Soil Moisture Dynamics Across Landscape Types in an Arid Inland River Basin of Northwest China

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Abstracts: A combination of field measurements, continuous monitoring, and numerical modeling were used to evaluate soil moisture regimes at four sites across a landscape gradient of the Heihe River Basin (HRB). Recorded data of precipitation, irrigation, and floods were used to build the model, and an optimization technique was employed to calibrate the parameters. Based on the optimized parameters and estimates of future scenarios, the modeling structure was employed to predict the changes in the growing-season soil moisture regimes due to climate change and intensive management. The results suggest that the upper-reach Yeniugou and Xishui sites will become wetter due to alterations in the precipitation regime, and this trend could be strengthened by the expected amplified interannual variability. Precipitation features at middle-reach Linze and lower-reach Ejina, however, are not expected to change in the future. We assumed that a more water-saving irrigation system will replace the current traditional one, and hence the soil moisture probability density function (pdf) at the Linze site would tend to be narrowed to ranges around either the wilting point or the point of incipient water stress, depending on how the intervention point and target level are settled. Ejina is expected to experience the most extreme ecological conversion effects in the future, and soil moisture would be more frequently recharged by water delivery. However, the soil moisture regime would not change much due to the poor water-holding capacity and intensive evaporation. The revealed patterns and predicted shifts in soil moisture dynamics could provide a useful reference for identifying robust long-term water resource management strategies for the HRB.

Keywords: Soil moisture dynamics; Ecohydrology; Climate changes; Water management; Inland river basin

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1. Introduction

Soil moisture is widely recognized as one of the most important variables integrating the water balance components of land surface hydrology. It plays important roles in ecosystem dynamics and biogeochemical cycles (Rodriguez-Iiturbe and Porporato, 2005), partitioning energy at the ground surface into sensible and latent heat exchanges (Vivoni et al., 2010), and influencing how precipitation is converted into evapotranspiration, infiltration, and runoff (Daly and Porporato, 2005). Through its dominant control on critical physical processes, soil moisture exerts a strong influence over interactions among the hydrosphere, biosphere and atmosphere (Daly and Porporato, 2005), and provides the link between terrestrial and atmospheric water, energy, and carbon cycles (Robock et al., 2000). Therefore, characterizing the dynamics of soil moisture fields is a critical facet of ecohydrology (Porporato et al., 2002), offering a potential strategy for improving our understanding of complex interactions among climate, soil, and vegetation (Ridolfi et al., 2003).

The past decade has witnessed an increasing concern about the importance of soil moisture dynamics in linking water, energy, and carbon cycles (Gedney and Cox, 2003). In particular, a number of researches have focused on water-limited environments, and a variety of solutions have been proposed for modeling soil moisture dynamics in ecosystems (Rodriguez-Iiturbe et al., 1999; Guswa et al., 2002). Simple yet realistic stochastic models that aim to understand the processes at the heart of water-limited systems have been developed, and are turning out to be one of the most promising methods (Rodriguez-Iiturbe and Porporato, 2005). Using this kind of model, previous work in the literature has already assessed the effects of climate variability (D’Odorico and Porporato, 2004), soil physical properties (Fernandez-Illescas et al., 2001), plant water strategies (Teuling et al., 2006), and groundwater table dynamics, on statistical soil moisture dynamics and water balance (Tamea et al., 2009).

Significant advances have also been made in the measurement of soil moisture dynamics, promoting unique opportunities to explore spatio-temporal variations in soil moisture at very high resolution and across a range of scales (Vereecken et al., 2007). Micrometeorological method are considered to be a reliable and practicable method for long-term measurements of ecosystem water, energy and carbon fluxes (Miller et al., 2007). Continuous measurements of soil moisture have been collected at many micrometeorological sites, such as GCOS (Global Climate Observing System) (Robock et al., 2000), FLUXNET (Flux Network) (Wilson et al., 2002), and CZO (Critical Zone Observatory) (Takagi and Lin, 2011). These types of measurements provide information on soil moisture dynamics with the same accuracy and frequency as other important environmental variables such as temperature or precipitation (Seipal, 2002), and make possible comparison to models that predict soil moisture dynamics at multiple scales, providing a valuable link between theory and practice.

Arid inland river basins in Northwest China are unique ecosystems consisting of ice and snow, frozen soil, alpine vegetation, oases, deserts, and riparian forest landscapes, in a delicate eco-hydrological balance (Wang, 2007). This region occupies nearly 1/4 of the country’s total land area, with runoff from the mountains being its only water source (Xu et al., 2009). The inland rivers generate many oases in fluvial plains when running out the mountains, and finally disappearing in lower desert region (Wang, 2007). Eco-environmental deterioration of the river basins, that began to appear in the middle to late 20th century, and largely linked to climate variability and human activities, has fundamentally altered the water distribution pattern and circulation processes, and became a serious threat to the long-term sustainability of the systems (Zhang et al., 2011). In an attempt to address this problem, large annual
budget was allocated by the Chinese government, and a variety of water- and environment-related measures including scientific observations and researches, have been proposed and implemented since the past decade(Chen, 2007).

Among the inland basins, the Heihe river basin (HRB) is one of largest (Chen, 2007), i.e., the mountains in the upper reaches is the source region of almost all the river flow; the oases in the middle reaches are important localities for maintaining ecological biodiversity and supporting socio-economic development in HRB; and the desert riparian in the lower reaches separates the deserts of Xinjiang and Inner Mongolia and plays a barrier role in preventing dust storms from invading the north China (Zhang et al., 2011). The unique ecosystem of the HRB provides a precious landscape gradient for studying the soil moisture patterns of arid inland river basin under complex climate and management scenarios. A network of micrometeorological sites has been established across the landscapes. Intensely data collection has been ongoing for the past 10 years. No studies, however, have yet examined soil moisture dynamics spanning the sites. Indeed, long-term monitoring of soil moisture dynamics across the multiple landscapes in HRB may have far-reaching implications for ecosystem functioning, irrigation planning, agricultural management, and flooding and drought prediction in the arid northwestern China (Han, 2011). The modelling works, in addition to long-term soil moisture datasets, could further provide valuable insights to watershed managers, ecological planner, and policy makers.

Here we present an ecohydrological analysis of soil moisture dynamics at four observation sites in the typical river basin. This work aims to: 1) explore the trend of climate changes affecting HRB and identify dominant controls of soil moisture in different landscapes of HRB using the field measurements and numerical modeling efforts, 2) and project future hydrological changes due to changes in the precipitation regime, irrigation strategies, and flooding patterns. We used a stochastic model to find a probabilistic description of soil moisture dynamics at each site, and then incorporated predictions of future precipitation patterns and water strategies into the model to examine the shifts in soil water dynamics.

2. Materials and methods

2.1 Site description

The Heihe River is 821 km in length, and has a drainage area of 1.429×10⁵ km². Four sites (Yeniugou, Xishui, Linze and Ejina) spanning a range of climate, vegetation, and soil types in the river basin, were selected for analysis (Fig. 1, Tab. 1). Yeniugou and Xishui sites are located in the permafrost-meadow and mountain-forest landscape zones in the Qilian Mountains, in the upper reaches. Although they share a similar temperate alpine climate, Yeniugou has a lower mean annual temperature (-3.2 °C) and higher precipitation rate (403.3mm year⁻¹), due to its higher altitude, compared to Xishui (0.8 °C, 435.5mm). Vegetation at the Yeniugou site consists predominately of short graminoids and forbs (He et al., 2012). The Xishui site is located in shady grassland where vegetation is similar but in better condition. The Linze site is located in the margin oasis of the middle reaches. It has a temperate arid climate with mean annual precipitation of 117.1mm and temperature of 7.6 °C. The Ejina site is a desert riparian forest located in the lower reaches; it has an extremely arid climate, intensely hot in summer and severely cold in winter, with mean annual precipitation of 37.9 mm and average temperature of 8.2 °C (Zhu et al., 2012). The four sites have almost identical seasonal patterns: the growing seasons start in early April or May and run through late October (Fig. 2).
2.2 Data preparation and analysis

This study used data from each site as reported by Linze station of the Chinese Ecological Research Network (CERN). Historical precipitation and temperature data before 2001 were obtained from the China Meteorological Data Sharing Service Network. After 2001, all the observation sites were installed and equipped with ENVIS systems (IMKO, Germany) to continually monitor microclimate factors (Fig. 3). Observational terms and sensor types were as follows: incoming and reflected radiation, CMTB (KIPP&ZOEN, Holland); net radiation, TYPE 8110 (Wein GmbH & Co. KG, Austria); air pressure, PTB100 (Vaisala, Finland); geothermal flux, HFT-3 and HFP01 (Campbell, Britain); wind velocity and direction, RITA and LISA (Sigelkow Geratebau, Germany); precipitation, RG50 (SEBA Hydrometrie, Germany); moisture profile, T8 (IMKO, Germany). The following data were included in the analysis: daily precipitation and temperature, and soil moisture (taken at 20, 40, 60, 80, 120 and 160 cm in depth). At least four complete years of data were available for each site, generally between 2002 and 2008. All the observation data were daily averaged to be consistent with the time-step of soil moisture dynamics modeling in this research.

The time series charts of the course of the daily volumetric soil moisture are shown in Fig. 4; from these, trends in year-to-year variability, seasonal patterns, and soil moisture at various depths can be determined. The TDR-measured volumetric soil moisture ($\theta$) was converted to relative value ($s$) as: $s = \theta / n$, where $n$ is soil porosity. A profile relative soil wetness factor ($W_p$) was employed as a convenient measure of the moisture condition of any layer between the soil surface and a given depth $d$ located within the profile:

$$W_p = \frac{\theta_{d-d}}{\theta_{0-160}}, \quad 0 < d < 160cm \quad (0)$$

where $\theta_{0-d}$ is the mean water content in the soil layer between the surface and depth $d$ estimated over the entire monitoring period, and $\theta_{0-160}$ is the mean soil moisture in the profile (Fig. 5a). The variation of water content at each depth was quantified through the standard deviation (Std.); the $Std$ for each of the growing seasons were averaged to represent the overall variability (Fig. 5b).

The root-zone average soil moisture is estimated by summing the water stored in the layers within which the measurements were made. If the profile is divided into $n$ layers, then the integrated water content of the profile is $\theta = \sum_{i=1}^{n} \theta_i \Delta Z_i$, where $\theta_i$ is the soil moisture of layer $i$ and $Z_i$ is the layer thickness. The layer boundaries were assumed to be located at the mid-points between measurement nodes, except in the top layer, whose upper boundary is the soil surface, and the bottom layer, whose lower boundary is at estimated root-zone depth, i.e. (Fernández-Gálvez et al., 2006). For each site, a series of histograms were generated from the daily relative soil moistures at root-zone depth (Fig. 6).

2.3 Model description

The soil moisture dynamics model adopted here is the one originally developed by Rodriguez-Iturbe et al. (1999) and further improved by Laio et al. (2001). Water balance in the modeling framework is given by the equation:

$$nZ_i \frac{ds}{dt} = I[s(t), t] - E[s(t), t] - L[s(t), t], \quad (1)$$

where $n$ is the soil porosity; $s$ is the relative soil moisture; $Z_i$ is the root-zone soil depth ($L$); $I$ is the infiltration rate; and $E$ is the evapotranspiration, while $L$ combines deep infiltration and runoff losses.
The occurrence of rainfall is idealized as a series of point events, arising as a Poisson process of rate \( \lambda \), each carrying a random amount of rainfall \( h \), extracted from an exponential distribution with mean \( \alpha \).

Soil is treated as a storage medium with porosity \( n \) and depth \( Z \); rainfall results in an infiltration depth into the soil, \( I \), which is taken to be the minimum of \( h \) and \( nZ(1 - s) \). Canopy interception is included by assuming a threshold of rainfall depth, \( \Delta \), below which no rainfall reaches the soil. \( E \) is modeled as a linear dependence on soil moisture from zero at wilting point \( s_w \) up to a maximum rate \( E_{\text{max}} \) at the point of incipient stomatal closure \( s' \), and then remains constant \( E_{\text{max}} \) for higher moisture levels until soil moisture reaches a threshold \( \theta_{fc} \) (soil capacity). After that point, leakage \( L \) would dominate the water losses from soil, and is assumed to increase exponentially up to the saturated hydraulic conductivity \( K_s \) from field capacity \( s_f \) to soil saturation \( s = 1 \); the described function reads:

\[
L[s(t), t] = K_s \frac{e^{\theta(s-fc)} - 1}{e^{\theta(1-fc)} - 1}, \quad s_f < s < 1
\]

where \( \beta = 2b + 4 \), and \( b \) is the pore size distribution index (Laio et al., 2001).

Soil moisture dynamics here were simulated based on the model, but including an additional term to account for anthropogenic water input for the Linze and Ejina sites, i.e. traditional irrigation was concentratedly applied (160–300 mm in several hours) to the land around the Linze site when soil moisture reaches a certain stress level \( s = 0.24–0.28 \) (Fig. 7); and intermittent floods caused by water released from the middle HRB could randomly submerge the riparian site at Ejina. We assumed the soil moisture dynamics were decoupled from the groundwater dynamics at the sites. Both irrigation and floods were modeled as additional forcing elements, independent of, but supplemental to, precipitation input. Since irrigation was not directly applied to the Linze site, we assumed that the soil moisture jumps to \( s_{fc} \), whenever there is an irrigation event, i.e. Vico and Porporato (2010). For the Ejina site, flooding event may occur at any day of year, and there are no fixed schedule for the water release, as a result, we assumed it occurred randomly like storm events (arising as a Poisson process of rate \( \lambda \) in a very lower value, i.e. 1.5 events per growing season), but each event can bring the soil moisture to saturate \( s = 1 \).

A numerical approach was applied to solve the model by discretizing the differential equation at a daily time scale. For each time step, water inputs were added to the soil moisture value from the previous time step, resulting in an intermediate \( s \) value used for the determination of the loss function. Although analytical solutions are available for the probabilistic model, the numerical procedure offers a high degree of flexibility regarding the conditions to be simulated and data requirements. The numerically simulated values are placed in a histogram to estimate the probability distribution functions (pdfs) of soil moisture dynamics.

### 2.4 Parameter estimation

#### Season identification

The soil water content varies throughout the growing season, mostly through strong interactions with vegetation, and tends to stay constant over the winter, due to snow cover and negligible root activity. We therefore considered the growing season to be the modeling period of interest here. We believe that focusing on this period would highlight the most important time of year for climate and vegetation in the HRB. Analysis of monthly precipitation and temperature reveals similar seasonal patterns of change: high in summer and autumn, and low in spring and winter (Fig. 2), suggesting the coincidence of the growing season and the rainy season in the HRB. For convenience,
the growing season was defined as the period for each year during which the daily minimum temperature did not fall below the index value, i.e. 32°F (or 0°C). The estimated beginning of the growing season was taken to be the last occurrence of the index value on, or prior to, July 31. The end of the growing season was defined as the first occurrence of the index value on, or after, August 1 (Tab. 1). We assumed soil moisture was not affected by rainfall seasonality during the growing season.

**Parameter initialization.** Annual precipitation ($P$) was estimated from the historical data, generally between 1960 and 2008 (except in Xishui, where the weather station was installed in 1994). Precipitation days ($n$), average time between rainfall events ($\lambda$), and average amount of rainfall per event ($\alpha$) during each growing season, were then calculated. Here precipitation days were estimated as the days with precipitation exceeding 0.2 mm day$^{-1}$; the average storm depth ($\alpha$) was estimated as the mean precipitation rate averaged over all raining days, and the average time of storm arrival ($\lambda$) was the number of days with data divided by number of raining days (Tab. 2). Year-to-year variations of the parameters were statistically described in terms of coefficient of variation, i.e. $CV_n$ and $CV_{\alpha}$ (Tab. 2). Initial values of the soil parameters, $n$, $\beta$, $K_n$, $s'$ and $s_1$, were collected from the annual report of the Linze Station and some other reporting literature (Liu et al., 2007; Gao et al., 2008; He et al., 2012). Interception capacity, $\delta$, was considered to be small and we assumed it to be either 1 mm—for the Yeniugou and Xishui sites—or negligible (i.e., $\delta=0$)—for the Linze and Ejina sites, because of the grassland at the former two sites and the sparse vegetation at the latter two. The maximum evapotranspiration, $E_{\text{max}}$, was estimated by using the Priestly-Taylor equation or available experimental data.

**Parameter optimization and model validation.** The shuffled complex evolution method (SCE-UA) was used to calibrate the model to soil moisture measurements by varying local soil and vegetation parameters within physically plausible ranges at the selected sites (Duan et al., 1994). We collected or estimated the initial parameter values, and then set a range of ±25 % to search the set of parameter values that could lead to a best fit of the modeled soil moisture behavior with the measured data. The objective function was settled as the minimization of the root mean square error (RMSE) between the observed and modeled soil moisture time series over the calibration period. Two growing seasons (DOY 150-265 of 2006 and 2007) were chosen as the calibration periods, and another two independent periods (DOY 150-265 of 2008 and 2009) were chosen to validate the parameters. Tab. 3 lists the parameters and their optimized values used in the stochastic model. As a check of model performance, we also compared the empirical probability distribution functions (pdfs) of data and model output. The Kolmogorov-Smirnov (KS) test was used to check the null hypothesis that data and modeled series are drawn from the same distribution.

**3. Results and Discussion**

**3.1 Climate characteristics and observed soil moisture regimes**

**3.1.1 Rainfall regime**

The mean annual behavior of temperature and precipitation shown in Fig. 2 reveals a significant seasonality. Relatively wet conditions could be seen at the Yeniugou and Xishui sites between March and October, while a relatively dry state was shown at the Linze and Ejina sites during the same period. The observed seasonality could substantially affect the soil moisture dynamics, i.e. some of the sites receive a non-trivial fraction of precipitation in the form of snow, which still beyond our modelling.
ability, so that we narrowed our analyzing and modelling scope into growing season (generally in between May or Jun. to Sept., see Tab. 1). A summary of the main statistics relative to the historical precipitation at the sites is presented in Tab. 2. Significantly higher annual precipitation (P) was received at the upper-reach sites (408.6 mm at Yeniugou and 370.5 mm at Xishui, compared with 115.4 mm at Linze and 33.5 mm at Ejina). During growing season, Yeniugou and Xishui were dominated by small but frequent rainfall events (α = 4.2 and 4.8 mm; λ = 0.61 and 0.42 day⁻¹), while the Linze and Ejina sites were characterized by small and rare rainfall events (α = 2.9 and 2.1 mm; λ = 0.18 and 0.09 day⁻¹). Both α and λ were relatively less variable at Xishui and Yeniugou (CVα = 0.14~0.16, CVλ = 0.12~0.18) than at Linze and Ejina (CVα = 0.26~0.47, CVλ = 0.18~0.34) (Tab. 2). No significant correlation between these rainfall parameters was detected at any site (pα,λ > 0.05). Fig. 3 also shows the time series of P, α, and λ, for the growing seasons at the four sites of the HRB, and long-term trends with statistical significance (p < 0.05) can be found at some of the involved sites (i.e. Yeniugou and Xishui, Fig. 3ab). Although the revealed trends were proved to be significant for the growing season data, there are not significant for the yearly averaged data (precipitation in Fig. 3ab), suggesting that the overall magnitude of rainfall at those sites were not altered significantly by climate change, however, its seasonal distribution and interannual variability changed essentially. Similar results have been reported for many different ecosystem, i.e. Feng et al. (2013).

### 3.1.2 Soil conditions and vegetation cover

The four sites exhibited remarkable differences in soil profile features; however, we noticed that the root-zone soils were generally uniform at all the profiles. The Yeniugou and Xishui sites were characterized by a textural heterogeneity along the profile; a relatively shallow rooting system, varying from 20 to 40 cm, significantly reduced this kind of heterogeneity. The root-zone depths at Linze and Ejina were relatively deeper; however, the texture distribution was also more homogeneous throughout the 0-160 cm profile. The Yeniugou site was dominated by alpine meadow soils with porous loam and rich root systems (n =0.45, Zr ≈ 35 cm); vegetation around the site was dominated by moderately drought-intolerant grasses (Chen et al., 2007); we assumed the initial values of model parameters as s_w = 0.13, s* = 0.51, and s_f = 0.80. Similarly, these parameters at the Xishui site were initialized as 0.13, 0.36, and 0.89, respectively, where soils are dominated by a montane grey drab soil and a montane chestnut soil (Liu et al., 2007). In contrast, the soil type at both the Linze and Ejina sites was uniformly sandy with a low content of organic matter and low adhesion forces caused by a soil matrix resulting in low soil moisture values at field capacity. These parameters were initialized as s_w = 0.10, s* = 0.24 and s_f = 0.31, respectively, at the Linze site, and s_w = 0.05, s* = 0.23 and s_f = 0.33, respectively, at the Ejina site. Porosity, n, was assumed to be equal to 0.41 and 0.43, respectively, at the sites, according to Gao et al. (2008) and the annual report of the Linze station (Tab. 3).

### 3.1.3 Soil moisture time series

Fig. 4 shows the time series of soil moisture across the sites during 2005-2008, and the descriptive statistics of them are given in Tab. 4. The soil moisture regimes have a significant seasonal cycling character at the upper-reach sites (Yeniugou and Xishui), where soil moisture changes between the states of extremely low values in winter and early spring (Oct. to Apr.), and relatively wet conditions during the summer because of the monsoon season. The mean soil moisture values follow the rainfall patterns at the sites, with lower CV during growing seasons and higher CV during non-growing seasons

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Different soil moisture regimes were observed at Linze and Ejina, where sporadic showers characterize precipitation, so that the induced infiltration depth is smaller. Either irrigation or floods control soil moisture over these sites. The Linze site is located in an agroecosystem of desert oasis; soil moisture followed the irrigation regime, where traditional irrigation was regularly applied in the lands surrounding the site when soil moisture reaches a certain stress level (s=0.24–0.28). Due to the poor water-holding capacity of the sandy soil, soil moisture can be quickly increased to field capacity by irrigation events, and then lost as evapotranspiration in a short time. As a result, soil moisture at Linze had a relatively lower average but higher variance compared with Yeniugou and Xishui. Because irrigation could occur during any season, not much difference was found among the statistics of soil moisture dynamics for the different seasons at Linze (Fig. 4c). The Ejina site was randomly recharged by intermittent flood events, and the flood-raised groundwater table (especially at depths below 80 cm) affected the drying processes; hence soil moisture could vary from extremely arid (wilting point) to saturation, and show a statistic similar to the Linze site (Tab. 4).

3.1.4 Profile features of soil moisture

The soil moisture profiles vary among the selected sites, showing generally wetter conditions at Yeniugou and Xishui, with higher soil moisture values and less temporal variability of soil moisture during the growing season, as compared to the yearly average conditions (Figs. 4, 5a). The temporal standard deviation (std.) of the profile soil moisture averaged over the growing seasons between 2005 and 2008 changed with depth (0–180 cm) and was within a range of 1% to 17% (in v/v, Fig. 5b). Decreased variability with depth was observed at all the selected sites (except Ejina), suggesting combined effects of dampened maximum moisture content when infiltration fronts propagated through the soil column, and reduced root water uptake. The different trend observed at the Ejina site can be attributed to the extreme fluctuation of the water table due to its proximity to the river. Estimates of the profile relative wetness factor for layers at several different depths are shown in Fig. 5a. There were large differences among the vertical structures of soil moisture at the four sites, with their differing climates and vegetation. Soil moisture showed less vertical variation at Xishui and Linze, i.e. nearly uniform relative soil moisture distributions over the soil profile, whereas much more heterogeneous profiles were observed at the Ejina and Yeniugou sites (Fig. 5b). In particular, Yeniugou exhibited relatively wetter soil moisture conditions at shallow depths, and Ejina showed relatively drier shallow layers and wetter deeper layers. These variations highlight the strong dependence of soil moisture on local soil/vegetation conditions.

3.1.5 Probability density functions (pdfs) of the root-zone soil moisture

Characteristics of the soil moisture pdfs at specific profile depths across different landscapes were studied for four consecutive years (2005–2008) (Tab. 4, Fig. 6). Yeniugou and Xishui had similar pdf patterns. A dry mode and a wet mode were observed at s=0.2 and s=0.6, corresponding to the growing season and non-growing season, respectively. It is clear that the growing season also coincides well with the wet season at the Yeniugou site. This situation is also true for the Xishui site, where the dry mode appears at s=0.15, while the wet mode appears at s=0.3. Probability density functions of the root-zone soil moisture at both the Yeniugou and Xishui sites during the growing season are typical of cold and arid climates (Fig. 6a,b) (Rodriguez-Iturbe and Porporato, 2005). Because of the arid climate and intense irrigation, the pdfs at the Linze site show an extremely arid mode at s=0.15 (close to wilting point), and a relatively wet mode at s=0.25 (close to field capacity). The Ejina site was irregularly
recharged by flood events, and the pdf of the root-zone soil moisture was almost not affected by the sparsely occurring rainfall events. There was an extremely dry mode around s=0.05, and the soil moisture pdf shows a large range, from s=0 to 1 (Fig. 6).

3.2 Modeling the soil moisture dynamics

3.2.1 Parameter optimization and model validation

An optimization procedure of the model parameters was completed based on the initial values collected from reported or published materials (Tab. 3). In consideration of the uncertainty associated with model parameters involved, we allowed them to vary over a pre-determined fixed interval (±25% of the initial values), and the combination that minimized the averaged squared differences between the measured data and the model output during the growing seasons of 2005-2006 was selected to be optimal (Tab. 3). Because saturation or near saturation states were never observed at Yeniugou or Xishui (Figs. 4 and 6), the leakage (L) was completely eliminated in the model calibration at the two sites to avoid uncertainties that might be introduced. The model with optimized site-specific parameters was tested against the measurements of root-zone soil moisture during the growing seasons of 2007-2008. This simulation was forced by the observed precipitation and irrigation/flood data at the daily scale during the same periods, and the calibrated model was able to effectively hold the soil moisture dynamic behavior at the root-zone depth, and reproduce well the soil moisture data with an average square deviation of less than 5% between the simulation and observation at all selected sites. An example of the soil moisture dynamic at the four sites during the growing season of 2008 is shown in Fig. 7. We also compared the pdfs estimated from the model simulation with those from the observed histogram (insets in Fig.7). The Kolmogorov-Smirnov (KS) test suggests that the possibility that the simulated and observed soil moisture series were drawn from the same distribution could be as high as 95%.

3.2.2 Estimation of the long-term soil moisture pdf

We adopted a Monte Carlo procedure described by D’Odorico et al. (2000) to quantify the probability distribution of long-term average soil moisture with the random interannual fluctuation frequency (λ) and mean depth (α) of precipitation and irrigation/floods. The rainfall statistics were constructed from long-term rainfall records (Tab. 2, Fig. 3). We assume the observed rainfall parameters, α and λ are independent of each other. Year-to-year variations in α and λ were described using random numbers generated from the probability distributions. Irrigation at the Linze site was assumed to be sporadically applied during short concentrated periods with water in amounts sufficient to raise the soil moisture to Srzc throughout the rooting depth when soil moisture reached s∗ F Flood events at the Ejina site were assumed to randomly occur during growing seasons with an average frequency of 1.5 events per growing season, and each event was assumed to increase the soil moisture to saturation at the daily scale. All the other parameters were set as the previously calibrated ones. Through the probabilistic model, the pdfs of long-term average soil moisture dynamics at the four sites were numerically estimated (Fig. 8). Compared with the measured histogram calculated for 2004-2008, the Yeniugou site showed a similar pattern in the long-term soil moisture pdf, and adding an additional 10-20% of the interannual variability will not significantly change the shape of pdf (Fig. 8a and Fig. 6a). A different situation was observed at Xishui, where the long-term average soil moisture pdf (mode appeared at s=0.1-0.2) tends to be dryer than that during the growing seasons of 2004-2008 if not considering the inter-annual variance. If the interannual variability in precipitation were included, the soil moisture pdf...
would substantially move toward wetter soil conditions, and agree well with the measured histogram calculated for 2004-2008 (s=0.1-0.5) (Fig. 8b and Fig. 6b).

For the Linze site, accurate historical irrigation data before 2001 is not available. Based on the available data during 2001-2008, we assumed that irrigation was regularly applied according to a fixed schedule during the first 105 days of each growing season as a supplementary water source whenever soil moisture dropped to or below s*, followed by a period of 91 days without irrigation (rainfall would be the only input). The simulated pdfs of soil moisture at the Linze site can describe the general behaviors present in the observed soil moisture series (Fig. 8c, Fig. 6c). Frequent irrigation results in a wet modal between the wilting point and field capacity during first half of the growing season; irrigation was not applied during the latter half of the growing season, and soil moisture tended to stay at around the wilting point, i.e. s=0.1. Inter-annual variance in precipitation seems not to affect the soil moisture pdfs (Fig. 8c). The Ejina site is located in a riparian environment, the river stream, but only occasionally has water running through it and triggering inundation of the buffer zones for a short period. Since the water table cannot last long in the root-zone depth of the soil profile (100 cm, Fig. 4d), we assumed that root-zone soil moisture was not affected by the water table at this site, and that flood events occurred randomly at the site, similar to, but independent of, precipitation. The pdfs of soil moisture were therefore numerically estimated, and found to be rational when compared with experimentally measured histogram (Fig 8d, Fig. 6d). The soil moisture can be raised instantly to saturation by sparsely occurring floods, and then quickly drawn down to very arid conditions, because of the poor water-holding capacity and intense ET.

3.2.3 Predictions of future scenarios

Our analysis suggests that the annual precipitation at Yeniugou did not obviously change during the past decades (p>0.05). The rainfall pattern, however, has been altered significantly, i.e. the mean depth (α) of precipitation events increased by 10.3 % (p<0.01), and the rainfall frequency (λ) decreased by 5.6 % (p<0.01) during the growing seasons between 1961 and 2008 (compared with the long-term average) (Fig. 3). A different trend was observed at the Xishui site, where annual precipitation did not change significantly, nor did the mean growing season rainfall depth (α), during the period 1994-2008 (p>0.05), even though the average value of rainfall frequency (λ) increased by 31.5 % (p<0.01) during the same period. We assume the rainfall features will retain these trends in the coming 2 decades at the upper catchment sites (Yeniugou and Xishui), and ETmax will not be significantly changed at any of the sites in coming decades, as posited by Wang and Zhao (2011). The parameters of rainfall were assumed to be extracted from a Poisson distribution with average rate λ, and an exponential distribution with mean α, i.e., α=0.58, 0.52, 0.18, and 0.19, and λ=4.69, 4.85, 2.91, and 2.06, at Yeniugou, Xishui, Linze, and Ejina, respectively. The interannual variability of precipitation (CV_p, CV_s) was assumed to either remain the same, or increase by 10%, 20% and 30%. Under this assumption, the modeled pdfs of root-zone soil moisture were compared (Figs. 8a,b). We noticed that the distribution of pdf would move slightly toward wet conditions at the Yeniugou site due to the increased λ, and change from unimodal to bimodal by strengthened interannual variability in precipitation. The probability of generating runoff and deep leakage could thus be substantially increased, as indicated by an intuitively expected modal at close to the field capacity. Although the pdf of soil moisture at Xishui would also therefore move toward wetter conditions (from s=0.26 to s=0.35), the soil moisture pdfs would remain largely the same shape and range with increased interannual variability.

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Since the soil moisture at the Linze site comes mainly from irrigation, and no significant trends were detected in precipitation parameters, the most likely changes in the future 2 decades are expected to be improvements in the irrigation methods: i.e. traditional ways will be replaced by water-saving ones like deficit-irrigation and micro-irrigation. Three different scenarios with combined deficit- and micro-irrigation are shown here—i.e. the intervention point and the target level: $s^* \mp 10\%$, $s^* \mp 20\%$ and $s^* \mp 30\%$. Intensive management of irrigation would cause the soil moisture to stabilize at two preferred points: one around $s_w$ and another around $s'$ (Fig. 8c). With the improvement in irrigation methods, the wet mode observed around $s'$ in soil moisture pdf will be significantly narrowed. The smaller the range between the intervention point and the target level, the more concentrated was the observed pdf (Fig. 8c). For the Ejina site, soil moisture was controlled mainly by random flooding, which in turn was determined by the water distribution strategy of the HRB. Given the deteriorating environment in the lower reaches, more frequent water delivery to this region is predictable (Zhu et al., 2012). We assume three alternative scenarios for this site, i.e. the frequency of floods would increase by 50 $\%$, or by 100$, during each growing season, or water would be delivered to this region whenever soil moisture dropped to the wilting point, so that the risk of vegetation degradation can be effectively lowered. The simulated pdfs suggested that soil moisture cannot be significantly increased by flood events if their frequency were increased, and the distribution would remain in the same wide range as before (Fig 8d).

3.3 Implications for water resources management

Our analysis reveals three main types of soil moisture regimes in the HRB. Because precipitation is the only input of the water balance in the mountainous region of the HRB, the amount and timing of precipitation will be a significant determinant of future soil moisture dynamics (Zang et al., 2012). Not surprisingly, the Yeniugou and Xishui sites, which are both located in this region, showed very similar precipitation patterns. The soil moisture regime at the two sites can be characterized mostly as favorable with a good water availability during the growing season, a condition that can be attributed to the small but frequent event-dominated precipitation pattern. Our modeling results suggested that the pdf of soil moisture at the two upper-reach sites of the HRB could become wetter in the future, and thus improved vegetation cover and increased ET are largely predictable in the coming 2 decades. Given the predicted changes in water balance, more green water flow consumed at the upper reaches of the HRB would result in decreased blue water availability in the middle and lower reaches, and may potentially raise their vulnerability to water stress (Zang et al., 2013).

Oases are groundwater-dependent systems, where groundwater circulation controls the overall water quality and ecosystem dynamics (Huang et al., 2013). The expanding oases have consumed too much water and significantly lowered the groundwater table; recharge from traditional irrigation has resulted in nutrient loss and groundwater pollution (Zhu et al., 2012). Competition for water, high pumping costs, and concerns for environment have made good water management more important than ever before in this region, and created a urgent need for improvements in common irrigation strategies toward sustainable target scenarios, a strategy that requires timely application of the right amount of water (Vereecken et al., 2007). Our analysis suggests that irrigation events can be adjusted as a precise scheme to prevent drought stress while minimizing nutrient loss by reducing the probability of soil moisture’s dropping below $s'$ or rising above $s_w$ (Fig. 8c). However, precise irrigation is not necessarily the most profitable choice, due to its high costs of installation and maintenance (Vico and Porporato, 2010). Careful analysis should thus be performed before strategy planners decide to update the current irrigation systems.
Development of vegetation in the riparian zones of lower HRB depends on the subsurface water storage, which is recharged by intermittent floods, and variability of stream flow is the dominant factor influencing the vulnerability (Zhang et al., 2011). For the purpose of rehabilitating and reconstructing the ecosystems in the Ejina, a long-term basin planning process that redistributes runoff to the lower reaches was initiated in 2000, and the water usage patterns in the middle and lower reaches has significantly changed since then. Those efforts were considered to be an effective intervention for the treatment of the degrading ecosystem (Zhu et al., 2004). Considerable amounts of water have been purposely delivered to the extremely arid Ejina region to raise the groundwater level and recover the vegetation, but the timing and volumes are scheduled based on the received water in the middle reaches in this procedure (Zhang et al., 2011), without considering the needs of lower reaches, possibly resulting in an unproductive and expensive endeavor. These matters present substantial challenges for regional authorities charged with day-to-day water resource management, and with managing flood control and drainage schemes. Innovative approaches, such as fostering seasonal water shortages, will be called for.

4. Concluding remarks

This study suggested that soil moisture conditions for the upper-reach sites (Yeniugou and Xishui) are likely be wetter in future 2 decades. The probability of generating surface runoff would also be significantly increased at the Yeniugou site if the variance were increased 10-20%. Precipitation features at Linze and Ejina seem not to have changed much in past decades and are also assumed not to change in the coming ones. We presume that a more water-saving irrigation system will replace the current traditional ones, and consequently soil moisture pdfs at the Linze site would tend to be narrowed to ranges around either the wilting point or the point of incipient water stress point, depending on how the intervention point and target level are settled. Ejina is expected to experience the greatest ecological conversion stress in the future, and as a result, soil moisture would have to be more frequently recharged by water delivery. However, the soil moisture pdf would not change too much, due to the poor soil water-holding capacity and intensive evaporation. These revealed patterns and predicted shifts in soil moisture dynamics could be a useful method of identifying the robust long-term water resource management strategies for the HRB and other arid inland river basins in Northwest China.

Acknowledgements

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References:


Han E. 2011. Soil moisture data assimilation at multiple scales and estimation of representative field scale soil moisture characteristics. Purdue University.


er parameters were estimated from the data collected during the growing season, i.e. initial ΔEs and ςb.

Table 3. Initialized (Int.) and Optimized (Opt.) parameter values of climate, soil and vegetation characteristics used in the simulation of soil moisture dynamics at the selected sites in the HRB. The optimized parameter values were estimated with the SCU-UA method based on the monitoring data during the growing seasons of 2006 and 2007.

<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Altitude</td>
<td>35.0</td>
<td>39.0</td>
<td>40.0</td>
<td>40.0</td>
</tr>
<tr>
<td>Location</td>
<td>38°25'N, 99°35'E</td>
<td>38°32'N, 100°17'E</td>
<td>39°21'N, 100°17'E</td>
<td>42°01'N, 101°14'E</td>
</tr>
<tr>
<td>Vegetation</td>
<td>Silt loam</td>
<td>Silt loam</td>
<td>Silt loam</td>
<td>Silt loam</td>
</tr>
<tr>
<td>Soil type</td>
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<td>37.3</td>
<td>37.6</td>
<td>37.6</td>
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<td>Description</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Growing season</td>
<td>134-267</td>
<td>122-281</td>
<td>94.288</td>
<td>98-289</td>
</tr>
<tr>
<td>Typical LAI (m²/m²)</td>
<td>0.53</td>
<td>2.97*</td>
<td>2.25</td>
<td>2.78</td>
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<tr>
<td>NDVI</td>
<td>0.71-0.78</td>
<td>0.71-0.78</td>
<td>0.71-0.78</td>
<td>0.71-0.78</td>
</tr>
</tbody>
</table>

*Data were collected mainly from Chen (2006), Tian et al. (2011), and He et al. (2012).

The number of years considered is given in parentheses.

Table 2. Precipitation characteristics for the sites considered along the landscape gradient in the HRB: annual precipitation was estimated from year-round data, while other parameters were estimated from the data collected during the growing season, i.e. precipitation days (n), average storm depth (α), average time of storm arrival (λ), precipitation variance (CVp, CVg), and correlation significance (p_corr) between α and λ.

<table>
<thead>
<tr>
<th>Sites</th>
<th>Observation Period</th>
<th>R, mm/year</th>
<th>α, mm</th>
<th>λ, day</th>
<th>CVp</th>
<th>CVg</th>
<th>p_corr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yenigou</td>
<td>1994-2000 (15)</td>
<td>37.5</td>
<td>4.85</td>
<td>0.24</td>
<td>0.31</td>
<td>0.55</td>
<td>0.13</td>
</tr>
<tr>
<td>Xishui</td>
<td>1994-2000 (15)</td>
<td>37.5</td>
<td>4.85</td>
<td>0.24</td>
<td>0.31</td>
<td>0.55</td>
<td>0.13</td>
</tr>
<tr>
<td>Linze</td>
<td>1994-2000 (15)</td>
<td>37.5</td>
<td>4.85</td>
<td>0.24</td>
<td>0.31</td>
<td>0.55</td>
<td>0.13</td>
</tr>
<tr>
<td>Ejina</td>
<td>1994-2000 (15)</td>
<td>37.5</td>
<td>4.85</td>
<td>0.24</td>
<td>0.31</td>
<td>0.55</td>
<td>0.13</td>
</tr>
</tbody>
</table>

*The number of years considered is given in parentheses.

Table 3. Initial (Init.) and Optimized (Opt.) parameter values of climate, soil and vegetation characteristics used in the simulation of soil moisture dynamics at the selected sites in the HRB. The optimized parameter values were estimated with the SCU-UA method based on the monitoring data during the growing seasons of 2006 and 2007.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Tz</td>
<td>cm</td>
<td>Root-zone depth</td>
<td>35.0</td>
<td>39.0</td>
<td>40.0</td>
<td>40.0</td>
<td>40.0</td>
<td>45.0</td>
<td>90.0</td>
<td>96.0</td>
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<tr>
<td>C</td>
<td>g/cm³</td>
<td>Soil bulk density</td>
<td>1.03</td>
<td>0.94</td>
<td>1.50</td>
<td>1.46</td>
<td>1.51</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>v/v</td>
<td>Soil porosity</td>
<td>0.45</td>
<td>0.44</td>
<td>0.64</td>
<td>0.42</td>
<td>0.41</td>
<td>0.43</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>Ksat</td>
<td>cm/hr</td>
<td>Saturated hydraulic conductivity</td>
<td>36.5</td>
<td>49.5</td>
<td>216</td>
<td>210</td>
<td>19.3</td>
<td>205</td>
<td></td>
<td></td>
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<tr>
<td>s</td>
<td>cm</td>
<td>Slope of the retention curve</td>
<td>5.07</td>
<td>5.11</td>
<td>4.42</td>
<td>4.42</td>
<td>14.1</td>
<td>14.8</td>
<td></td>
<td></td>
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<tr>
<td>W</td>
<td>v/v</td>
<td>Wilting point</td>
<td>0.13</td>
<td>0.14</td>
<td>0.14</td>
<td>0.10</td>
<td>0.10</td>
<td>0.05</td>
<td>0.07</td>
<td></td>
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<tr>
<td>nsc</td>
<td>v/v</td>
<td>Incipient stomatal closure point</td>
<td>0.51</td>
<td>0.55</td>
<td>0.36</td>
<td>0.36</td>
<td>0.24</td>
<td>0.24</td>
<td>0.23</td>
<td>0.24</td>
</tr>
<tr>
<td>fc</td>
<td>v/v</td>
<td>Field capacity of soil</td>
<td>0.80</td>
<td>0.86</td>
<td>0.89</td>
<td>0.95</td>
<td>0.31</td>
<td>0.32</td>
<td>0.33</td>
<td>0.40</td>
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<tr>
<td>Ksat</td>
<td>cm/d</td>
<td>Maximum rate of ET</td>
<td>0.30</td>
<td>0.31</td>
<td>0.32</td>
<td>0.40</td>
<td>0.50</td>
<td>0.61</td>
<td>0.90</td>
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<tr>
<td>α</td>
<td>cm</td>
<td>Canopy interception threshold</td>
<td>0.10</td>
<td>0.12</td>
<td>0.10</td>
<td>0.11</td>
<td>0.00</td>
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<tr>
<td>λ</td>
<td>cm</td>
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<td>0.10</td>
<td>0.12</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

*Initial values of parameters were collected from the annual report of the Linze Station (2002-2009) and other sources, i.e. Gao et al. (2008), He et al. (2012), Liu et al. (2007), Zhou et al. (2004), Zhu et al. (2009), Hou et al. (2010).
Table 4. Statistical results of the soil moisture (in percentage, v/v) at the different depths of the four selected soil profiles in the HRB.

<table>
<thead>
<tr>
<th>Sites</th>
<th>Depth (cm)</th>
<th>Growing season</th>
<th>Non-growing season</th>
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<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Min</td>
<td>Max</td>
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<tr>
<td>Yeniugou</td>
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<td>25.9</td>
<td>14.8</td>
</tr>
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<td></td>
<td>40</td>
<td>29.0</td>
<td>23.2</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>28.2</td>
<td>18.7</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>18.8</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>13.5</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>7.5</td>
<td>5.6</td>
</tr>
<tr>
<td>Xishui</td>
<td>20</td>
<td>23.0</td>
<td>13.0</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>22.7</td>
<td>12.4</td>
</tr>
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<td></td>
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<td>24.1</td>
<td>11.0</td>
</tr>
<tr>
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<td>80</td>
<td>23.5</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
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<td>14.4</td>
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</tr>
<tr>
<td></td>
<td>160</td>
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<td>9.6</td>
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<tr>
<td>Linze</td>
<td>20</td>
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<td>0.1</td>
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<td></td>
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</tr>
<tr>
<td></td>
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<td>8.4</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>6.7</td>
<td>3.8</td>
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<tr>
<td>Ejina</td>
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<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
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<td>6.8</td>
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<td>60</td>
<td>9.8</td>
<td>4.1</td>
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<td>7.0</td>
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<td>4.5</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>6.7</td>
<td>3.8</td>
</tr>
</tbody>
</table>
Figure 1. Location and topography of the Heihe River Basin (HRB) in northwest China.
Figure 2. Climate diagram of the Yoniugou, Xishui, Linze, and Ejina sites (left to right) in the HRB, following Walter and Lieth (1967). The diagram displays monthly averages for temperature (black line) and precipitation (gray line) over a year with a fixed plot scale ratio of 1:2. When the precipitation curve undercut the temperature curve, the area in between them is filled with orange color, indicating dry season, while when the precipitation curve supersedes the temperature curve, the area in between them is filled with blue color, indicating moist season. To be comparable, only the data collected between 1994 and 2008 at each site were used in this calculation.
Figure 3. Time series of total annual rainfall ($P$, top panels), the estimated rate of arrival of storms ($\sigma$, middle panels), and the average storm depth ($\lambda$, lower panels) during growing seasons of past decades, based on daily data collected from the 4 sites: a) Yenigou, b) Xishui, c) Linze, d) Ejina. The regression line is shown where significant ($p < 0.05$).
Figure 4. Time series plots of average daily volumetric water content (in percentage, v/v) in the soil profiles at the selected sites. 
a) Yeniugou, b) Xishui, c) Linze, and d) Ejina.
Figure 5. a) The relative soil wetness factor ($W_p$) and b) the mean temporal standard deviations (Std.) of observed soil moisture for 0-4 cm depth in the soil profiles across all the four selected sites during the growing seasons (chain lines) and non-growing seasons (solid lines). Measurements obtained throughout years 2004-2008.
Figure 6. Observed soil moisture probability distribution functions [pdf(s)] in root-zone soil profiles during growing seasons and non-growing seasons of 2005-2008 at a) Yenaugou, b) Xishui, c) Linze, and d) Ejina. See Table 1 for detailed information on growing season and non-growing season at the involved sites.
Figure 7. Time series and frequency diagram of observed relative root-zone soil moisture at the four selected sites during the growing season of 2008. Inset shows frequency distribution in which ordinate values represent frequency of $s$ within a bin interval of 0.02, relative to the total number of soil moisture values.
Figure 8 Predicted probability density function of soil moisture (pdf) at the four sites of the HRB, and each panel refers to a different location and each line to a different scenario. a,b) Yeniugou and Xishui, using rainfall parameters estimated from historical data ($\lambda = 0.61$ and $0.42$, $\alpha = 4.25$ and $4.85$ for the two sites, respectively) without considering year-to-year variations in rainfall (deep blue line), or takes into consideration the year-to-year variations in rainfall (blue line), or using the predicted rainfall parameters for the coming two decades ($\lambda = 0.58$ and $0.52$, $\alpha = 4.69$ and $4.85$ for the two sites, respectively) with assumed amplified year-to-year variations in rainfall (Cyan, $+10\%$, Yellow, $+20\%$, and Red, $+30\%$). c) Linze, using traditional irrigation (assumed only occurred during the first 105 days in a growing season) and rainfall parameters ($\alpha = 2.91$, $\lambda = 0.18$) without considering the interannual variance in precipitation, deep blue, or considering the interannual variance, blue; micro-irrigation with the intervention point and target level as $10\%$ (Cyan), $20\%$ (Yellow), and $30\%$ (Red), respectively. d) Ejina, with random floods ($\alpha = 300 +$, $\lambda = 0.02$) and rainfall ($\alpha = 2.06$, $\lambda = 0.19$, in blue), floods increase with $50\%$ (Cyan), $100\%$ (Yellow) in frequency during each growing season, or water would be delivered to this region whenever soil moisture dropped to the wilting point (Red); the corresponding probability density function lines, calculated using the rainfall parameters averaged throughout the study period, are also presented as a reference (deep blue).