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Groundwater-surface water interactions, vegetation dependencies and implications for water resources management in the semi-arid Hailiutu River catchment, China – A synthesis

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Abstract

During the last decades, large scale land use changes took place in the Hailiutu River catchment, a semi-arid area in northwest China. These changes had significant impacts on the water resources in the area. Insights into groundwater and surface water interactions and vegetation-water dependencies help to understand these impacts and formulate sustainable water resources management policies. In this study, groundwater and surface water interactions were identified using the baseflow index at the catchment scale, and hydraulic and temperature methods as well as event hydrograph separation techniques at the sub-catchment scale. The results show that almost 88 % of the river discharge consists of groundwater. Vegetation dependencies on groundwater were analyzed from the relationship between the Normalized Difference Vegetation Index (NDVI) and groundwater depth at the catchment scale and along an ecohydrogeological cross-section, and by measuring the sap flow of different plants, soil water contents and groundwater levels at different research sites. The results show that all vegetation types, i.e. trees (willow (*Salix matsudana*) and poplar (*Populus simonii*)), bushes (salix (*Salix psammophila*)) and agricultural crops (maize (*Zea mays*)), depend on groundwater as the dominant water source for transpiration. The comparative analysis indicates that maize crops use the largest amount of water, followed by poplar trees, salix bushes, and willow trees. For sustainable water use with the objective of satisfying water demand for socio-economical development and to prevent desertification, more water use efficient crops such as sorghum, barley and millet should be promoted to reduce the consumptive water use for irrigation. Willow trees should be used as windbreaks in croplands and along roads, and dry resistant and less water use intensive plants (for instance native bushes) should be used to vegetate sand dunes.

1 Introduction

Arid and semi-arid areas occupy around one third of the terrestrial earth surface (Scanlon et al., 2006). In arid areas, water resources are extremely scarce and environment is very fragile. Surface water is usually limited and depends on groundwater discharge. Vegetation plays a crucial role in protecting desertification, and mostly depends on groundwater. Groundwater is often the only resource for supporting socio-economical development and for maintaining the health of groundwater dependent ecosystems. Sustainable use of groundwater resources is fundamental for co-existing of human society and nature in arid and semi-arid areas. However, achieving sustainable use of groundwater remains a major challenge (Gleeson et al., 2012). The practice of using groundwater based on the "safe yield" policy has led to stream flow reduction and loss of wetlands and riparian ecosystems (Sophocleous, 2000). In a river basin where complex interactions exist between groundwater, surface water and ecosystems, the simplistic safe yield concept based on groundwater balance equations is not capable to deliver a sustainable groundwater use plan. Sustainable use of groundwater requires balancing the water requirements for societal use, stream environmental flow, and terrestrial vegetation (Sophocleous, 2007; Zhou, 2009). The scientific challenges include quantifying groundwater and surface water interactions, estimating environmental flow requirements for groundwater dependent ecosystems, and to link these inter-dependencies to a sustainable water resources management.

Groundwater and surface water interactions can be identified and quantified using a number of methods (Sophocleous, 2002; Kalbus et al., 2006; Brodie et al., 2007). Apart from traditional hydraulic methods, temperature methods (Constantz et al., 2002; Constantz and Stonestrom, 2003) and hydrograph separation techniques using environmental isotopes as tracers (Sklash and Farvolden, 1979; Buttle, 1994) are widely used. Groundwater is an important source for terrestrial vegetations in arid and semi-arid areas (Miller et al., 2010). A number of methods have been developed for identifying vegetation dependency on groundwater (Eamus et al., 2006). Actual total evaporation rate

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(soil evaporation and transpiration) can be measured directly by the eddy-correlation method (Moreo et al., 2007). Transpiration rates of the vegetation can also be measured in-situ with sap flow sensors (Granier, 1985; O'Grady et al., 2006), and the part of transpiration originating from groundwater can be estimated from diurnal groundwater level variations (White, 1932; Loheide et al., 2005; Butler et al., 2007; Lautz, 2008).

The Hailiutu River catchment is located within the Erdos Plateau in northwest China (Fig. 1). The catchment area is around 2645 km^2, characterized by a semi-arid climate. Land cover is dominated by sparsely vegetated sand dunes and crop land is only found in river valleys and flat areas on upland part of the catchment. The area suffers from frequent sandstorms, and farmland has been threatened by moving sand dunes. Since the beginning of the 1980s, the Chinese government started an afforestation project called "Three North Forest Shelterbelts" project (Wang et al., 2010). Since the year 2000, a project called "Return Farmland to Forest and Grassland" has being implemented (Wang et al., 2009). Meanwhile, large scale development of natural resources (coal and natural gas) is taking place (Yin et al., 2011). Allocating scarce water resources for socio-economical development and maintaining ecosystem health must be based on scientific information. However, the groundwater-surface water interactions and vegetation dependencies on groundwater have not yet been systematically investigated. The implications of these multiple interactions on sustainable water resources management have not been analyzed so far.

The objectives of this study are to analyse groundwater-surface water interactions and to identify vegetation dependency on groundwater in order to formulate sustainable water resources development polices for the semi-arid Hailiutu catchment. Groundwater-surface water interactions were quantified using the baseflow index at the catchment scale, and using hydraulic, temperature and hydrograph separation methods at the sub-catchment scale. Vegetation dependencies on groundwater were identified using the relationship between groundwater depth and Normalized Difference Vegetation Index (NDVI) at the catchment scale and along an ecohydrological cross-section; and using in-situ sap flow, soil water and groundwater measurements at vegetation research sites. Synthesis of research results led to conclusions which have significant implications for land and water management in similar semi-arid areas in northwest China and in the world.

2 Materials and methods

2.1 Meteorological stations

One meteorological station is located in the catchment, and three other stations are located in the surrounding areas (Fig. 1). All stations have been measuring daily precipitation, air temperature, pan evaporation, relative humidity and wind speed since 1961. Daily precipitation has also been recorded at Hanjiamao hydrological station since 1957. Correlation analysis shows that monthly precipitation among the stations is highly correlated (Table 1). Yang et al. (2012) analyzed meteorological variables for the time period 1961–2006 and found no significant trends in annual precipitation and pan evaporation. Only seasonal average air temperature from April to October showed an increasing trend since 1997.

2.2 Hydrological stations

Hanjiamao hydrological station is located at the outlet of the catchment (Fig. 1) and measures daily river discharge since 1957. Yang et al. (2012) analyzed changes of discharges and found four flow regime shifts in 1968, 1986, 1992 and 2001. The causes of flow regime changes could be related mainly to changes of crop area and land use policies.

2.3 Vegetation cover and depth to groundwater table

Lv et al. (2012) used Landsat-5 Thematic Mapper (TM) derived NDVI data to interpret the current vegetation cover. They classified vegetation cover into low-density shrubland, high-density shrubland, meadow, farmland, riparian zone and grove. A groundwater contour map was constructed with field measurements taken in July 2010. A contour map of depth to groundwater table was prepared by subtracting the groundwater level contour map from the land surface elevation map.

2.4 Field measurements in the Bulang sub-catchment

A discharge gauging station was installed at Yujianwan in the Bulang sub-catchment in 2010 (Fig. 1). The sub-catchment area monitored by the discharge station is around 90 km^2. Automatic water level recorders (e+WATER L) were installed to register water levels at hourly intervals. In a cross-section close to the discharge station, eight groundwater monitoring wells were constructed, and groundwater levels were recorded hourly with automatic recorders (MiniDiver). Furthermore, five temperature sensors (HOBO Pro v2) were installed below the riverbed at various depths to detect the interactions between groundwater and surface water.

2.5 Research site for bush water use

At the bush water use research site (Fig. 1), various instruments were installed to determine the salix bush water use and rates of transpiration. The investigated salix was carefully selected so that it was representative of features such as size, number of branches, type and density of surrounding vegetation and micro-climatic conditions. The water use by salix was measured with a sap flow sensor (Flow 32 1K). The meteorological variables were measured by a weather station. Rainfall was recorded by an automatic rain gauge (HOBO RG3), soil water contents at various depths were measured by TDR, and groundwater table depth was measured by a monitoring well equipped with an automatic recorder (MiniDiver). The measurements started from 29 May up to 12 July 2011 and hourly data were stored for analysis.

2.6 Research site for tree water use

Instruments were installed at the tree water use site to determine the tree water use of a willow and a poplar tree and the water sources for transpiration. The examined trees were selected carefully; they are representative for the region in terms of physiological development, age, surrounding vegetation and micro-climatic conditions. The water use of tress was measured with sap flow sensors (FLGS-TDP XM1000). Soil water contents were monitored using a TDR at various depths. Groundwater levels were measured hourly using an automatic recorder (MiniDiver) installed in a borehole under the tree. The measurements covered the period from 27 April to 7 November 2011. Hourly data were stored for analysis.

2.7 Research site for crop water use

An experimental site to investigate the crop water use was constructed in May 2011. Since the dominant crop in the catchment is maize, maize water use at a representative site was studied systematically. The measurements include transpiration measurements of six maize stems monitored with sap flow sensors (Flow 32 1K), soil water content recorders (TDR, miniTrase), mini lysimeters to observe soil evaporation, groundwater levels (MiniDiver), and irrigation water application observations.

3 Groundwater-surface water interactions

3.1 Catchment scale

The automated hydrograph separation tool HYSEP (Sloto and Crouse, 1996) was used to separate baseflow from daily average river discharges using three baseflow separation methods: fixed interval, sliding interval, and local minimum. Annual averages of daily discharges and baseflow are plotted in Fig. 2. River discharges have decreased since 1970s because of the constructions of reservoirs and diversion works for irrigation. River discharges decreased to less than half of natural discharges during 1990's due to the increase of crop areas (Yang et al., 2012). River discharges recovered since 2000 to values comparable to the 1980s after the implementation of the policy to return farmland to nature (Yang et al., 2012).

The ratio of baseflow to total discharge is defined as baseflow index. From Fig. 3 it can be seen that the baseflow constitutes 80 % to 95 % of the total discharge. The average baseflow index for the last 40 yr is around 0.88, indicating that on average 88 % of the discharge is formed by groundwater discharge in the Hailiutu River.

3.2 Sub-catchment scale

Temperature measurements clearly indicate groundwater discharges to the river (Fig. 4). In the winter time, groundwater temperature is higher than the river temperature. Upward seepage of groundwater increases water temperature in the riverbed deposits, so that water temperature increases with the increase of depths. In the summer time, river temperature is much higher than groundwater temperature; diurnal fluctuation of river temperature did not appear in the riverbed deposits, indicating also the upward seepage of groundwater.

Groundwater levels decrease in general from the hillslope (Well_a) towards the flood plain (Well_b), at the river bank (Well_c), and in the mid river (Well_d) from 1 September to 28 October 2011 (Fig. 5), a clear indication of groundwater discharge to the river in the measurement period.

Groundwater contribution to river discharges during a heavy rainfall event in 1 to 2 July 2011 was estimated with the two component event hydrograph separation technique (cf. Buttle, 1994, for methodology) using the stable isotope oxygen-18 (^{18}O) as a tracer (Fig. 6). The results clearly indicate that the flood discharge consists of mainly increased groundwater discharge. Even during the peak time of the event the discharge consists of more that 70 % of pre-event water (i.e. groundwater). The dominance of pre-event water is also visible in the ascending and receding limbs of the stream hydrograph during the event. A rapid reaction of the pre-event runoff component could be caused by fast groundwater discharge from the near stream riparian zone, whereas the delayed behavior of the event-water, showing the peak contribution after the maximum of the stream hydrograph, is likely due to a delayed contribution of surface runoff components.

4 Vegetation dependency on groundwater

4.1 Catchment scale

Lv et al. (2012) investigated the dependency of vegetation on groundwater in the Hailiutu River catchment with Normalized Difference Vegetation Index (NDVI) data and observation data of groundwater depth. The statistical characteristics of NDVI values (mean, standard deviation and coefficient of skewness) change systematically in relation to the groundwater depth. A decreasing trend of both mean and standard deviation of NDVI values with increasing groundwater depth was shown. This demonstrates that the NDVI value of shrubs decreases almost linearly with increasing groundwater depths. However, the NDVI value of grassland, represented by the meadow land cover type was not sensitive to groundwater depth because of the shallow root systems. The relationship between NDVI and groundwater in farmlands was more complex because of the influences of human activities. *Salix matsudana and Populus tomentosa* are the dominant species in groves of trees, and they can access deep groundwater with their deeply extended root network.

4.2 At the ecohydrogeological cross-section

The relationship between land surface elevation, groundwater depth, and vegetation distribution can be investigated along ecohydrogeological cross-sections. The ecohydrogeological cross-sections should run cross the river valley from the water divide on one side to the water divide on other side. On these cross-sections, large variations of groundwater depths and vegetation types are expected. The investigated ecohydrogeological cross-section is running from the western water divide (W) across the Hailiutu River to the eastern water divide (E) (Fig. 1). The surface elevation, groundwater depth, and NDVI are shown in Fig. 7. At the west (W) and east water divides and at hilly areas in the catchment, the depth to the groundwater is large, and NDVI is low; represented by a low density shrubland vegetation type. In the Bulang River and Hailiutu River valleys, groundwater levels are shallow, and NDVI is very high, as indicated by crops and trees. In local depressions on the west and east slope areas, groundwater levels are shallow; NDVI is also high, as indicated by upland crop areas mixed with wind-breaking trees. The cross-section clearly shows the dependency of the vegetation on groundwater depth in different geomorphologic locations.

4.3 In-situ ecohydrogeological research sites

At the bush water use research site, the plot of the cumulative sap flow of a salix bush in relation to the groundwater depth changes in the dry period from 29 May to 12 June clearly shows the increase of groundwater depth caused by the water use of the salix bush for transpiration (Fig. 8). The hourly change of soil water and groundwater storage shows the depletion of the storage of the upper soil water (ΔSWC1c, from 6 cm to 55 cm), lower soil water (ΔSWC2c, from 55 cm to 130 cm), and groundwater (ΔGWc, below 130 cm) (Fig. 9). The total soil evaporation and transpiration of salix is around 41 mm (2.9 mm d^{-1}), which uses groundwater of 25 mm (60 %); lower soil water of 12 mm (30 %), upper soil water of 4 mm (10 %). It is clear that salix uses predominantly groundwater for transpiration in this dry period.

At the tree water use research site, sap flow of a willow tree, soil water, and groundwater levels were measured. Figure 10 plots the cumulative sap flow of the willow tree in relation to groundwater level during the dry period from 19 May to 11 June 2011. It is also clear that the transpiration of willow tree causes the decrease of groundwater level. The hourly change of soil water and groundwater storage was calculated for the same period. Figure 11 shows the depletion of the storage of the soil water from 15 cm to 85 cm, and groundwater. The total transpiration rate of willow in 24 days is

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about 31.2 mm (1.3 mm d^{-1}). In the same period, the estimated groundwater storage depletion from groundwater level hydrograph amounts to 16 mm (Fig. 11), the depleted soil water storage was estimated to be 15.2 mm from measured soil water contents (Fig. 11). Therefore, it can be concluded that the willow tree is also a groundwater-dependent plant under the conditions prevailing in the Hailiutu River catchment.

5 Comparison of water use by different plants

5.1 Comparison of sap flow velocities of poplar and willow trees

Water scarcity is a natural phenomenon in the semi-arid Hailiutu River catchment. For water and soil conservation, it is very important to select plants which use little water for transpiration. Figure 12 compares the sap flow velocity of a representative willow tree with a representative poplar tree in the tree water use research site at 4 different growing stages. The sap flow velocity of the poplar tree is much larger than that of the willow tree in all growing periods. Especially from late August to late September, the sap flow velocity of the willow tree is very low, but the sap flow velocity of the poplar tree remains very high, at least two times higher than the willow tree. It can be concluded that the poplar tree uses more water than the willow tree.

5.2 Comparison of sap flow of salix bush and willow tree

It is not straight forward to compare the water use of a salix bush with other plants since salix have various numbers of branches. Figure 13 compares sap flow of a salix bush with 60 active branches with the sap flow of a willow tree. It shows that the salix bush with 60 branches use twice the amount of water of the willow tree. Salix bushes with about 60 active branches are typical in the Hailiutu River catchment. It is remarkable to see that the salix consumes more water than the willow tree since salix is perceived as a dry resistant plant and widely planted in the catchment as a measure for soil conservation.

5.3 Comparison of transpiration rates of maize and willow tree

In the growing period from July to August, the transpiration rate of the maize is almost three times higher than that of the willow tree (Fig. 14). Therefore, it can be concluded, that maize uses much more water than the willow tree, and most likely also more water than the poplar tree.

6 Implications for water resources management

The previous analysis concludes that both the surface water and the vegetation system depend on groundwater. The water resources and ecosystem management requires essentially a sustainable groundwater resources management approach in the Hailiutu catchment.

Under natural conditions, net groundwater recharge (gross recharge from precipitation infiltration minus total evaporation) equals the baseflow component of river discharge. The consumptive use of groundwater for irrigation (gross abstraction minus return flow) reduces groundwater discharge to rivers. Therefore, river discharge is a good indicator of the water and vegetation management in the Hailiutu catchment. Maintaining a stable river discharge is not only important for the riparian ecosystem and local communities, but also for downstream water users. The water resources management objectives must satisfy both the environmental water use by vegetation and the water use for social-economical development. Technical measures can be developed including the minimization of consumptive water use by agricultural crops and water use by plants for vegetating sand dunes.

The research results clearly show that the consumptive water use in the catchment is responsible for the reduction of the river discharges (cf. Yang et al., 2012). The consumptive water use is mainly irrigating crops. The findings from the crop water use site show that maize consumes significant amounts of water (Hou et al., 2012). The total water use of maize during 159 growing days was estimated to 607 mm, which comprises precipitation of 157 mm (26 %), irrigation water of 177 mm (29 %), and soil and groundwater of 273 mm (45 %). In the river valley, irrigation water is taken directly from the river by water diversion. In the upland, irrigation water is pumped from groundwater abstraction wells. Therefore, in order to reduce the consumptive water use, more dry resistant crops, such as sorghum, barley, and millet should be promoted. Fang et al. (2011) found also these crops are more suitable in semi-arid areas with an average annual precipitation of less than 300 mm a^{-1}. In Nebraska, maize water use was estimated to 658 mm (Kranz et al., 2008), while sorghum water use was around 530 mm; thus, sorghum is a more water use efficient crop (CropWatch, 2012).

A rough estimate at catchment scale shows that almost 90 % of precipitation is consumed by evaporation and transpiration of plants (Zhou, 2012). The presented research concluded that poplar trees use more water than willow trees; and salix bushes may use much more water than generally perceived. Poplar trees use more water because they have large leafs and remains physically active till late autumn (Fig. 15). Willow trees (locally called dry willows) use less water because they have small branches with a lower leaf area index (Fig. 16). Salix bushes use more water because they have many branches with a large leaf area index (Fig. 17).

Therefore, considering that water is a major limiting factor in semi-arid environments such as the Hailiutu catchment, poplar trees should not be used as wind-breaking barriers in the crop lands and along the roads. Instead, willow trees are a better alternative for these purposes. For vegetating sand dunes, it seems better to select native bushes which use less water, such as *Artemisia Ordosica* (Fig. 18), *Korshinsk Peashrub* (Fig. 19), and *Hedysarum Laeve Maxim* (Fig. 20). Other studies (Xiao et al., 2005; Zhou et al., 2011) have demonstrated that these species can be established in desert dunes in dry environments. However, transpiration rates of these species need to be further investigated.

7 Conclusions

River discharges heavily depend on groundwater in the Hailiutu River catchment. On annual average, river discharge consists of around 88 % of groundwater discharge. Measurements of hydraulic heads and temperatures as well as isotope investigations at the sub-catchment scale indicate that groundwater discharge is the most important component of river flows. Even during heavy rainfall events, the flood hydrographs consist of more than 70 % of groundwater discharge.

Vegetation also depends heavily on groundwater. At the catchment scale, the vegetation cover is much dense in places where groundwater table is shallow. The Normalized Difference Vegetation Index decreases with the increase in the depth of the groundwater table. At the ecological research sites, it was demonstrates that both trees and bushes use groundwater for transpiration during the long dry period in spring season.

Preliminary analysis of water use for different species indicates that maize crops transpire the largest amount of water. Salix bushes use much more water than generally perceived. However, water use efficiency of other corps and plant species should be further investigated.

Under natural conditions, net groundwater recharge equals river baseflow. When groundwater is abstracted for irrigation, groundwater discharge is reduced, resulting in the reduction of river discharge (cf. Yang et al., 2012). However, a relatively shallow groundwater table must be maintained for supporting groundwater dependent vegetation systems.

The water resources management objectives must satisfy both the environmental water use by vegetation and the water use for social-economical development. For conservation of water resources, net groundwater recharge can be increased by reducing evaporation and transpiration from selecting more dry resistant plants for stabilising sand dunes. However, groundwater table cannot be lowered to reduce the evaporation and transpiration since healthy vegetation must be maintained to prevent desertification. The general strategy should be to promote more dry resistant plant species with lower transpiration rates to reduce the total evaporation in the catchment and to maintain stable river discharges. Therefore, maize should be replaced by more water use efficient crops, while salix bushes should be replaced by more dry resistant native vegetation species in the Hailiutu catchment.

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Table 1. Correlation coefficients of monthly precipitation among meteorological stations.

	Hanjiamao	Yulin	Wushenqi	Henan	Hendshan
Hanjiamao	1.00				
Yulin	0.89	1.00			
Wushenqi	0.81	0.89	1.00		
Henan	0.87	0.85	0.82	1.00	
Hengshan	0.91	0.89	0.82	0.90	1.00

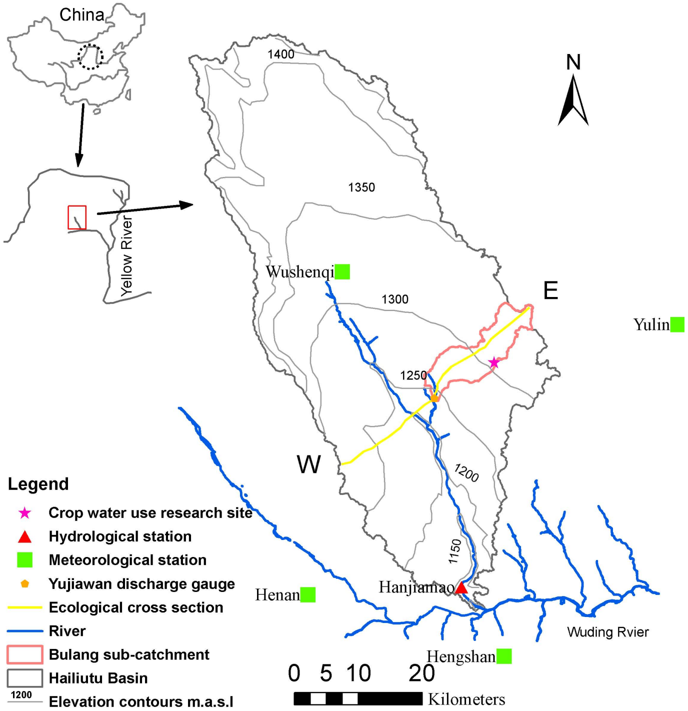

Fig. 1. Location of the Hailiutu catchment and measurement sites.

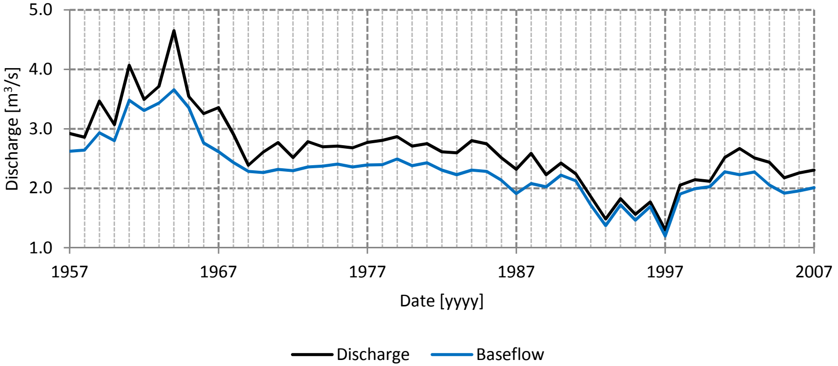

Fig. 2. River discharge and baseflow of the Hailiutu River at Hanjiamao station.

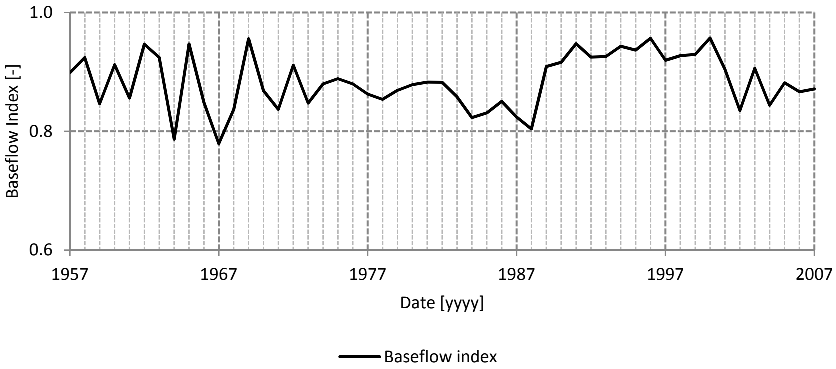

Fig. 3. Baseflow index of the Hailiutu River at Hanjiamao station.

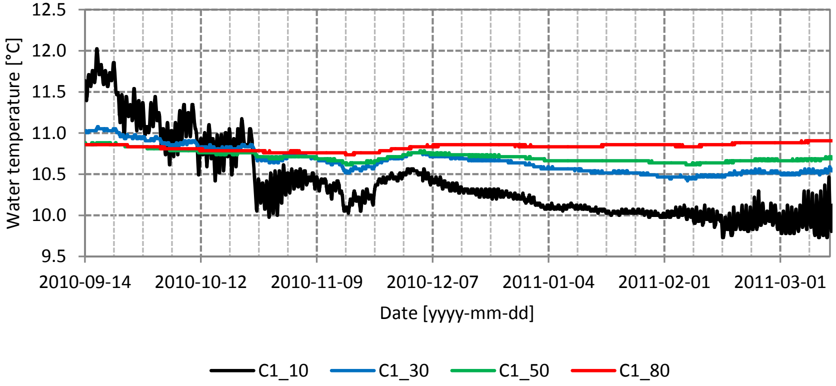

Fig. 4. Temperature measurements at various depths in the riverbed deposits at Yujiawan station: C1_10 at 10 cm depth, C1_30 at 30 cm depth, C1_50 at 50 cm depth, and C1_80 at 80 cm depth below the riverbed.

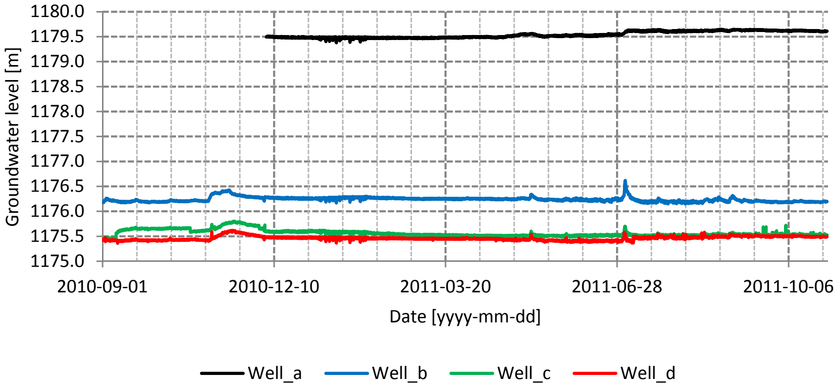

Fig. 5. Groundwater level measurements at Yujiawan cross-section. The distance between Well_a and Well_b is 284 m; 22 m between Well_b and Well_c; and 4 m between Well_c and Well_d.

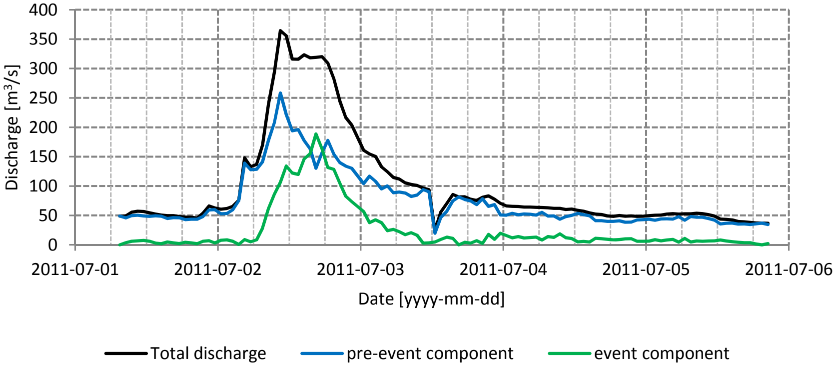

Fig. 6. Results of two-component hydrograph separation with Oxygen-18 as tracer at Yujiawan station.

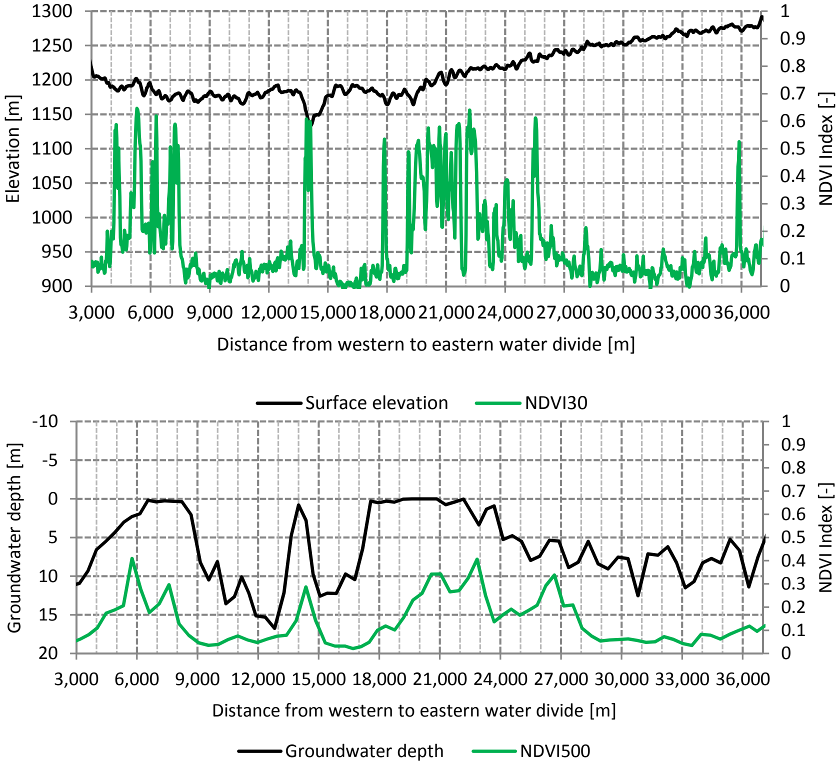

Fig. 7. Relations between NDVI and surface elevation, NDVI and groundwater depth along a ecohydrogeological cross-section in the Hailiutu River catchment.

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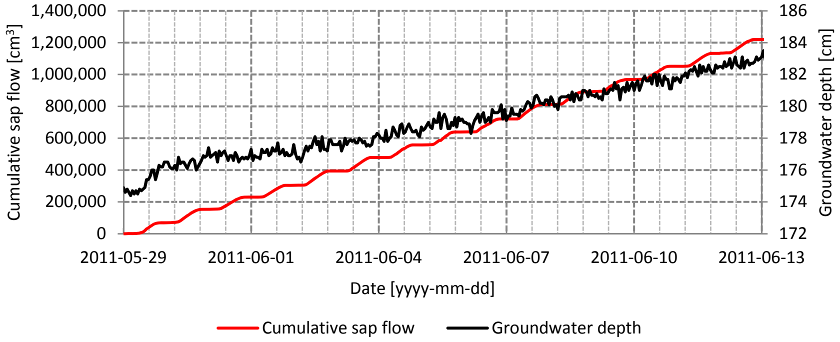

Fig. 8. Cumulative sap flow and water table depth at the bush water use measurement site during the dry period.

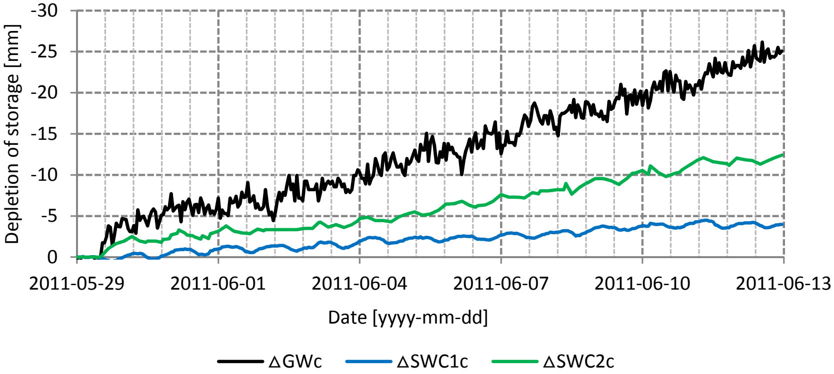

Fig. 9. Depletion of storage of soil water and groundwater by the transpiration of salix bush.

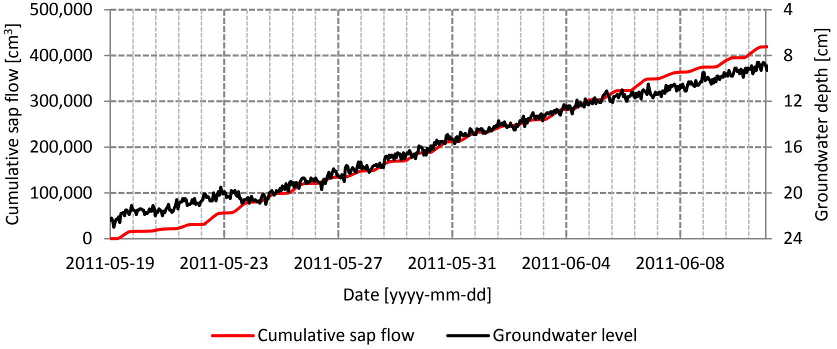

Fig. 10. Cumulative sap flow of willow tree and groundwater level at the tree water use research site.

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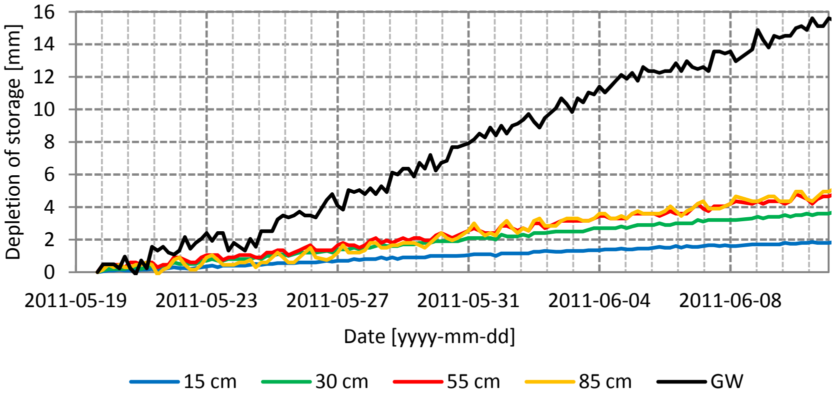

Fig. 11. Depletion of soil water and groundwater by the transpiration of the willow tree during the dry period from 19 May to 11 June 2011.

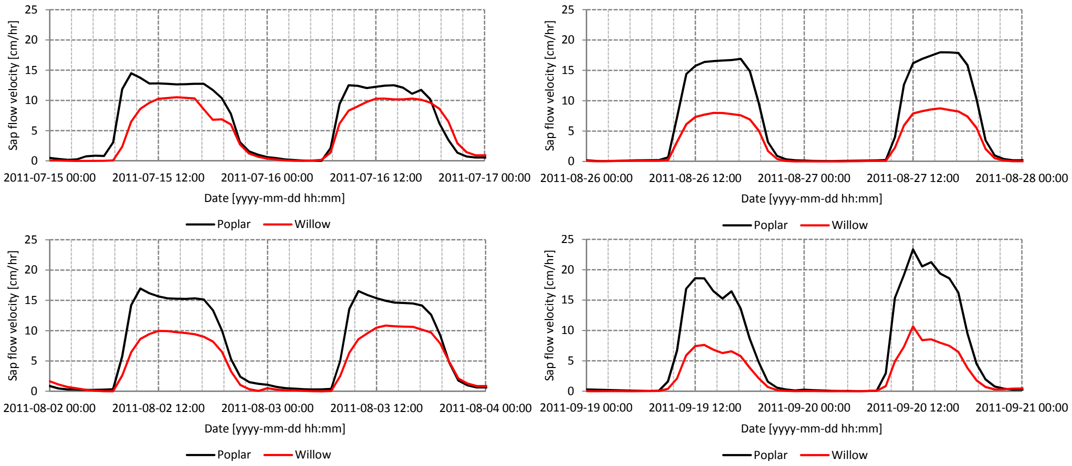

Fig. 12. Comparison of sap flow velocities of poplar and willow trees in the tree water use research site at 4 different growing stages.

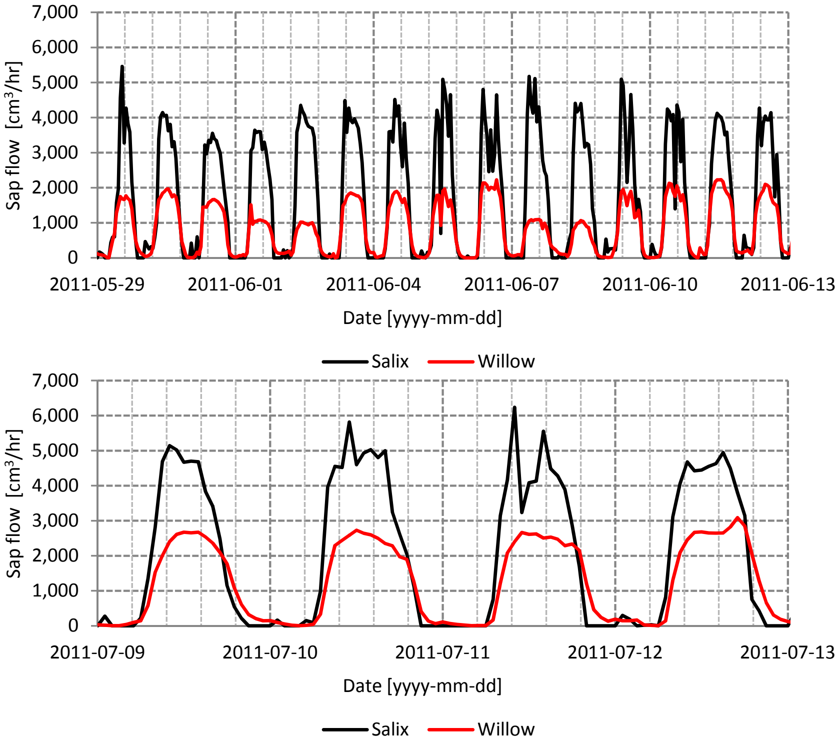

Fig. 13. Comparison of sap flow velocities of a salix bush (60 active branches) with a willow tree in two measured periods.

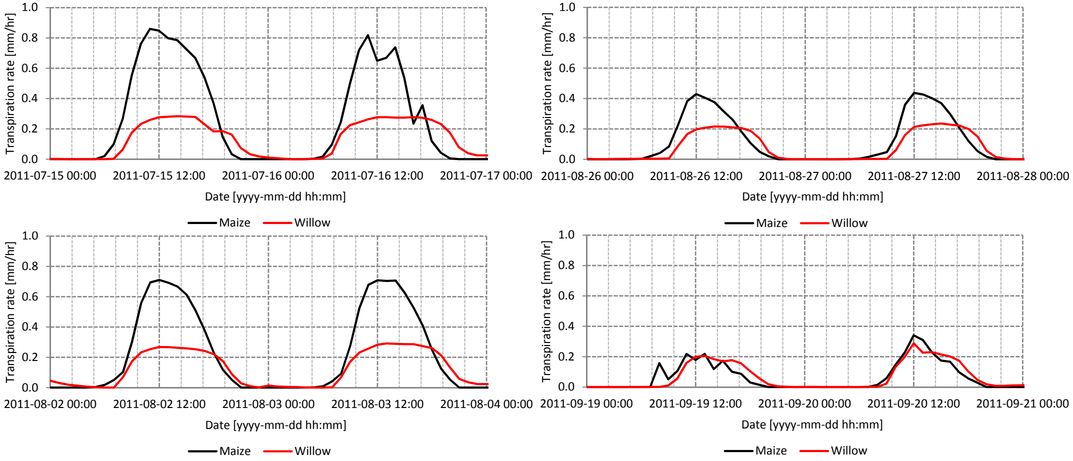

Fig. 14. Comparison of transpiration rates of a willow tree and maize plants at 4 different growing stages.

Fig. 15. Row of poplar trees as wind-breaking barrier, picture taken in May 2010.

Fig. 16. Rows of willow trees as wind-breaking barrier, picture taken in May 2010.

Fig. 17. Salix bushes planted for soil conservation, picture taken in August 2010.

Fig. 18. *Artemisia Ordosica*, picture taken in May 2010.

Fig. 19. *Korshinsk Peashrub*, picture taken in May 2010.

Fig. 20. *Hedysarum Laeve Maxim*, picture taken in May 2010.

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