SUBSURFACE DRIP IRRIGATION - PAST, PRESENT, AND FUTURE

C. R. Camp, F. R. Lamm, R. G. Evans, and C. J. Phene*

ABSTRACT

Subsurface drip irrigation (SDI) has been a part of agricultural irrigation in the USA for about 40 years but interest has increased rapidly during the last 20 years. Early drip emitters and tubing were somewhat primitive in comparison to modern materials, which caused major problems, such as emitter plugging and poor distribution uniformity. As plastic materials, manufacturing processes, and emitter designs improved, SDI became more popular but emitter plugging caused by root intrusion remained a problem. Initially, SDI was used primarily for high-value crops such as fruits, vegetables, nuts, and sugarcane. As system reliability and longevity improved, SDI was used for lower-valued agronomic crops, primarily because the system could be used for multiple years, reducing the annual system cost. Design guidelines have also evolved to include unique design elements for SDI, including air entry ports for vacuum relief and flushing manifolds. Specific installation equipment and guidelines have also been developed, resulting in more consistent system installation, improved performance, and longer life. Crop yields with SDI are equal to or better than yields with other irrigation methods, including surface drip systems. Water requirements are equal to or lower than surface drip and fertilizer requirements are sometimes lower than for other irrigation methods. Interest in the use of wastewater with SDI has increased during the last decade. The future of SDI is very promising, including its use in wastewater systems, and especially in areas where water conservation is important or water quality is poor. SDI is a very precise irrigation method, both in the delivery of water and nutrients to desired locations and the timing and frequency of applications for optimal plant growth.

Keywords: Microirrigation, Trickle irrigation, Emitter, System design, Water quality, Agronomic crops, Horticultural crops, Forage crops

INTRODUCTION

Interest in subsurface drip irrigation (SDI) has increased during the last two decades primarily due to increased pressure to conserve water resources and the availability of reliable system components. While interest in this technology has existed in the USA for over 40 years, there have been few attempts to summarize available information until recently. Discussions of subsurface drip irrigation was included in several reviews of drip irrigation (Howell et al., 1980; Bucks et al., 1982; and Bucks and Davis, 1986). Jorgenson and Norum (1992) presented an overview of SDI theory and various applications, Camp (1998) provided a comprehensive review of the subject, and Ayars et al. (1999) published a review of SDI research at Fresno, CA.

Subsurface drip irrigation is defined by ASAE S526.1 "Soil and Water Terminology" (ASAE, 1999a) as "application of water below the soil surface through emitters, with discharge rates generally in the same range as drip irrigation." Earlier, "subirrigation" and "subsurface irrigation" sometimes referred to both SDI and subirrigation (water table management), and "drip/trickle irrigation" could include either surface or subsurface drip/trickle irrigation, or both. Other definitions of SDI require

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* C. R. Camp, Agricultural Engineer, USDA-ARS, Florence, SC; F. R. Lamm, Research Agricultural Engineer, Kansas State Univ., Colby, KS; R. G. Evans, Agricultural Engineer, Washington State Univ., Pullman, WA; and C. J. Phene, Consultant, SDI+, Fresno, CA. Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the USDA, Kansas State Univ., Washington State Univ., or SDI+, and does not imply approval of a product to the exclusion of others that may be suitable.

drip lateral placement below specified depths, such as normal tillage depths or a depth that would ensure use for several years. SDI has been generally used to describe drip/trickle application equipment installed below the soil surface only for the past 15-20 years. All drip systems with laterals installed below the soil surface (>2 cm deep) will be included in this report.

Availability of plastic (polyethylene (PE) and polyvinylchloride (PVC)) following World War II allowed the development of drip irrigation, initially in Great Britain and possibly other countries, and later in Israel and the USA. SDI was part of drip irrigation development in the USA, beginning about 1959, especially in California and Hawaii. During the 1960s, plastic pipe with cut or punched holes was used because manufactured drip laterals were not available. By 1970, trial installations on commercial farms and sugar plantations were being installed using a variety of both experimental and commercial drip emitters and laterals and equipment developed for that purpose. As commercial drip emitters and tubing became more reliable, surface drip applications grew at a greater rate than did subsurface applications, probably because of problems with emitter plugging and root intrusion. Interest in subsurface drip increased during the 1980s, especially during the last half of that decade, when many research reports were published and appropriate commercial products became available. Interest and activity in both the research and commercial sectors continued during the 1990s, especially in areas with declining water supplies and environmental issues related to irrigation. There was also special interest in the use of wastewater, especially for turf and pastures.

PAST DEVELOPMENT AND USE

Early Tubing and Emitters

Initially, drip laterals were constructed using plastic pipe with holes or slits drilled, punched, or cut into the pipe (Braud, 1970; Hanson et al., 1970; Zetzsche and Newman, 1966), or discrete emitter inserts punched into the pipe (Whitney, 1970). Typically, these systems were operated at low pressures with varying levels of water quality and filtration. Whitney and Lo (1969) evaluated plugging and performance of several emitters, concluding that the plastic insert orifice was preferred. Most system performance problems were related to poor uniformity, system maintenance, and emitter plugging, which was typically caused by iron oxide or soil particles.

By the 1970s, field installation equipment included devices that either punched holes or inserted plastic emitters in the tubing (Zetzsche and Newman, 1966; Whitney, 1970). About the same time, advances were being made in surface drip irrigation systems in Israel (Goldberg and Shmueli, 1970). Porous tubes were also used in both surface and subsurface drip installations (Mitchell and Tilmon, 1982; Phene and Beale, 1976). Commercial drip emitters and tubing became more reliable for surface applications but emitter plugging and root intrusion remained as problems for SDI. However, reports of lateral life up to 10 years (Mitchell and Tilmon, 1982) and successful commercial installations Tollefson (1985a,b) caused increased interest in SDI.

System Design, Installation, and Operation

Most early SDI systems were designed in the same manner as surface drip systems, especially with regard to system hydraulics. However, mathematical theory for movement of water from buried point sources and models to describe water infiltration, plant extraction, and lateral depth and spacing were developed relatively early (Philip, 1968; Gilley and Allred, 1974a,b; and Zachman and Thomas, 1973).

In a review, Camp (1998) reported that drip lateral depths ranged from 0.02 m to 0.70 m, depending upon both soil and crop. In most cases, lateral depth was probably optimized for prevailing site conditions and knowledge of the soil and its water characteristics. Little crop yield difference was reported in experiments where several lateral depths were evaluated. Where systems were used for multiple years and tillage was a consideration, drip lateral depths ranged from 0.20 to 0.70 m. Where tillage was not a consideration (e.g., turfgrass, alfalfa) drip lateral depths were closer to the surface (0.10 to 0.40 m). Lateral spacing also varied considerably (0.25 to 5.0 m), with narrow spacings used primarily for turfgrass and wide spacings often used for vegetable, tree, or vine crops on beds. For the wider spacings in uniformly spaced row crops, drip laterals were usually located under either alternate or every third mid-row areas (furrows). For crops with alternating row spacing patterns (sugarcane and pineapple in Hawaii and some cotton), drip laterals were located about 0.8 m from each row, usually in the narrow spacing of the pattern. Closer spacings were used for some high-value crops on sandy soils (Phene and Sanders, 1976) and/or in arid areas to ensure adequate salt balance and consistent crop quality and yield. In one study, drip lateral location relative to the row or bed location did not affect yield (possibly because of ground water at 1.5-m depth), but mechanical damage to laterals was greater when they were located under the furrow than when located under the row for tomato and cotton (Ayars et al., 1995).

If seed germination and seedling establishment and growth were important, either sprinkler or surface irrigation was used for germination when initial soil water contents were not adequate. However, the need for two systems increased expense and decreased net economic return. If subsurface drip was used for germination, an excessive amount of irrigation was often required to wet the seed zone for germination, which could have resulted in excessive leaching and off-site environmental effects as well as increased cost. Sprinkler irrigation may also be required in some areas to control salinity if precipitation is inadequate for several consecutive years.

Past Applications

Initially, subsurface drip was used predominantly in California, Hawaii, and Texas for sugarcane, cotton, citrus, pineapple, vegetables, avocado, fruits, turfgrass, sweet corn, and potato. Later, the application expanded to other areas and the number and variety of crops increased, including agronomic and vine crops. SDI applications using recycled or wastewater sources began to emerge in the 1990s. These applications were primarily for landscape plants, forest, and grasses except in Israel where wastewater was used for corn, cotton, wheat, peas, and alfalfa.

CURRENT STATUS AND USE

System Design and Installation

Design of SDI systems is similar to that of surface drip systems, especially with regard to hydraulic characteristics. However, special attention to water filtration, proper number and location of air-vacuum relief and check valves, pressure regulation, flow measurement, and flushing is required for successful SDI systems. Air-vacuum relief valves are needed to prevent aspiration of soil particles into emitter openings when the system is depressurized. Water filtration is often more critical for SDI systems than for surface drip systems because the consequences of emitter plugging are more severe and more costly. The specific crop and soil essentially determine the system capacity, emitter spacing, and lateral depth and spacing. If water supplies are not limiting, system capacity, along with effective precipitation and stored water, must satisfy peak crop water requirements.

For multiple-year, long-term SDI systems, the lateral depth should be deep enough to prevent damage by tillage equipment but shallow enough to supply water to the crop root zone without wetting the soil surface. Generally, laterals in SDI systems are installed at depths of 0.1-0.5m, with shallower depths on coarse-textured soils and slightly deeper on finer-textured soils. In some cases, surface wetting is required for seed germination and seedling establishment. In SDI systems, surface wetting occurs primarily from longer irrigation durations and when the emitter flow rate exceeds the hydraulic conductivity of the soil surrounding the emitter. It is affected by many variables, including soil texture, lateral depth, emitter flow rate, and soil compaction. Emitter spacing and flow rate are determined by crop rooting patterns, lateral depth, and soil characteristics, but emitters should provide overlapping wetted areas along the lateral for most row crops. Lateral spacing is determined primarily by the soil, crop, and cultural practices and should be narrow enough to provide a uniform supply of water to all plants and to manage salinity, if necessary. For row crops, laterals should be parallel to crop rows and crops should be planted at the same location relative to the row each year, usually at consistent row spacings. Generally, laterals are spaced 1- 2 m apart in row crops but may be spaced closer for irrigation of pasture, forage crops, and turf.

Many types of tubing have been used successfully for SDI. Thin-walled (0.15 mm to 0.30 mm), flexible tubes are typically used more for short-term installations and typically are installed at shallow depths. Thicker-walled (0.38 mm to 0.50 mm), flexible tubes have been used successfully for several years provided that they are installed deep enough to avoid tillage, cultivation, and harvest equipment. In non-bridging soils where the soil profile does not provide sufficient support, thicker-wall tubing (>1.50 mm) may be required to prevent deformation or collapse of the tubing by equipment or soil weight. Rigid tubing with even thicker walls is often used on perennial crops or on annual crops for longer time periods (>10 years).

Most SDI laterals are installed by tractor-mounted shanks equipped with feed tubes mounted on the backside of the shank to install the tubing at the proper depth. During installation, care should be taken to avoid stretching or kinking of the tubing. Care should also be taken to install the drip tubing at a uniform depth throughout the field, especially around the field perimeter, so that there is no question about the maximum allowable tillage depth. During installation, drip laterals should be oriented so that the emitters are on top to minimize plugging from particulate matter that accumulates along the bottom of the lateral. Manifold or header pipes are installed deeper than laterals to reduce interference with tillage operations, to prevent them from draining, to accelerate pressurizing the system, to avoid damage from field equipment, and to prevent particulate matter from entering the lateral. Manifolds, mains, and sub-mains are plastic, usually PVC, and are connected to laterals using a variety of connectors, depending upon the type of tubing. When flushing manifolds are a part of the system, these manifolds should be carefully sized to provide sufficient velocity to transport particles out of the system.

Current Applications

SDI is currently being used on a wide variety of crops, including tree, fruit, vine, agronomic, pasture, landscapes, and turf. In a review of published research results for SDI, Camp (1998) listed over 30 different applications. Most applications were for food and fiber crops, but some applications included trees, turf, and landscape plants, especially with recycled or waste water sources. While this review related primarily to published research results, the mix of applications should be somewhat representative of commercial practices. For SDI use on fruit and vegetable crops, tomato (fresh market and processing) was the most popular, followed by lettuce, potato, and sweet corn. Other crops included apple, asparagus, banana, bell pepper, broccoli, cabbage, melons, carrot, cauliflower, pea, green bean, okra, onion, papaya, rape, squash, and floriculture. For agronomic crops, cotton and corn were the most popular. Others included alfalfa, grain sorghum, peanut, pearl millet, and wheat. There are multiple reasons for adoption of SDI on specific crops. For example, plant diseases may be reduced on crops such as strawberry by using plastic mulch and SDI, which keeps the soil surface and foliage relatively dry. Multiple-year use of SDI may reduce the annual system cost so that it is profitable for use with lower-value crops such as cotton and corn. The precise placement and management of water and fertilizers, an inherent capability of SDI, is an important factor with tree and vine crops.

Water Supply - Quantity and Quality

The water supply capacity directly affects the design and operation of a SDI system. The size of the irrigated field or zone is often controlled by the available capacity of the water supply. For example, in some humid areas, when high-capacity wells are not available multiple low-capacity wells can be distributed throughout a farm. Fortunately, with SDI, the size and shape of fields can be economically adjusted to correspond to water supply capacity and other factors (O'Brien et al., 1998). Quality of the water supply is extremely important and significantly influences the type of water filtration required. Generally, the better the water quality the less complex the filtration system, but surface, recycled, or waste water supplies require the most elaborate filtration. However, good filtration is the key to good system performance and long life, and should be a major concern in system design. In some cases, chemical injection may be required to adjust acidity, to control biological activity, or to correct other water supply deficiencies. Several reports with special emphasis on water supplies (saline, deficit, and wastewater) for SDI were listed by Camp (1998).

Root Intrusion and System Longevity

Emitter plugging caused by root intrusion can be a major problem with SDI systems, but can be minimized by chemicals, emitter design, and irrigation management. Chemical-based control techniques include the use of herbicides, either slow-release growth-retarding compounds embedded into emitters and filters or periodic injection of low-concentration solutions into the irrigation stream, or injection of other chemicals, such as fumigants, into the irrigation stream. Periodic injection of phosphoric acid and chlorine can modify the environment immediately adjacent to emitters and reduce root intrusion. Emitters that are plugged by roots may be cleaned using periodic injections, such as acids and chlorine, but some of these chemicals can cause long-term, adverse soil effects and/or damage other system components.

Emitter design may also affect root intrusion. Smaller orifices tend to have less root intrusion but are more susceptible to plugging by particulate matter. Some emitters are constructed with physical barriers to root intrusion. Root intrusion appears to be more severe where emitters are located in areas of preferential root growth, such as along seams of thin-walled tubes. However, root intrusion problems appear to be greater for emitters, tubes, and porous tubes that are not chemically treated.

Irrigation management can influence root intrusion by controlling the environment immediately adjacent to the emitter. High frequency pulsing that frequently saturates the soil immediately surrounding the emitter can discourage root growth in that area for some plants but not others. Conversely, deficit irrigation, sometimes practiced to increase quality or maturity or to control vegetative growth, can increase root intrusion because of high root concentrations in the emitter area. When injecting chemicals into SDI systems, the entire system should be thoroughly flushed after each injection event.

System Operation and Chemical Injection

SDI systems offer the potential for precise placement and management of water, nutrients, and pesticides if the system is properly designed and managed. Water can be applied in a variety of modes, varying from multiple continuous or pulsed applications each day to one application in several days. Likewise, fertilizers can be injected into the irrigation water and delivered to the plant root zone at similar frequencies. The application frequency used depends upon several factors, including soil characteristics, crop requirements, water supply, system design, and management strategies. When proper flow measuring devices are provided, SDI systems can be managed to optimize use of limited water supplies. Camp (1998) reviewed several reports comparing application frequency using SDI, reporting that some crops responded to high-frequency irrigation while others did not.

Some systemic pesticides and soil fumigants can be safely injected via SDI systems. This technique has the potential to minimize chemical exposure of workers and environment contamination, to reduce the cost of pesticide rinse water disposal, and to improve precision of application to the desired target (e.g. root pests). However, a high level of management with system automation and feedback control is required to minimize chemical movement to the ground water when chemicals are used.

SDI must be managed properly to obtain an acceptable (economical) system life (>10 years), especially when used in lower-valued crop production systems. A consistent, proactive management strategy of preventing problems, such as emitter plugging, is required instead of one where components are repaired or replaced after they fail. Locating and repairing or replacing failed components is more difficult and more expensive with subsurface systems than with surface systems. In fact, a major complaint with SDI from system managers is that most system components are buried and cannot be directly observed. Consequently, operational parameters such as frequent measurements of flow rate and pressure must be used as indicators of system performance. Global positioning systems (GPS) can now be used to better locate specific points. A major factor in maintaining consistently good system performance is constant attention to maintaining good water quality and proper filtration. Periodic system flushing to remove particulate matter is also used to prevent emitting plugging. Some commercial systems in the southwestern USA have been in use for almost 20 years. Research-based SDI systems have performed well for 8-11 years with little indication of degradation (Phene et al., 1992; Camp et al., 1997; Lamm and Trooien, 1999).

Crop Water Requirements and Application Uniformity

When properly managed, subsurface drip is one of the most efficient irrigation methods with typical application efficiencies exceeding 90% . In a review, Camp (1998) found that yields for subsurface drip irrigated crops were equal to or greater than yields from other methods of irrigation. He also found that the water requirement for SDI systems was generally similar to or slightly less than for any efficient, well-managed irrigation system. Some investigators reported irrigation water requirements as much as 40% less than for other irrigation methods.

Typically, irrigation applications are very uniform for SDI systems that have been properly designed, installed, and maintained. Assessment of system application uniformity is more difficult for SDI systems than for surface drip irrigation because most components are buried and not available for direct assessment. Indirect methods, including computer models, are available to assist in uniformity evaluations (Phene et al., 1992; ASAE, 1999b; Burt et al., 1999). However, once significant emitter plugging has occurred, many of the statistical sampling methods are unreliable because basic assumptions used in their development are no longer satisfied (Camp et al., 1997).

Salinity Management

Compared to conventional surface drip systems, concentration of salts on or near the surface causing germination and other problems tends to be reduced under properly designed and managed SDI systems. However, salinity may still be a problem with SDI in arid and semi-arid areas since any leaching above the tubing occurs only as the result of rain. Thus, salts tend to accumulate in this area during the season as the plants extract water and leave the salts behind. High salt concentrations exceeding 10 dS/m have been found in the top 6-10 cm of the soil profile (Ayars et al., 1995). Salinity distribution measurements have shown that salts were moved to below the plant row when the laterals were placed under the furrows rather than under the beds (Ayars et al., 1995). The chloride concentration increased as the distance from the lateral increased.

FUTURE TRENDS

Declining Water Resources

As competition with municipalities and industry for available water resources increases, the quantity of water available for irrigation will generally decline. Many areas of the USA have already experienced decreasing water supplies, even in humid areas, where water supplies traditionally have not been limiting. Water conservation programs, both voluntary and mandatory, have been implemented in many irrigated areas. Generally, SDI has increased in areas where water conservation is critical. Lamm and Trooien (1998) concluded from a case study of four western Kansas counties that the useful life of the Ogallala aquifer in that area could be extended a significant number of years through adoption of SDI over the existing furrow irrigation and that the cost for conversion could be amortized over the 10-20 year life of the system.

Use of Recycled Water

As competition for good quality water increases, there will be increased interest in using water of lower quality, e.g. recycled domestic waste and animal waste waters. Use of wastewater for irrigation has been actively practiced in other countries for many years, especially in Israel, where wastewater reuse has been a part of national resource planning since 1955. Oron et al. (1995) reported up to 85% of the consumed domestic water was returned to the environment after municipal water treatment. Subsurface drip irrigation has recently received particular attention in Israel because of its ability to utilize secondary treated wastewater on fresh market vegetables and fruit (Oron et al., 1990). During the last decade, interest in use of wastewater for subsurface drip irrigation in the USA has increased. Camp (1998) reviewed four research reports related to use of wastewater for subsurface drip irrigation, ranging from concept studies to results for applications on trees and landscapes. Interest in the use of animal wastewater with SDI has increased in recent years, primarily to utilize nutrients, to manage surface phosphorus levels, to control odors, and to reduce human contact with the applied wastewater. The major challenge for wide use of recycled and/or wastewater in SDI is the economical treatment and filtration of these waters to reduce emitter plugging and removal or deactivation of pathogens. Before wastewater can be used for irrigation of food crops, even with SDI where water does not directly contact edible portions of the crop, regulations in most states will have to be modified.

Future Applications

Application of subsurface drip irrigation will continue to increase in the near future, depending primarily upon the economic benefit of this technology in comparison to other irrigation methods. It will continue to have applications for perennial tree and vine crops as well as for many crops on established production beds and row systems. If the cost of SDI systems should decrease relative to other irrigation systems, SDI could become economical for additional crops, especially more agronomic, pasture, and forage crops. There is increased interest in use of this technology for grasses, pasture, and forage crops, especially for alfalfa (Hutmacher et al., 1992). One reason for this is that SDI maintains a relatively dry soil surface, which reduces the need for the required drying period prior to harvest of these crops..

Total Area Installed/Fraction of Market

There is general consensus that use of SDI is increasing, but data to confirm this growth is difficult to obtain. A recent survey of irrigation in the USA reported 156,070 ha of SDI, which is about 0.6% of the total irrigated area of 25, 501, 831 ha (Anon., 2000). Another survey of irrigation in the USA reported 850,600 ha of total drip irrigation, which is 4.2% of the total irrigated area of 20,254,400 ha (Anon., 1998).

SUMMARY

Subsurface drip irrigation (SDI) has been a part of drip irrigation development in the USA since its beginning about 1959. Most early systems were primitive by current standards and consisted of holes or slits punched or cut into plastic pipe or discrete emitters punched into the pipe. As plastic tubing and emitters improved to provide more uniform and reliable operation, surface drip applications grew more rapidly than SDI applications, probably because of emitter plugging caused by root intrusion. Interest in SDI has increased rapidly during the last 20 years, probably because of improved commercial products, use of the system for multiple years when installed below the root zone, and the need for water conservation. Initially, SDI was used primarily for high-value vegetable, fruit, and nut crops but later expanded to include agronomic and forage crops such as cotton, corn, and alfalfa. Early designs for SDI systems were essentially the same as for surface drip systems but more recent design guidelines include specific recommendations for SDI, including air entry ports and flushing manifolds. Crop yields and water use efficiency with SDI were either equal to or greater than with other irrigation methods, including surface drip irrigation. Fertilizer requirements were similar to or less than those for other irrigation methods. The inherent ability of SDI to maintain a relatively dry soil surface is an advantage for some crop situations, especially when needed for crop harvest or to reduce weed growth, but is a disadvantage in other situations such as germination of shallow-planted seeds. The most effective method for prevention of root intrusion into emitters appears to be the use of herbicides, either as a slow-release from emitters or other system components or direct injection into the irrigation water. During the last decade, there has been much interest in the use of wastewater for irrigating crops using SDI. Advantages include less odor and deeper placement of phosphorus into the soil profile.

The future of SDI appears to be good. As competition for water resources and the need for water conservation increases, applications of SDI should also increase. This technology offers the ability to very precisely place water, nutrients, and other chemicals in the plant root zone at the timing and frequency needed. With proper design, installation, and management, SDI systems can provide good and reliable performance for 10-20 years.

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