger than BWF in all seasons, and there almost no BWF in winter, as illustrated in Figure 3. GWC was the lowest in summer compared to other three seasons. Simultaneously, each landscape possessed its own uniqueness. The highest annual GWC was generated in forest hillslope while lowest in bare soil/rock (Figure 3). In winter, BWF of bare soil/rock was much larger than GWF while this flow was almost zero in other landscapes. Likewise, GWC of bare soil/rock reached its maximum value while this indicator achieved its minimum value in other landscapes in summer (Figure 3). The different between precipitation and the total water flow in each season was much smaller in riparian area but much larger in bare soil/rock, compared to other landscapes. GWC of bare soil/rock arrived its top and bottom respectively in summer and winter, which was exactly the opposite in other landscapes. In addition, GWC fluctuated slightly in forest hillslope while heavily in grass hillslope.

This study showed high green water coefficient in forest hillslope (0.91), which meant that most of the rainfall was consumed for evatranspiration. This result was supported by other researches. Since the total water flow, closely approached to the precipitation in each landscape in our study, the green water coefficient could be regarded as the ratio of evatranspiration to precipitation (E/P). Wang et al (2004) studied the annual water balance of shrub in theInner Mongolian Highland Region and found that E/P was approximate 0.94. Wang et al (2008) concluded that the the E/P was larger than 0.95 for forest in a small catchamen in the Liupan Mountains, Northwest China. As for grass hillslope, green water coefficient was 0.58 in our study while Wang et al (2008) argued that E/P for grassland was higher than 0.6. These results were accordance with ours though the values varied to a slight degree,
which could be attributable to the difference of the landscape classification.

![Figure 3](image.png)

**Figure 3.** Seasonal variation of green water coefficient of UHB and each hydrological landscapes.

4. Conclusions
In this study, FLEX-Topo model was adopted to simulate the processes in different hydrological landscape, such as riparian area, grass hillslope, forest hillslope and bare soil/rock. The conclusions include that (1) FLEX-Topo model provided a good simulation of discharge at the outlet of the study site. (2) Majority of precipitation and water reserve in riparian area, grass hillslope, forest hillslope became green water flow, especially in forest hillslope while more than half of these water in bare soil/rock turn to blue water flow.(3)as for seasonal variation, both green water flow and green water flow of the four hydrological landscapes synchronized with precipitation.

5. References
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