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Spatio-temporal Variability of Soil Water at Three Seasonal Floodplain Sites: A Case Study in Tarim Basin, Northwest China

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Abstract: The floodplain vegetation of the Tarim River in Northwest China is strongly influenced by irrigated agriculture. The abstraction of river water disturbs the natural dynamics of the floodplain ecosystem. The human impact on the hydrological system by bank dams and the irrigation of cotton plantings have caused adverse changes of the Tarim River and its floodplains, so the current stocks of the typical Tugai vegetation show significant signs of degradation. Field studies of soils and statistical analysis of soil moisture data have shown that the vitality of the Tugai vegetation is primarily determined by its position to the riverbank and the groundwater. There exist complex interactions between soil hydrological conditions and the vitality of the vegetation. But the availability of water is not only influenced by the groundwater level and seasonal flood events. The spatial distribution of stocks at different states of vitality seems also to be decisively influenced by physical soil properties. Our results show that the water supply of plant communities is strongly influenced by the soil texture. Spatial differences of soil moisture and corresponding soil water tensions may be the decisive factors for the zonation of vegetation. Physical soil properties control the water retention and rising of capillary water from deeper soil layers and the phreatic zone and may supply the root systems of the phreatophytic vegetation with water.

Keywords: soil moisture; soil texture; soil water tensions; Tarim River; water retention

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1 Introduction

In the region of the Tarim River in Northwest China water is one of the most sensitive factors and it plays a crucial role in both natural and social environments (Song *et al.*, 2000; Chen *et al.*, 2009). Due to the fact that the human interventions in the Tarim River region over the last decades have caused a significant imbalance in the natural distribution of water resources, studies about the regional water balances are of increasing importance. Chen *et al.* (2013) have recently summarized the progress, challenges and prospects of eco-hydrological studies in the Tarim River Basin. Therefore knowledge about water is very important for utilization of water resources and protection of its ecological and environmental features in this region (Wei, 1996; Song *et al.*, 2000; Liu *et al.*, 2014). The soil water plays an important key role in this hydrologic cycle, because the soil acts as an interface between hydrological processes in the atmosphere and hydrological processes in the subsurface. The availability of soil water controls the dynamics of natural vegetation. Furthermore the vertical

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dynamic of soil water controls also the (re-) distribution of salts in the soil profile (Chen *et al.*, 2009).

Compared to many studies in the Tarim River region about climate change (Chen and Xu, 2005; Chen F H *et al.*, 2006; Shi *et al.*, 2007; Zhang *et al.*, 2010; Tao *et al.*, 2011), land-use and land cover change (Wu and Cai, 2004; Zhou *et al.*, 2008; Zhao *et al.*, 2009), water resources and groundwater (Xu *et al.*, 2005; Hai *et al.*, 2006; Hao *et al.*, 2009; Zhou *et al.*, 2009; Chen *et al.*, 2010; Aishan *et al.*, 2014), vegetation or environmental management (Xu *et al.*, 2005; Fu *et al.*, 2006; Huang and Pang, 2010; Zhuang *et al.*, 2010; Pei *et al.*, 2011; Aishan *et al.*, 2013), there are several studies about soil (Zhuang *et al.*, 2007; Jin *et al.*, 2008; Gui *et al.*, 2009; Zhang *et al.*, 2013) and soil water dynamics of this region (Ji *et al.*, 2001; Ishizuka *et al.*, 2005; Chen *et al.*, 2007; Hu *et al.*, 2009; Ma *et al.*, 2011; Kuba *et al.*, 2013). As emphasized by Chen *et al.* (2013), eco-hydrological processes at a basin level are very complex with spatial and temporal changes in water dynamics. Especially on a small scale it is very important to reflect soil characteristics in this region (Ma *et al.*, 2011), to describe and quantify vertical soil water dynamics. However, mostly the volumetric water content or the percentage of soil moisture is used to describe soil water dynamics. Important parameters like soil textures and corresponding water retention functions are unconsidered by all known studies about soil water dynamics in this region. This paper will point out the spatio-temporal dynamics of soil water fluxes at three particular sites along the Tarim River by using pedospecific transferfunctions and statistical analyses to describe the vertical soil water fluxes by the corresponding matric potentials.

2 Materials and Methods

2.1 Study area

The Tarim River Basin (Fig. 1) is located in the south of Uygur Autonomous Region of Xinjiang, Northwest China. It covers an area of 1.04×10^6 km^2 and is flanked by the Tianshan Mountains to the north and by the Kunlun

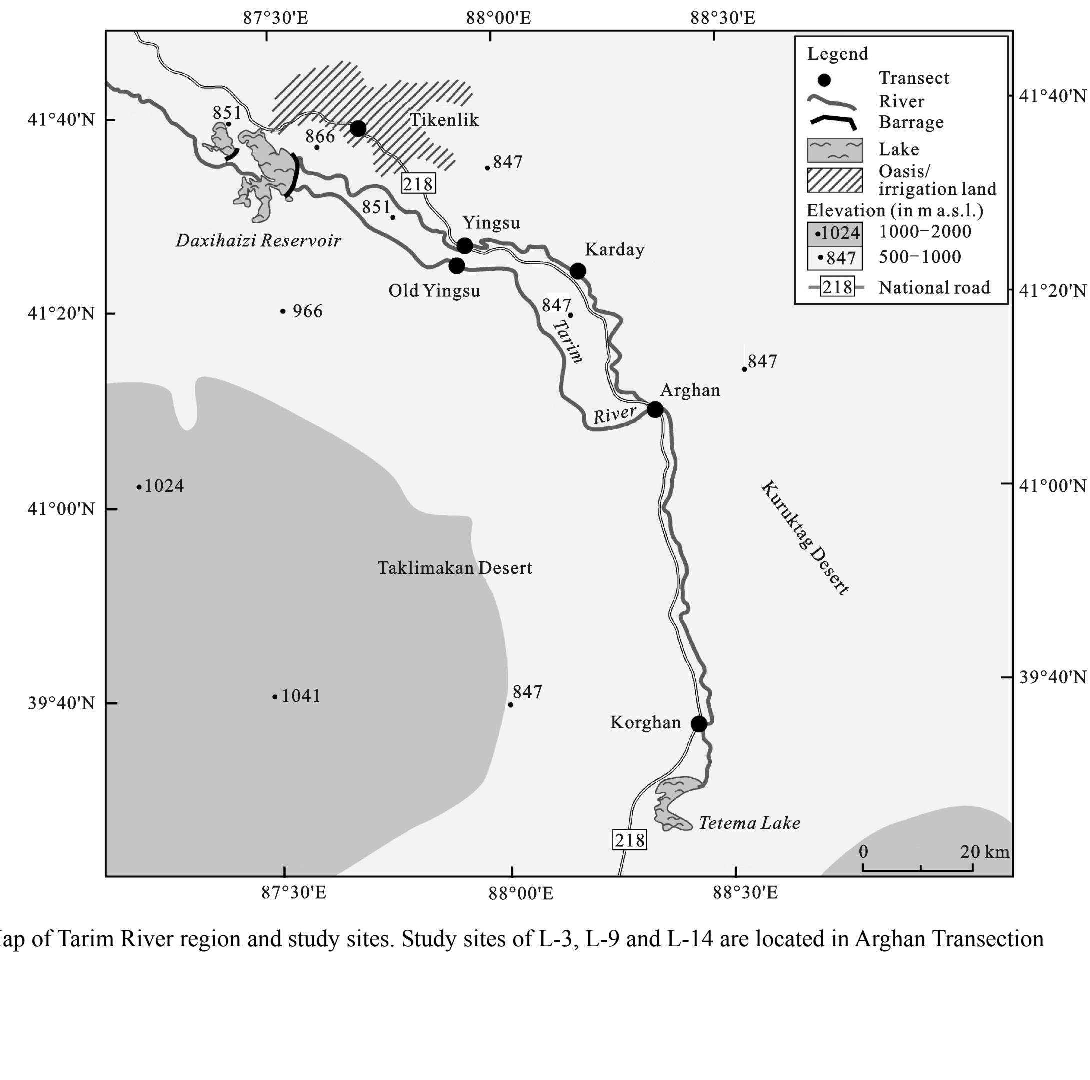

Fig. 1 Map of Tarim River region and study sites. Study sites of L-3, L-9 and L-14 are located in Arghan Transection

Mountains to the south (Huang and Pang, 2010). This basin is one of the driest regions in the world (Liu *et al.*, 2010). The Taklimakan Desert is located in the center of this basin and occupies an area of 3.37×10^5 km^2 (Zhu and Chen, 1994; Wang *et al.*, 2002). Annual precipitation is about 50–80 mm on the boundary area of the basin and 17–25 mm in the central basin (Tang and Chen, 1992; Chen Y *et al.*, 2006). The total annual potential evaporation is approximately 2500–3000 mm (Chen *et al.*, 2010).

The endorheic Tarim River Basin in Northwest China is part of this flat and continental desert region. The Tarim River and its tributaries in the peripheral zones of the basin are supplied with water from the precipitation and seasonal snow/glacier melting of the surrounding mountain ranges.

2.2 Phytogeography and environmental conditions

The main natural plants growing in the extremely arid Tarim River Basin are *Populus euphratica*, *Tamarix* spp*.*, *Halimodendron halodendron*, *Alhagi sparsifolia*, *Lycium ruthenicum*, *Halostachys caspica*, *Glyzrrhiza inflate*, and *Karelinia caspica* (Zhang *et al.*, 2005; Halik *et al.*, 2009; Liu *et al.*, 2010). This C3-plants can tolerate the dry and hot conditions there. The floodplain vegetation of the Tarim River is primarily composed of *Populus euphratica*, *Tamarix ramosissima* and *Phragmites australis* (Walter, 1974; Hai *et al.*, 2006; Thevs *et al.*, 2008b; Ma *et al.*, 2011). These formations are referred to as Tugai vegetation (Zerbe and Thevs, 2011). The arid and continental climatic conditions of Central Asia (average annual precipitation less than 20 mm, potential evapotranspiration less than 3000 mm) place high demands on the ecosystem (Tashi *et al.*, 2010). The Tugai vegetation is concentrated in linear areas along the Tarim River and has adapted to these conditions. Chen *et al.* (2010) examined the response of groundwater and plant communities to a recharge regime in the lower reaches of the Tarim River. Their results showed that the water recharges considerably raised the groundwater table to about 4 m in the vicinity of the river beds in the transects closer to the Daxihaizi Reservoir along the lower reaches of the Tarim River.

Under natural conditions the Tugai system relies on a high fluvial dynamic with episodic floodings and high contents of sediment load. These floodings fulfill different functions, like eluviation of salt accumulations on soil surfaces (Hai *et al.*, 2006), creation of sandbanks (important for the germination of seeds of *P. euphratica*) and creation of ideal soil moisture conditions for the establishment of new plants in the years after germination (Wang *et al.*, 1996; Thevs *et al.*, 2008a; Zerbe and Thevs, 2011; Aishan *et al.*, 2013). This dynamic leads to the typical composition of the Tugai forests in gallery formations alongside the Tarim River (Thevs *et al.*, 2008a; 2008b; Westermann *et al.*, 2008).

Schickhoff (2011) refers to the soil moisture conditions and soil-nutrient content as the decisive factors for a development of differentiated vegetation within an area of climatic homogeneity. Already minor variations of these factors lead to specific forms of vegetation. Also Rodriguez-Iturbe and Porporato (2004) and Daly and Porporato (2005) consider soil as a key variable and prime for the development of specific functional ecosystem structures. Especially in arid and semi-arid areas, soil moisture is the most important factor within the climate-soil-vegetation-soil moisture system as illustrated by many authors (Rodriguez-Iturbe and Proporato, 2004; Daly and Porporato, 2005; Breshears *et al.*, 2009; Nijland *et al.*, 2010; Turnbull *et al.*, 2010; Ma *et al.*, 2011; Miller *et al.*, 2011). Own studies, partially presented in this paper, try to find out how the spatial pattern and vitality of the deep rooting Tugai vegetation represents not only the availability of groundwater but also of plant available soil moisture. The influence of soil texture and soil composition on the vitality of the Tugai vegetation has not been studied so far.

2.3 Environmental changes and current situation

The Tugai vegetation of the Tarim River floodplain has significantly declined since the 1950s due to an unsustainable and irrigated agriculture with high water requirements (Xu *et al.*, 2005; Thevs *et al.*, 2008a; Chen *et al.*, 2010). Especially in the downstream section of the Tarim River, the Tugai formations are strongly influenced by extensive agriculture and grubbing (Thevs *et al.*, 2008b). This is proven by data of Giese *et al.* (2005). The excessive abstraction of river water for the irrigation of the state-owned cotton plantings endangers the Tugai vegetation increasingly. These water abstractions and the construction of retaining lakes resulted in desiccation of the last 320 km of the Tarim River since the 1970s (Hai *et al.*, 2006). In addition river course changes in the past decades have caused site changes from flooded to dry with groundwater levels deeper than 10 m and increasing salinization of the floodplain soil (Thevs *et al.*, 2008a). With the beginning of the 21st century water from the catchment basin of the Bosten Lake is (episodically) made available for ecological functions (Halik *et al.*, 2006).

Revitalization measures such as water diversion project were implemented for massively degraded floodplain ecosystem in the lower course of the Tarim River. Existing research suggested that these efforts are still insufficient for overall restoration of the region (Chen *et al.*, 2010; 2013; Aishan *et al.*, 2013; 2014). Large-scale stocks of the riparian forest have died. Their important role for the ecosystem and their protective functions with regard to sandstorms is becoming irrecoverable (Halik *et al.*, 2005). Desertification, degradation of riparian vegetation and salinization are the main ecological consequences of the interferences into the natural water balance and the ecological balance of the Tarim Region.

2.4 Soil physical and hydrological analysis

In the entire survey, 15 study sites were chosen to quantify the soil hydrological processes in view of the vitality of the Tugai formations, and three of these study sites (L-3, L-9, L-14), located in Arghan Transection, are described in this paper. Soil samples were taken from the horizons on the soil profiles of all locations. Detailed soil profile descriptions according to the Guidelines for Soil Description and Soil Mapping Guidelines were done in field. The particle size distribution was measured with a particle size analyzer (Malvern Mastersizer®, United Kingdom, Master Sizer 2000) for particles in a range from 0.3 μm to 2000 μm. Groundwater tables were measured with an electric level gauge in the soil drillings.

Each study site was equipped with three soil moisture sensors (10HS Decagon®) in different soil depths. Volumetric soil water contents were collected by these sensors in a temporal resolution of 60 minutes. The collected soil moisture data were converted to the corresponding soil matric potentials (Ψ_m) by using pedotransfer functions, because the soil matric potentials provide important information about the volume of water that is really available for the Tugai vegetation. The pedotransfer functions which were used for this study describe the relationship between the water content (θ) as a dependent variable and the p (F) -value as an independent variable by nonlinear regression functions (Grashey-Jansen and Timpf, 2010). The computed soil-specific model parameters of the regression functions have been described in detail by Grashey-Jansen (2014). The corresponding regression models were computed with PASW Statistics® and the free programming language of *R*.

These calculations, conducted for the different depths, also aided in calculating the vertical water flux in the soils by calculating hydraulic potential-gradients (i) in Equation (1). In a salt-free soil, the level of total potential is determined by two component potentials, the matric potential (ψ) and the gravitational potential (z).

$$i = \frac{(\psi_1 + z_1) - (\psi_2 + z_2)}{z_1 - z_2} = \frac{\Delta\phi}{\Delta z} \quad (1)$$

where i is hydraulic gradient; ψ_1 and ψ_2 are matric potential of different soil depths (1, 2); z_1 and z_2 are gravitational potential of different soil depths (1, 2); ϕ is hydraulic potential; z is total gravitational potential.

According to Ehlers and Goss (2003) the soil surface was taken as reference level for the gravitational potential z for identifying the direction of water flow.

2.5 Geobotanical studies and vegetation mapping

For the geobotanical mapping, the composition, age structure and vitality of poplar trees within a corridor of 10 m along the transect lines were considered. Tree vitality is a key parameter to assess overall situation of forests, their health condition, integrity and resilience (Schulz and Hartling, 2003). The applied method is an integrated concept associated with forest′s growth status and development trends (including crown, leaves, stems and branches) as well as the extension of canopy (Halik *et al.*, 2009; Aishan *et al.*, 2014).

Data of vitality were collected by Xinjiang University in Ürümqi. The vitality of trees was categorized in seven classes (1: high vitality with leaf loss less than 10%; 2: good vitality with leaf loss of 10%–25%; 3: medium vitality with leaf loss of 26%–50%; 4: senescent tree with leaf loss of 51%–75%; 5: dying tree with leaf loss of 76%–99%; 6: dead tree and no evidence of residual vitality; 7: fallen tree and stumps) according to Halik *et al.* (2009). As mentioned by Kuba *et al.* (2013), this is quite a subjective way to determine the condition of the investigated vegetation but still very suitable for giving an impression on how trees in various locations vary in vitality. The age structure was determined using a three-class-scale divided into new poplar shoots (≤ 1 year), juvenile trees (1–13 years) and adult poplar specimen (>13 years).

2.6 Computation and statistical analysis

In addition to initial analyses of the measured soil moisture data, the time series were used to detect quantitative and mutual dependencies. Calculations of (partial) auto correlation functions (PACF) served to identify location and depth specific inertia-influenced reaction speed and repetition patterns. The auto correlation coefficients at lag *k* were estimated by Equation (2):

$$r_k = \frac{\sum_{i=1}^{n-k}(x_i - \overline{x})(x_{i+k} - \overline{x})}{\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{2}$$

where r_k is the *k*th lag sample autocorrelation; x_i is the *i*th observation of input series (i = 1, …, n); $\overline{x}$ is average of the *n* observations.

In order to be able to quantify in the soil-hydrological processes the natural temporal delays as well as the dependencies and reaction speeds connected with them, the relevant time-lags were calculated by cross-correlations and the quantification of corresponding cross correlation coefficients (CCF). The cross correlation coefficients at lag *k* were estimated by Equation (3):

$$r_{xy}(k) = \frac{C_{xy}(k)}{S_x S_y} \tag{3}$$

where $r_{xy}(k)$ is sample cross correlation coefficient at lag *k* (with *x* and *y* as indepent random variables); S_x is standard deviation of series *x*; S_y is standard deviation of series *y*; $C_{xy}(k)$ is sample cross covariance at lag *k* (with *x* and *y* as indepent random variables).

The statistical analyses were performed using the proprietary software SPSS® and the free statistical software environment R.

3 Results and Analyses

3.1 Results of field studies

Figure 2 shows the situation of the transectural measurement of study site 14 (L-14) in May 2012. The investigations showed a typical zonation of vegetation in the rivershore area. In a small zone with a width of 5–10 m young shoots of *P. euphratica* and *T. ramosissima* can be found. It can be assumed that they have been deposited on the river bank during the recession of the flood event in November 2011. Their further growth depends largely on the hygric and hydrological conditions of the following years (Thevs *et al.*, 2008a).

This semi-terrestrial area is followed by a vegetation zone with 3–8 years old seedlings of both species. The culmination of the bank slope is covered with adult exemplars of *P. euphratica*. With increasing distance from the river the vegetation changes to older stocks of *Populus* of lower vitality. Often there also exist large areas with dead stocks of *Tamarix*. Only favourable locations are vegetated with young and vital *Populus*-stocks or even *Phragmetis*-stocks. These locations are often found in depressions (mostly oxbows) with higher levels of groundwater.

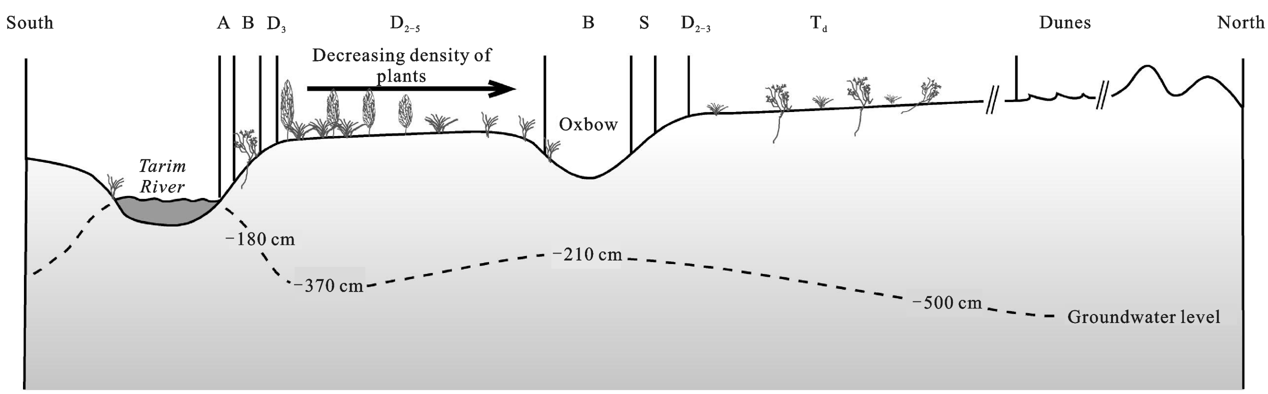

Fig. 2 Typical zonation of vegetation and measured groundwater levels in study site L-14. A, fresh plant shoots (~ 1 year); B, seedlings (3–7 years); D_i, vitality index of adult *Populus*; T_d, dead stocks of *Tamarix*; S, sand

Near the bank the groundwater table was measured in a depth of –180 cm, and 28 m northward the table was measured in a depth of –370 cm (Fig. 2). The measurement point of groundwater in the oxbow is at a distance of 111 m from the riverbank. The groundwater level was measured in a depth of only –210 cm. This area is stocked with vital specimens of *P. euphratica* (3–7 years old). With increasing distance from the riverside the groundwater level sinks down to –500 cm. The vitality index varies in the range of 6–7 (nearly dead and dead stocks and scrubs).

Table 1 shows the main differences of the three sites of this case study relating to altitude, topography and vegetation vitality.

There are small scaled differences in the composition of the soil sites (Fig. 3). The upper soil profile (70 cm soil depth) of L-3 is composed of coarse silt in contrast to the deeper soil layers (120 cm and 175 cm) with higher contents of the fractions from fine silt to coarse sand. L-9 is formed by a homogeneous soil profile with a constant particle size maximum in the range of 60–140 μm. The soil of site L-14 shows higher contents of the sand fraction in 130 cm soil depth. This soil depth is sandwiched between finer substrates (50–100 μm) in the upper and lower soil horizons.

Table 1 Main differences of study sites L-3, L-9 and L-14

	L-3	L-9	L-14
Distance from riverside (m)	100	1170	231
Topography	Elevated plain	Depression	Elevated plain
Vitality index	1–2	3–4	7

The soil matric potentials of L-3 and L-9 are < 10^2 kPa throughout the measuring period (Fig. 4). With respect to the Tugai vegetation this means that there is no water stress for the plants. Remarkable is the fact that the matric potentials at L-3 in 175 cm soil depth were consistently 800–900 hPa higher than in the upper soil. Measured values of L-9 correspond to the natural increase of soil moisture with increasing soil depth. The similarity of the particle size distributions in the soil pit (Fig. 3) is reflected in the soil water dynamic of this location.

Due to the fact that the total water potential is not the same at the different measuring points in the soil pits this inequality will cause water fluxes from points of higher potentials to points with lower potentials. The patterns of hydraulic gradients i show the vertical flux of soil water during the measured period (Fig. 5). There was a permanent downward water flux at location L-3. Minor differences of soil water potentials during the measured period at L-9 caused an upward flow of soil water which must not be overrated. The permanent low values of matric potential (Fig. 4) prove that there is a

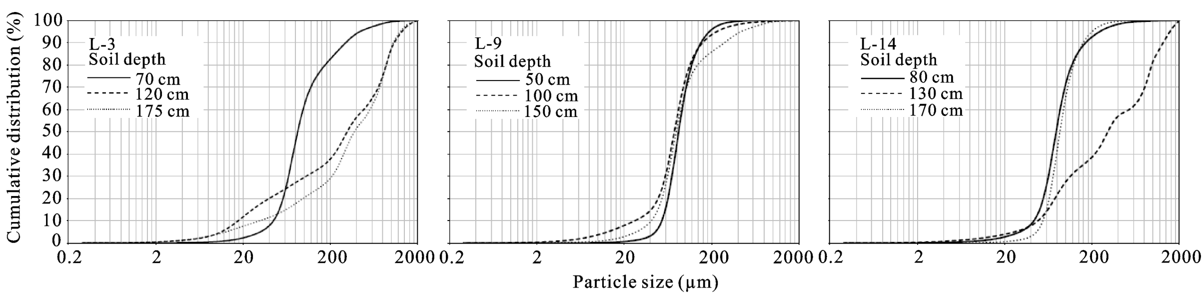

Fig. 3 Particle size distributions in different soil depths of study sites

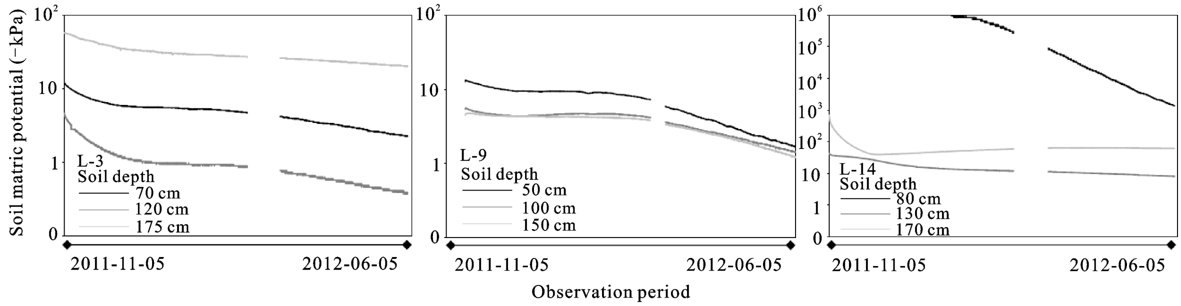

Fig. 4 Time series of soil matric potentials in different soil depths of study sites in Arghan

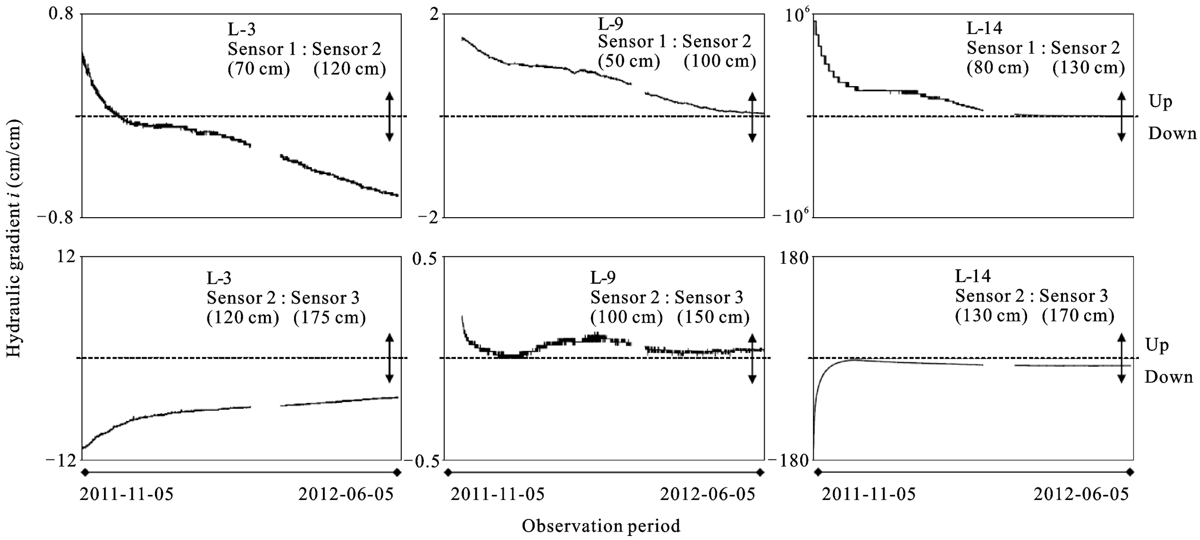

Fig. 5 Time series of hydraulic gradients *i* and direction of water fluxes between different soil depths

balanced and optimal water supply. L-14 showed upward soil water fluxes between –80 cm and –130 cm soil depth before it stagnated during the last third of the measuring period. Significant differences in soil texture (Fig. 3) could possibly have caused a strong (upward) hydraulic gradient between –80 cm and –130 cm during the measuring period.

3.2 Statistical analysis

For L-3 and L-9 the results of the autocorrelation functions (ACFs) show a progressive inertia of soil matric potential with increasing soil depth (Fig. 6). This implies that the soil water tensions lose their dynamics because they become increasingly coupled with the groundwater. L-14 shows opposite relations: the hydraulic inertance of soil water dynamic decreases with increasing soil depth.

The CCFs, which were calculated in a 240-hour time frame, show no time lags in any cases (Fig. 7). That implies that the signal takes less than 1 hour, so that it was not measurable with the temporal resolution used in this setup. It underlines a fast signal transfer between the sensors in the different soil depths (average vertical distance only 50 cm) so that a good hydraulic conductivity can be assumed for the selected study sites.

4 Discussion

First investigations have shown that the vitality of the Tugai vegetation is primarily determined by its position and nearness to the riverbank. Furthermore, the vitality can be modified by the structure and distribution of oxbows and local depressions. The most important supplier of plant available water is the groundwater. The species of the phreatophytic Tugai vegetation is provided with a special and deep reaching root system and able to benefit from the groundwater. It is noteworthy that the water supply of the Tugai vegetation at L-3 and L-9 was at no time in deficit (Fig. 4). In contrast the situation of the water supply at site L-14 was extremely critical down to –80 cm soil depth. A decline of these extreme values can be observed at the end of spring 2012. The water tension in the deeper horizons (–130 cm and –170 cm) was uncritical for the plants at all times during the measuring period. The atmospheric influences have an immediate effect on the soil water balance in the upper soil layers of this elevated plain site. The soil moisture supplies only the deeper soil layers (–130 cm and –170 cm). The results of the autocorrelation functions for L-14 show that the hydraulic inertance of soil water dynamic decreases with increasing soil depth (Fig. 6). The constant influence of the (hyper-) arid climate of the Tarim River Basin on the upper soil layer of site L-14 causes a high autocorrelation in the measured values of soil moisture. This serial correlation can be explained with the extreme kPa-values in the topsoil of L-14 and insensitivity to small fluctuations of the measured soil moisture values.

In addition to the studies of Chen *et al.* (2010) it must be assumed that the plant communities will benefit from the combination of overbank flows and stream aquifer recharges, but the water supply of the roots is decisively controlled by the composition of soils. This argument is strengthened by results of the CCFs in our case study: The lagplots of the cross correlation functions (Fig. 7) also represent the results of the particle size analysis (Fig. 3). High CCFs were calculated between time series of soil moistures in homogeneous soil profiles (L-3 for S2 ∶ S3, L-9 for S1 ∶ S2 and S2 ∶ S3). CCFs between measuring points in soil depths with different soil textures deliver lower coefficients (L-3 for S1 ∶ S2, L-14 for S1 ∶ S2 and S2 ∶ S3). So the influence of soil texture on the local soil water dynamic is evident.

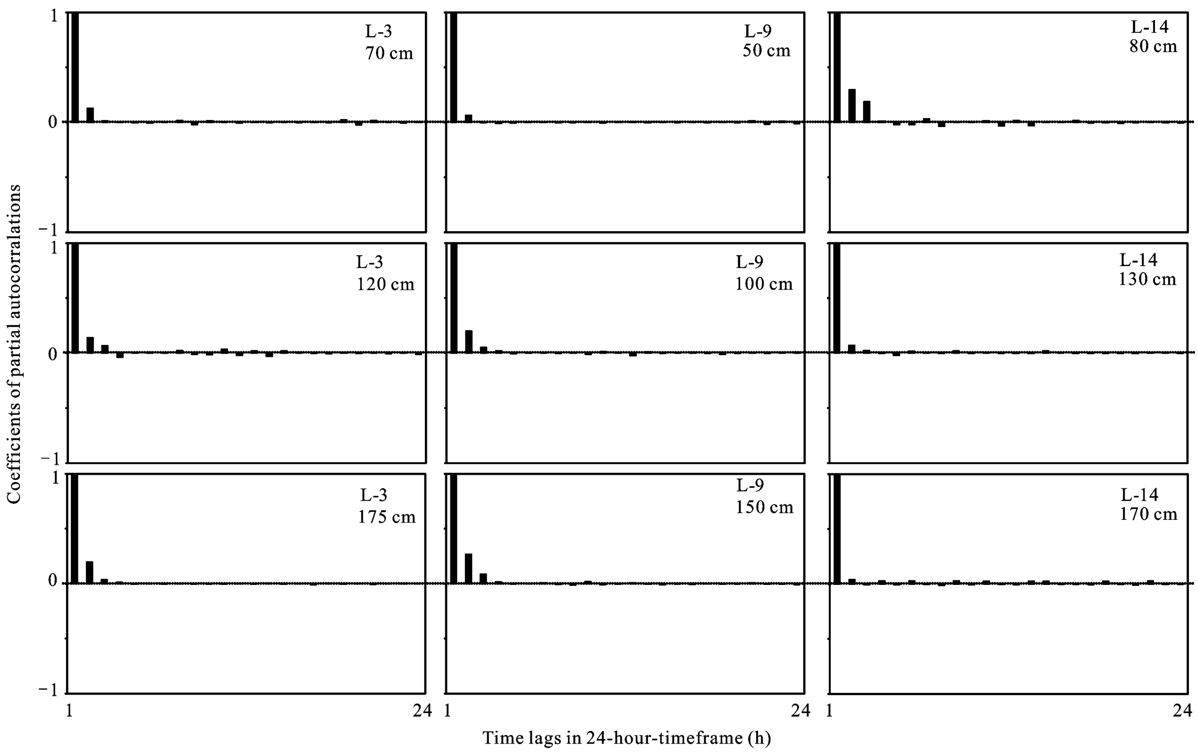

Fig. 6 Lagplots of partial autocorrelation functions (PACF) of sensor data in different soil depths. Significance level between $\alpha < 0.001$ and $a \leq 0.05$

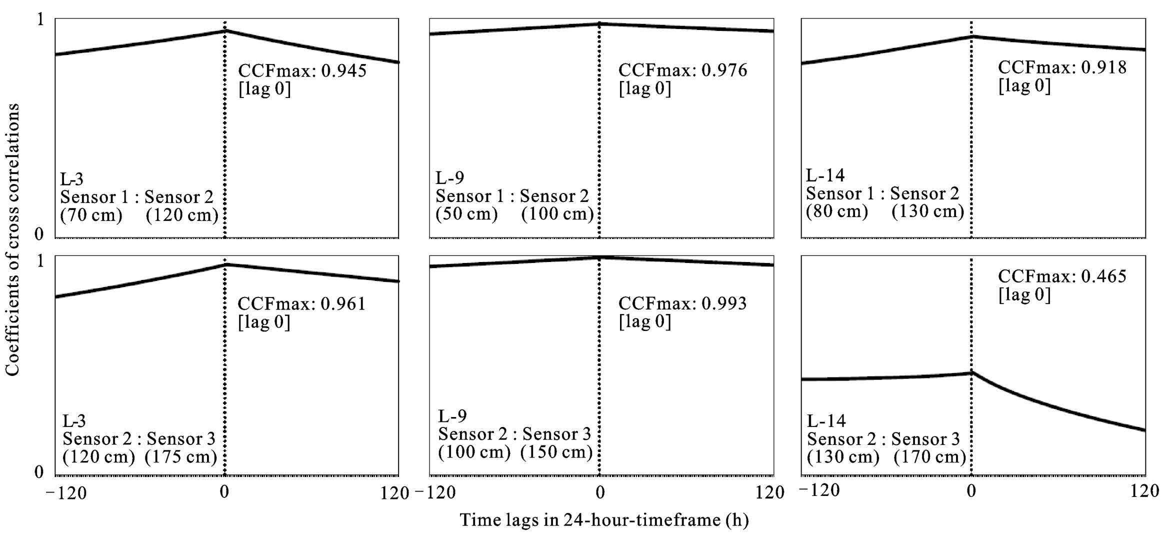

Fig. 7 Lagplots of cross correlation coefficients (CCF) of sensor data between different soil depths. Significance level $\alpha = 0.01$ and $\alpha \leq 0.05$

The observed matric potentials at L-3 in 175 cm soil depth remain unclear. The measured values were consistently 800–900 hPa higher than in the upper soil (70 cm and 120 cm soil depth) (Fig. 4). This indicates a better water supply of the topsoils. The reason for this situation has not been clarified so far. The soil texture in –120 cm is similar to the soil texture in –175 cm (Fig. 3). Perhaps one reason for this is the capillary suction of water by the plant root system in the corresponding soil depth. This alone is not able to give account for the continuously lower soil moisture in the depth of –175 cm. One reason may be a higher soil salinity which has a considerable effect on the osmotic potential. Further studies with measurements of the soil salinity are required to clarify this special situation.

However, the initial studies pointed out that the spatial distribution of stocks at different states of vitality is strongly influenced by soil properties (especially the soil texture). A favorable composition and texture of the soils may compensate the unfavorable climatic conditions by good water retention properties. The influence of soil texture on the soil water dynamic is of great significance. Partially capillary rising processes cause vertical water fluxes and help supplying the plant roots with fresh groundwater. Homogeneous and sandy soil profiles are featured with a good hydraulic conductivity at these sites. Especially in the topsoils on elevated plains a coarse soil texture seems to be more favorable.

5 Conclusions

Physical site conditions play an important role for the soil water supply of floodplain sites in the Tarim River Basin. The vitality of floodplain vegetation is directly linked to the complex interactions in the soil-water-nexus. The field researches and statistical analysis of soil moisture data presented in this case study underscore the particular importance of soil texture. This physical factor controls the water retention and capillary rising in the soil decisively. The combination of quantitative soil texture data and corresponding pedotransfer functions allow further conclusions concerning the spatial and temporal dynamic of soil water flux.

Our research findings indicate that the integration and consideration of site specific soil textures is very helpful to evaluate the vitality of floodplain vegetation. There are scarcely any studies of soil water dynamics concerning the soil textures available for this region. Own measurements and field studies will continue for a couple more years to gain more time series data of soil moisture from different soil sites with stocks of the Tugai vegetation of different vitality. This will enable a more comprehensive analysis of the interactions between Tugai stocks, groundwater, soil moisture and characteristics of soil in the Tarim River region. Further investigations on the relation between vitality of plants and soil properties along the Tarim River will give more information about the endangerment of the Tugai vegetation.

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