Estimation of phreatic evaporation in irrigation agriculture using stable isotopes

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Abstract

Agriculture in the Aral Sea basin is the main consumer of water resources and due to the current agricultural management practices inefficient water usage causes huge losses of freshwater resources. There is huge potential to save water resources in order to reach a more efficient water use in irrigated areas. Therefore, research is required to reveal the mechanisms of hydrological fluxes in irrigated areas. This paper focuses on estimation of one of the crucial components in the water balance of irrigated areas - phreatic evaporation (E_p), i.e. evaporation from (shallow) groundwater - using stable isotopes of water. Our main objective was to estimate the rate of phreatic evaporation on sites with different soil texture and ground water tables (GWT) and investigate the relationship between these environmental parameters and the E_p rate. Soil samples were collected in various soil depths from irrigated areas in Ferghana Valley (Uzbekistan). The soil water from these samples was extracted via a cryogenic extraction method and analyzed for the isotopic ratio of the water isotopes (2H and 18O) based on a laser spectroscopy method (DLT 100, Los Gatos USA). A total of 18 soil profiles in fields under cotton have been analyzed. Estimations of phreatic evaporation rates were evaluated in dependence of soil texture and groundwater table. Annual amounts of water losses via phreatic evaporation were calculated between 104 to 349 mm, accounting for 35.1 % of mean irrigation water. Ep rates significantly increase with decreasing depth to GWT. There also exist difference of Ep rate between different soil texture classes with lower rates on sandy and loamy soils as and higher rates on clay. We conclude that site specific groundwater level managing can reduce phreatic losses substantially, providing an efficient and easy adaptable way to improve irrigation and leaching practices.

Keywords

Deuterium, Oxygen-18, groundwater, evaporation, Ferghana Valley, Central Asia

1. INTRODUCTION

More than 90% of the water resources in the Aral Sea basin are used for irrigation (UNEP, 2005). This excessive utilization of water resources is the major reason that led to the drying out of the Aral Sea in the past decades (Micklin, 2007). There is huge potential to save water resources and increase land and water productivity in order to reach a more efficient water use in Central Asia, and to potentially restore the Aral Sea.

Water balance in the irrigated territory of Central Asia has been in the focus of research of many scientists for many years (Amanov, 1967; Ganiev, 1979; Kharchenko, 1979; Yakubov et al., 1985; Dukhovny, 1993; Ikramov, 2000).They have investigated various water balance elements, including water intake, return flow of irrigation water into the channel and river system, evaporation, transpiration, soil moisture, and groundwater dynamics.

In recent years, a groundwater table (GWT) rise has been observed in many irrigated areas of Central Asia as a result of inefficient irrigation practices (Ikramov, 2000; Ibrakhimov et al., 2011). This has also been observed by measurements of GWT dynamics over the vegetation periods in Ferghana Valley which will be in the focus of this study (IWRM Ferghana, 2002). A rising GWT induces a rise of the capillary fringe. This dynamic largely contributes to salinization of soils where a secondary precipitation of groundwater salts occurs by the transport into the unsaturated zone. The raised capillary fringe also maintains adequate soil moisture conditions in the root zone. This is a potential positive though not intended side effect for plants which are provided with an additional water source. However, the raised groundwater table is prone to indirect evaporation loss of groundwater through the unsaturated zone, which we will refer to as phreatic evaporation (E_p) subsequently. Studies on water losses through phreatic evaporation in Central Asia remain sparse. Ganiev (1979), Ikramov (2000) and Parfenova (1982) used lysimeters for long-term monitoring of upward and downward water fluxes. Ganiev [1979] estimated that 80 - 930 mm a^{-1} of water is lost through phreatic evaporation in cotton fields at various GWT depths.

However, lysimeter studies often are invasive and costly (in case large soil columns are used) or do not represent processes over an entire soil column down to groundwater. Therefore, isotope studies with much less destructive character provide an alternative to assess phreatic evaporation. More importantly, the isotope approach allows the investigation of hydrologic processes in the vadose zone in a more integrated way.

In recent years, stable isotopes of water have been used in studies to estimate evaporation from groundwater. The method makes use of the fact that during the process of evaporation, light and heavy isotopes fractionate, e.g. light isotopes of oxygen and hydrogen evaporate earlier than heavy isotopes, thus leading to an enrichment of heavy isotopes in the soil water. The theoretical background was first established through the development of a model by Craig and Gordon (1965) which describes the movement of isotopes that evaporate from an open water surface into the atmosphere. Zimmermann et al. (1968) describe an exponential depletion of deuterium with depth in a saturated soil profile, causing a distinct signature of the isotopes in the soil column. Muennich et al. (1980) and Barnes and Allison (1983) extended this concept to unsaturated soils. Fractionation of isotopes is due to different chemical potentials of the isotope species. This difference causes a slightly increased affinity for the vapor phase for lighter isotopes (Barnes and Turner, 2006). The effect can be used to identify hydrological processes and sources. The isotopic signature in a soil column can be used to quantify the intensity of upward water fluxes and the amount of evaporation from groundwater. Brunner et al. (2008) applied the concept in an arid catchment in north-western China to estimate phreatic evaporation rates. They found that in particular for very shallow GWTs (< 0.5 m), evaporation rates equal 0.55 m a^{-1} with potential evaporation approximately 1.4 m a^{-1}.

In this study we want to refine our knowledge of water losses through phreatic evaporation in agricultural areas in Uzbekistan. We make use of the stable water isotope approach that has the advantage of providing an integrated measure over relatively long periods of time. The aim of our study is to investigate the spatial patterns of the phreatic evaporation rate on irrigated cotton fields in Ferghana Valley. In specific, we want to quantify the relationship between various environmental parameters such as soil texture and groundwater table to the phreatic evaporation rate. The results will be essential for water management planners in order to allow a more sustainable use of irrigation water in the area.

2. METHODS

2.1. Study area

Our sampling sites are located in Ferghana Valley, Uzbekistan (Figure 1a). Ferghana Valley represents an intermountain depression surrounded by the Tien-Shan and the Alai Mountain Ranges. The valley is approximately 300 km long from west to east and up to 150 km wide from north to south, forming area of 22,000 km^2 (Maksudov and Abdullaev, 2001). The continental climate conditions in the region are characterized by a mean temperature of 27°C in July and -1.3°C in January (Chub 2007). The mean annual precipitation in this region is 150-200 mm (Chub 2007), while potential annual evapotranspiration is approximately 850-1200 mm (Chub, 2007). The Ferghana Valley is drained by the Syr Darya River (Figure 1b) and numerous mountain streams that are fed by glaciers in the mountains (Horst et al., 2005). The Great and the North Ferghana Canals deliver water from Kara Darya and Naryn to areas situated north and south of the Syr Darya (Figure 1b). Their waters are used for irrigation. The mean annual gross irrigation amount varies between 270 and 880 mm, and depends on soil type and GWT (Legostaev and Mednis, 1971).

The study area is located within a proluvial plain (Stulina et al., 2005) where the soils were formed from material which was washed down from the mountains (Jefferson, 2004). The prevalent soil types of the region are grey soils, which are heterogeneously layered, mainly light textured, gypsum-bearing and contain high contents of carbonates (Stulina, 2002). The particle sizes span the whole range from clay to sand with the dominant grain sizes in the lighter fraction (Stulina, 2002).

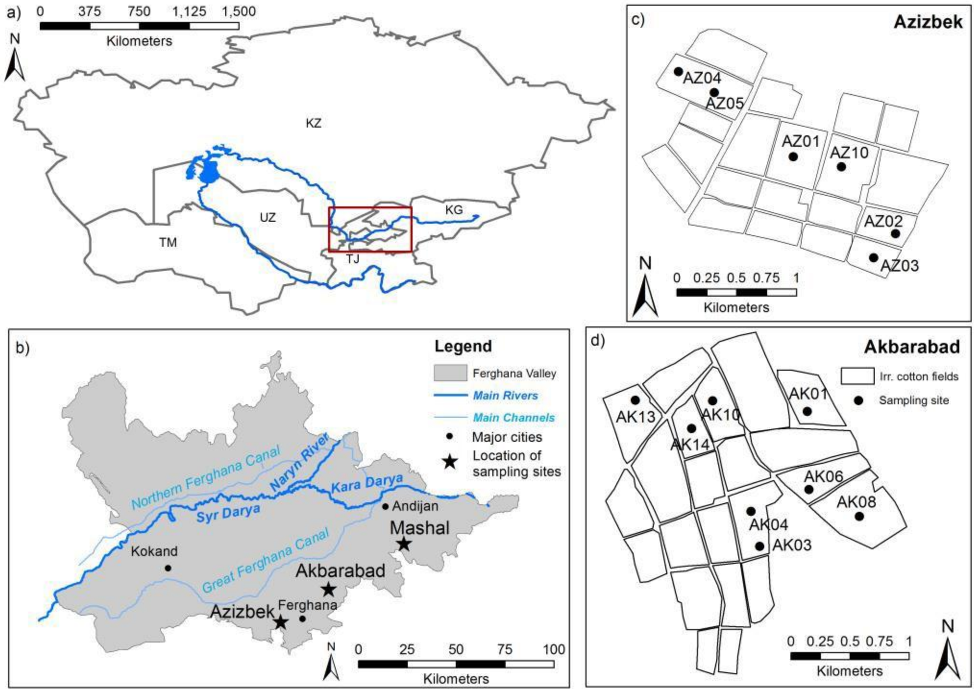

Figure 1. The location of Ferghana Valley in Central Asia (KG = Kyrgystan, KZ = Kazachstan, TJ = Tadjikistan, TM = Turkmenistan and UZ = Uzbekistan) (a) and the location of the three Water User Associations (WUAs) Akbarabad, Azizbek and Mashal in Ferghana Valley (b). The sampling sites within the WUAs Azizbek and Akbarabad are shown in (c) and (d), respectively.

2.2. Field work

Sampling was done on irrigated cotton fields in the three Water User Associations (WUAs) Azizbek, Akbarabad and Mashal (Figure 1b) which are situated in the southeast of the valley (Figure 1b). Soil samples were collected for isotope analysis of the soil water in July and August 2010. We used a stratified sampling design with soil type and depth to GWT as stratifying variables. Soil type and groundwater maps were provided by the Scientific Information Centre of Interstate Coordination Water Commission (SIC-ICWC). Soil types and depth to GWT were each classified into 3 classes (sand, loam, and clayey loam and 0-1 m, 1-2 m and 2-3 m, respectively). Both variables were combined which resulted in 9 sampling classes for the two WUAs Azizbek and Akbarabad. From each resulting class, 2 replicates were taken. In case no combination of soil type and depth to GWT was present in either of the two WUAs, samples were alternatively collected at 2 sampling points in the WUA Mashal. This applied for the combination clayey loam and depth to GWT < 1 m. Our sampling design added up to 18 samples collected in all three WUAs. The sandy and loamy soil sites were collected on consecutive days to increase the number of samples per soil type.

Soil samples were taken from surface soil till GWT in 0.1 m increments (from the surface to 0.5 m depth) and in 0.3 m increments (from 0.5 m depth to GWT), in order to determine the isotope profile over depth. Soil samples were filled into airtight glass vials (100 ml), sealed with Parafilm® to avoid evaporative losses and weighed. The soil samples were kept cool until water extraction in the laboratory to avoid evaporation loss. Additionally, soil samples were collected for analyses of soil moisture, bulk density and texture. Gravimetric water content and bulk density were analysed in the laboratory of the Ferghana affiliate of Central Asian Scientific Research Institute of Irrigation (SANIIRI). Samples of rain, irrigation and groundwater were sampled in 2 ml glass vials, sealed airtight with Parafilm® and also analysed for water isotopic signatures.

2.3. Soil water extraction

Soil water was extracted by cryogenic vacuum distillation at the Institute of Landscape Ecology and Resources Management (ILR) water isotope laboratory of Justus-Liebig-University, Giessen, Germany (Orlowski, 2010). The principle of the cryogenic vacuum distillation is to evaporate soil water at 70° Celsius under static vacuum ($2 \cdot 10^{-2}$ mbar). The evaporated water was captured and stored in Dewar flasks filled with liquid nitrogen. Before starting the extraction, atmospheric gas was completely drawn off the system to avoid changes of the original isotope composition. The extraction process was conducted for 3 h to assure that all water had been withdrawn. After extraction, the trapped water was subsequently thawed at room temperature. The water was then transferred into glass vials (2 ml). Soil samples were weighed before and after extraction to calculate gravimetric water content and compare them to the water content which was measured in SANIIRI shortly after sampling in the field to check whether water losses due to diffusion during soil storage occurred.

2.4. Isotope analyses

The isotopic composition of soil waters was determined using a liquid water isotope analyzer (DLT 100, Los Gatos Research) based on an off-axis integrated cavity output spectroscopy (OA-ICOS). This methodology uses the different absorption properties of molecules to determine the isotopic composition of a sample. The optical absorption is converted into the isotopic composition in the water sample by comparing it with a standard water sample of a known isotopic composition.

Our lab analyses followed the IAEA operating procedure (International Atomic Energy Agency, 2009) .The DLT 100 was used in combination with a LC-PAL autosampler (CTC Analytics). Each sample was injected 6 times from which the values of the first three injections were discarded to reduce memory effects, and the results of the remaining three injections were averaged. See also details given on the lab procedure in Barthold et al. (2010). All values are reported in per mil [‰] units relative to Vienna Mean Ocean Water Standard (VSMOW). Accuracy of the measurements for ^2H and ^{18}O are 0.56 ‰ and 0.13 ‰, respectively.

2.5. Calculation of phreatic evaporation

We applied the concept of Barnes and Allison [1983] to estimate phreatic evaporation rates in soil profiles with varying texture classes and GWTs. They propose a relationship between depth to groundwater and evaporation rate which in turn can be included in a groundwater model to calculate phreatic evaporation. Brunner et al. [2008] adopted the method, where the phreatic evaporation rate formula relates two environmental processes: Ficks law on isotopic composition between air/water and Darcy`s law on capillary rise in a soil profile:

$$\lambda = z_v + z_l = \frac{1}{E_p}\left(\theta \cdot f \cdot D + f \cdot D_v (n-\theta)\frac{N^{sat}}{\rho}\right) \qquad (1)$$

with λ – decay length of isotopes in soil profile (-); z_v and z_l – length scales of vapor and liquid water diffusion (m); E_p - phreatic evaporation rate (mm a^{-1}); θ – gravimetric water content (g cm^{-3}); f – tortuosity factor of soil (-); n – porosity factor of soil (m^3 m^{-3}); D (D_v) – self-diffusion (molecular) coefficient for liquid (vapor) water (m^2 s^{-1}); N_{sat} – density of saturated water vapor (kg m^{-3}); ρ – density of liquid water(kg m^{-3}).

To estimate the amount of irrigation water lost through phreatic evaporation, 3 different GWT classes were grouped and the mean annual E_p rate (estimated with δ^2H) was calculated for each class. Mean annual irrigation amounts for the same GWT classes were calculated using the concept of hydromodel zones by Legostaev and Mednis (1971) in order to estimate how much of the irrigation water is lost through phreatic evaporation. The classes are 0 – 1 m (class 1), 1 – 2 m (class 2) and 2 – 3 m (class 3).

3. RESULTS AND DISCUSSION

3.1. δ^2H in the soil profile

The isotopic composition of soil water on all sites depict the distinct profile over depth as described in Barnes and Allison (1983).We present the δ^2H composition of three of the profiles that differ in soil texture in Figure 2. The range of δ^2H values of soil water in sandy and loamy soils between 1.2 and 0.2 m depth are similar (-82 – -84 ‰). In the same depths of a clayey loam soil in WUA “Mashal”, deuterium is more depleted, the values of δ^2H range between -88 - -90 ‰. Isotopic composition (δ2H) of groundwater and irrigation water is in the range of -79.4 - -82.2 ‰ and -78.9 - -82.6 ‰, respectively, in WUA “Akbarabad”. WUA “Mashal” is located upstream of WUA “Akbarabad” and hence, the groundwater here is with a value of -87.3‰ for δ^2H much more depleted. This indicates that these are the source waters for the clayey loam soil. However, the soil water in the sandy and loamy soil are in parts even more depleted than the irrigation and groundwater and indicate mixing processes in the deeper soil layers.

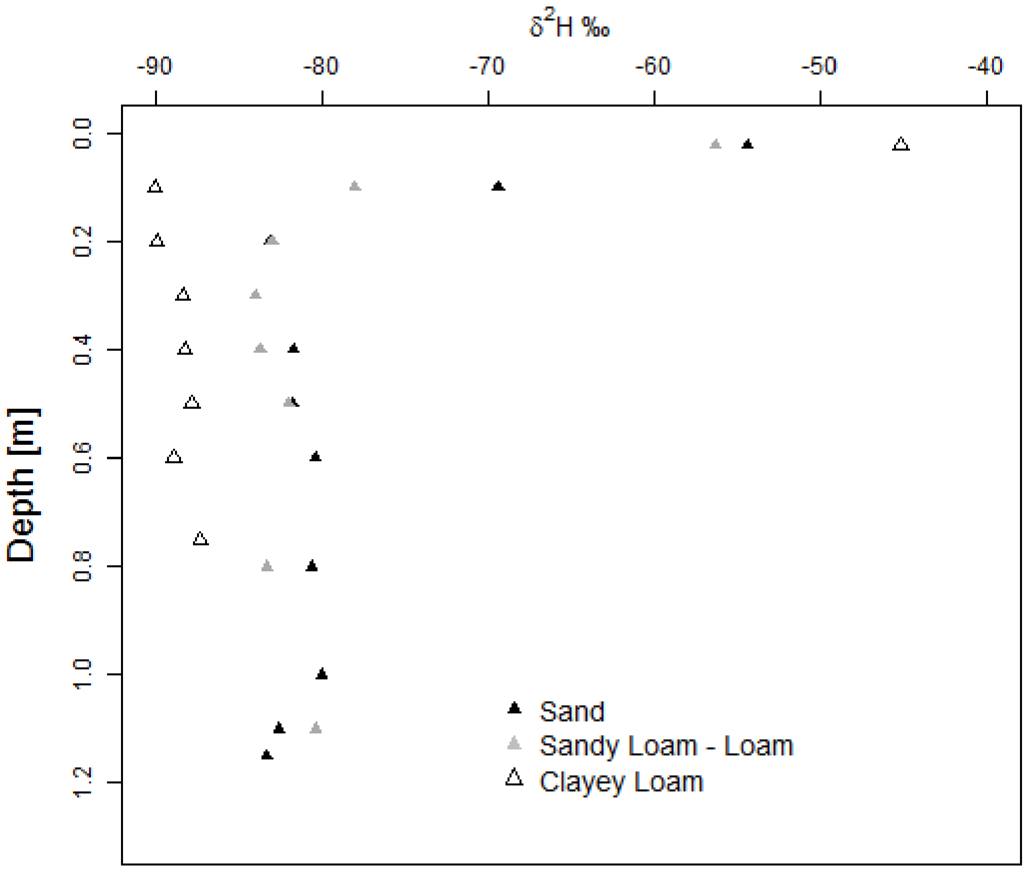

Figure 2. Example of deuterium enrichment in the upper soil layers of a sandy, loamy and clayey loam soil.

Above a depth of 0.2 m, soil water δ^2H increases in sandy and loamy soils, whereas the δ^2H enrichment in the clayey loam soil starts only above 0.1 m. At the ground surface level (0.02 m) the clayey loam soil is more enriched with heavy isotopes (-45‰) compared to loamy (-56.3‰) and sandy (-54.3‰) soils. Even when considering the accuracy of isotope measurements, these differences indicate a variable strong influence of soil texture on natural processes, i.e. evaporation. In the clayey loam soil, the capillary water rises higher than in loamy or sandy soils. This condition promotes evaporation of near surface soil water in clayey soils and may lead to this pronounced difference between δ^2H enrichment in near surface soil layers in clayey loam versus loamy and sandy soils. While soil water in clayey soils is more enriched in near surface soil layers than loamy and sandy soil, enrichment processes do not occur below a depth of 0.1 m. In contrast, in sandy and loamy soils enrichment takes place also in deeper depths than in the clayey loam soil. However, enrichment in loamy and sandy soils does not occur in depths below 0.2 m. The question now arises, which situation promotes a greater loss of water: clayey loam soil with higher water holding capacity but allowing evaporation in a very small surface soil layer only- or loamy and sandy soils where the pore space is much smaller?

3.2. Phreatic evaporation rate

The isotope profiles of all sites were used to estimate the phreatic evaporation rate by fitting an exponential curve to the isotope profile. This provides a decay length value (λ) (Table 1) which is a crucial factor of Equation 1. Solving Equation 1 for E_p results in an annual evaporation rate of 45-154 mm a^{-1} in sandy soils, while in loamy and clayey loam soils it reaches values of 129-245 mm a^{-1} and 167-349 mm a^{-1}, respectively (Table 1). These values were estimated using the δ^2H profiles. EP values estimated using d^{18}O result in slightly lower values (Table 1). Among the 18 sites, 1 profile showed an $R^2 < 0.6$ indicating a high uncertainty of the estimated E_p rate (AK07 on sand, Table 1). This uncertainty may be due to errors during the sampling campaign. This profile was excluded from further analysis. Also, samples from one clay loam site were lost which is why this class is represented by only 5 samples.

Soil texture	Ground water table by classes, m	GWL	R^2 of ^2H and ^{18}O	Field code	^2H			^{18}O		
					λ	R^2 of λ	E_P, mma^{-1}	λ	R^2 of λ	E_P, mma^{-1}
sand	0-1	0.8	0.99	AK06	0.073	0.879	154	0.079	0.923	143
		0.8	0.99	AK08	0.086	0.909	147	0.091	0.933	141.6
	1-2	1.05	0.96	AK07	0.219	0.341	45	0.355	0.403	28
		1.7	0.99	AK04	0.071	0.913	139	0.073	0.926	135
	2-3	2.1	0.99	AK03	0.095	0.68	104	0.098	0.69	101
		2.6	0.76	AK05	0.101	0.769	107	0.158	0.914	68
sandy loam-loam	1-2	1.10	0.99	OK07	0.064	0.859	226	0.061	0.865	237
		1.10	0.88	OK08	0.077	0.906	188	0.116	0.782	125
		1.2	0.95	OK04	0.059	0.779	245	0.071	0.859	203
		1.2	0.99	AK10	0.079	0.857	182	0.074	0.86	194
		1.5	0.96	AK11	0.053	0.776	230	0.064	0.87	190
	2-3	2	0.96	AK14	0.100	0.846	150	0.111	0.898	135
		2	0.93	AK01	0.124	0.844	129	0.174	0.848	113.0
		2.1	0.97	AK13	0.098	0.914	132	0.114	0.96	113
		2.4	0.95	AK02	0.094	0.82	131	0.115	0.897	107
Clay loam	0-1	0.75	0.99	MA01	0.048	0.88	349	0.065	0.87	258
	1-2	1.7	0.98	OK02	0.073	0.908	215	0.089	0.934	177
	2-3	2.2	0.99	OK03	0.078	0.87	198	0.075	0.875	206
		2.5	0.97	OK10	0.092	0.762	178	0.096	0.808	157
		2.6	0.93	OK09	0.090	0.743	167	0.139	0.816	108

Table 1. Estimated phreatic evaporation rate (Ep) in different soil types and at various groundwater tables (GWTs) is provided with the goodness-of-fit (R^2) for each profile (AK = WUA Akbarabad, AZ = WUA Azizbek, Ma = WUA Mashal.

The main objective of our study was to quantify the amount of water evaporating from groundwater under water management, and to investigate the influence of soil texture and depth to GWT on the estimated E_p rate. We plotted the estimated E_p rate in groups of soil texture as a function of the groundwater table (Figure 3). The E_p rate decreases with increasing depth to GWT. Linear regressions show that the E_p decreases are significant on a 0.01 significant level for all soils except for the clay loam estimated with $\delta^{18}O$ (Table 2). Figure 4 not only shows the significant influence of the GWT on the E_p rate (slope of regression > 0) but also shows the different y-intercepts that are produced by the different texture classes sand, loam and clay loam indicating differences in E_p due to the different texture class. The E_p rate increases from sandy soil to clayey loam soil. E_p rates estimated with ^2H and ^{18}O isotopes in sandy soil profiles give with very close values, which is not the case for loamy and clayey loam soil profiles. In these soil profiles, E_p rates estimated with ^2H are higher than with ^{18}O in most of the cases. The reason for that may be uncertainties of the water extraction process of soil samples. Further experiments on water extraction indicate that soil water in loamy and clayey loam soils have not been completely extracted during 3 hrs. The correlation coefficients (R^2) of ^2H and ^{18}O are 0.99 for sandy soil and 0.93-0.99 for isotopes of loamy and clayey loam soil (Table 2). However, these differences are not significant from each other.

Our results indicate that E_p increases with decreasing particle size. This contradicts the findings of Coudrain-Ripstein et al. (1998) who showed that soil texture does not influence the E_p rate. However, a test for statistical significance of this relationship due to the small sample size of clayey loam sites is not possible yet.

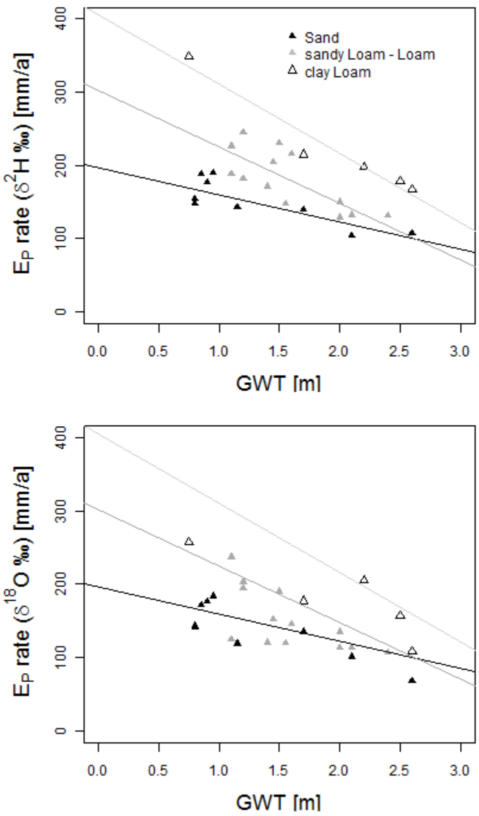

Figure 3. Relationship between phreatic evaporation rate (E_p) and depth to groundwate table (GWT) of soils with different texture.

We compared annual E_p rates estimated in our study with those calculated by Ganiev (1979) for the same region. Overall it is visible that in all soil profiles E_p rate is at maximum when the GWT is shallow (Figure 5). Annual E_p rates in loamy soils are much lower than in clay loam soils, despite that clay loam soils allow evaporation only in a very small surface soil layer (Figure 3 and Table 1). Our findings correspond well with results from Ganiev (1979) only for sandy loam soils. The author estimated annual E_p rates for sandy loam soils between 120-230 mm at GWTs between 1 and 2 m (Figure 5), while our values are 129-245 mm a^{-1}on ^{2}H and 113-237 mm a^{-1} on ^{18}O at the same GWT range (Table 1). Annual E_p rates for clay loam in our study are much lower (167-349 mm a^{-1} on ^{2}H and 108-258 mm a^{-1} on ^{18}O) in comparison to those from Ganiev (1979) (340-810 mm a^{-1}).

These differences between E_p rates in our study and in the experiment of Ganiev (1979) could be attributed to the fact that with the isotope approach we estimate the evaporation rate only, while in lysimeter studies evapotranspiration is calculated. In addition, some E_p rates estimated by Ganiev [1979] are equal to potential evapotranspiration (1000 mm a^{-1}) or to the amount of applied irrigation water for cotton (270-880 mm as cited in Legostaev et al. [1971]).

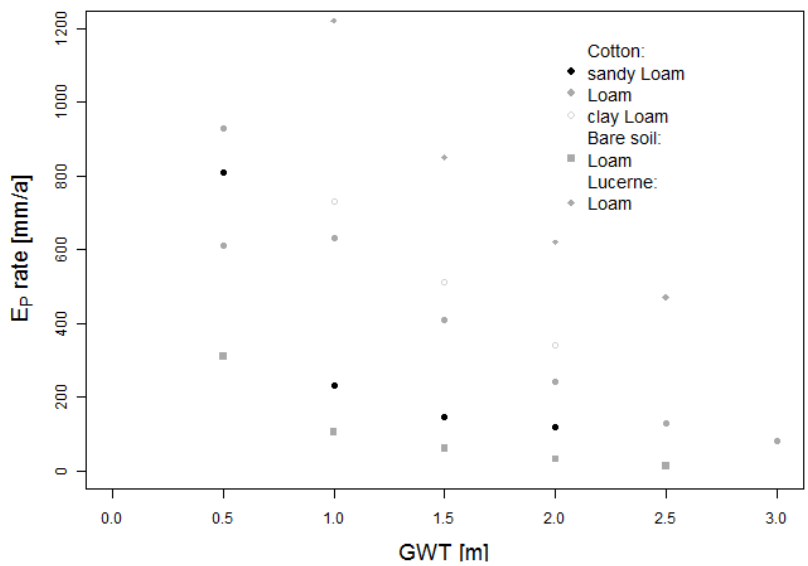

Figure 4. Estimated phreatic evaporation rates (E_p) in different soil types at various groundwater tables measured with lysimeters by Ganiev (1979).

The share of irrigation water to E_p was calculated for the 3 GWT classes 0 – 1 m (class 1), 1 – 2 m (class 2) and 2 – 3 m (class 3) from mean annual E_p rate for each GWT class and mean annual irrigation amounts for the corresponding hydromodel zone which are 500 mm (class 1), 613 mm (class

2) and 740 (class 3). Mean annual E_p for shallow GWTs (class 1) is 217 mm a^{-1} which is 43% of the mean irrigation water in hydromodel zones with GWT between 0 – 1 m. The mean E_p for class 2 is 184 mm a^{-1} (30 % of irrigation amount) and for class 3 it is 144 mm a^{-1} (19 % of irrigation amount). The annual mean E_p of all GWT classes is 181 mm a^{-1}. This is 29 % of the mean irrigation water amount on the three hydromodel zones. The differences of lost water through E_p depending on GWT already indicate that a more efficient management of the GWT would reduce water that is actually needed for irrigation.

4. CONCLUSIONS

We applied a stable isotope approach to estimate phreatic evaporation in irrigated cotton fields in Ferghana Valley, Uzbekistan, and established a relationship between the phreatic evaporation rate and soil texture and groundwater level. Our results show that due to their larger water holding capacity clay soils lose more water through evaporation than loamy and sandy soils. The results show that evaporation from groundwater is a major component of the field scale hydrological cycle in the study area, in particular when the groundwater table is close to soil surface. Water that is transported into the atmosphere through phreatic evaporation is not used for biomass production by plants and hence not used in an efficient way. Decreasing phreatic evaporation by introducing adjusted irrigation schemes hence could improve water use efficiency in irrigation agriculture in the study region. Further studies will assess whether there is a threshold depth of GWT which decreases phreatic evaporation significantly and thus a “GWT threshold target” could be implemented into field water management plans. A more profound look at the temporal development of GWTs and E_p rates can also help to develop efficient water management plans.

Acknowledgments

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5. REFERENCES

Amanov, H., 1967. Estimation of total water consumption in cotton field with high groundwater level. Hydrotechnique and Melioration 7, 57-61. (In Russian).

Barnes, C.J., Allison, G.B., 1983. The distribution of deuterium and 18O in dry soils: 1. Theory. Journal of Hydrology 60, 141-156.

Barnes, C.J., Turner, J.V., 2006. Isotopic Exchange in Soil Water, in: Isotope Tracers in Catchment Hydrology, Advances in Water Resources. Elsevier, Amsterdam, pp. 157-163.

Barthold, F.K., Wu, J., Vaché, K., Schneider, K., Frede, H.G., Breuer, L., 2010. Identification of geographic runoff sources in a data sparse region: hydrological processes and the limitations of tracer-based approaches. Hydrol. Process.

Brunner, P., Li, H.T., Kinzelbach, W., Li, W.P., Dong, X.G., 2008. Extracting phreatic evaporation from remotely sensed maps of evapotranspiration RID D-1372-2010. Water Resour. Res. 44.

Coudrain-Ribstein, A., Pratx, B., Talbi, A., Jusserand, C., 1998. Is the evaporation from phreatic aquifers in arid zones independent of the soil characteristics? Comptes Rendus Acad. Sci. Ser II-A 326, 159-165.

Craig, H., Gordon, L.I., 1965. Deuterium and oxygen-18 variations in the ocean and marine atmosphere, in: Stable Isotopes in Oceanographic Studies and Paleo-Temperatures. Consiglio Nazionale delle Ricerche Laboratorio di Geologia Nucleare, Pisa, pp. 9-130.

Chub,V., 2007. Climate change and its impact on hydrometeorological processes, agro-climatic and water resources in the Republic of Uzbekistan. «Voris-Nashriyot» Tashkent (InRussian)

Dukhovny, V.A., 1993. Land reclamation and water resources management in the arid zone. (In Russian).

Ganiev, K.G., 1979. Evaporation and infiltration of groundwater. Tashkent, Uzbekistan. (In Russian).

Hillel, D., 2003. Solute Movement and Soil Salinity, in: Introduction to Environmental Soil Physics. Academic Press, pp. 167-186.

Horst, M.G., Shamutalov, S.S., Pereira, L.S., Gonçalves, J.M., 2005. Field assessment of the water saving potential with furrow irrigation in Fergana, Aral Sea basin. Agricultural Water

Management 77, 210-231.
Ibrakhimov, M., Martius, C., Lamers, J.P.A., Tischbein, B., 2011. The dynamics of groundwater table and salinity over 17 years in Khorezm. Agricultural Water Management 101, 52-61.
Ikramov, R., 2000. Principles of water-salt regime management of irrigated lands in Central Asia under condition of water resources shortage. “HydroInGeo”, Tashkent (In Russian).
International Atomic Energy Agency, 2009. Laser Spectroscopic Analysis of Liquid Water Samples for Stable Hydrogen and Oxygen Isotopes, Trainings Course Series. Vienna.
IWRM Ferghana, 2002. Integrated Water Resources Management in Fergana Valley (No. 7). SIC ICWC, Tashkent, Uzbekistan.
Jefferson, I., 2004. The engineering geology of loess ground: 15 tasks for investigators - programme of loess research. Engineering Geology 74, 33-37.
Kharchenko, S.I., 1979. Hydrology of irrigated lands. Hydrometeoizdat, Leningrad. (In Russian).
Legostaev, V.M., Mednis, M.P., 1971. Irrigation regime and hydromodule zone of Uzbekistan. Tashkent, Uzbekistan (In Russian).
Letolle, R., Mainguet, M., 1995. Der Aralsee: Eine ökologische Katastrophe, 1st ed. Springer.
Maksudov, A., Abdullaev, M., 2001. Geography of Central Asia. Ferghana State University, Ferghana, Uzbekistan.
Micklin, P., 2007. The Aral Sea Disaster. Annual Review of Earth and Planetary Sciences 35, 47-72.
Micklin, P.P., Williams, W.D., 1996. The Aral Sea Basin, NATO ASI Series. Springer-Verlag.
Muennich, K.O., Sonntag, C., Christmann, D., Thomas, D., 1980. Isotope fractionation due to evaporation from sand dunes. 2. Mittl. Zentralinst. Isot. Strahlenforsch 29, 319-332.
Orlowski, N., 2010. Construction and specification of a cryogenic vacuum extraction device for application in stable water isotope analysis (MSc Thesis).
Parfenova, N.I., 1982. Prognoses of mineralisation of groundwater in irrigated areas. Hydrotechnique and Melioration, 7 (in Russian).
Stulina, G., 2002. Water and Salt Transfers. Experimentation and modelling with RZWQM, ISAREG and KCISA (No. Final scientific report). Department of Agricultural Engineering, Institute of Agronomy, Technical University of Lisbon, Lisbon, Portugal.
Stulina, G., Cameira, M.R., Pereira, L.S., 2005. Using RZWQM to search improved practices for irrigated maize in Fergana, Uzbekistan. Agricultural Water Management 77, 263-281.
UNEP, 2005. Severskiy, I., Chervanov, I., Ponamarenko, Y., Novikova, N.M., Miagkov, S.V., Rautalahti, E. and Daler. D. Aral Sea, GIWA Regional assessment 24. University of Kalmar, Kalmar, Sweden.
Yakubov, K.I., Kurbanbaev, E., Petrakova, S.K., 1985. Water-salt regime of Southern Karakalpaki´s soils and its management. Karakalpakistan, Uzbekistan (in Russian).
Zimmermann, U., Ehhalt, D., Muennich, K.O., 1968. Soil - water movement and evapotranspiration: Changes in the isotopic composition of the water. Proceedings of the Symposium on Isotopes in Hydrology, Vienna, 567-85.