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Presentation and validation of induction irrigation as an efficient and profitable method

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ABSTRACT

The scarcity of water resources along with population growth and low precipitation exert stresses on the agricultural sectors of arid regions. The evapotranspiration losses due to water use in the warm months of the year are high for walnut production, for example, which is one of the main Iranian agricultural exports. Also, the water losses occurring in flood irrigation, surface storage, and water conveyance, and the high costs of drip irrigation increase the need for efficient irrigation methods. This study proposes induction irrigation as a novel method for preventing evapotranspiration losses, increasing water-use efficiency, and raising agricultural profitability. Induction irrigation relies on recharge and extraction wells to inject treated sewage and withdraw groundwater, respectively, and create a saturated zone in the plants' root area. This paper demonstrates that induction irrigation applied to walnut orchards would lower costs and water losses, avoid surface pollution, and increase agricultural profitability.

Key words | groundwater, irrigation, recharge and extraction wells, sewage treatment

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INTRODUCTION

As the 21st century unfolds, the world faces worsening environmental conditions concerning land degradation and water shortages, which threaten water and food security. There is growing awareness of actions that must be taken to ensure sustainable water and food supplies, prevent famines and ensure societies' access to basic goods and services. The distribution of the world's water is such that 3% of the existing water resources are made up of freshwater. The percentages of freshwater that are found as ice sheets and glaciers, groundwater, and surface equal 69%, 30%, and 1%, respectively (Oki & Kanae 2006). The relative scarcity of surface water resources and its propensity to be polluted has increased reliance on groundwater, especially to meet agricultural needs. This is the case in Iran, where 70% of its land is arid or semi-arid. In these regions, average annual precipitation is less than 50 mm and the only natural reservoir of freshwater is groundwater. About 70% of water resources in Iran are allocated to agriculture, with 60% of the allocation being groundwater (Alizadeh & Keshavarz 2005; Madani 2014).

The importance of groundwater in meeting Iran's and other countries' water demands highlights the need to protect this resource from pollution and wasteful use. A common deleterious practice is to extract groundwater and store it in surface reservoirs to be conveyed to points of use. This practice produces losses to evaporation and exposes good-quality groundwater to surface pollutants. Much of the groundwater that is applied to irrigation through surface storage and conveyance is lost to evaporation. Induction irrigation is a new method herein proposed to apply groundwater to meet irrigation water requirements bypassing surface storage and conveyance, and without mobilizing dissolved salts, fertilizers, and pesticides towards underlying aquifers. The latter adverse

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impacts call for alternative methods for supplying irrigation with groundwater in semi-arid and arid regions.

METHODOLOGY

The method applied in this paper is based on a fundamental principle of groundwater movement: groundwater moves driven by the hydraulic gradient established between the root zone (at relatively low hydraulic head) and the nearby moist soil (at relatively high hydraulic head). It is possible to mobilize groundwater to the desired area (i.e., the root zone) to meet irrigation requirements. Inducing methods can be used as a way of altering the water table and to help provide moisture to the root zone, and hence the novel method proposed in this study is called induction irrigation.

Induction irrigation

Providing water during the summer months (June, July, August and September) is very effective in walnut production in Iran, where potential evapotranspiration is large during those months. Eliminating evapotranspirative losses would increase walnut production. Induction irrigation appears suitable for reducing such water losses. Induction irrigation can be implemented with recharge and extraction wells as explained next.

Recharge water

One method of groundwater recharge is using wells drilled through the unsaturated (or vadose) zone bottoming above the phreatic surface (or water table). Another recharge method relies on deep wells through one or more aquifers (Payne 2005). This article is concerned with the former method of recharge. Recycled and properly treated gray water can be used for recharge. The recharge of treated municipal sewage into aquifers for later extraction is currently a well-established practice in many water-scarce regions (Loáiciga 2015). The properties of wastewater depend on the type of treatment that takes place prior to injection into recharge wells. Common pollutants in wastewater include: total suspended solids (TSS), biochemical oxygen demand (BOD), nutrients such as nitrogen and phosphorus, and pathogens (helminths, protozoa, bacteria, and viruses) (Cogger 1995). Soil texture and structure have a pronounced influence on the level of wastewater treatment that occurs in a soil. Fine-textured soils (those having 50% or more clay- and silt-sized particles by dry mass) have a much greater surface per unit volume of soil than would a coarse texture (sandy/gravelly) soil. As the surface area increases, so does that soil's chemical reactivity which is responsible for removing some of the incoming pollutants. This means that soil treatment can help provide a suitable environment to purify the wastewater for plant use and aquifer recharge (Dow & Loomis 1996).

Porous recharge wells

The method herein proposed relies partly on porous recharge wells that inject treated sewage into the subsurface. A porous recharge well is a borehole filled with coarse gravel to a depth equal to the bottom of the root zone of the walnut trees or other type of orchard being irrigated. The injected treated sewage must undergo enhanced secondary treatment prior to injection. The injected treated sewage undergoes further purification in the aquifer. This recharge increases groundwater storage that is largely free of evaporative losses. The column of treated sewage present in the porous recharge wells produces lateral, radial injection in the unsaturated zone driven by the hydraulic gradient that exists between the recharge well and the surrounding soil, that is, by the action of capillarity within the soil. The column of water in the recharge wells encompasses the root zone to allow water to move by capillarity from the recharge areas toward the plants' roots. The radius of influence of a recharge well defines a zone surrounding the well that is wetted by injected sewage. The extent of the wetted zone depends on soil characteristics and the hydraulic head within the recharge well at any depth.

The main difficulty regarding recharge wells is clogging of the void space in the soil surrounding the wells. The main causes of clogging of the annular space surrounding recharge wells are as follows:

1. The presence of air bubbles in the recharge water, which can be corrected by installing de-airing tubes that move air particles upward and away from the recharge zone.

2. The presence of suspended sediments and microbial colonies in the recharge water. Such matter can be treated by improving the treatment of recharge sewage, and/or by flushing and cleaning the annular space surrounding wells within the recharge zone on a regular basis. Flushing is achieved by injecting pressurized water and air through the annular space. Cleaning of the annular space is by injection of chemicals to disinfect, loosen, and dissolve extraneous material (Donham 1991; Payne 2005). Chemical injection must be applied with great care to avoid subsurface chemical contamination, and is generally inferior to pretreatment of recharged sewage. Methods include acidizing to remove the acid-soluble, hydrofluoric acid treatment and strong oxidizing agents such as sodium hypochlorite to restore the injectivity of the recharge wells (Donham 1991).

Porous extraction wells

Extraction wells are located near recharge wells to raise groundwater and create a zone of saturation surrounding and near the root zone, thus supplementing the sources of water to meet irrigation requirements and relying largely on recharged water. Well pumps are used to raise the groundwater in extraction wells up to the point of saturation created by injecting sewage into recharge wells where it exits the extraction wells through perforations or screens. This dual mechanism of root zone wetting by capillarity created by recharge and discharge wells would meet irrigation requirements with minimal evaporation besides the plant-transpired water. Surface drainage water from irrigated fields can also be directed to recharge wells in this method.

The radius of influence and the inter-well distance

There are formulas and models for calculating the inter-well distance and the radii of influence associated with recharge and extraction wells (Fileccia 2015). Most of the formulas are based on the soil's hydraulic conductivity. The radius of influence increases with increasing hydraulic conductivity. The drawdown caused by extraction wells decreases with increasing hydraulic conductivity for a given extraction rate.

Table 1 lists the calculated radius of influence for several soil types and hydraulic conductivity. For medium sand the radius of influence equals 100 m, and this is used as the inter-well distance between porous extraction wells. The recharge wells would be installed with an inter-well distance equal to 50 m, filled with coarse gravel, to a depth equal to the bottom of the root zone of the walnut trees. Applying Darcy's law with an effective porosity equal to 30% and a hydraulic conductivity equal to 10 m/d, it would take 18 days for water from the porous extraction wells to spread over a radius of 50 m. It would take five days for water from the porous extraction wells to spread over a radius equal to 25 m. Therefore, placing recharge wells 50 m from the extraction wells would ensure that the walnut trees would receive irrigation water if they were irrigated every seven days. Figure 1 displays a generic 3D arrangement of recharge and extraction wells. Figure 2 depicts a plan view of recharge and extraction wells in relation to irrigated trees (walnuts in this instance). Figure 3 shows the movement of groundwater in the zone affected by recharge and extraction wells, resulting in the formation of a virtual water table, which is the upper boundary of the zone of saturation created by the recharge and extraction wells. A $400 \times 400\ m^2$ walnut orchard would require 16 porous extraction wells 100 m apart from each other in both directions, and 64 recharge wells (boreholes filled with coarse gravel). With an irrigation schedule of seven days, each one of the recharge wells needs to be filled with water and each extraction well needs pumping every seven days in order to create a wetted zone in the root area of the walnut trees and provide their water needs.

Table 1 | The radius of influence of recharge wells as function of the hydraulic conductivity (Bogomolov & Silin 1955)

Soil type	*K* min (m/day)	*K* max (m/day)	Minimum discharge (L/s)	Maximum discharge (L/s)	Radius of influence (m)
Silt	0.5	5	0.03	0.1	65
Fine sand	10	25	0.14	0.5	75
Medium sand	20	50	0.16	5.5	100
Coarse sand	35	75	5	14	125
Gravel	60	125	11	30	150

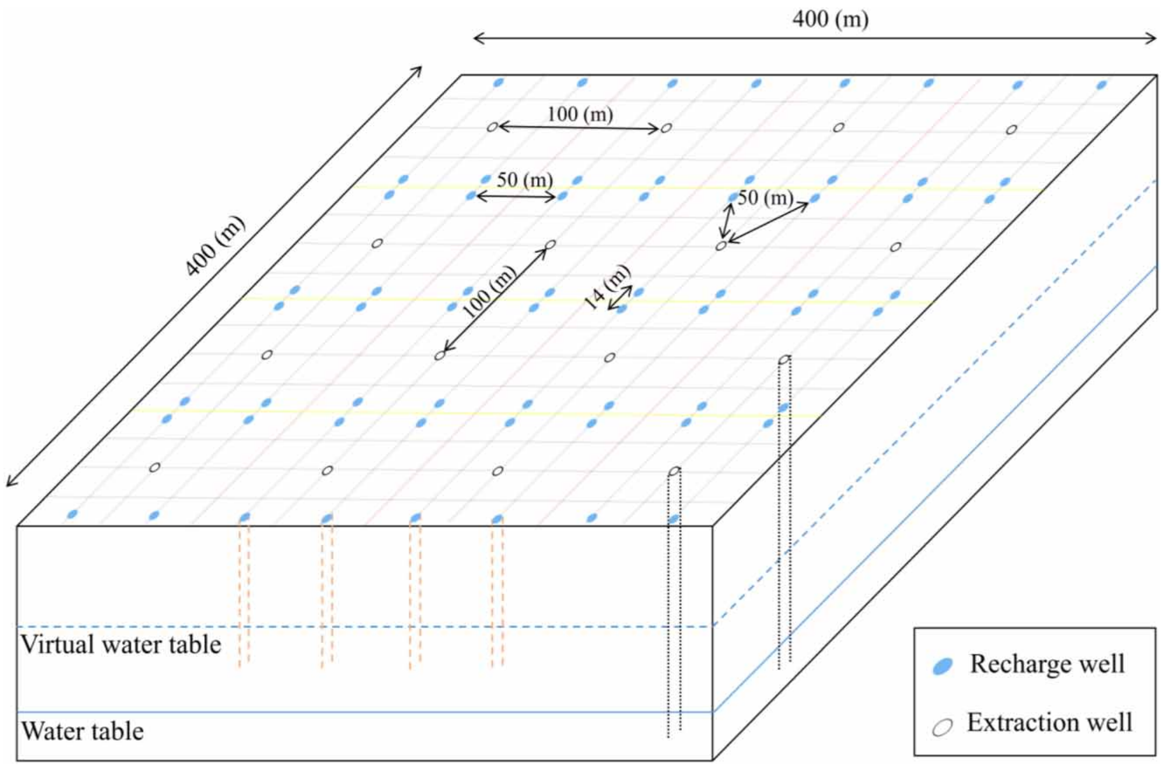

Figure 1 | General layout of extraction and recharge wells with induction irrigation.

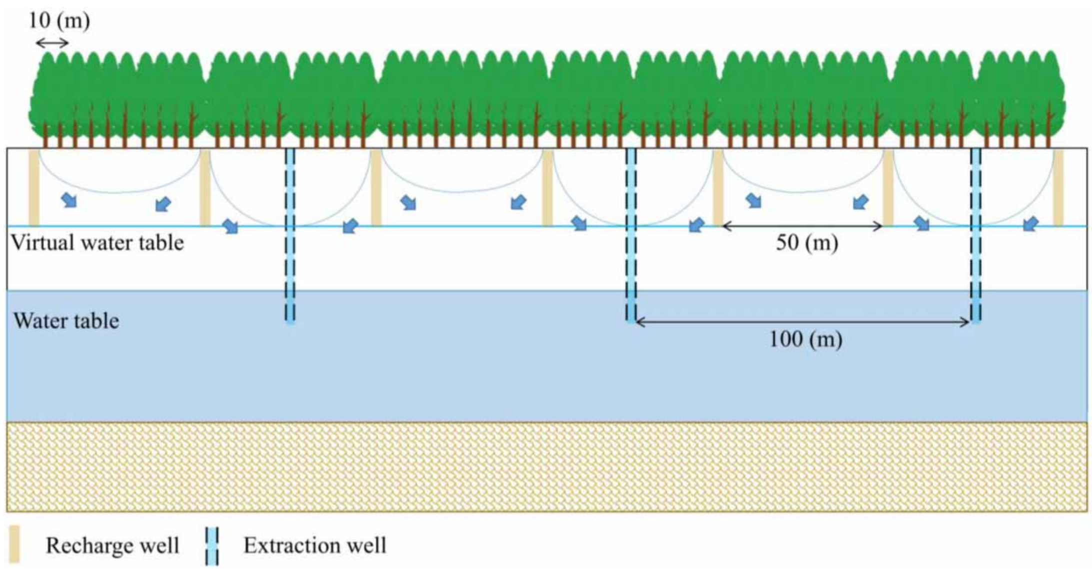

Figure 2 | Elevation view of extraction and recharge wells displaying the direction of water movement due to the potential difference and the arrangement of walnut trees.

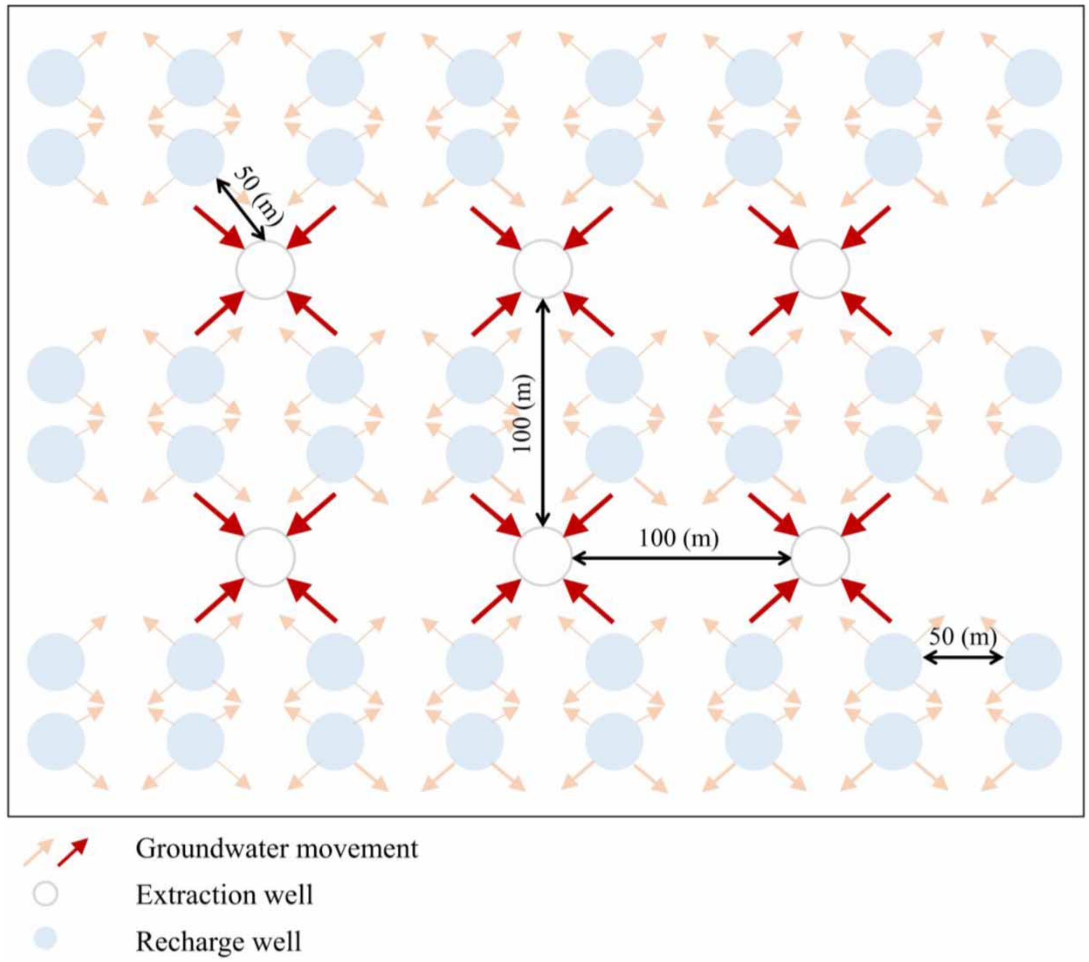

Figure 3 | Plan view of the movement of groundwater caused by recharge wells and extraction wells near walnut trees.

Caveats of induction irrigation

- Injection of treated sewage with porous recharge wells increases groundwater storage and raises the groundwater level.
- The distance between recharge wells must be designed to allow recharge water to move in the soil by capillarity within an adequate time. Such distance must avoid overlapping of the zones of influences of wells (that is, it must avoid well-interference).
- The water level in the porous extraction wells must rise above the bottom of the root zone. This creates space for water to move radially outward towards the root zone.
- Recharged treated sewage through the porous recharge wells may percolate to the porous injection wells, thus enhancing their wetting performance.

RESULTS AND DISCUSSION

According to the statistics provided by the Food and Agriculture Organization of the United Nations (FAO) in 2007 Iran is the third largest walnut producer in the world after China (top producer) and the United States. The Iranian annual production of walnuts was about 290,000 tons and the harvested land area was 185,000 ha in 2008 (Banaeian &

Zangeneh 2011). Walnut groves require between 3,000 and 4,000 cubic metres of irrigation water per hectare annually applied with drip irrigation. The application rate can rise to between 5,000 and 7,000 cubic metres per hectare annually when delivered by flood irrigation. Assuming 50% irrigation efficiency, the amount of water (evaporative) losses incurred in irrigating walnut trees in Iran may be as high as 460 million cubic metres annually. Applied to a $400 \times 400\ m^2$ walnut orchard, induction irrigation demonstrated low levels of evaporative losses compared with flood irrigation. The economic strengths of induction irrigation must be addressed given that there are competing irrigation methods such as drip irrigation, which is an efficient method in terms of water use.

Economic evaluation

Reducing evaporative losses with induction irrigation would allow planting an additional 115,000 ha of walnut trees, which would add 184,000 tons of annual production. Consequently, this would increase annual exports, which currently equal 5,000 metric tons worth $35 million.

It was cited above that flood irrigation raises water use between 1,000 and 3,000 cubic metres per hectare. This means the cost of water increases per hectare compared with drip or induction irrigation. On the other hand, installation of drip irrigation costs around 3,000 $/ha. However, induction irrigation reduces the network costs for pipes, tubes, valves and emitters, and with the decrease in water requirements due to low losses, induction irrigation is more advantageous than either flood or drip irrigation. The seven-day schedule for pumping the extraction wells makes it possible to use few pumps. For example, the 16 ha orchard presented in Figure 1 with 16 extraction wells would pump two or three times daily.

CONCLUSION

This work introduces induction irrigation as a new method to apply groundwater to meet irrigation water requirements bypassing surface storage and conveyance. This practice avoids the evaporation losses caused from surface storage and groundwater is not exposed to any surface pollutants. Effective irrigation in warm periods of the year with a high range of evapotranspiration losses can be possible using this method.

Induction irrigation is applied through recharge and extraction wells. Treated sewage is injected into the recharge wells, which creates a saturated zone in the root area of the soil. Soil infiltration further purifies recharge sewage. After injecting, the water extraction wells are used to pump groundwater, which causes a drawback in the virtual water table created by injected water. This helps with a better distribution of the water in the root area of the plants. A network of recharge and extraction wells is needed to implement induction irrigation. An example of induction irrigation of a walnut orchard has shown that water losses associated with flood irrigation are avoided. This would raise walnut production in Iran by as much as 63%. Induction irrigation costs per hectare with a properly chosen irrigation schedule would be lower than those associated with drip irrigation. These benefits plus its high water-efficiency and the use of treated sewage signal the potential of induction irrigation. Evaporation losses along with overuse of groundwater resources are two major water resource problems that occur in different climates and environments. The methodology advised in this paper tackles these two important issues and would minimize their effects, which would be advantageous for sustainable water resources management and improve the economic aspects of irrigated agriculture.

CONFLICTS OF INTEREST

None.

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DATA AVAILABILITY STATEMENT (DAS)

All data, models, and code generated or used during the study appear in the submitted article.

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