Subsurface Drip Irrigation: Maximizing Crop Yields and Water Efficiency

Abstract

Comment [U1]: Include general objective at the beginning, Experimental design used, treatments (quantity and its repetitions), parameters evaluated, analyzes used and the most important results.

One of the main finite input resources for crop production in the upcoming decades for sustained food production will be irrigation water. On the other hand, there is a concern for irrigation water availabilityto have environmental and ecological sustainability. Urban activities, which are the primary sector competing with agriculture for water as the global economy grows daily as a result, it begs the question of whether thesame amount of water utilized in irrigated agriculture can continue. It is estimated that the global population will be about 9 billion to 10 billion by 2050, and more water will be thus needed (FAO, 2021, Cheng *et al.*, 2021). Today, irrigation is the largest single consumer on the earth. Competition for water from other sectors will force irrigation to operate under water scarcity. To meet the twin challenges of conserving water and increasing the food supply, irrigated agriculture will have to improve water productivity, e.g. “more crop per drop”. The subsurface drip irrigation SDI could be one such alternative like drip irrigation which uses less water. It could save up to 25% - 50% of water regarding to surface irrigation.

Keywords: irrigation, crop production, ecological sustainability, groundwater

Introduction

Comment [U2]: Use citations not older than 10 years.

Include results of other previous studies, in addition the general objective is not observed at the end of the introduction

Water status in the world and India:

In fact, underground water supplies are necessary for over 50% of the metropolitan population on the planet. More and more aquifers are being contaminated, overused, and dried up by humans, sometimes with terrible consequences. According to Margaret and Van der Gun

(2013), groundwater supplies 49% of the water extracted for residential consumption by the worldwide population, and around 25% of the water withdrawn for irrigation, which supplies 38% of the world's irrigated area (Siebert *et al.*, 2013). The 2030 Agenda relies heavily on groundwater, hence proper groundwater expertise and local hydro geological understanding are necessary for its successful implementation (Velis et al., 2017; IAH, 2017). The three nations with the most land under irrigation are China (73 Mha), India (70 Mha), and the United States (27Mha) with an estimated 251 km^3 of groundwater being extracted annually, India is the world's largest user and 85% of that water is used for cultivation. China, India, Iran, Pakistan, and the USA make up the majority of the unsustainable water footprint, which is around 70%. Food and fodder crops accounted for 90% of the overall unsustainable water footprint, whereas crops used for fibre, rubber, and tobacco accounted for 10%. (Mekonnen and Gerbens-Leenes, 2020). Groundwater development in India has been mostly fueled by rural electrification (Smith and Urpelainen, 2016).

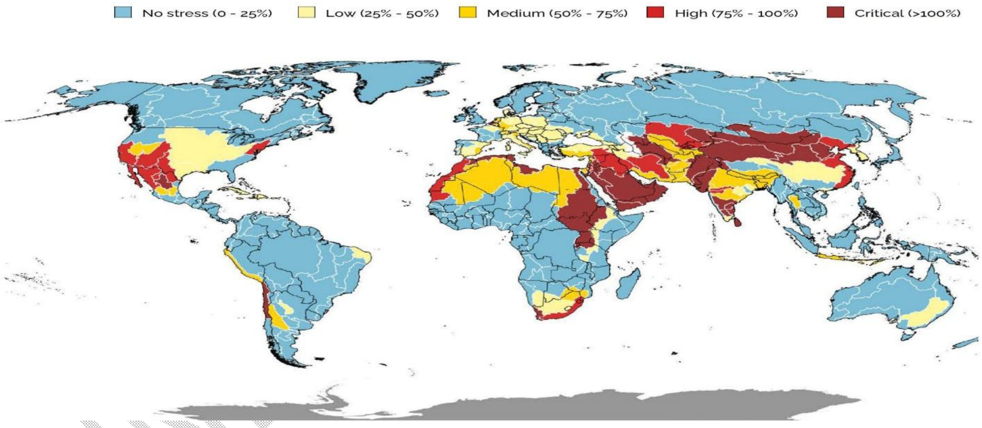


Fig.1 water starved status of the world (Source: FAO 2021)

Water-starved status

Water stress levels are close to or above 100% in nearly all of the Middle East and North African nations, with Kuwait, the United Arab Emirates, and Saudi Arabia having the highest percentages (fig.1). In the middle of the 1980s, the Middle East region started to produce enough food grains to meet the majority of its needs, and it was ready to start exporting considerable amounts of wheat to international markets (Allan, 1997). The nation used a lot of its fossil water to cultivate crops until the early 1990s (Allan, 1999) as a result now Middle East is the first area in the world to run out of water because of indiscriminate exploitation of fossil water which isnon-renewable. Now, these Middle East and North African region has been importing 40 $\times 10^6$ Mg of cereals and flour annually whichreveals that more virtual water flows into the region each year. According to estimates, the Middle East imported around 25% of their virtual water needs. By 2050, it's likely that countries like India, where the population is growing at an unprecedented rate, won't have enough water.The water requirement in India by 2050 will be in the order of 1450 km^3, which is significantly higher than the estimated water resources of 1122 km^3 per year. Therefore to meet the shortfall requirement, it is necessary to harness an additional 950 km^3 per year over the present availability of 500 km^3 per year (Gupta and Deshpande, 2004)

Status of Groundwater and energy in India

India is the world’s largest user of groundwater. It has an annual draft of around 251 km^3, 89% of which is used for irrigation (Figure. 2), withdrawn through an estimated 20 million wells and tubewells. An estimated 60% of the irrigated area in India is served by groundwater (Shah, 2009). Groundwater led irrigation was instrumental in the success of the Green Revolution in India from the 1960s. However, it has become apparent that gains in irrigated agricultural production have progressively led to a significant decline in groundwater levels in parts of the country, particularly in northwestern and peninsular southern India (Shah, 2009).

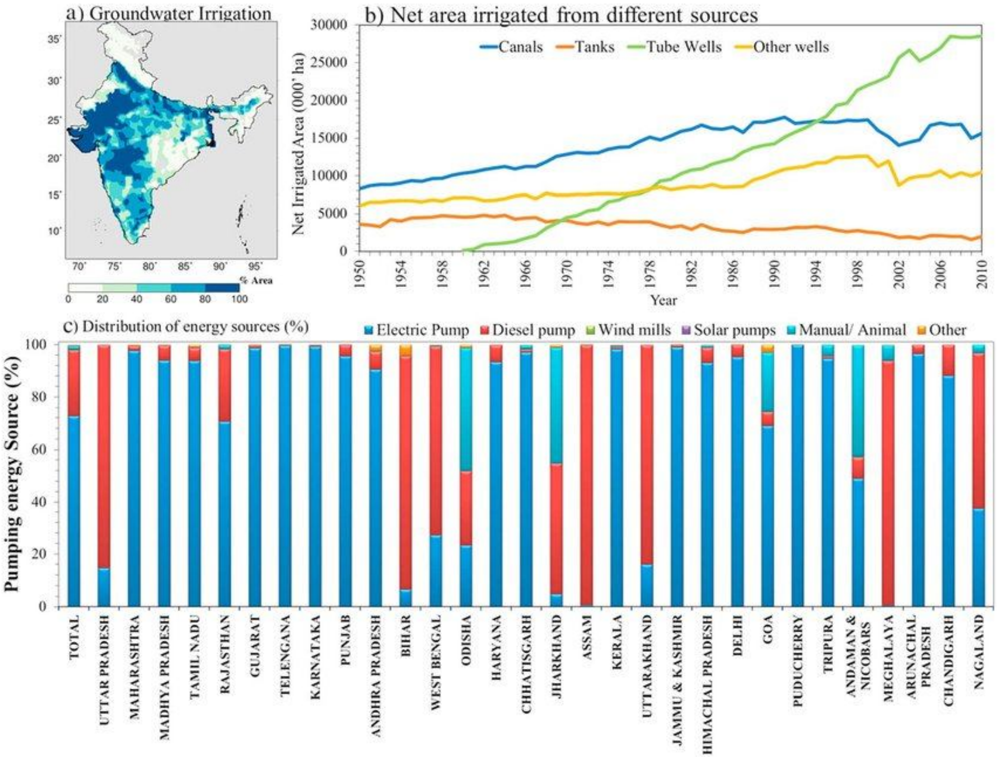


Fig. 2 Ground water and energy use from different source in India (Mishra *et al*, 2018)

Currently, India’s water crisis can be largely traced to the expansion of groundwater irrigation, a trajectory set on course by India’s food and electricity policy since the late 1970s. The food policy guaranteeing cheap food to consumers dictates the need to keep input prices low, including the level of electricity tariffs for pumping groundwater. Reduced electricity tariffs or free electricity to agriculture, as exist in many Indian states, coupled with assured state or government procurement of crops, encourage farmers to grow water-intensive crops, such as sugarcane, including in semi-arid regions with low natural recharge. This is responsible for unprecedented groundwater depletion in large parts of India (Mukherji, 2020). Groundwater overwithdrawal in India can be traced to a lack of coherence between water, energy and food policies. Hence, solutions to India’s groundwater problems should be positioned within broaderwater–energy– food nexus context (Shah *et al.*, 2012). Indirect management of groundwater through electricity policies have been attempted in many states in India. This has ranged from metering agricultural electricity connections and charging farmers near-commercial rates for irrigation e.g. in the state of West Bengal (Mukherji *et al.*, 2009); to rationing electricity to farmers to a limited number of hours in a day, made possible by bifurcation of electric feeders into agricultural and domestic feeders e.g. in the states of Gujarat, Karnataka and Punjab (Shah *et al.*, 2008; Mukherji, 2017). Both these measures, the pricing and the rationing of electricity, are meant to reduce demand for groundwater by giving price and scarcity signals, respectively (Sidhu *et al*., 2020). More recently, concerns about high carbon emissions from India's groundwater pumping and about the mounting subsidy burden on the electricity utilities, have led to pilots of Solar-Powered Irrigation Systems (SPIS). Grid-connected SPIS are being promoted to incentivize farmers to pump less groundwater while selling electricity back to the grid rather than using it for pumping groundwater (Shah *et al*., 2018), but evidence of whether grid-connected SPIS actually reduce groundwater pumping is still not available. Estimates of greenhouse gas emissions from groundwater pumping relative to the total national emissions from energy use range from 0.5% in China (Wang *et al*., 2012) and 3.6 % in Mexico (Scott, 2013) to 8–11% in India (Rajan *et al*., 2020). Compounding the situation, methane embedded in deep anoxic groundwater, released as groundwater is pumped to the surface, may also add to this budget (Kulongoski and McMahon, 2019).Nearly 40% of water demand in urban India is met by ground water. As a result ground water tables in most cities are falling at alarming rate of 2-3 meters per year. As per OECD environmental outlook 2050, India would face severe water constrains by 2050. Indian agriculture accounts for 90% water use due to fast track ground water depletion and poor irrigation systems. A dearth of storage procedure, lack of adequate infrastructure, inappropriate water management has created a situation where only 18-20% of the water is actually used. Globally, about 40% of irrigation water is supplied from groundwater and in India it is expected to be over 50%(Aeschbach-Hertig and Gleeson 2012). In India, groundwater irrigation covers more than half of the total irrigated area (around 42 million ha). Agriculture is the largest single user of water with 65–75% of freshwater being currently used for irrigation (Bennett, 2000; Prathapar, 2000). In some cases, it draws as much as 90% of the total water (Allan, 1997).

Agriculture water use sector wise in world:

Irrigated agriculture still accounts for 70% of freshwater withdrawals (Fig. 3). Use for food processing is also significant, up to 5% of global water use (Fig. 3). Subsurface drip facilitates the use of degraded quality water (Palacios-Díaz *et al*., 2009;Boretti and Rosa, 2019), by increasing irrigation frequency thus minimizing the matric and osmotic stress, and in cases of treated wastewater reducing pathogen movement, odors, and animal and human contact.

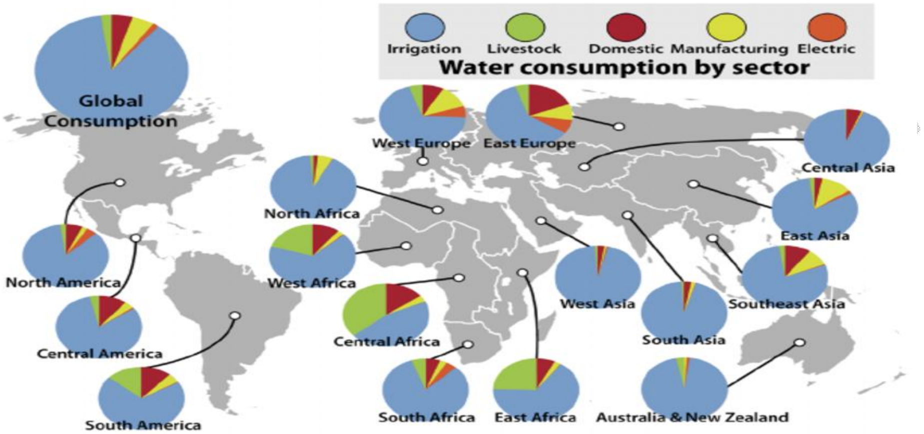


Fig.3 Sector-wise water use in the world

Subsurface Drip irrigation

The application of water below the soil's surface using micro irrigation emitters is known as SDI. Typically, the emitters' discharge rate is less than 7.5 L/h (ASAE , 2001). The irrigation network system in the plough layer directly flows water and liquid fertilizer into the root zone for the growth of crops. SDI might be a significant factor in improving irrigation water use efficiency (IWUE). Although SDI has been widely employed in agricultural production as an effective water-saving irrigation technique, its effects on crop yield, irrigation water productivity (IWP), and water productivity (WP) depend on the management of the field, the climate, and the characteristics of the soil.SDI is a water conservation technique that exposes crops to a particular level of water stress during a certain developmental phase or throughout the entire growing season without a significant reduction in yield. The use of a pressurized irrigation system applying water below the soil surface at a small operational pressure and minimizing soil evaporation has been popular for saving water and improving IWUE (Ayars*et al*., 2015).

In comparison to other forms of irrigation, SDI reduces water loss through evaporation, runoff, and deep percolation. As a result, the irrigation water that was saved may be used in other areas. In addition, it increases crop yields by maintaining a consistent level of soil moisture throughout the crop's effective root zone. As there is no direct irrigation water interaction with the human operating system in SDI, treated waste water can be used with little risk to human and animal health. We can choose SDI in peri-urban locations where there is a lot of potential for utilizing treated waste water. Also, because agrochemicals are applied precisely using the SDI system, it decreases the amount applied. SDI is a technology for climate-smart agriculture.due to smaller intake heads; the SDI operating system uses less energy than traditional irrigation techniques. Therefore, in addition to increasing energy efficiency, SDI may also stop the anaerobic degradation of plant materials, significantly reducing methane gas emissions.

Brief history of subsurface drip irrigation

China is the pioneer in using SDI where in clay vessels were buried in the soil and filled with water. The water moved slowly across the soil wetting the plants' roots (Bainbridge, 2001). The modern SDI systemas we know it nowadays, developed around 1959 in the United States(Vaziri and Gibson, 1972; Camp *et al.*, 2000), especially in California and Hawaiias a drip irrigation variant. SDI laterals consisted of polyethylene or polyvinyl chlorideplastic pipes with punched holes or with punched emitters. Initially, SDI systemswere often having the problem of emitterclogging , root intrusion, rodent damage, and poor uniformity.

As per the recent estimatesduring the past 50 years of intensive irrigation, approximately 50 % of the water originally present in the aquifer has been depleted. The result is that many areas are running short of water. Farmers have therefore been forced to switch from conventional irrigation to water-saving irrigation methods such as low-energy precision application (LEPA), sprinkler irrigation, and subsurface drip irrigation.

Design and installation

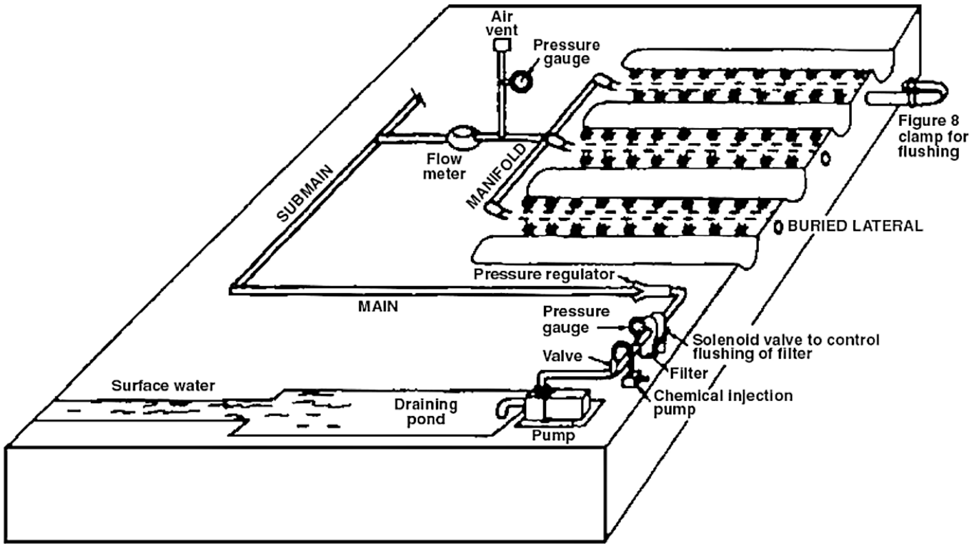


Fig.4 Design and installation of Subsurface drip irrigation

The main components of SDI comprise of main supply tube (Lateral drip lines), submains laterals and emitters(fig.4)

- *Lateral drip line*

Tapes and tubes are used as laterals. Generally, tube wall thickness ranging from 0.4 mm to 1.5 mm (Hanson *et al.*, 2000) is commonly used in SDI. There are two classes of tape wall thickness. Flexible Thinwalled (0.15 mm to 0.30 mm) which are used for shallow installation whereas whilst thicker- walled (0.38 mm to 0.50 mm) tapes are installed deeper where the soil does not provide sufficient support to prevent collapse by equipment or soil weight (Camp *et al.*, 2000).

- *Tape installation depth*

The tape depth is often decided by the crop, soil climate characteristics and anticipated cultural practices, but it generally ranges from 20 to 70 cm depth. In shallow systems, relatively deeper installation should reduce soil evaporation and also allow for a wider range of cultural practices. However deeper installation may limit the effectiveness of the SDI system for seed germination/ crop establishment.Deeply placed drip lines may require an excessive amount of irrigation for germination/ crop establishment due to uneven distribution of water. It reduces the WUE. Deeper placement may restrict the availability of subsurface appliednutrients chemicals (Camp and Lamm, 2003).

- *Lateral spacing*

Lateral spacing of 0.25 to 5 m is commonly practiced in SDI, as determined by crop behavior, cultural practices soil and properties. Wider lateral spacing is practiced in heavy textured soil. Closer spacing is recommended for sandy soil (Phene and Sanders, 1976). Lateral spacing of 2 m intervals on a 1:2 drip tape:crop row has shown successful results in cotton (Raine *et al.*, 2000).

- *Installation*

The first and foremost step in installing successful SDI system is adapting a proper hydraulic design to have ease of flow of water through hydraulic gradient. This facilitates the system to overcome the frictions related to soil characteristics, field size, shape, topography and water supply. Lateral diameter and length influence water application uniformity (Kang *et al.*, 1999). Lamont *et al.* (2002) found that tape diameter of 125-200 mm was the industry standard and common for subsurface drip irrigation whereas the length of laterals range from 90 m to 180 m.

- *Emitters*

Widely spaced crops such as vines, ornamentals, shrubs and trees line source emitters were used. Point source emitters are used for small fruits, vegetables and closely spaced row crops. The emitters used for SDI are much the same as those used for surface drip, but the emitter is fixed internally in the drip line (Harris, 2005).SDI systems generally consist of emitters that have discharge rates less than 8 L/hr (ASAE, 2001).

- *Emitter spacing*

Emitter spacing should normally be less than the drip lateral spacing and it mainly depends on the spacing of crops (Lamm and Camp, 2007).

- *Flushing capacity*

Flushing capacity is the major component of SDI system which decides the performance of the sytem. Many SDI systems appear to have been installed with inadequate flushing capacity, resulting in sediment deposition, decreases in flow volumes and blockages (Pitts *et al.*, 1996). This will produce higher backpressures in the mains, which may also affect system performance (Lamm and Camp, 2007). Retrofitting large valves or increasing the number of valves may solve some flushing problems (Raine *et al.*, 2000).

- *Soil wetting pattern*

The wetting pattern with SDI can be affected not only by irrigation management, but also SDI design aspects such as emitter spacing and drip line depth. Dripper function can also be modified after installation. In one study, heterogeneity of the soil in the neighborhood of a subsurface emitter that had been disturbed by farm equipment resulted in low emitter flow (Shaviv and Sinai, 2004).

SDI and its prospective in crop management and cropping systems

The SDI provides solutions for a variety of issues, including poor WUE, declining water quality, lower risk of aquifer pollution due to reduced deep percolation of fertilizers and other chemical compounds, and improved yields. The ability to supply water and nutrients to the most active area of the root zone, protection of drip lines from damage caused by cultural techniques, and maintaining of a dry soil surface for better weed control and crop health According to recent studies, crop yields can be maximized with SDI while reducing pollution from leaching losses of N with adequate management (Thompson *et al.*, 2000). Irrigation with SDI allows the maintenance of low root-zone salinity, even when using irrigation waters containing appreciable salts (Oron *et al.*, 1999). Operating pressures are often less than in drip irrigation thus, reducing energy costs. Improvement in plant health, less disease and fungal infection due to drier and less humid crop canopies. There are certain types of soil fumigation that can be done with this technology. Since fertilizer and pesticides are applied precisely and on time through the system, improved fertilizer and pesticide management can lead to greater efficacy and, in some cases, a reduction in their use. As the system doesn't have to be taken out during harvest and put back in before the second crop is planted, double cropping chances could be improved.Farming operations and management of many field operations can occur during irrigation events. Fewer field operations result in less soil compaction, and soil crusting caused by irrigation is greatly reduced. Variability in soil water regimes and redistribution are often reduced with SDI as compared to surface drip irrigation. Additionally, weather-related application constraints such as high winds, freezing temperatures and wet soil surfaces are less important and the ability to irrigate during freezing conditions can be particularly beneficial where preseason irrigation is used to effectively increase seasonal irrigation capacity.

Shortfalls in SDI

The major shortcomings of SDI are its high initial cost and the potential for the development of soil salinity, conversion from conventional irrigation system to SDI requires high capital inputs and increase in time required for irrigation design implementation and management. Soil salinity problem is quite often associated with SDI. Even though there is an advantage of Precise application of water and nutrients to the effective root zone , due to upward flow of water from the SDI emitter to the surface and loss of water by evaporation and transpiration can lead to high soluble salt concentration at the soil surface(Dasburg and Or 1999) however, it can be overcome by use of sprinklers which further increases the labor and capital inputs(Hillel,2000).The problem of salt accumulation is more common in arid and semi-arid regions where there is a deficit in rainfall to leach out the salt below the root zone. Specialized tillage methods, and planting salt tolerant crops can help in minimize salinity problems with SDI (Roberts *et al*., 2008).Drip lines should be monitored regularly for root intrusion, system operational and design procedures must employ safeguards to limit or prevent further intrusion. Certain perennial crops' roots may encroach on drip systems and prevent water flow reduction. In order to prevent accumulations of silt and other precipitates in the laterals, drip lines must be flushed periodically. Similar to previous systems, SDI needs more operational management. Depending on installation depth and soil conditions, the wetting pattern of SDI will be too small in coarse textured soils, resulting in a crop root zone that is too small and possible limited germination. This may be especially problematic on soils with vertical cracking.

Challenges and opportunities for SDI design and installation

Creating a flexible SDI can be difficult since farmers may not be aware of their long-term agricultural plans or their farms' potential for increasing cropping intensity. Destruction to laterals by field equipment and machinery and damage to drip lines by rodents and other animals are also significant challenges in SDI, but these issues can be resolved by using a GPS guiding system. (Sorensen, 2019). Although they add complexity and raise initial expenses, automated monitoring and controlling systems and agrochemical injection systems can be profitable in the long run. Many SDI system designs that are solely based on crop requirements will not be able to perform in a variety of conditions. This need for flexibility is also a major driver for the creation of reliable monitoring and control systems that can evaluate the status of plants and soil water and make adjustments as needed. Installation of a smaller SDI system can aid in obtaining expertise with SDI management and operation; nevertheless, this strategy may not result in the successful adoption of SDI because farmers with little free time may be unwilling to invest the time required to master a tiny system.

Advancement in technologies such as sensor data collection, management, and analysis, with the assistance of IOT (internet of things), models and automation systems in SDI will help in developing robust systems and monitoring strategies that could help in overcoming this impediment. Improved characterization of the soil water content (in two and three dimensions) with better soil water sensors and modeling could help in irrigation managers apply water at the right placeand at right time. The continued search for more sustainable irrigation systems provides opportunities for SDI as an efficient delivery method with greater uniformity of crop production. Additional environmental benefits of SDI will likely include reduction in GHG emissions with these combined environmental benefits may become an important overall reason for SDI adoption in the near future among major farming community.

Performance of different crops as influenced by SDI system

SDI can help in improving the crop yields, quality and water use efficiency of the crops , earlier findings revealed that growing of crops under SDI system found better than the conventional irrigation system, in various vegetable, field and perennial crops which were briefly reviewed below

Yield, Water saving, IWUE under SDI system

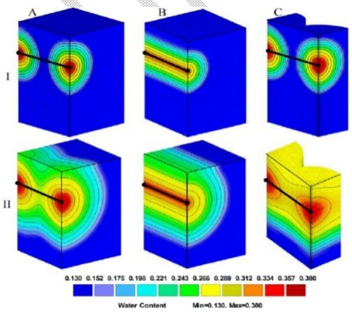
Pheneet *et al*. (1987) demonstrated significant yield increases in tomatoes with the use of high frequency SDI and precise fertility management. Enciso *et al*. (2015) found that the total onion yield obtained with the SDI systems was more than 93% higher than the yield obtained with furrow irrigation systems due to SDI allowing for more frequent and smaller irrigation depths with higher irrigation efficiency than furrow irrigation systems.Sidhu *et al.*(2020)confirmed that in rice- wheat cropping system under conservation agricultureirrigation use efficiency obtained with the SDI system ranged from 17.5 to 25.2 kg/ m^3 and from 4.2 kg /m^3 to 6.2 kg /m^3 in flood irrigation for riceand wheat . However, grain yield and irrigation water input in rice and wheat were generally similar under different SDI treatments and conservation agriculture. Irrigation water savings were 48–53% in rice and 42–53% in wheat under a combination SDI and conservation agriculture compared to flood irrigation systems. Both rice and wheat needed 20% less N fertilizer under SDI system to obtain grain yields similar to that under flood-irrigated crops.Cui *et al.* (2008) pointed out SDI can improve IWUE by 26.7–46.4% and the fruit quality of table grape without detrimental effect on the fruit yield in arid region. The results demonstrated that the minimum amount of water along with highest use efficiency is delivered through SDI and Surface drip irrigation, respectively. Higher tomato crop yields were achieved by SDI as compared to surface drip irrigation in sandy soil (Del Amor and del Amor 2007). Al-Omran *et al.* (2010) concluded that SDI increased the IWUE and yield of their tomato crop by producing a good moisture distribution in the root zone, leading to conservation of irrigation water. Three irrigation strategies: 1.0 of full irrigation supply (T1), 0.8 of full irrigation supply (T2) and 0.6 of full irrigation supply (T3). The results showed that the highest yields were found in the plots irrigated by subsurface drip irrigation at T1 (94.1 t/ha) and T2 (81.4 t/ha). Conversely, the fully stressed treatment (T3) reduced the amount of irrigation water by 40%, but significantly decreased mean tomato yield by 25.6% and 26.1% under subsurface and surface drip irrigation, respectively, as compared to T1.The maximum IWUE tended to be higher for subsurface drip than for surface drip irrigation system. The greatest IWUEs were obtained from subsurface drip and surface drip at T3 (19.7 kg/m^3 and 18.3 kg/m^3), whereas the lowest IWUEs were those estimated in T1 (15.9 kg/m^3 and 14.8 kg/m^3, respectively). Jose *et al.*(2008) opined that based on field experiments conducted under SDI system for irrigation scheduling in corn a good relationships obtained in the study between crop performance indicators and seasonal ETc demonstrate that accurate estimates of ETc on a daily and seasonal basis can be valuable for making tactical in-season irrigation management decisions and for strategic irrigation planning and management under SDI system that will help in saving water.

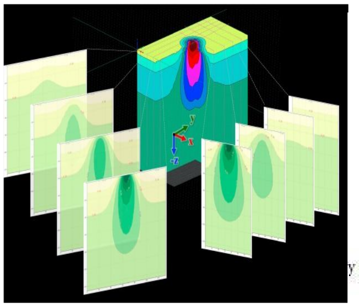
Table1. Performance of SDI under different crops and cropping system in different regions of world

Sl.no	Country	Crop	Yield increase (%)	Water use efficiency	Water saving	References
1	Spain	Olive	30 % compared to drip irrigation	7.75 kg/m^3 compared to drip irrigation 6.75 kg/m^3	8-10 % compared with drip	J. Martínez and J. Reca 2014

2.	Australia	Corn	37% increase in yield	23.5 %	25%	Jose *et al.*(2008)
3	USA	Maize	35-40 % increase in yield compared to rainfed	0.8-3.1 kg/m^3 increase	25 % water saving	Irmak*etal.*(2016)
4	USA	onion	93% higher yield than furrow irrigation	10 kg/m^3 over Furrow irrigation	44 % water saving	Enciso *et al.* (2015)
5	China	Wheat	10 % increase in yield over surface irrigation	4.50 kg/m^3 over surface irrigation	26% water saving	Umair *et al.*(2019)
6	India	Rice	8-10 % higher yieldover drip irrigation	1.20 kg/m^3 over drip irrigation	10-15 % water saving	Rajwade *et al.*(2014)
7	India	Paddy	10-15 % decrease in yield over flooding	2.0 Kg/ha mm Over flooding	40-45 % water saving	Rana*etal.*(2022)
8	India	Soybean, Chickpea Pumpkin	15-43 % over control	2-16 % increase in WUE	-	Bhattari*et al.*(2008)
9	Saudi Arabia	Potato	15-25 % over drip irrigation	1-2 kg/m^3 over drip irrigation	10-20% water saving	Mattar *et al.*(2021)

Modelling, Sensors and automation in SDI





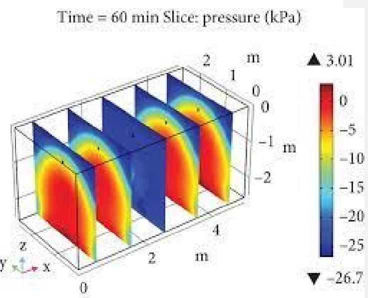


Fig.5Illustrative examples of simulation modeling under SDI for wetting volume, depth of emitters (Kandelous*et al.*, 2011)

The knowledge of both the horizontal and vertical dimensions of the soil volume to wet, where the roots are located and the initial soil water content, allows one to evaluate the duration of irrigation; in addition when the SDI plant has to be designed, the horizontal dimension of the wetted volume also permits the evaluation of emitter spacing (Provenzano, 2007).Theuse of simulation modeling techniques will also help in understanding the processes of hydrolysis, nitrification, mineralization, and ammonium adsorption in cropping system that will save the resource inputs in crop production (Eltarabily*et al.,* 2019).Simulations studies conducted by Arbat*et al.*(2020) using HYDRUS-2D model show that dripline depth of 0.15 m combined with one or two daily irrigation events maximized water extraction and reduced percolation in rice. Moreover, simulations with HYDRUS-2D could be useful to determine the most appropriate location of soil water probes to efficiently manage the SDI in rice.Fully automated sensor based subsurface irrigation system for Ratoon crop reduce the water usage(40%) and increases cycle of the Ratoon crop with the minimum maintenance cost of irrigation system (Krisnhapriya*et al*., 2017).SDI has also had influence on canopy temperature and spectral reflectance of crop canopy since water is available uniformly throughout the crop growth period spectral reflectance of cotton were significantly influenced under SDI (Attia *et al.*,2015).Use of Hydrus 2 D Models under SDI based conservation agriculture (CA) system could simulate the daily changes in profile soil water content with reasonable accuracy and can Simulate soil water balance indicated higher cumulative root water uptake, lower cumulative evaporation and higher soil water retention helps in saving irrigation water by saving the deep percolation losses and reducing irrigation frequency(Patra *et al.,* 2021).

Tillage Management practices and SDI

Combining of agronomic innovations like CA coupledwith SDI and fertigation may be a sustainable option to deal with the emerging troubles of water scarcity, declining groundwater desk (Patra *et al*., 2021). There is a big capability for water savings in CA by using minimizing the deep drainage and evaporation losses and probably diverting the soil moisture use for consumptive use of crop. CA coupled with SDI is a better choice for irrigation water saving, soil moisture conservation, precision irrigation and nutrient management. Besides, reductionin denitrification and volatilization losses through fertigation the use of SDI in CA may even help in lowering global warming potential inside the long -run.

Effect of depth of dripper lines and emitter discharge on performance of SDI

To maximize potential water savings of subsurface drip irrigation (SDI) systems, it is necessary to optimize its design and irrigation management, highlighting depth of emitters and frequency of irrigation.Depth of dripper lines also plays a significant role in crop performance under SDI.Hutmacher *et al*. (1996) demonstrated yield increases in alfalfa production using SDI systems buried at depths of 0.7 m.Dukes *et al*. (2004) noticed that in sweet corn -peanut rotation under automated SDI system, laterals buried at a depth of 23 cm performed better in terms of both the crop yield as compared to laterals buried at depth of 33 cm in sandy soils due to deep percolation of irrigation water under SDI.

References:

Adger, A., Tompkins, E.L. (2005). Successful adaptation to climate change across scales. Global Environment Change Part A,**15**: 77–86.

Aeschbach-Hertig, W., & Gleeson, T. (2012). Regional strategies for the accelerating global problem of groundwater depletion. *Nature Geosciences*, **5**(12): 853-861.

Allan, J.A. (1997). Virtual water: a long term solution for water short Middle Eastern economies. *International Proceedings of the Paper Presentation at the 1997 British Association Festival of Sciences, University of Leeds, Water and Development Session, 9 September 1997*.

Allan, J.A. (1999). Water in international systems: a risk society analysis of regional problem sheds& global hydrologies. *International Proceedings of the Paper Presentation at the Department of Geography, Oxford University Conference on Water Resources and Risk, March 1999*.

Al-Omran, A. M., Al-Harbi, A. R., Wahb-Allah, M. A., Nadeem, M.and Al-Eter, A. (2010). Impact of irrigation water quality, irrigation systems, irrigation rates and soil amendments on tomato production in sandy calcareous soil. *Turkish Journal of Agriculture and Forestry*, **34**(1):59-73.

Amor, M. A.and Amor, F. M. (2007). Response of tomato plants to deficit irrigation under surface or subsurface drip irrigation. *Journal of Applied Horticulture*, **9**(2):97-100.

Arbat, G., Cufí, S., Duran-Ros, M., Pinsach, J., Puig-Bargués, J., Pujol, J.and Ramírez de Cartagena, F. (2020). Modeling approaches for determining dripline depth and irrigation frequency of subsurface drip irrigated rice on different soil textures. *Water*, **12**(6):1724.

ASAE. (2001) ASAE Standard S526.2. Soil and Water Terminology, ASAE, St.Joseph, Michigan.

Attia, A., Rajan, N., Ritchie, G., Cui, S., Ibrahim, A., Hays, D. and Wilborn, J. (2015). Yield, quality, and spectral reflectance responses of cotton under subsurface drip irrigation. *Agronomy Journal*, 107**(4)**: 1355-1364.

Ayars, J. E., Fulton, A. L. A. N. and Taylor, B. (2015). Subsurface drip irrigation in California—Here to stay. *Agricultural water management*, **157**: 39-47.

Bennett, A.J. (2000). Environmental consequences of increasing production: some current perspectives. *Agriculture Ecosystem Environment*, **82**: 89-95.

Bhattarai, S. P., Midmore, D. J.and Pendergast, L. (2008). Yield, water-use efficiencies and root distribution of soybean, chickpea and pumpkin under different subsurface drip irrigation depths and oxygation treatments in vertisols. *Irrigation science*, **26**: 439-450.

Boretti, A.and Rosa, L. (2019). Reassessing the projections of the world water development report. *NPJ Clean Water*, **2**(1): 15.

Camp, C. R. (1998) Subsurface Drip Irrigation: A review. Transactions of the ASAE 41(5): 1353-1367.

Camp, C. R., Lamm, F. R., Evans, R. G. and Phene, C. J. (2000, November). Subsurface drip irrigation–Past, present and future. In *Proc. Fourth Decennial Nat'l Irrigation Symp., Nov* pp. 14-16.

Camp, C.R. and Lamm, F.R. (2003). Irrigation systems: Subsurface drip. Encyclopaedia of Water Science P: 560-564.

Cheng, H. Wang, J. Fan, S. Zhang, Z. Liao, F. Zhang, Y. and Wang (2021). A global meta-analysis of yield and water use efficiency of crops, vegetables and fruits under full, deficit and alternate partial root-zone irrigation. *Agriculture Water Management*.

Clark, G. A. and Smajstrla, A.G. (1996). Design considerations for vegetable crop drip irrigation systems. Hort Technology,**6**(3): 155-159.

Dasberg, S.and Or D. (1999). Applied Agriculture: Drip Irrigation. Springer-Verlag, New York, NY.

Dukes, M. D.and Scholberg, J. M. (2004). Automated subsurface drip irrigation based on soil moisture. In *2004 ASAE Annual Meeting* (p. 1). American Society of Agricultural and Biological Engineers.

Eltarabily, M. G., Bali, K. M., Negm, A. M. and Yoshimura, C. (2019). Evaluation of root water uptake and urea fertigation distribution under subsurface drip irrigation. *Water*, **11**(7): 1487.

Enciso, J., Jifon, J., Anciso, J.and Ribera, L. (2015). Productivity of onions using subsurface drip irrigation versus furrow irrigation systems with an internet based irrigation scheduling program. *International Journal of Agronomy*, **10**(1) :456-492.

FAO, 2021. http://www.fao.org/aquastat/en/.

Gupta, S. K. and Deshpande, R. D. (2004). Water for India in 2050: first-order assessment of available options. *Current science*, 1216-1224.

Harris, G.A. (2005) Sub-surface drip irrigation - System components, DPI&F Note, Brisbane.

Harris, G.A. (2005). Sub-surface drip irrigation – Advantages and limitations, DPI&F Note, Brisbane.

Hillel D. (2000). Salinity Management for Sustainable Agriculture: Integrating Science, Environment and Economics. The World Bank. Washington D.C.

Hutmacher, R. B., Mead, R. M.and Shouse, P. (1996). Subsurface drip: Improving alfalfa irrigation in the west. *Irrigation Journal*. **45**: 48-52.

Irmak, S., Djaman, K.and Rudnick, D. R. (2016). Effect of full and limited irrigation amount and frequency on subsurface drip-irrigated maize evapotranspiration, yield, water use efficiency and yield response factors. *Irrigation Science*, **34**(1):271-286.

Kandelous, M. M., Šimůnek, J., Van Genuchten, M. T.and Malek, K. (2011). Soil water content distributions between two emitters of a subsurface drip irrigation system. *Soil Science Society of America Journal*, **75**(2): 488-497.

Kang, Y., Yuan, B. and Nishiyama, S. (1999). Design of micro-irrigation laterals at minimum cost. *Irrigation. Science.* **18**: 125-133.

Krishnapriya, D. P. (2017). Sensor Based Subsurface Irrigation Monitoring System for Ratoon Crop. *Mediterranean Journal of Basic and Applied Sciences*, **1**(1):71-75.

Kulongoski, J. T. and McMahon, P. B. (2019). Methane emissions from groundwater pumping in the USA. *npj Climate and Atmospheric Science*, **2**(1): 11.

Lamm, F. R. and Camp, C.R. (2007). Subsurface drip irrigation. Microirrigation for crop production design, operation and management, Eds. Lamm, F.R., Ayars, J.E., and Nakayama, F.S. Elsevier, **1**(1): 473-551.

Margat, J. and Van der Gun, J. (2013). *Groundwater around the world: a geographic synopsis*. Crc Press.

Martínez, J. and Reca, J. (2014). Water use efficiency of surface drip irrigation versus an alternative subsurface drip irrigation method. *Journal of Irrigation and Drainage Engineering*, **140**(10): 0401-4030.

Mattar, M. A., Zin El-Abedin, T. K., Al-Ghobari, H. M., Alazba, A. A., & Elansary, H. O. (2021). Effects of different surface and subsurface drip irrigation levels on growth traits, tuber yield, and irriga`tion water use efficiency of potato crop. *Irrigation Science*, **39**(1): 517-533.

Mekonnen, M. M. and Gerbens-Leenes, W. (2020). The water footprint of global food production. *Water*, **12**(10): 2696.

Mishra, V., Asoka, A., Vatta, K. and Lall, U. (2018). Groundwater depletion and associated CO2 emissions in India. *Earth's Future*, **6**(12):1672-1681.

Misra, A. K. (2014). Climate change and challenges of water and food security. *International Journal of Sustainable Built Environment*, **3**(1): 153-165.

Mukherjee, I. and Singh, U. K. (2020). Delineation of groundwater potential zones in a drought-prone semi-arid region of east India using GIS and analytical hierarchical process techniques. *Catena*, **194**: 104-681.

Neufeld, J., Davison, J. and Stevenson, T. (1993). Sub-surface drip irrigation. Fact sheet No: 97-13. University of Nevada.

Oron G., De Malach Y., Gillerman L., David I. and Rao V. P. (1999). Improved saline-water use under subsurface drip irrigation. Agricultural Water Management, **39**:19-33.

Palacios-Díaz, M. P., Mendoza-Grimón, V., Fernández-Vera, J. R., Rodríguez-Rodríguez, F., Tejedor-Junco, M. T.and Hernández-Moreno, J. M. (2009). Subsurface drip irrigation and reclaimed water quality effects on phosphorus and salinity distribution and forage production. *Agricultural water management*, **96**(11): 1659-1666.

Phene, C. J. (1996). Shovel versus computer. Irrig. Business Tech., 4(**3**): 6.

Phene, C.J. and Sanders, D.C. (1976). Influence of combined row spacing and highfrequency trickle irrigation on production and quality of potatoes. *Agronomy Journal*, **68**: 602-607.

Phene, C.J., Davis, K.R., Hutmacher, R.B.and McCormick, R.L., (1987). Advantages of subsurface drip irrigation for processing tomatoes. *Acta Horticulture*, 200 **(1):** 101-113.

Prathapar, S. A. (2000). Water shortages in the 21st century. *The Food and Environment Tightrope. Australian Centre for International Agricultural Research, Canberra, Australia*, 125-133.

Provenzano, G. (2007). Using HYDRUS-2D simulation model to evaluate wetted soil volume in subsurface drip irrigation systems. *Journal of Irrigation and Drainage Engineering*, **133(**4):342-349.

Raine, S. R., and Foley, J. P. (2001). Application systems for cotton irrigation—are you asking the right questions and getting the answers right. In *Growing opportunities. Irrigation 2001 National Conference* pp. 11-12.

Rajwade, Y. A., Swain, D. K. and Tiwari, K. N. (2014). Subsurface drip irrigation for wet season rice production under climate variability in India. In *31st Conference on Agricultural and Forest Meteorology/2nd Conference on Atmospheric Biogeosciences*.

Rana, B., Parihar, C. M., Nayak, H. S., Patra, K., Singh, V. K., Singh, D. K. and Jat, M. L. (2022). Water budgeting in conservation agriculture-based sub-surface drip irrigation using HYDRUS-2D in rice under annual rotation with wheat in Western Indo-Gangetic Plains. *Field Crops Research*, **282**: 108519.

Roberts T L, White S A, Warrick, A. W. and Thompson T L. (2008). Tape depth and germination method influence patterns of salt accumulation with subsurface drip irrigation. Agricultural Water Management. pp 01-3.

Shah, M. T., Ara, J., Muhammad, S., Khan, S., and Tariq, S. (2012). Health risk assessment via surface water and sub-surface water consumption in the mafic and ultramafic terrain, Mohmand agency, northern Pakistan. *Journal of geochemical exploration*, **118**:60-67.

Shah, T. (2009). Climate change and groundwater: India's opportunities for mitigation and adaptation. *Environmental Research Letters*, **4**(3):035005.

Shah, T., Rajan, A., Rai, G. P., Verma, S.and Durga, N. (2018). Solar pumps and South Asia's energy-groundwater nexus: exploring implications and reimagining its future. *Environmental Research Letters*, **13**(11), 115003.

Shaviv, A.and Sinai, G. (2004). Application of conditioner solution by subsurface emitters for stabilizing the surrounding soil. *Journal of irrigation and drainage engineering*, **130**(6): 485-490.

Sidhu, H. S., Jat, M. L., Singh, Y., Sidhu, R. K., Gupta, N., Singh, P. and Gerard, B. (2019). Sub-surface drip fertigation with conservation agriculture in a rice-wheat system: A breakthrough for addressing water and nitrogen use efficiency. *Agricultural Water Management*, **216**:273-283.

Siebert, S., Henrich, V., Frenken, K.and Burke, J. (2013). Update of the digital global map of irrigation areas to version 5. *Rheinische Friedrich-Wilhelms-Universität, Bonn, Germany and Food and Agriculture Organization of the United Nations, Rome, Italy*.

Smith, M. G.and Urpelainen, J. (2016). Rural electrification and groundwater pumps in India: Evidence from the 1982–1999 period. *Resource and Energy Economics*, **45**: 31-45.

Sorensen, R. B. and Lamb, M. C. (2019). Three soil water potential strategies to schedule irrigation events using S3 DI in cotton. *Journal of Cotton Science*,**23**(1):14-20.

Thompson T L, Doerge T A. (1996). Nitrogen and water interactions in subsurface tricle-irrigated leaf lettuce. II. Agronomic, economic, and environmental outcomes. Soil Science Society of America Journal, **60**: 168-173.

Thompson T L, Doerge T.A.and Godin R E. (2000). Nitrogen and water interactions in subsurface drip-irrigated cauliflower. I. Plant response. Soil Science Society of America Journal, **64**: 406-41.

Umair, M., Hussain, T., Jiang, H., Ahmad, A., Yao, J., Qi, Y.and Shen, Y. (2019). Water-saving potential of subsurface drip irrigation for winter wheat. *Sustainability*, **11**(10): 2978.

Vaziri, C. M. and Gibson, W. (1972). Subsurface and drip irrigation for Hawaiian sugarcane. *Rep Hawaii Sugar Technol Annu Con ference*.

Velis-A Sese-Minguez, S., Boesveld, H. S., Van der Kooij, S.and Maroulis, J. (2017). Transformations accompanying a shift from surface to drip irrigation in the Cànyoles Watershed, Valencia, Spain. *Water Alternatives*, **10**(1): 81.

Wang, J., Rothausen, S. G., Conway, D., Zhang, L., Xiong, W., Holman, I. P.and Li, Y. (2012). China’s water–energy nexus: greenhouse-gas emissions from groundwater use for agriculture. *Environmental Research Letters*, **7**(1): 014035.