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Full Length Research Paper

Use of Stable Isotopes to Determine Evaporation, Transpiration and Efficiency of Irrigation Water Use in Cultivated Areas in Egypt

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Abstract

The largest consumptive use of water resources in Egypt is for agricultural purposes. The water balance and efficiency of irrigation water use in agricultural fields is greatly affected by loss of water to the atmosphere through evapotranspiration. The present work is devoted to partition evapotranspiration discharge (ET) into evaporation (E) and crop evapotranspiration (ETc) and to explore irrigation water use efficiency and how it is improved by using modern irrigation techniques in the newly reclaimed zones in Egypt; stable isotopes (Oxygen-18 and Deuterium) as being differently affected by evaporation and transpiration, have been employed for that. The evaporation loss (E) has been determined (5% - 6%) using heavy isotopes enrichment factor of a drying pan, as well as the slope of Oxygen 18 vs Deuterium evaporation trend of collected groundwater samples. The eastern zone of the study area shows a water use efficiency of about 33% where flooding techniques are applied for irrigation using Nile water. In the western zone, groundwater is used for irrigation with spray techniques, the crop transpiration domains, the water loss to atmosphere and water use efficiency is highly improved. The soil infiltration of evaporated return water in the eastern and western zones has been discussed.

Keywords: Stable Isotopes, Evaporation, Transpiration, Water use efficiency, ElMinia.

INTRODUCTION

Under current economic and population growth, Egypt is rapidly facing serious water scarcity issue. The rate of water availability per capita in Egypt is already one of the lowest in the world. Egypt does not receive rainfall except for a narrow strip along the Northern coastal area and limited mountainous catchments where the average rainfall does not exceed 200 mm/year. This amount cannot be considered as a reliable source of water due to its spatial and temporal variability. Nile river is the basic freshwater resource in Egypt, on which a rely of more than 95 percent, its quantitative terms are highly stressed by the huge evaporation loss, inefficient irrigation canals network, as well as dams construction in upstream countries. On the other hand, its qualitative terms are stressed by effluents and contaminated discharge of different activities along its flow path. Groundwater is the major second water resource in Egypt, it occupies two major reservoirs; the Nile Valley Aquifer System -NVAS- which extends in the Nile Valley and adjacent desert fringes with a major recharge from Nile water and the Nubian Sandstone Aquifer System –NSAS- which deeply underlies the whole Western Desert, parts of Eastern Desert and Sinai and contains fossil water got recharged before thousands of years under more humid climatic conditions, other than that prevailing nowadays; less potential groundwater occurrences also exist in local aquifers that get recharged on account of the mentioned two major reservoirs and occasional rainwater (eg; the Moghra aquifer system, mainly occupies the western edge of the Delta and flows toward Qattara depression and the Coastal aquifer systems, occupy the north western and eastern coasts; its recharge is limited

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by rainfall and may be affected by sea water intrusion and the carbonate aquifer system, essentially in the north and middle parts of the Western Desert, and other local occurrences.

The main fresh water consumer in Egypt is agriculture which consumes more than 85% of annual water resources; it would be adversely impacted by shortage of water resources, as well as, non-efficient water use in irrigation (where flooding irrigation in the River valley flood plains causes high water losses and decline in land productivity). The urgent tasks are thus to reassess the efficiency of irrigation water use and sustainably manage its development.

The greatest loss of water to the atmosphere during irrigation occurs through two distinct pathways: (1) transpiration through crop plants, (2) evaporation from storage reservoirs, delivery canals, surface distribution systems and moist soil. Evaporation and transpiration occur simultaneously; both of them are controlled by energy supply, vapor pressure gradient, air temperature, air humidity and wind terms. The transpiration -distinguished from evaporation is controlled by more factors (soil water content, ability of soil to conduct water to the root, water logging, soil water salinity, crop types and characteristics, environmental aspects and cultivation practices). The efficiency of using water for irrigation depends on the ratio between the water required for the plant to grow solely (crop evapotranspiration) and that already delivered to the field and affected by loss under effect of evaporation . As the ratio of water lost by crop evapotranspiration to that lost by evaporation increases, the water use efficiency for crop growth increase.

Partition of evapotranspiration (ET) into its two principle components; Evaporation (E) and crop Transpiration (Tc) is crucial for better understanding water balance, efficient management of hydrological processes and water use improvement. Traditional eddy covariance techniques among various methods helps to estimate evapotranspiration but encounters difficulties in its partitioning. The methods involve sophisticated and expensive climate stations or flux towers (Mauder et al. 2007), lysimeters (Lewis 2009), and water balance and soil water depletion (Jensen et al. 1990). All these methods are poor spatially represented and instrumentally limited for the density of the measurements.

Stable isotopes of water (oxygen 18 and deuterium) have been widely used as a powerful ideal tracer tool to identify and understand environmental processes, including soil water movement and solute transport, groundwater recharge, flow pathways, plant water uptake, isotopic sub-daily patterns in groundwater and ponding water (Groh et al., 2018, Beyer et al., 2015; Houben et al., 2014 ; Mueller et al., 2014; Stumpp and Maloszewski, 2010; Windhorst et al., 2014; Priyadarshini et al., 2016; Mahindawansha et al., 2018b), (Chiogna et al., 2018), (Mahindawansha et al., 2018a). These two isotopes are efficiently applied to determine the atmospheric water loss of irrigation water due to evapotranspiration and to partition that into its two principal components. The two isotopes (δ^2H and δ^{18}O) are differently affected by the evaporation and transpiration, they are enriched by the first and don't be affected by the latter, this renders isotopic monitoring of the residual irrigation water a sensitive indicator of water loss by evaporation exclusive transpiration. Using isotopic techniques for measuring evaporation from lakes are theoretically sound (Dincer 1968; Gonfiantini 1986; Gat and Bowser 1991; Gat and Matsui 1991; Simpson et al. 1987; Froechlich et al. 2005) but few applications to irrigation waters are reported. However, direct monitoring of heavy isotopes enrichment trends in residual water of an open pan in the climate zone of interest (where agricultural irrigation takes place) can provide empirical relationship for irrigation water evaporation estimation, (Simpson et al 1987).

This work is conducted in a cultivated area in mid Upper Egypt, to simply apply the stable isotopic content of a (drying pan water & irrigation and return flow water & groundwater) to partition evapotranspiration into evaporation and crop evapotranspiration and to determine irrigation water use efficiency and the impact of modern irrigation techniques on increasing efficiency and saving water in the new cultivated zones.

The Study Area

The study area is located in the middle portion of west Nile Valley of Egypt, (Fig. 1), its ground surface elevation increases from 75 m.a.m.s.l to 100 m.a.m.s.l (Moftah, 2012) westward. It is classified geomorphologically into three major units, from east to west; young alluvial plains, old alluvial plain and plateau. The young alluvial plain is of lowest elevation, directly bounds the Nile River, covered by alluvial sediments (mud and silts), containing extensively cultivated land and is dissected by irrigation canals and drainage systems that run generally parallel to River Nile main channel. The old alluvial plain bounds the young alluvial plain to the west, covered by loose sand and gravel, it is about totally cultivated. The limestone plateau is structurally formed, composed mainly of limestone covered with alluvial deposits of sands and gravels.

Stratigraphically, the study area is essentially covered by a sedimentary succession covering the ages from Middle Eocene to Pleistocene and Holocene, the surface distribution of the stratigraphic units is shown in Fig. (2, a), Abdel Moneim etal, (2016) modified after Conoco, 1987). Hydrogeologically, two main aquifers are encountered in the study area, namely the Quaternary Nile Valley (alluvium) aquifer and the fissured Eocene limestone aquifer. In addition to them, the deep Nubian sandstone aquifer which underlains the whole Western

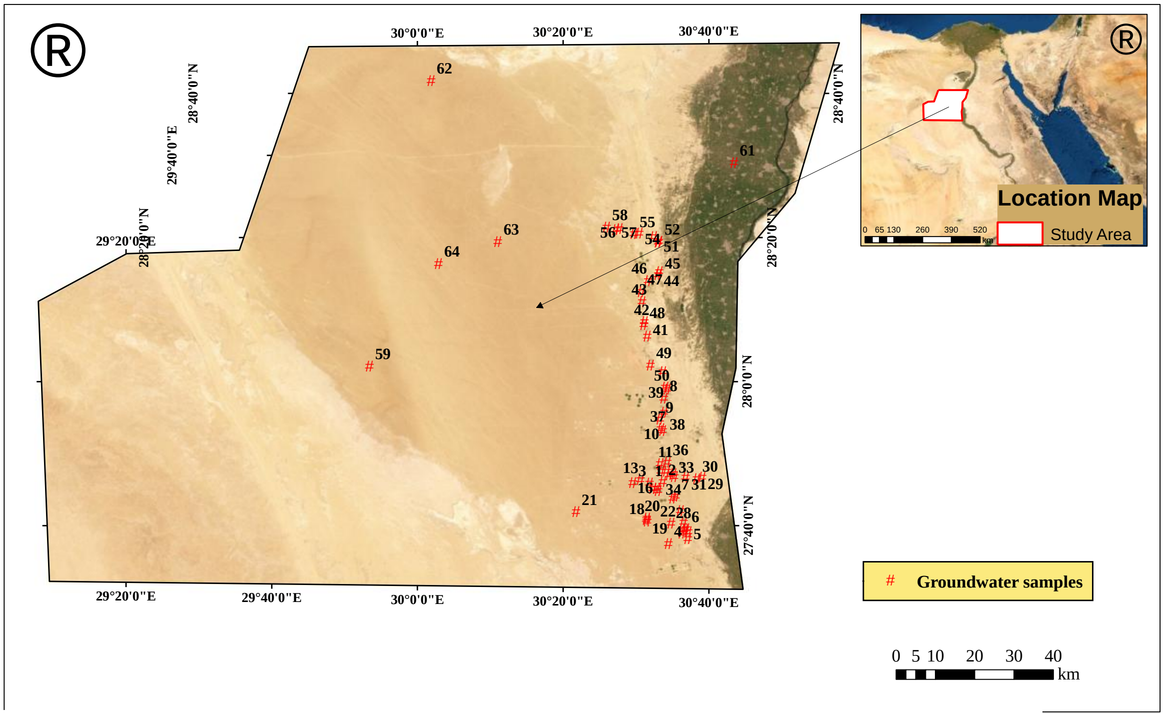

Fig. (1). Location of the study area and groundwater sampling.

Desert containing paleowater of no recent recharge gets its pass upward under high pressure in the presence of joints and fractures. Fig. (2, b) Abdel Moneim etal, (2016) modified after Conoco, 1987).

The Nile Valley Aquifer System (NVAS) represents the main source of groundwater in the young and old alluvial plains of the study area. It mainly consists of Pleistocene graded sands and gravels of thickness increasing eastward (from about 5m to about 100m), it is overlain (in the majority of the region) by a semi-confining clays and silts layer of Holocene age that decreases in thickness and completely disappears from east to west.

The recharge of (NVAS) basically comes from Nile water by seepage of irrigation canals and infiltration of irrigation return.

The Eocene limestone aquifer is mainly represented by Samalut Formation which is made up of hard, white and highly fossiliferous limestone with shale and marl intercalations. It is unconfined aquifer, dominating the western sides of flood plain and desert fringes, underlying the alluvium aquifer and overlying the Nubian sandstone one (Tantawy, 1992). This limestone aquifer contains fissures, fractures, and joints which represent the conduits of the groundwater flow; it gets a mixed recharge from the two aquifer systems of Nile Valley and deep seated Nubian Sandstone.

Agriculture is the major land use within the study area. Diverted river water canals are used for irrigation in the young flood plain and mixed with shallow groundwater in parts of the old flood plain. Only groundwater is used for irrigation in the newly cultivated lands of the western desert reaches. The irrigation takes place by flooding techniques in the young flood plain and parts of the old one and takes place by modern spray techniques in the newly reclaimed desert reaches. The main crops in the study area include Barley, Wheat, Onion, Alfalfa, Potato, Corn, and Dry Beans.

TECHNIQUES AND METHODOLOGY

The actual crop evapotranspiration ETc has been estimated using the daily evaporation rate of a Class-A evaporation pan according to the FAO-56 methodology which relates the pan evaporation rate (Epan in mm/d) to Potential Evapotranspiration (EP) through a Pan Coefficient (kp) and relates potential evaporation to the actual crop evapotranspiration (ETC) through crop coefficient (Kc), according to the following equations :

$$Ep = Kp * Epan \qquad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$ETcrop = Kc * Kp * Epan \qquad \ldots\ldots(2)$$

Whereas ETc can be estimated with the help of FAO56 methodology, actual evaporation is difficult to quantify through conventional methods. In this study, the relationship of heavy isotopes (δ^2H and $\delta^{18}O$) enrichment

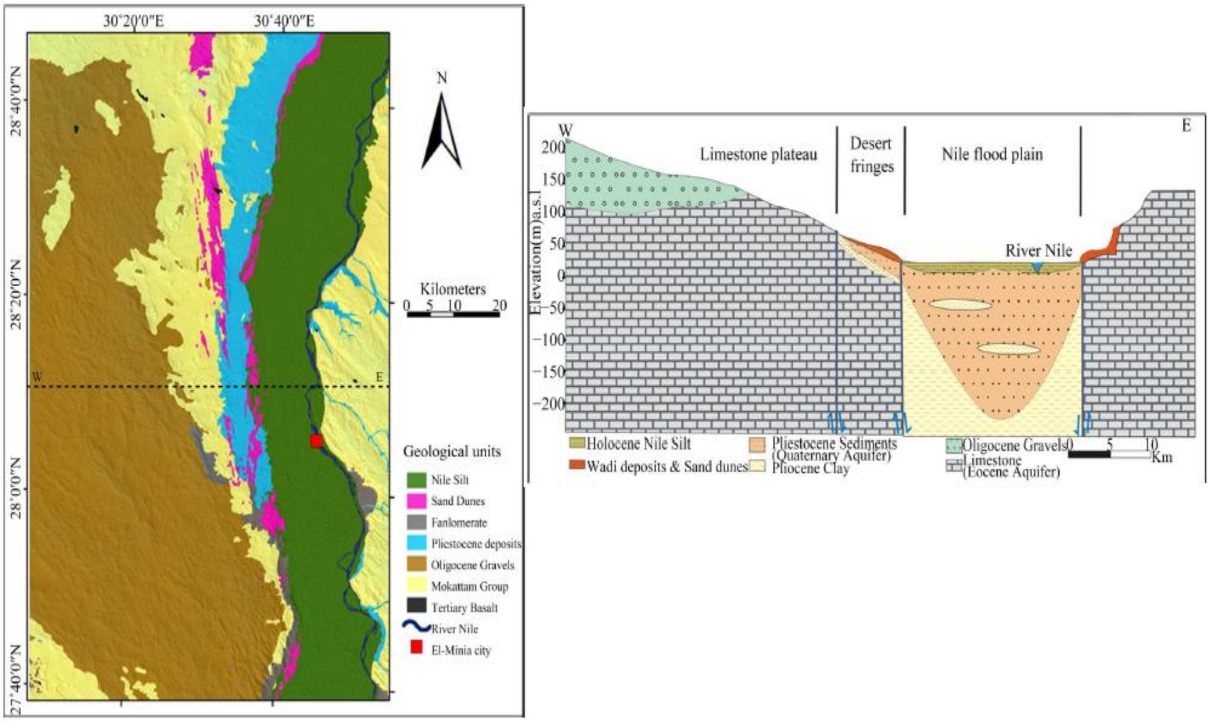

Fig. (2). (a) Geological map of the study area, (b) General hydrogeological cross section, with the geomorphological units in El-Minia area (Abdel Moneim etal, 2016 modified after Conoco, 1987).

with the fractional water losses subsequently taking place in an evaporation pan experiment is used for estimating evaporation losses according to the analytical models developed by Gonfiantini (**1986**) and Simpson et al. (1987).

The stable isotopes (^{2}H and ^{18}O) have been measured using Laser spectroscopy Piccaro (Model 2120i) in a sixty seven groundwater samples collected from the study area, Fig.(1), the results are reported in permil (‰) deviation from isotopic standard reference material using the conventional δ notation, where:

$$\delta ‰ = ((R\ sample / R\ standard) - 1) \times 1000 \quad \ldots\ldots\ldots\ldots(3)$$

R sample and R standard are the measured isotopic ratios ($^{18}O/^{16}O$) and ($^{2}H/^{1}H$) of sample and standard reference material. The reference material is Vienna Standard Mean Ocean Water (VSMOW). All results are evaluated, corrected and reported against VSMOW. The typical standard deviation for oxygen is ±0.1‰ and ± 0.6‰ for hydrogen.

The methodology used in this work is graphically summarized in Fig.(3).

RESULTS AND DISCUSSION

Determination of Evaporation exclusive transpiration

Two methods have been used for determining the evaporation rate (exclusive transpiration) in the study area; (1) the isotopic enrichment trend of an evaporation pan, (2) the slope of $^{18}O/^{2}H$ evaporation line of groundwater samples, these two methods are described as follow:

(1) Isotopic enrichment evaporation pan technique was applied in several works in different localities in Egypt (Simpson et al, 1992), (El-Bakri et al, 1996), (Hamza et al, 1999), (Abdel Samie and Ahmed, 2006). The results are highly compatible. Two of these pan experiments have been performed in the study area in the spring and summer by El-Bakeri, et al (1996). The rate of water loss from the spring evaporation pan was 8.9 mm day and that of summer pan was 11.3 mm day, (average 10 mm/day). Each 1% loss by evaporation leads to an increase in deuterium of about 0.78‰ and 0.64‰, while ^{18}O increases by about 0.20‰ and 0.18‰ in the spring and summer pan experiments, respectively, the slope of the ^{18}O vs. ^{2}H relationships was 4.1 for the spring pan and 3.4 for the summer one. The evaporation rate determined by evaporation pan represents the evaporation from open surface water; it could be comparable with evaporation that takes place during flooding irrigation in an area of same climatic and environmental conditions.

In the eastern parts of the study area, the cultivated lands in the River valley flood plains are irrigated using canal water diverted from Nile. The original isotopic content of Nile water used for irrigation (average ^{18}O about 3‰) is exposed to an isotopic enrichment; this enrichment could be reflected by the increase of isotopic content of the

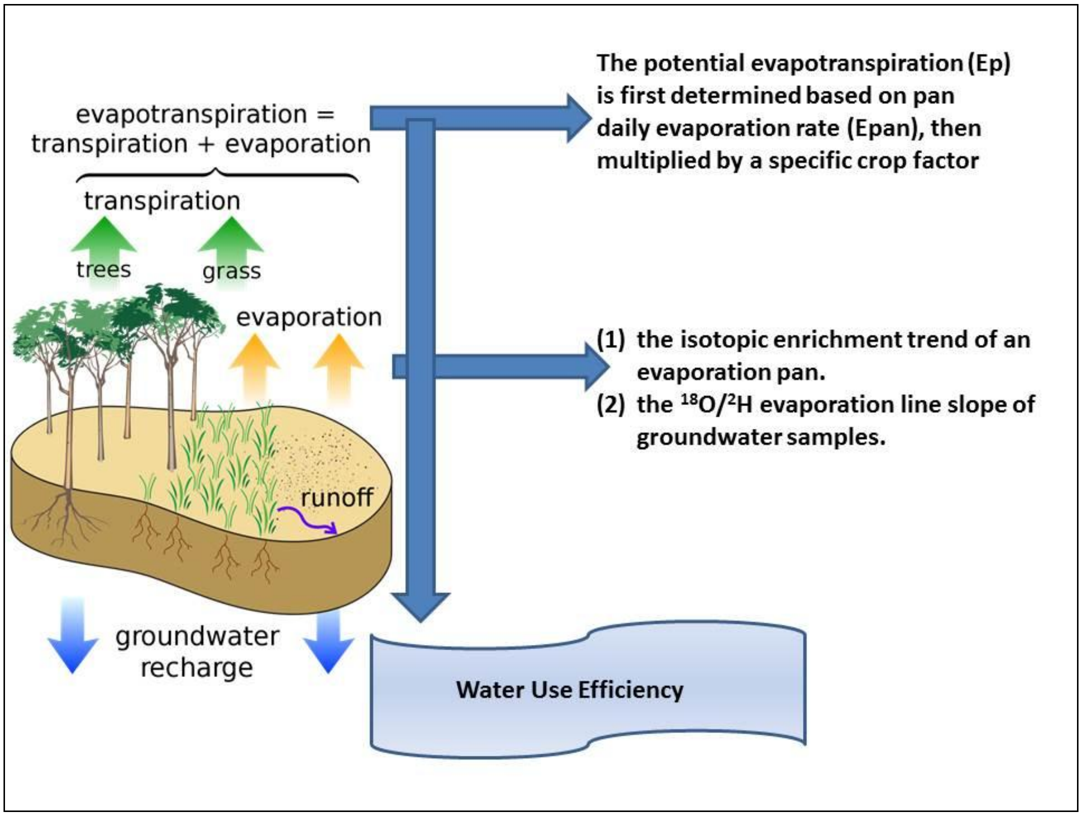

Fig.(3). Graphical representation of methodology used.

return flow or drainage water compared to original irrigation water. The isotopic content of return water was reported by Hamza et al (1999) as being equal to 4.2‰ in the study area, relating this isotopic content to that of original Nile water and considering the rate of isotopic enrichment indicated from El-Bakeri, et al. 1996 pan experiment, about 1.2 ‰ ^{18}O enrichment could be inferred as a result of evaporation only without transpiration, this is equivalent to about 6% water loss which is comparable to previous reviewed work, (El Bakri et al., 1996), (Tantawi, 1992) and **(**Tantawi et al., 1998), this 6% water loss is equivalent to the evaporation rate of the pan upon which it is determined (i.e., avg.10 mm/day).

(2) The results of isotopic analysis (^{18}O and ^{2}H) of five groundwater samples reported in the work of Reda and Lyons (2017) in the eastern zone of the study area are cross plotted, Fig. (4), the data follows a strong evaporation line of a slope equal to 5.6 which is compatible with the slope equal 5.9 determined by Tantawi (1992) and (Tantawi et al., 1998). The difference between the slope of the (^{18}O vs ^{2}H) relationship of the groundwater (i.e.5.6 or 5.9) and that of the evaporation pans (i.e. 4.1 or 3.4) could be due to mixing with residuals of Nile water prior to High Dam construction as well as the through flow of the isotopically enriched irrigation return water with the bulk of the subsurface water.

The evaporation rate has been determined based on the slope of δ ^{18}O / δ ^{2}H regression lines (5.6) of the groundwater samples, according to (Clark and Fritz, 1997; Murad and Krishnamurthy, 2008), using the following equations :

δ^{18}O evaporated water – δ^{18}O original non evaporated water, (δ^{18}O) = ε δ^{18}O total * ln$f$ …………..…(4)
Where ε total is the isotopic enrichment factor which accounts for both equilibrium and kinetic effects under which evaporation takes place, which for ^{18}O would be:

ε δ^{18}O total = ε δ^{18}O v–l + Δ^{18}O εv–bl ………(5)

The kinetic fractionation factor (Δεv–bl) is strongly dependent on the humidity (h), and is estimated in terms of humidity (h) using the following relationship (Gonfiantini, 1986; Clark and Fritz, 1997):
$\Delta\varepsilon^{18}$Ov–b l= −14.2 (1−h) ‰ ……..(6)

h is estimated by using the slope of the δ^{18}O–δ^{2}H relationship according the relation given in the work of (Gonfiantini, 1986; Clark and Fritz, 1997).

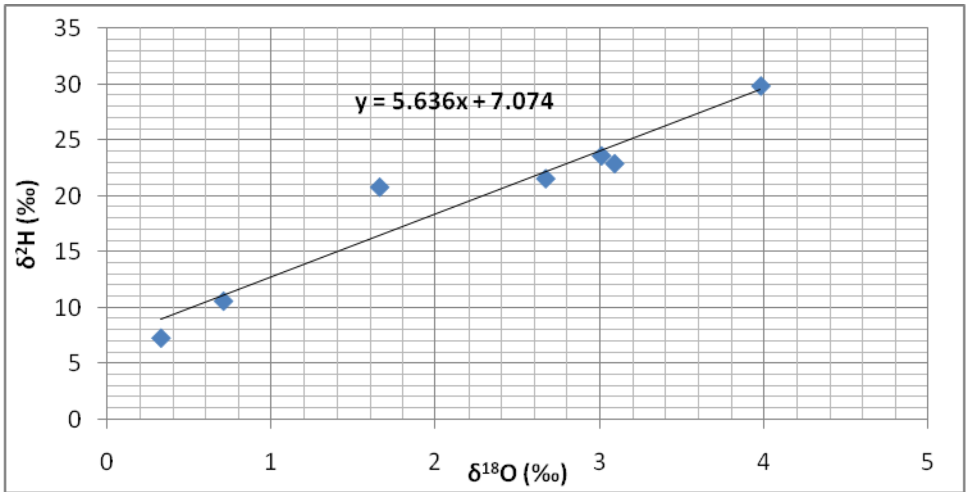

Fig (4). $\delta^{18}O$ vs $\delta^{2}H$ relation of groundwater to the east of the study area.

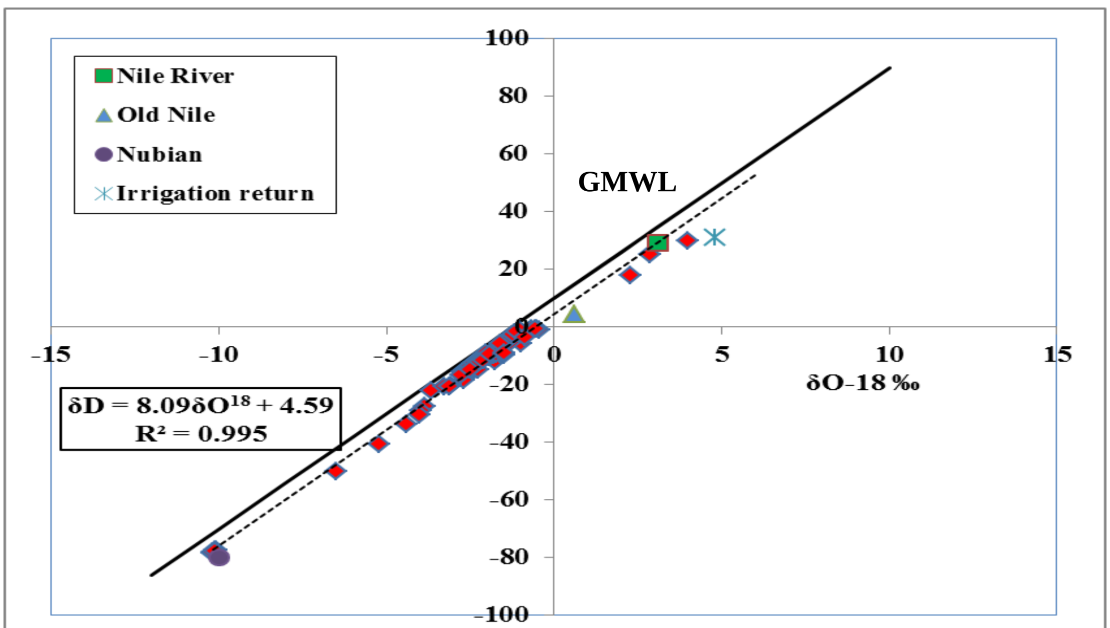

Fig. (5). Conventional $\delta^{18}O$ / δD relationship of collected samples

The equilibrium fractionation of ^{18}O between liquid water and vapor $\varepsilon^{18}O_{v–l}$ (103 lnα 18Ov–l) is strongly dependent on temperature, its values in the temperature range between 0 and 30°C are given in the work of (Majoube, 1971; Clark and Fritz, 1997, Ward and Elliot, 1995).

The slope of the $\delta^{18}O$ vs $\delta^{2}H$ relation of the groundwater samples of the flood plain, Fig. (3) equals 5.6, it is equivalent to a relative humidity (h) about 0.75 according to Gonfiantini 1985, Clark and Fritz 1997), this gives kinetic enrichment factor ($\Delta\varepsilon^{18}O_{v–b\ l}$) equals -3.6 ‰ according to equation (6). The average temperature of the study area can be used as 30°C, this corresponds to an equilibrium enrichment factor = -8.6 ‰ according to Ward and Elliot, 19950. The total enrichment factor equals -3.6 -8.6, (i.e -12.2 ‰) and the increase of isotopic content of evaporated return water relative to non evaporated Nile water (1.2‰) gives a fraction of remaining water about 95 % according to equation (4), (i.e evaporation rate equals 5% which is comparable with the value determined by the pan).

Determination of Crop Evapotranspiration and Water Use Efficiency

To determine the actual crop evapotranspiration (ETc), the potential evapotranspiration (Ep) or (in other term)

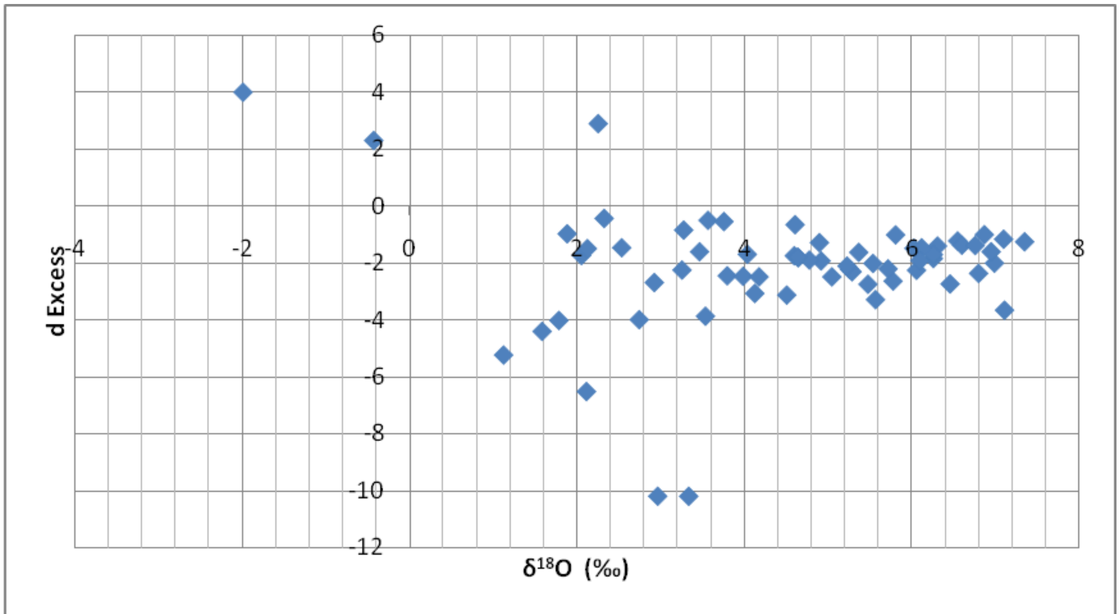

Fig. (6). Relationship of **δ^{18}O** with d-excess.

reference evapotranspiration (ET0) is first determined based on pan daily evaporation rate (Epan), then multiplied by a specific crop factor. The average value of pan evaporation rate (Epan) equal 10mm/day is used in this work for determining the reference evaporation (ET0) through a suitable pan parameter (Kp) which depends on climatic variables mostly not available. Using the empirical relationship between (Epan) and (ET0) that was constructed as a cross plot in the work of Conceição (2002), the reference evapotranspiration (ET0) that corresponds to the average (Epan) of 10 mm/d equals about 6 mm/d (i.e. Kp equal 0.6), this ET0 value agrees well with that determined in the work of (Ouda and Noureldin, 2017) based on long time records (10 years, 20 years and 30 years) of several weather parameters. A crop coefficient value (K_C) of about 0.8 has been retrieved as being specific for the two major crops cultivated in the study area (corn and wheat), (Moftah, 2012); this gives a value of crop evapotranspiration (ETc) equals 4.8 mm/day corresponding to the determined (ET0 = 6 mm/day). Relating the determined (ETc) value to the sum of (E+ ETc), a water use efficiency equal about 33% could be determined which represents the case of flooding irrigation in the eastern flood plains.

In the desert reaches of western ElMinia (to the west of flood plains and desert fringes) the national programs of agricultural expansion are directed where only groundwater is used for irrigation by applying the spray techniques. To explore the impact of applying these modern irrigation techniques in the newly reclaimed areas and to determine how this saves water and improves water use efficiency, sixty seven groundwater samples were collected from the groundwater in the study area, Fig. (1) and analyzed for $\delta\,^{18}$O, $\delta\,^{2}$H and TDS. The conventional δ^{18}O vs δD diagram has been constructed (Fig. 5) and the points of major recharge sources are plotted for comparison. The isotopic values of the samples points are highly co relatable to each other with a linear pattern δD‰ = 8.09 δ^{18}O‰ + 4.59 (with very strong correlation, $R^2 = 0.99$). The slope (close to 8) of the linear fitness of the samples indicates that recharge takes place directly in the two interconnected aquifers (Pleistocene and Eocene), with limited chance for surface evaporation. The limited impact of evaporation is also reflected by the absence of inverse pattern in the ^{18}O vs d-excess relation, Fig. (6). The non-appearance of considerable signs of evaporative isotopic enrichment in the groundwater used for irrigation in the western desert reaches indicates that atmospheric water loss is only dominated by crop transpiration and that water use efficiency is highly improved (> 90%), as compared to the values indicated in eastern zone.

General Outflow Components of cultivated Fields

At the scale of cultivated fields, the water used for irrigation either diverted from irrigation canals in the eastern zone of the study area or pumped from groundwater resources in the western zones are affected by four major discharge components (evaporation, transpiration, infiltration, drainage). The value determined for irrigation water loss by evaporation is about 10mm/d (equivalent to 6%) and that lost by crop evapotranspiration equal 4.8mm/d (equivalent to about 3%). According to Simpson et al 1997, about 35% of irrigation water diverted from Nile is generally drained out in drainage canals during flooding irrigation in Egypt. The rest of water used for irrigation (i.e. above evaporation,

in drainage canals during flooding irrigation in Egypt. The rest of water used for irrigation (i.e. above evaporation, evapotranspiration and drainage discharge) would determine the percent of infiltrated water in eastern zone of the study area, it lies in the range expected using the soil type steady-state infiltration rate values referenced by Hillel, (1982) (0.04 - 0.2 inch/h for clayey /silty soil), as well as that reported by Tantawy 1992.
In the western reach of the study area where deserts reclaimed fields are irrigated with groundwater using spray techniques, water transpired by the plants to grow is the major water loss component with a very low evaporation loss and nearly absent drainage or infiltration. The determined crop evapotranspiration rate determines an average for the major water needs for irrigation.

CONCLUSION

The stable isotopic content of water (^{18}O and D) integrated with classical hydrogeological techniques have been used in this work , to determine the percentage of irrigation water lost by evapotranspiration in cultivated zones in Egypt (i.e. Nile flood plains and western reaches of ElMinia Governorate). The relevance of isotopes for partitioning evapotranspiration into its two principle components (evaporation and crop transpiration) has been employed where they affect isotopes differently. The efficiency of using irrigation water has been estimated and the ratio of infiltrated return water has been discussed. These information are important for better understanding water balance, efficient management of hydrological processes and water use optimizing.

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Compliance with ethical standards

Ethical approval and informed consent: Not applicable.

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