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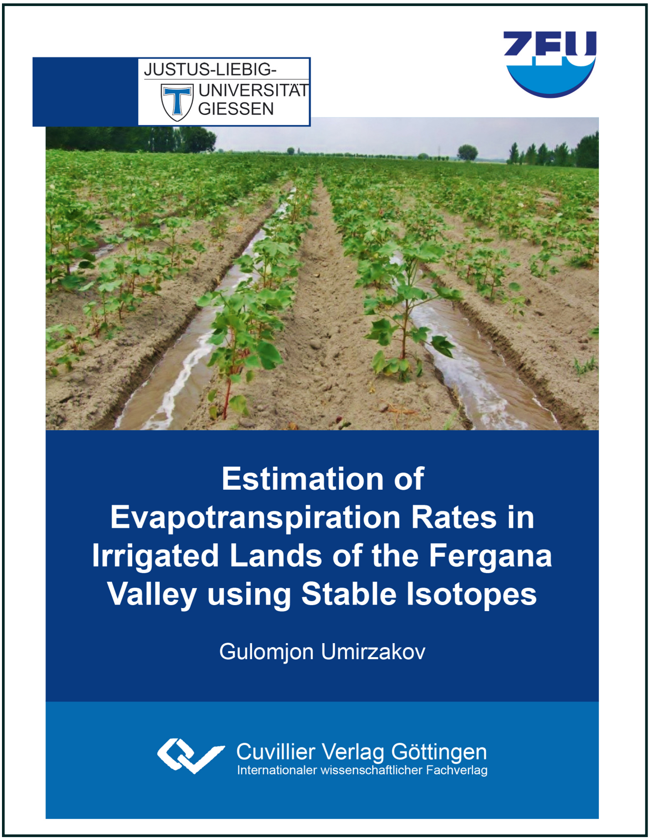

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Estimation of Evapotranspiration Rates in Irrigated Lands of the Fergana Valley using Stable Isotopes

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1 INTRODUCTION

1.1 BACKGROUND

Water plays a vital role in agricultural sector of Uzbekistan, which is situated in the Aral Sea basin. Although huge water resources (133 km^3) exist in the Aral Sea basin (Dukhovny, 2010), water distribution is a “hot” topic in Uzbekistan during last decades (Dukhovny and Schutter, 2011). Inadequate seasonal distribution of the transboundary rivers’ water flow leads to water scarcity problems in Uzbekistan. A simple solution for this problem would be a water flow regulation. In the last century large water reservoirs, e.g. Tokhtagul, Kayrakkum, Chardara, Tuyamuyin reservoirs were constructed for the multipurpose use of water resources in the Aral Sea basin. Changes in political and socio- economic situation in nineties of the last century in the region have increased the tension over the water resources (Dukhovny, 2010; O’Hara, 2000) which triggered issues and conflicts among different water users, especially between agricultural and energy sectors (Abbink et al., 2005). Positive population growth (1.4±0.2 %; UzStat, 2014) in the country is also being the main factor of increasing water scarcity in Uzbekistan. Moreover, under global climate change there is a change in water resources formation and distribution (Chub, 2007; Radchenko et al., 2014) and at the same time increase in evaporation loss due to global warming (Lioubimtseva and Henebry, 2009).

Namangan, Fergana and Andijan regions in the Fergana Valley, which belong to the Republic of Uzbekistan, constitute 4.3% of the total area of the country, and population in these regions constitute more than ¼ of total population of the republic (UzStat, 2014). The socio-economic situation in the Fergana Valley is getting complicated by population growth that dramatically increases the ecosystem load on using natural resources (IWRM-Fergana, 2009). Agriculture plays a leading role in the economy of the Fergana Valley, providing 30 % of the GDP in 2009 (IWRM-Fergana, 2009). Moreover, about 50 % of the population of the region is employed in agriculture (IWRM-Fergana, 2009). It is expected, agriculture will retain its leading role in the economy of the Fergana Valley in the future (IWRM-Fergana, 2009).

Welfare of the social and environmental sustainability of the Fergana Valley is largely determined by the quality and availability of water and land resources. Water in the Valley is formed in the mountain areas – in the upper river basins, where total mineralization is less than 0.3 g l^{-1} and chloride and sulfates concentration is low. Water quality then significantly worsens in the downstream of the Syrdarya River in the Fergana Valley, as a result of contaminated wastes from industry and households, as well as polluted collector-drainage water. For example, annually collector-drainage water washes off about 20 mil. tons of salts from the irrigated lands into the Syrdarya River. This causes increase in water mineralization in the Syrdarya River from 0.3-0.6 mg l^{-1} at the upstream up to 3.0m l^{-1} at the downstream of the Fergana Valley.

In arid regions, the evapotranspiration is one of the main components of the water balance at irrigated fields (Abtew and Melesse, 2001). An accurate estimation of evapotranspiration is important to calculate a water balance at various scales. It is also essential to partition the evapotranspiration into soil evaporation and plant transpiration in order to better understand the water dynamics and the soil-plant-atmosphere interaction, and evaluate water use efficiency (Forkutsa, 2006). Many studies have been conducted to estimate the evapotranspiration at irrigated fields in arid areas (Alimov, 1965; Allen et al., 1998; Angus and Watts, 1984; Dukhovny et al., 2005; Dukhovny and Milkis, 1977; Ganiev, 1979; Priestley and Taylor, 1972; Rysbekov, 1986; Shuttleworth, 1993) using various methods, like sub-flow, lysimeter, Bowen ratio, Eddy covariance. However, all those methods have some specific limitations, which were mostly based on empirical assumptions. Some other authors in their hydrological studies (Allison et al., 1983; Allison and Barnes, 1983; Melayah et al., 1996a; Singleton et al., 2004; Sonntag et al., 1985; Zimmermann et al., 1967) successfully used stable water isotopes (δ^2H and $\delta^{18}O$) to estimate the evaporation and transpiration. One of the main properties/behavior of stable water isotopes is that changing concentration ratios of molecules' isotopes during water movement from one phase to another, which causes *isotope fractionation*. Isotope fractionation usually occurs during the transition of water phases, e.g. condensation – vaporization, melting-freezing. The stable isotope mass balance method is one of the most used approaches in isotope hydrology in the last 20 years (Ferretti et al., 2003; Hsieh et al., 1998; Robertson and Gazis, 2006; Sutanto et al., 2012a; Wang et al., 2012; Wenninger et al., 2010). As a result of evaporation, the soil water content and soil water isotope composition change due to isotope fractionation. Although transpiration process also leads to the fractionation of the water isotopes, it only occurs on the leave stomata, while root uptake does not fractionate (Ehleringer and Dawson, 1992). Therefore, the soil water content is influenced by both, soil evaporation and plant transpiration, whereas soil water isotope composition is formed by only evaporation process. This allows to partition the soil evaporation from transpiration, while observing soil moisture and isotope signatures of the soil profile (Hsieh et al., 1998).

1.2 GOAL AND OBJECTIVES OF THE STUDY

The main aim of the research is to estimate evaporation and transpiration rates as well as deep percolation at the irrigated lands under cotton in the Fergana Valley using stable isotopes mass balance. In addition, the soil water extraction investigations were conducted to better understand the isotope behavior and properties.

Although a number of studies were conducted to estimate evaporation at the irrigation fields in Uzbekistan (Alimov, 1976; Forkutsa, 2006; Ganiev, 1979; Kenjabaev, 2014; Rysbekov, 1986), the method using stable water isotopes in the Fergana Valley was not applied before.

1.3 STRUCTURE OF THE THESIS

The dissertation consists of six chapters. Following the introduction part, Chapter 2 describes the different evapotranspiration estimation methods applied in irrigated lands, as well as properties of water stable isotopes (δ^2H and $\delta^{18}O$) and their application in hydrology. In addition, scientific investigations of water stable isotopes on estimation evaporation, transpiration and phreatic evaporation are summarized. After a general description of the study area given in Chapter 3, Chapter 4 is dedicated to the research methodology. Here description of the study site is provided and sampling period and processes are characterized in details. Soil water extraction techniques and cryogenic vacuum distillation processes are described as well. In addition, the laboratory work on analyzing the stable isotopes (δ^2H and $\delta^{18}O$) of the extracted water is demonstrated and consistency of the isotope mass balance formula is described.

In Chapter 5, the results and discussions are presented. Here the observed soil moisture condition and irrigation activities are validated. Then the isotope signatures of different water sources (irrigation, groundwater, precipitation) as well as soil and plant water are analyzed. Experiments on cryogenic water extraction of different soil types are evaluated. The effect of gypsum in the soil on isotope composition of extracted water is examined. Temporal changes of isotope profiles of soil water are analyzed and their behavior is studied. Isotope mass balance application for both stable isotopes – δ^2H and $\delta^{18}O$ – is carried out. Finally, assessment of evaporation partitioning from the total evapotranspiration, including deep percolation estimation, is performed. Chapter 6 closes with conclusions. In this chapter, the results of the research and the outcomes of the isotope mass balance are summarized. Based on the results, various recommendations and the feasibility of implication of those recommendations are described and analyzed.

The last section of the chapter gives an overall conclusion of the research and discusses the benefits of the modeling as well as modeling framework, research limitations and a need for further research.

2 LITERATURE REVIEW

2.1 EVAPOTRANSPIRATION ESTIMATION: BACKGROUND

Evaporation losses is one of the main components of the environmental water balance and hydrological cycle (Penman, 1948). Estimation of evaporation is the main objective of many scientific disciplines. Evaporation can be determined by direct measurements or estimated through hydro meteorological parameters. Evaporation pan and lysimeter are equipment for direct measurements, when Eddy correlation, Energy balance, and Bowen ratio are methods that are known as indirect empirical methods.

Pan evaporation measurements are based on estimation of the evaporation from the open water by monitoring the water level (Roderick and Farquhar, 2002). The pan evaporation rate is estimated from mass balance differences. Evaporation from the open water is estimated from the pan evaporation rate using pan coefficient, which depends on local environmental condition measurement operation (Abtew and Melesse, 2001). Reference crop evapotranspiration can also be estimated from the pan measurement using reference crop coefficients, which depend on the local meteorological parameters. Although this method represents direct evaporation measurement, the errors in calculations can be high and they are associated with the location of the evaporation pan, inaccuracies in installation, in finding flow abstraction, heat losses in the area surrounding the pan, etc. (Abtew and Melesse, 2001). Also, inaccuracy in rainfall measurements lead to errors in results (Strangeways, 2003).

Lysimeter measurements have been widely used in the past (Ayars and Hutmacher, 1994; Evett et al., 2012; Ganiev, 1979; Howell et al., 2004; Hutmacher et al., 1996; Ikramov, 2001; Kharchenko and Tishenko, 1966; Makkink, 1957; Rysbekov, 1986; Subbotin, 1976; Villalobos and Fereres, 1990). Lysimeter is the large measuring device installed in the field or laboratory to monitor the water balance in the selected section of the surrounding environment (Strangeways, 2003). There are two types of lysimeters: weighing and water balance lysimeters. Weighing lysimeters, mostly used in dry climatic conditions are constructed in a way allowing measurements of the evaporation and transpiration through the differences of the mass of the lysimeter. Water balance lysimeters are commonly used in the wet areas where precipitation rate is high (Abtew and Melesse, 2001). During installation of the lysimeters, it is very important not to disturb the natural conditions of the soil cover and soil profile. Disturbed soil profiles cause changes in the soil-water-plant interaction compared to the natural soil profile, and thus may increase uncertainties of the measurements. When properly installed, lysimeters provide rather accurate measurements of the evaporation (Strangeways, 2003). However, installation and operation of the lysimeters is laborious and costly.

There are several indirect evaporation and evapotranspiration (ET) estimation approaches based on wind speed and moisture content fluctuation correlation, such as Eddy correlation (Shuttleworth, 1993), use of Bowen ratio value in energy balance (Angus and Watts, 1984), among others. Beside indirect methods, there were many empirical models developed to estimate ET. These empirical models are based on a single or reduced number of weather parameters to compute ET (Shahidian et al., 2012). For example the temperature-based models such as Blaney-Criddle (Blaney and Criddle, 1950) and Hargreaves-Samani (Hargreaves and Allen, 2003) or the radiation models that are based on solar radiation, such as Priestly-Taylor (Priestley and Taylor, 1972) and Makkink (Makkink, 1957) models; the combining temperature and radiation model as Turc method (Turc, 1961), Abtew model (Abtew, 1996); and the combining models which are based on the energy balance and mass transfer principles (Penman, 1948), modified Penman (Monteith, 1965) and FAO Penman-Monteith (Allen et al., 1998). However, models based on mass balance, energy balance, Penman and Penman-Monteith methods are very complex (Allen et al., 1998). The Penman-Monteith (Monteith, 1981) method performs better than other ET methods compared to the lysimeter data (Chiew et al., 1995) and therefore is widely used in various regions (Allen et al., 1998; Baldocchi and Xu, 2007; Biggs et al., 2008; Shi et al., 2008; Summer and Jacobs, 2005).

In the last decades a remote sensing method has been successfully developed to estimate ET (Bastiaanssen et al., 1998; Nishida et al., 2003; Courault et al., 2005; Long et al., 2014). The estimation of ET in this method is based on the evaluation of the surface energy balance (Strangeways, 2003).

Another way to estimate evaporation is the application of stable isotopes. This method has been developed since the second part of the last century (Craig and Gordon, 1965; Zimmermann et al., 1967) and is currently widely used (Braud et al., 2005; Ferretti et al., 2003; Fry, 2006; Gat, 2010; Gaye and Edmunds, 1996; Gazis and Feng, 2004; Gibson, 2002; Hsieh et al., 1998; Kendall and McDonnell, 1998; Singleton et al., 2004; Stumpp et al., 2012; Sutanto et al., 2012; Wenninger et al., 2010; Yakir and Sternberg, 2000). Since the objective of this research is to study evaporation using stable isotopes, the background on stable isotopes and the application of the method to estimate evaporation is described in details in the following sub-chapter.

2.2 Studies on estimation of the evapotranspiration in the irrigated lands of Central Asia

There were number of studies on estimation of the evaporation conducted by many researchers in Uzbekistan (Alimov, 1976, 1965; Alpatev, 1969; Bespalov, 1970; Budiko, 1948; Ganiev, 1979, 1974, 1964; Ivanov, 1939; Ivanov and Chub, 1979; Kharchenko, 1962, 1975; Konstantinov, 1968; Milkis, 1973; Milkis et al., 1969; Rasulov et al., 2003; Rysbekov, 1986; Subbotin, 1976). In these studies, authors applied different methods to measure and calculate evaporation and transpiration from the irrigated fields. Rysbekov (1986) proposed five methods to estimate evapotranspiration at agricultural lands in Central Asia:

1. based on plant specific demand for water during the vegetation period;
2. based on water balance studies in irrigated lands;
3. based on the dependence of evapotranspiration from the climatic factors (energy balance);
4. combined methods of calculation of the total water consumption;
5. turbulent diffusion method

The crop water demand is characterized by the "transpiration coefficient" (K_T), which reflects the amount of water consumed by the plant during a certain time period (Allen et al., 1998). The transpiration coefficient changes depending on vegetation period, crop variety, fertilization and crop productivity level (Alpatev, 1969). According to Rysbekov (1986), the estimation of evapotranspiration using K_T was not widely used due to high instability and uncertainties of this method.

The "water balance" method is the most common method to estimate the total evapotranspiration from the irrigated lands (Rysbekov, 1986). During last years, several authors developed water balance equations for the irrigated lands in Central Asia (Dukhovny and Milkis, 1977; Kharchenko, 1979; Rysbekov, 1986; Dukhovny et al., 2005). According to Dukhovny and Milkis (1977), the general water balance of the irrigated lands is:

$$\Delta W= (I_S+O_S)+(I_G+O_G)+(P-I_F)+(V-w)-(E+T)-E_w-D\pm q \qquad (2.2.1)$$

where, ΔW represents total change in water stock within the boundaries of the balance site over the estimated period; I_S- surface water inflow; O_s- surface water outflow; I_G – groundwater inflow; O_G – groundwater outflow; P – precipitation; O_F –surface run-off ; V – irrigation water supply ; w – surface water outflow; (E+T) – evaporation and transpiration; E_w – surface water evaporation; D-drainage run-off; ±q – vertical water exchange between soil and ground water (all units mm).

All water balance parameters except evapotranspiration can be measured using lysimeters in a field condition. Dukhovny et al. (2005) in their study presented water balances for the soils under natural conditions and for irrigated lands. The authors studied significant effects of irrigation on natural hydrogeological, environmental and soil conditions of the lands, which lead to intensive soil salinization and waterlogging processes in irrigated lands. As a result of waterlogging process, the groundwater table rises and consequently the phreatic evaporation rate increases. Dukhovny et al. (2005) emphasize drainage construction in irrigated lands to be a more realistic solution to prevent those negative environmental processes in irrigated lands.

Meteorological parameters are also important factors to estimate evaporation, and several scientists (Budiko, 1948; Turc, 1958) attempted to find quantitative relationship between meteorological parameters and evapotranspiration. According to authors, wind speed, air temperature, radiation and humidity are the main meteorological parameters when estimating evapotranspiration using weather data. Dependence of the evaporation from the climatic parameters and moisture condition was also investigated by Oldekop (1911) (via Kharchenko, 1979) and later modified by Budiko (1948), Turc (1958) and Mezentsev (1976).

The potential evapotranspiration governs the use of irrigation water in agriculture. The term “evaporability” used by Rysbekov (1986) is equivalent to the term “potential evapotranspiration (ET_0)” in FAO (Allen et al., 1998), but the definition and estimation methods of the evaporability and ET_0 differ. Budiko (1948) suggested calculating evapotranspiration through analyzing water and energy balance equations. Since evaporation depends on soil moisture content in a certain profile, the total (actual) evapotranspiration was taken as equal to “evaporability”. Many researches showed that total evapotranspiration from the agricultural field and “evaporability’ are proportional (Dukhovny and Milkis, 1977; Ikramov, 2001; Kharchenko, 1975; Penman, 1968).

During Soviet times majority of the evapotranspiration investigations in Central Asia were conducted in lysimeters and calculations were done with the use of ***water balance methods*** (Alimov, 1976, 1965; Bespalov, 1970; Ganiev, 1979, 1964; Kats, 1964; Kharchenko, 1968, 1975; Kharchenko and Tishenko, 1966; Rysbekov, 1986; Subbotin, 1976; Usmanov, 1985). Ganiev (1979) summarized results of the lysimetric measurements, which were carried out in different environmental conditions and described the relationship between groundwater evaporation (phreatic evaporation) and groundwater depth (GWT), soil physical properties and biomass of the vegetation.

According to Ganiev (1964), in eastern part of the Fergana Valley under natural conditions (i.e. non-irrigated lands) in “suglinok” soils (by Kachinsky classification, (Kachinsky, 1958)) or loam (USDA classification, (Brady, 1990)) the average phreatic evaporation rate decreases from 310 mm year^{-1} to 12.5 mm year^{-1} when groundwater table is at 0.5 m and 2.5 m depth, respectively. Phreatic evaporation rates in cultivated lands were much higher than those in non-irrigated lands and amounted to 1320 mm year^{-1} when groundwater table was at 0.5 m depth (Table 2.1).

Table 2.1: Average phreatic evaporation rates obtained in lysimeter studies for irrigated and non-irrigated lands of eastern Fergana Valley for the period 1954-1971 (mm year^{-1}) (Modified from Ganiev, 1979)

Land use	Groundwater table, m					
	0.5	1.0	1.5	2.0	2.5	3.0
Non-irrigated lands, natural conditions	310	105	60	32	12.5	no data
Irrigated lands, cotton	1320	700	430	230	90	5.5

Ganiev (1979) also analyzed the connection of phreatic evaporation and soil texture under cotton. Thus, he found that on light soils (“supes” by Kachinsky and sandy loam by USDA classification) under cotton phreatic evaporation amounts to 120-610 mm year^{-1} when groundwater table varies between 2 and 0.5 m. On heavy soils (“heavy suglinok” by Kachinskiy or silty and clay loam by USDA classification), with similar groundwater tables (2 m to 0.5 m), phreatic evaporation constitutes 810- 340 mm year^{-1}. Ganiev (1979) also measured the infiltration rate at irrigated fields. He found that infiltration rate was higher at the beginning of the vegetation period and it consistently decreased during the vegetation, while evaporation from the groundwater increased from the beginning to the end of the vegetation period. In Central Fergana, on medium soils (suglinok by Kachinsky or loam by USDA classification) under cotton the average percolation changed from 80 mm year^{-1} at GWT=1.0 m to 1 mm year^{-1} at GWT=3.0 m (Ganiev, 1979). Later Ikramov (2001) continued lysimeter experiments. The author concluded that the main factors that affect the phreatic evaporation rate are groundwater depth, soil texture properties and surface coverage (with or without plants). Ikramov ing his findings, several groundwater evaporation estimation equations were then established for some irrigated territories of Central Asia.

In Central Asia, widely used lysimeters for the estimation of evapotranspiration have several limitations regarding constructive structure, methodological and economical expenditures. Constructive limitations include increasing mineralization of groundwater in lysimeters in a long run; soil temperature and moisture measurements are affected by lysimeter sides made from metal. Maintenance and exploitation of lysimeters is costly. Another limitation of lysimeters is that evaporation and transpiration rates cannot be directly measured, but they are estimated from the water balance.

In the last decades empirical methods, to estimate evapotranspiration mostly Penman-Monteith equation (Allen et al., 1998), have been widely used in agricultural lands of Uzbekistan (Forkutsa, 2006; Ibragimov et al., 2007; Kenjabaev, 2014; Webber, 2008). Penman-Monteith equation was adopted by FAO to standardize and simplify evapotranspiration calculations around the world (Allen et al., 1998).

2.3 STABLE WATER ISOTOPES AND THEIR APPLICATION TO ESTIMATE EVAPOTRANSPIRATION

2.3.1 Definition, Terminology and Standards

Isotopes are atoms with the same number of protons, but with different numbers of neutrons (Kendall and McDonnell, 1998). Some isotopes are heavier or lighter than others, some are stable and some will break down through radioactive decay (Gat, 2010). Many elements have two or more stable, naturally occurring isotopes (Mook and Rozanski, 2000). Stable isotopes do not decay into other elements (Mook et al., 2001). Oxygen and hydrogen are found in many forms in the earth's hydrosphere, biosphere, and geosphere, and they combine to form water (Gat, 2010). Hydrogen has two stable isotopes, ^{1}H and ^{2}H (deuterium); oxygen has three stable isotopes, ^{16}O, ^{17}O, ^{18}O (Gat, 2010). There are nine possible molecular weights and isotopic configurations for water: $^{1}H_2{}^{16}O$, $^{1}H^{2}H^{16}O$, $^{1}H_2{}^{17}O$, $^{1}H^{2}H^{17}O$, $^{2}H_2{}^{16}O$, $^{1}H_2{}^{18}O$, $^{2}H_2{}^{17}O$, $^{1}H^{2}H^{18}O$, $^{2}H_2{}^{18}O$ (Gat, 2010). However, because heavier isotopes are not very abundant, almost all water molecules are of three isotopic combinations: $^{1}H_2{}^{16}O$, $^{1}H^{2}H^{16}O$, $^{1}H_2{}^{18}O$ (Mook and Rozanski, 2000). The water isotopes of $^{1}H_2{}^{16}O$ are very abundant (relative abundance R=99.731 %) in nature. Average isotope abundances of $^{1}H^{2}H^{16}O$ and $^{1}H_2{}^{18}O$ are 0.0345 % and 0.200 %, respectively. Most applicable isotope combination of the water molecules are $^{1}H^{\mathbf{2}}\mathbf{H}^{16}O$