WATER TABLE MANAGEMENT TO ENHANCE CROP YIELDS IN A WETLAND RESERVOIR SUBIRRIGATION SYSTEM

B. J. Allred, L. C. Brown, N. R. Fausey, R. L. Cooper, W. B. Clevenger, G. L. Prill, G. A. La Barge, C. Thornton, D. T. Riethman, P. W. Chester, B. J. Czartoski

ABSTRACT. *A Wetland Reservoir Subirrigation System (WRSIS) allows for capture, treatment, storage, and reuse of runoff and subsurface drainage waters from cropland, in turn providing both environmental and agricultural production benefits. The three WRSIS sites presently in operation are all located within the northwest Ohio portion of the Maumee River Basin and have been in use for five to six complete growing seasons. WRSIS components include an underground drainage pipe network tied to both a constructed wetland and a water storage reservoir. With this type of system, the drain pipes can be used at different times to either add water (subirrigation) or remove water (subsurface drainage) from the root zone, thereby enhancing crop yields, especially in dry years. Obtaining these crop yield benefits requires a proper water table management approach that includes practicing suggested operational guidelines and initiating as needed system modification improvements. By incorporating a proper water table management approach, and in comparison to control plots, WRSIS subirrigated field crop yield increases for corn and soybeans, respectively, were 34.5 and 38.1% during drier growing seasons, 14.4 and 9.7% during near average to wetter growing seasons, and 19.6 and 17.4% overall.*

Keywords. *Subirrigation, Subsurface drainage, Water table management, Wetlands, Water storage reservoirs.*

An innovative agricultural water storage and routing system was developed and continues to be tested at three northwest Ohio locations in the Maumee River Basin. Called a Wetland Reservoir Subirrigation System (WRSIS), it is comprised of a wetland and a water storage reservoir linked to a network of subsurface pipes used at different times to either drain or irrigate crops through the root zone. Runoff and subsurface drainage are collected in a constructed wetland. Natural processes in the wetland treat the water by removing some of the nutrients, pesticides, and sediment. The water is then routed to a storage reservoir and held until needed for subirrigation. The storage reservoir also provides a further opportunity for sediment and adsorbed nutrients to settle out of the water. Weir–type hydraulic control structures are used to manage shallow ground water levels in soil, regulate surface water levels in the wetland, and limit offsite discharge. The integration of these components allows WRSIS to operate in a closed loop mode most of the time (fig. 1), thus restricting offsite water release.

WRSIS is rather unique because there are no other systems presently being studied that first treat and then recycle drainage water for crop irrigation. Albeit, there has been research conducted on some of the components that comprise WRSIS. Kovacic et al. (2000) found that constructed treatment wetlands removed 28% of nitrate (NO_3–N) but only 2% of total phosphorous from subsurface drainage waters. Conventional subsurface drainage typically increases the amount of nitrate while reducing the sediment and total phosphorous load lost from agricultural fields (Baker and Johnston, 1977; Schwab et al., 1985). Subirrigation, in comparison to conventional subsurface drainage, reduces the amount of nitrate that is released offsite (Fausey et al., 1995; Belcher and Protasiewicz, 1995; Zucker and Brown, 1998). The yield benefits of subirrigation have been well established for crops such as corn, soybeans, navy beans, and sugar beets (Cooper et al., 1991; LeCureux, 1995; Cooper et al., 1999; Fisher et al., 1999). Through a multi–step process, agroforestry systems that are being tested in California's San Joaquin Valley sequentially reuse subsurface drainage water from one field to provide irrigation in another field containing vegetation with greater salt tolerance (Tanji and Karajeh, 1993; Cervinka et al., 1995). Some of the water in these agroforestry systems gets reused several times from one field to the next, however, unlike WRSIS, runoff and subsurface drainage waters are never captured, treated, and then re–applied to the same field.

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The authors are **Barry J. Allred, ASAE Member Engineer,** Research Agricultural Engineer, USDA/ARS/SDRU, Columbus, Ohio; **Larry C. Brown, ASAE Member Engineer,** Professor, FABE Department, Ohio State University, Columbus, Ohio; **Norman R. Fausey, ASAE Member,** Research Leader, USDA/ARS/SDRU, Columbus, Ohio; **Richard L. Cooper,** Research Agronomist, Retired, USDA/ARS/CSRU, Wooster, Ohio; **William B. Clevenger,** Agricultural Extension Agent, Ohio State University, Defiance, Ohio; **Gary L. Prill**, Agricultural Extension Agent, Ohio State University, Van Wert, Ohio; **Gregory A. LaBarge,** Agricultural Extension Agent, Ohio State University, Wauseon, Ohio; **Duane T. Riethman, ASAE Member Engineer,** Project Engineer, USDA/NRCS, Van Wert, Ohio; **Paul W. Chester, ASAE Member Engineer,** Area Engineer, USDA/NRCS, Findlay, Ohio; **Clifford Thornton,** Coordinator, and **Bernard J. Czartoske,** Past Coordinator, Maumee Valley RC&D, Defiance, Ohio. **Corresponding author:** Barry J. Allred, USDA/ARS/SDRU, 590 Woody Hayes Drive, Room 234, Columbus, OH 43210; phone: 614–292–9806; fax: 614–292–9448; e–mail: allred.13@osu.edu.

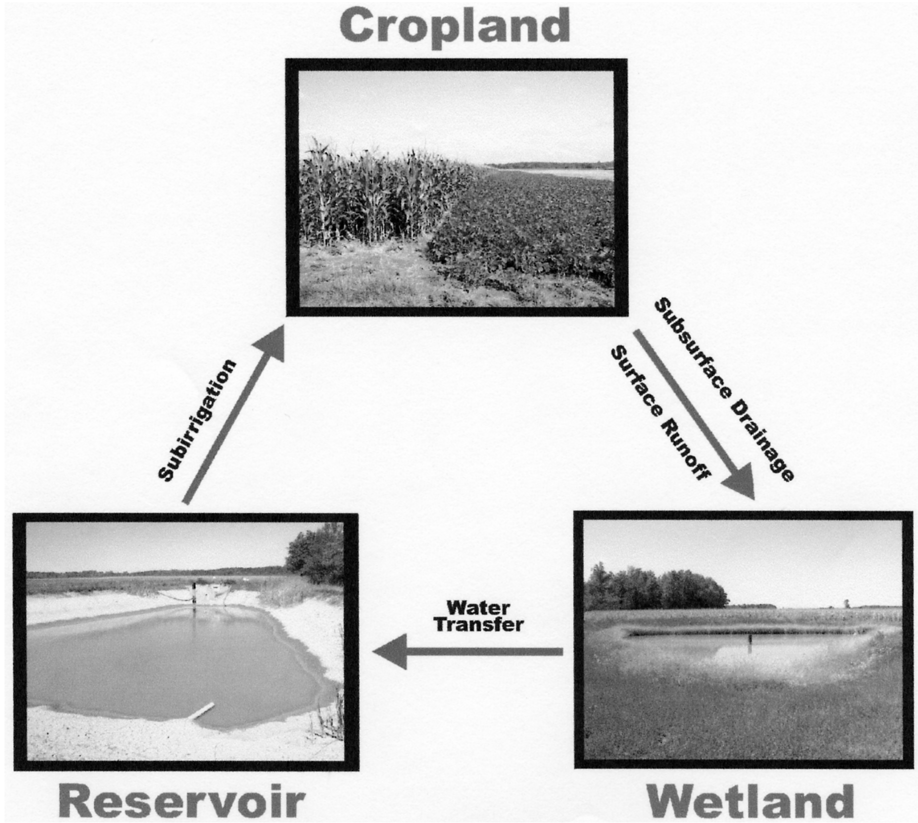

Figure 1. Schematic of the WRSIS concept showing interrelationship between wetland, reservoir, and subirrigated cropland components.

Nutrients, pesticides, and eroded topsoil that escape via runoff and subsurface drainage from Corn Belt farmland are responsible for substantial adverse environmental impacts, both regionally and nationally, including the hypoxic condition in the Gulf of Mexico (Patrico, 2001), degraded surface water quality in the Midwest (Warner and Schmidt, 1994), and sediment clogging of harbors and navigation channels in the Great Lakes (Sohngen and Rausch, 1998). Since one expected benefit of WRSIS is reduction in the offsite release of nutrients, pesticides, and sediment, widespread implementation of these systems within the Corn Belt could provide a partial solution to these regional and national environmental problems. Other potential environmental benefits from WRSIS include additional wetland vegetation and wildlife habitat (Luckeydoo et al., 2002), decreased flooding potential downstream, and more carbon sequestration in soil. However, the environmental benefits of WRSIS at a large scale cannot be achieved unless it can be shown to farmers that these systems are capable of increasing crop yields significantly over time. The increased crop yields are in turn dependent upon proper water table management, which itself can be improved through: (1) continued development of better operational protocols, and (2) implementation of as needed infrastructure modifications that enhance system effectiveness. Simply stated, the guiding hypothesis for this investigation was that a proper water table management approach results in significant crop yield increases at WRSIS sites.

Materials and Methods

Initial Design Considerations

The three WRSIS demonstration sites are located within the Ohio portion of the Maumee River Basin, one each in Defiance, Fulton, and Van Wert Counties. All sites have been in operation long enough to experience five to six complete growing seasons. The sites in Defiance, Fulton, and Van Wert Counties were chosen from an initial list of 14 applicants. Key advantages for the Fulton and Van Wert County locations were that they already had some of the needed WRSIS infrastructure installed, including storage reservoirs and a functioning subsurface drainage system.

In fields where subirrigation is planned, since the water table is to be maintained at a substantially higher level than with conventional subsurface drainage, it is often necessary to design the drain spacing using a high drainage coefficient of 38 to 51 mm (1.5 to 2 in.) per day in order to remove water from the soil quickly enough during heavy or prolonged rainfall events. The consequence of using a high drainage coefficient for design purposes is narrower drain spacing for subirrigated fields, typically 33% to 50% of what is used in fields having only subsurface drainage. In addition to allowing faster water removal while in drainage mode, a narrower spacing is also important in providing a more uniform water distribution in the soil during subirrigation. Determination of acceptable drain line spacing at each WRSIS site was facilitated by accurate measurement of horizontal hydraulic conductivity values in the soil profile using a velocity permeameter (Merva, 1995). For reasons just discussed, new drain lines at both the Fulton and Van Wert County sites were placed between the old ones already present and then integrated into the pre–existing subsurface drainage system. Control plot(s) having subsurface pipe for drainage only were included at each site for comparison with crop yields obtained through subirrigation.

Subirrigation requirements were established through model simulations with the computer program, DRAINMOD (Skaggs, 1978). From this program, the size of the storage reservoir at the Defiance County site was determined based on the irrigation water needed for crops in eight out of every ten years. Designing the reservoir to meet crop irrigation needs in more than eight out of every ten years was not considered feasible, because to do so, reservoir construction would become too costly, and its increased size would take more land out of agricultural production. The existing reservoirs at the other two locations did not meet optimal storage requirements; however, other water sources were available which could be used for subirrigation, including a ground water well at the Van Wert County site and a local stream at the Fulton County site. The wetland at the Van Wert County site was constructed to hold the 2–year, 24–hour storm event runoff and subsurface drainage from all 20 ha (50 acres) of the encompassing watershed. In northwest Ohio, a storm event of this magnitude provides approximately 66 mm (2.6 in.) of rainfall (Hershfield, 1961). The designed wetland storage capacities at the other two sites were somewhat less. Should the need arise; all three locations were built with the capability to allow direct offsite release of water from either the wetland or storage reservoir. Although similar in concept, design details differ among the three WRSIS locations.

Demonstration Site Descriptions

Construction of the first site occurred in Defiance County, Ohio during June 1995, principally with volunteer contractors and donated material during an Ohio Land Improvement Contractors Association field exhibition. This location contains two 1.4–ha (3.5–acre) subirrigated fields (fig. 2) and 8.1 ha (20 acres) of cropland (not shown in fig. 2) with various conventional drainage treatments. Runoff and subsurface drainage are funneled into a 0.12 ha (0.30 acre) wetland having a storage capacity of 700 m^3 (185,000 gal). A 2.4–m (8–ft) wide bench at an elevation coinciding with the permanent pool position was excavated along one side of the

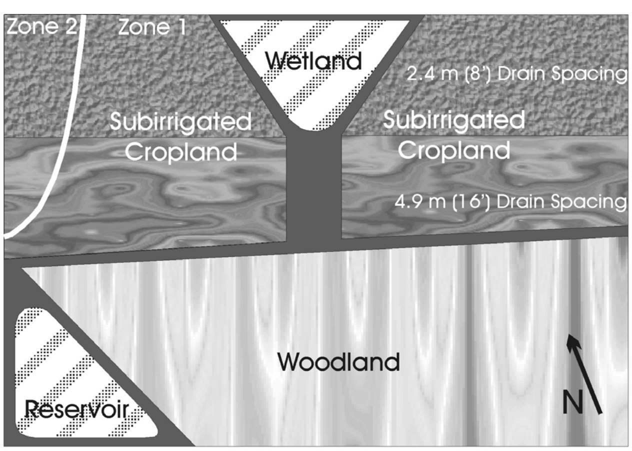

Figure 2. Defiance County WRSIS site schematic. The control plots with conventional drainage are not shown.

Defiance County wetland in spring 1999, providing additional wildlife/vegetation habitat and better water treatment capability. After detention within the wetland, water is routed through an adjacent concrete sump, containing two 0.75–kW (1–hp) submersible pumps, to a 0.16–ha (0.39–acre) reservoir having 2950 m^3 (780,000 gal) of storage. Water held in the reservoir is used for subirrigation of corn and soybeans during periods when rainfall alone is not sufficient to meet crop demand. Although both subirrigated fields are downgradient from the reservoir, a 0.37–kW (0.5–hp) submersible pump located in a concrete sump next to the reservoir is used to enhance flow rate.

Subsurface drain pipes at all three sites were installed at a nominal depth of 0.76 to 0.91 m (2.5 to 3 ft) beneath the surface. Half of the 2.8 subirrigated ha (7 acres) at the Defiance County site contain 10–cm (4–in.) diameter corrugated plastic tubing (CPT) drain line spaced 2.4 m (8 ft) apart, and the other half has 10–cm (4–in.) diameter CPT drains spaced 4.9 m (16 ft) apart (fig. 2). The site is mostly covered by Paulding clay (mesic Typic Haplaquepts) with some Roselms silty clay (mesic Aeric Ochraqualfs) also present. From particle size analysis of samples taken at the surface, percent sand was 0 to 11%, silt ranged from 34 to 50%, and the amount of clay was between 48 and 66%. Saturated horizontal hydraulic conductivity values measured within the soil profile [0 to 0.8 m (0 to 2.8 ft)] with a velocity permeameter ranged from 7×10^{-6} cm/s (0.01 in./h) to 2×10^{-5} cm/s (0.03 in./h). These are dense, very low permeability clayey materials which hinder water transfer from the drain pipe to the soil during subirrigation, in turn making it difficult to maintain the target range of water table depths [25 cm (10 in.) at the drain and 46 to 51 cm (18 to 20 in.) midway between drains]. (Note: The values of "water table depth" referred to in this text are referenced from the ground surface down to the position where the water level would be found in a shallow observation well installed in the soil.) In comparison to the 4.9–m (16–ft) spacing, the 2.4–m (8–ft) spacing is better adapted for consistently keeping ground water levels within the desired range, but expected crop yield increases may not be enough to offset the cost of having to install twice the amount of drain pipe. Initially, two hydraulic control structures, one for each subirrigated field, were installed to regulate ground water levels. A wet area within the northwest corner of the west subirrigated field required installation of an additional hydraulic control structure in September of 1999. By doing this, the west field is now divided into two separate zones for water table management (fig. 2). Capital costs for WRSIS construction at the Defiance County site totaled $44,700 US. (Richards et al., 1999).

The Fulton County, Ohio WRSIS site was completed by local contractors during spring 1996 at a total capital cost of $60,100 US (Richards et al., 1999). Corn and soybeans are grown predominantly on Nappanee loam (mesic Aeric Ochraqualfs). From particle size analysis of samples taken at the surface, percent sand was 17 to 66%, silt ranged from 12 to 37%, and the amount of clay was between 20 and 46%. Saturated horizontal hydraulic conductivity values measured with a velocity permeameter ranged from 4×10^{-4} cm/s (0.6 in./h) near the surface to 7×10^{-5} cm/s (0.1 in./h) through the rest of the soil profile down to a depth of 1.2 m (4.0 ft). The site has two 8.1–ha (20–acre) fields, one that is subirrigated and the other a control plot with drain pipe for subsurface drainage only (fig. 3). Drain pipes within the subirrigated field are spaced about 4.6 m (15 ft) apart, with two newer 10–cm (4–in.) diameter CPT lines placed between each of the existing drains comprised of 10–cm (4–in.) diameter clay tile. The control plot contains only the clay tile lines and the spacing is 13.7 m (45 ft). To regulate the subirrigated field ground water levels, three hydraulic control structures were installed. These hydraulic control structures provide three separate water table management zones within the subirrigated field (fig. 3).

Subsurface drainage from both fields is routed by gravity to a 0.57–ha (1.4–acre) wetland having a storage capacity of 3790 m^3 (1.0 million gal). Very little surface runoff enters the wetland. Water transfer between the wetland and a 0.64–ha (1.57–acre), 8706–m^3 (2.3–million gal) capacity reservoir occurs via a 3.7–kW (5–hp) submersible pump or a 1.5–kW (2–hp) submersible pump, both located within an adjacent concrete sump. Either pump can also be used to route water to the field when the system is in subirrigation mode.

Local contractors completed the Van Wert County, Ohio WRSIS construction in fall 1996 at a total capital cost of $86,300 US (Richards et al., 1999). This site has Hoytville clay (mesic Mollic Ochraqualfs) covering three 6.1–ha (15–acre) fields, two that are subirrigated, and one with buried pipe used for subsurface drainage only (fig. 4). From particle size analysis of samples taken at the surface, percent sand was 2 to 36%, silt ranged from 18 to 41%, and the amount of clay was between 47 and 56%. Saturated horizontal hydraulic conductivity values measured with a velocity permeameter ranged from 4×10^{-4} cm/s (0.6 in./h) near the surface to 2×10^{-4} cm/s (0.3 in./h) through the rest of the soil profile down to a depth of 1 m (3.3 ft). Surface and subsurface drainage from all 18.2 ha (45 acres) of corn and soybean cropland are routed, via two 1.11–kW (1.5–hp) submersible pumps contained in a concrete sump, to a 0.79–ha (1.95–acre), 8710–m^3 (2.3–million gal) capacity wetland and then a 1.21–ha (3.0–acre), 12,870–m^3 (3.4–million gal) capacity reservoir. The sump is located directly south between the wetland and reservoir. A 0.75–kW (1–hp) submersible pump, also located in the concrete sump, is used for subirrigation. A shallow earth embankment extending out into the wetland from the middle of its east side was built during summer 1999 to increase the residence time of water flowing from the inlet to the outlet. By doing this, wetland effectiveness for water treatment is improved.

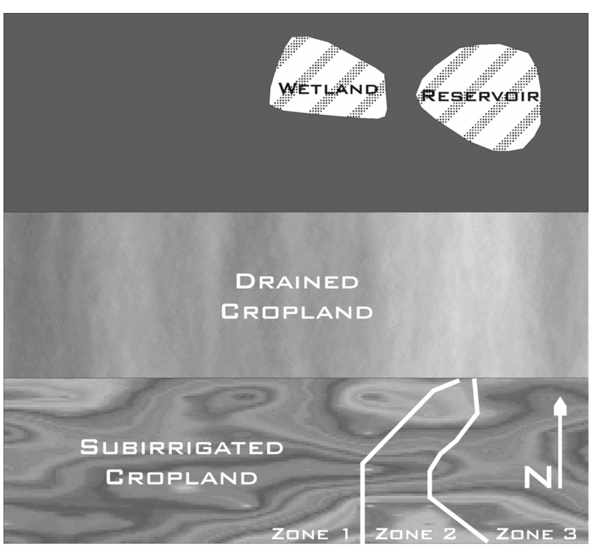

Figure 3. Fulton County WRSIS site schematic.

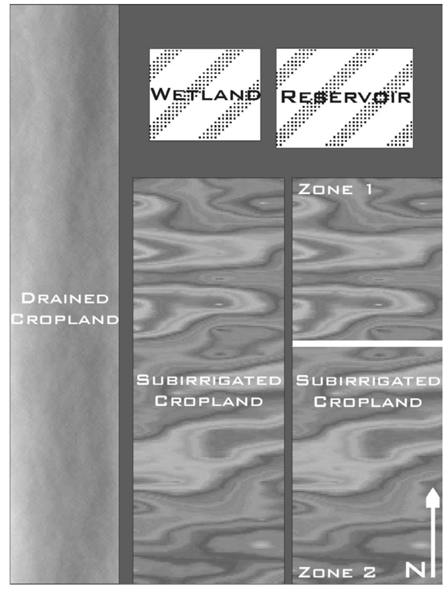

Figure 4. Van Wert County WRSIS site schematic.

Drain lines within the two subirrigated fields have a spacing distance of 5.3 m (17.5 ft), and older 10–cm (4–in.) diameter clay tile pipe alternates with newer 10–cm (4–in.) diameter CPT. The control plot has only the clay tile drain lines which are spaced 10.7 m (35 ft) apart. Initially, two hydraulic control structures, one for each subirrigated field, were installed to regulate shallow ground water levels. However, much like the Defiance County site, a wet area in the north end of the east subirrigated field necessitated integration of an additional hydraulic control structure in June 1999. Consequently, the east subirrigated field is now partitioned into north and south zones for water table management purposes (fig. 4).

Crop Production and Yield Measurement

Corn at the three test sites was grown in 76–cm (30–in.) rows. For soybeans, the High–Yield–System–In–Place concept (Cooper, 1989) was instituted at all three locations with solid seeded planting [18–cm (7–in.) rows] of semi dwarf varieties. The two crops are usually rotated each year with corn being grown where soybeans had previously been planted and vice versa. The corn and soybean varieties oftentimes varied from year–to–year and from site–to–site. However, for any year at a particular site, the same varieties of corn and soybeans were grown using the same standard farming practices in both subirrigated fields and control plots.

Average corn and soybean yields have been obtained since 1996 at the Fulton County location and since 1997 at the Defiance and Van Wert County locations. Crop yields at the Defiance County WRSIS were measured with an Ag Leader PF3000 Precision Farming System with grain flow and moisture sensors. Crop yields at the Fulton County WRSIS were measured two ways, first using a John Deere GreenStar Precision Farming System with grain flow and moisture sensors, and second, using weigh wagons with load cells and a hand held moisture meter. Likewise, the same two methods were used to measure crop yields at the Van Wert County WRSIS, with the only difference being that an Ag Leader PF3000 Precision Farming System was employed instead of the John Deere GreenStar Precision Farming System. Yield maps are now compiled after each growing season at all three sites in order to determine spatial variation in crop productivity.

Environmental–Hydrologic–Hydraulic Monitoring Program

The main goal of the WRSIS project is to provide the environmental benefits listed in the Introduction section, particularly reductions in offsite release of nutrients and sediment, while at the same time improving crop yields. A plan for obtaining environmental, hydrologic, and hydraulic measurements along with crop yields has now been fully implemented. These measurements are then stored and tabulated for use in optimizing the system's design, management, and operation.

The WRSIS environmental–hydrologic–hydraulic monitoring program is focused most intensively on the site in Defiance County where a weather station (Campbell Scientific, Inc. with CR10X datalogger), flumes (Plasti–Fab, Inc. Models H and HS), v–notch weirs, flow sensors (Isco, Inc. Model 750 Low–Profile Area–Velocity probes, Isco, Inc. 720 Submerged probes, and Scientific–Pittsburg/Panametrics Model XMT868 ultrasonic flow meters), pressure transducers for water level measurement (Electronic Engineering Innovations Model 2.0/100 CM), wetland/reservoir multi–level sampling masts, suction lysimeters (SOILMOISTURE Equipment Corp. Model 1900), and automatic water samplers (Isco, Inc. Model 6700) have been installed (Myers et al., 1998; Oztekin et al., 1998). The measurement program now in place at the Defiance County WRSIS site allows each component of the system to be monitored with regard to movement and storage of water, sediment, and nutrients in response to weather events and their corresponding wetland, reservoir, and cropland water management activities. A reduced level of monitoring occurs at the Fulton and Van Wert County locations, however, as a special consideration towards achieving the project's overall goal, average crop yields along with the amount of water, sediment, and nutrients entering/leaving the wetland and released offsite are examined at all three WRSIS sites.

Monitoring equipment installation began in December of 1998 and was not finished until March of 2001. The information collected is now being placed in a computer database. This database will over time provide a complete picture of overall system effectiveness along with guiding future design and management improvements, so that WRSIS can achieve its goal of protecting the environment, while at the same time increasing crop yields.

Water Table Management Guidelines

Fausey and Brown (2000) compiled a preliminary set of WRSIS subirrigation guidelines, many of which are presented in this section. The goal of proper water table management is to consistently maintain field ground water levels within an optimum range of depth beneath the ground surface, thereby minimizing plant stress by allowing crops to readily obtain water for growth, while at the same time preventing damage due to root zone flooding. During parts of the growing season, when there is a significant moisture deficit, shallow ground water levels at a WRSIS site are managed by putting water back into the soil through the subsurface drainage pipe network. Subirrigation water table depths are regulated using a weir–type hydraulic control structure (fig. 5) placed between the drainage pipe network and its outlet. The weir, whose height governs the water table position, is comprised of a number of flashboards inserted within the control structure at its base, one on top of the other. Experience gained by subirrigating corn and soybeans at the three WRSIS sites and at two other research locations (Wooster and Hoytville, Ohio), shows that 25 cm (10 in.) is the desired water table depth to be maintained at drain line positions. As a result of the fine–grained silt and clay soils present in northwest Ohio, typical subirrigated drain spacings of 4.6 to 6.1 m (15 to 20 ft), and a ground water level kept at 25 cm (10 in.) beneath the surface along the drain itself, the water table depths found at the midpoint between drain lines are normally between 46 and 51 cm (18 and 20 in.).

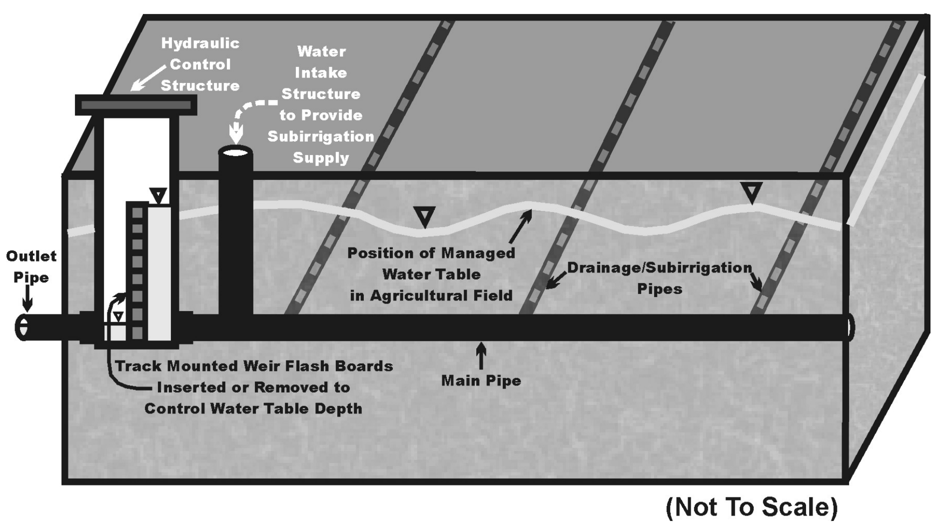

Figure 5. Schematic of weir–type hydraulic control structure used to regulate water table depth in subirrigated fields. The hydraulic control structure is constructed of 1.3–cm (0.5–in.) thick PVC and can be described simply as an adjustable weir enclosed inside a box with upstream and downstream pipe connections.

Measurement Tools for Subirrigation

Two very important tools are needed for water table management of WRSIS subirrigated fields, a rain gage and observation wells. These tools are crucial for making decisions on adding or removing flashboards from a hydraulic control structure and whether the subirrigation water supply should be continued or shut–off. The rain gage is placed in an open area adjacent to the subirrigated fields and is to be checked after each storm event. Observation wells need to be installed at several locations, including along drain lines, at midpoints between drains, and especially areas within depressions. The water level in the wells should be monitored daily to determine if the water table is at the desired depth. Small diameter observation wells work best because they respond quickly to changing ground water levels in fine–grained soils. The simple observation wells used are comprised of 2.5–cm (1.0–in.) diameter perforated PVC pipe capped at one end and wrapped along its length with a sheet of fiberglass screen taped securely in place.

Typical Procedures in the Early Growing Season

Establishing a base water table early in the growing season is essential, making it easier to raise ground water levels later. In northwest Ohio, the base water table is held about 15 cm (6 in.) above the outlet pipe in the control structure (fig. 5) beginning 1 June. After all post emergence field operations are completed and the crops are at the V4 growth stage (third trifoliate leaf stage for soybeans, collar of the fourth leaf visible for corn), the ground water level can be raised for the remainder of the growing season, especially in near average or wetter years, to 25 cm (10 in.) beneath the soil surface along drain lines. This procedure is usually done around 15 June at the Ohio WRSIS sites.

Procedures for Growing Seasons with Near Average Rainfall

WRSIS water table management strategies are contingent on whether the growing season climate, with regard to precipitation, is wetter than average, near average, or drier than average. Determination of growing season climate by the farm manager is based on rainfall to date, and to a lesser extent, long range weather forecasts. A simplified schematic of near average, wetter, and drier growing season water table management strategies is provided in figure 6, with detailed discussion as follows. In regard to storm events during a near average growing season, the following guidelines are in practice.

a) For rainfall less than 5 mm (0.2 in.), no changes are required to subirrigation water supply or a field hydraulic control structure. Subirrigation can continue uninterrupted with hydraulic control structure flashboards placed to maintain, as closely as possible, a 25–cm (10–in.) water table depth along the drain lines.

b) For rainfall greater than 5 mm (0.2 in.) but less than 13 mm (0.5 in.), the subirrigation water supply should be shut off. The water supply should remain off for 24 hours and then be restarted if no additional rainfall has occurred. If further rainfall does occur [greater than 5 mm (0.2 in.) but less than 13 mm (0.5 in.)], the water supply should remain off and water level measurements in observation wells should be used to gage when to restart subirrigation. It is advisable to recommence subirrigation only after time has allowed shallow ground water levels to drop to a position 25 cm (10 in.) below the surface along drain lines. Under these conditions, no changes are made to the hydraulic control structure.

c) For rainfall greater than 13 mm (0.5 in.), the subirrigation water supply should again be shut off. Additionally, the hydraulic control structure flashboards should be removed to allow unrestricted maximum discharge of subsurface drainage. Failure to remove all flashboards reduces the hydraulic gradient driving subsurface drainage, thereby delaying the removal of excess soil water. Flow through the control structure needs to remain unrestricted for at least 24 h followed by reinsertion of flashboards if no more rain has occurred and measurements in observation wells indicate that the water table has dropped to desired levels [25 cm (10 in.) beneath the surface along drain lines]. Supply of water for subirrigation can begin again once the hydraulic control structure flashboards are replaced.

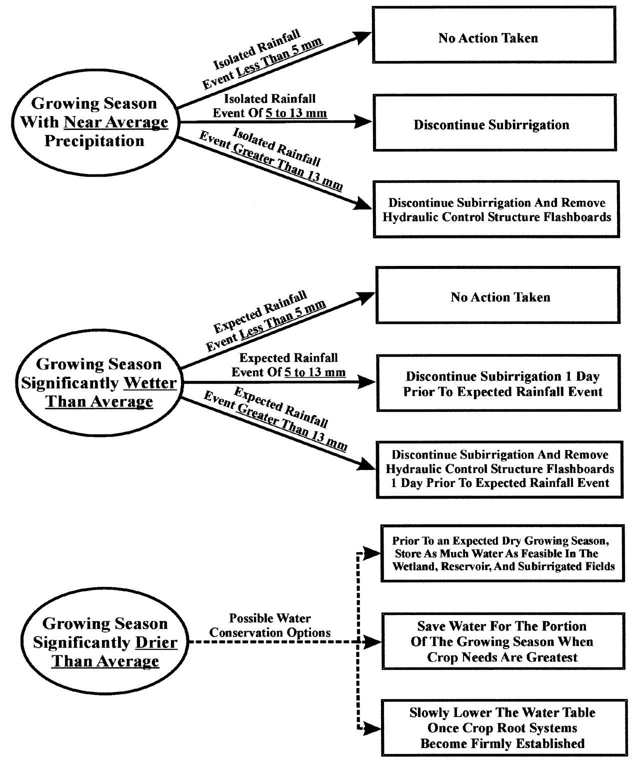

Figure 6. Simplified illustration of WRSIS water table management strategies for the growing season.

These procedures have been adopted because one of the major concerns with subirrigation is that rainfall can raise the water table quickly above the desired level. This scenario is possible because the water table in the soil is already high and the hydraulic control structure at the outlet restricts discharge. A higher than desired water table can produce waterlogged conditions that result in significant crop injury. It has been shown, depending on growth stage, that root zone flooding over a period as short as three days can affect a substantial decrease in yield for both corn (Larson and Hanway, 1977) and soybeans (Sullivan et al., 2001). It therefore becomes imperative to either avoid or quickly drain away any higher than desired water table conditions. As already mentioned, the spacing between drains in a subirrigated field is substantially less than that in a field with subsurface drainage only, and this reduced spacing greatly expedites water removal from soil. However, measures such as shutting the subirrigation supply off and removing hydraulic control structure flashboards are oftentimes still needed to avoid problems with root zone flooding. Consequently, it is always important to keep in mind that recovering from a temporary lowering of the water table is much easier than recovering from crop flooding injury.

Procedures for Wetter Growing Seasons

One effect of wetter climate periods is that the soil moisture content between the water table and the ground surface tends to remain higher for longer than in times that are near average or drier. WRSIS subirrigation guidelines in a wetter growing season are essentially the same as ones implemented for near average conditions. However, to ensure that waterlogged soils do not become a problem, system operational procedures are often conducted, as much as is feasible, in advance of anticipated rainfall events. In particular, the second guideline (b) for "normal" conditions is modified such that attempts should be made to discontinue subirrigation 24 h prior to an expected rainfall of 5 to 13 mm (0.2 to 0.5 in.). Likewise, for the third guideline (c), subirrigation should be shut off and hydraulic control structure flashboards removed 24 h prior to an expected rainfall greater than 13 mm (0.5 in.). There is a realization that even short–term 24–h rainfall predictions are often inaccurate, overall however, the implementation of these modifications, when possible, will help prevent crop injury due to root zone flooding, which is of special concern in wetter than average years. Again, it is worth restating that recovering from a temporary lowering of the water table is much easier than recovering from crop flooding injury.

Water storage in the wetland is managed the same for both near average and wetter growing seasons. Here, the water level is kept at the permanent pool elevation just above the top of the wetland outlet pipe. Maintaining the water at this level allows establishment and continued vitality of wetland vegetation and wildlife habitats, while also providing storage capacity for natural treatment of inflow from runoff and subsurface drainage due to storm events or overflow from subirrigation. The reservoir is kept as full as possible during near average and wetter growing seasons, so that water will be available when needed for subirrigation. Direct offsite discharge from the reservoir occurs only when the reservoir is full and additional storage capacity is needed for water routed from the wetland.

Options to Consider During a Drier Growing Season

WRSIS water table management with respect to subirrigation in a drier growing season is much more problematic and a set of firm rules has yet to be formalized. The strategy implemented will depend largely on severity of drought conditions. There are several options for system operation that can be contemplated during a drought period. As a first option, and considered more of a safety precaution for when long–range weather forecasts indicate the possibility of a very dry growing season, the amount of water initially stored in the wetland, reservoir, and subirrigated fields can be maximized. Starting in spring, given that there is adequate rainfall during this period, as much runoff and subsurface drainage as possible is captured, first to fill the reservoir and then the wetland. Although this is not a deviation in the normal management strategy for the reservoir, it is for the wetland. Instead of operating the wetland to naturally treat water or establish vegetation and wildlife habitat, its main function becomes that of a second storage reservoir. Under these circumstances, the wetland water level may begin the growing season substantially above the permanent pool elevation. This initial level will be allowed to drop only when subirrigation begins and water is routed from the wetland to refill part of the reservoir. Water can also be stored in the subirrigated fields. As the wetland and reservoir become filled, the base water table can be raised to 15 cm (6 in.) above the outlet pipe in the control structure prior to the normal date of 1 June stated previously for early growing season procedures. This course of action allows a certain net amount of water to be held within the soil and drainage pipes that may otherwise escape offsite. Operating under these conditions should not adversely impact field trafficability, since the water table is still low enough [0.61– to 0.76–m (2.0– to 2.5–ft) depth] to keep the near surface soil adequately drained.

A second WRSIS option is to conserve water for the portion of the growing season when subirrigation requirements are greatest. Doorenbos et al. (1979) used calculated yield response factors to determine water needs for various crops over the whole growing season, and more notably, for specific stages of plant development. The yield response factor, k_y, is defined as the ratio of the relative crop yield loss to relative water deficit and is expressed:

$$k_y = \frac{1 - \frac{Y_a}{Y_m}}{1 - \frac{ET_a}{PET}} \qquad (1)$$

where Y_a is actual grain, vegetable, fruit, fiber, or forage crop yield; Y_m is the maximum (potential) grain, vegetable, fruit, fiber, or forage crop yield; ET_a is the actual amount of evapotranspiration during a period of growth; and PET is the potential (maximum) amount of evapotranspiration during a period of growth. The relationship shown in equation 1, a form of which was initially suggested by Stewart et al. (1977), has found widespread acceptance and utilization (Hillel, 1987; Kirda and Kanber, 1999).

Simply put, large yield response factors for a particular plant development stage reflect the importance of providing an adequate amount of water to the crop during this period. The most critical time for corn in terms of water need is the flowering stage, including tasselling and especially silking, which in Ohio typically occurs during the month of July (Beuerlein et al., 1996). The corn k_y value for flowering is 1.5, which is one of the highest for any crop at any growth stage (Doorenbos et al., 1979). The next most important stage for corn is yield formation (August through early September in Ohio) with a k_y value of 0.5. The vegetative growth stage (June in Ohio) that precedes flowering has a k_y value of 0.4. These k_y values indicate that, with respect to corn, subirrigation water in a drier season should be saved until needed to fully satisfy crop needs during flowering. Limiting subirrigation during the vegetative growth stage is the best way to conserve. Any water that remains after flowering can then be used in the following yield formation stage. Doorenbos et al.

(1979) also suggested that when water is not sufficiently available during the flowering stage for the entire planted acreage, then it is best to fully irrigate, only part of the corn crop.

Portions of this subirrigation strategy for corn were applied with success in 1999 and 2001 at the Van Wert County WRSIS site. The 1999 growing season was dry overall and the 2001 growing season, while classified as marginally wet, had a relatively dry period from mid–June through mid–July. (The growing season wetness/dryness classification criteria are provided in the next section.) Consequently, due to a lack of rainfall, the supply of water available for subirrigation became limited. The subirrigated field corn crop in 1999 was fully watered through flowering (31 July), and afterwards, the supply was discontinued. The 1999 subirrigated field corn yield averaged 11918 kg/ha (190 bu/acre), or 2074 kg/ha (33 bu/acre) greater than that obtained from the subsurface drainage only control plot. In 2001, the subirrigated field corn crop was fully watered through 24 July, near the end of flowering, and afterwards water was supplied only in the evening, night, and early morning hours (5:00 P.M. to 7:00 A.M.) through 20 August. The subirrigated field corn yield for 2001 averaged 12,911 kg/ha (205 bu/acre), or 1056 kg/ha (17 bu/acre) greater than that obtained from the subsurface drainage only control plot. More data will be needed to sufficiently assess the effectiveness of partial subirrigation in regard to crop yields.

The soybean k_y values are 0.8 for the flowering stage and 1.0 for the yield formation stage (Doorenbos et al., 1979). The vegetative growth stage has a k_y value of just 0.2. In Ohio, based on a typical planting date, flowering is spread over July, mostly in the second half of the month. Yield formation usually occurs in August, with pod development in the first half of the month and pod fill in the last half (Fausey and Cooper, 1995). The vegetative stage preceding flowering is normally from late May through early July. Doorenbos et al. (1979) stated that the most crucial time with regard to soybean water requirements is the period that included late flowering and pod development (~15 July to 15 August in Ohio). The importance of this period has been confirmed by Fausey and Cooper (1995) who found a strong correlation between soybean yield and rainfall during pod development at two sites in Ohio. Therefore, a viable drought season WRSIS strategy regarding soybeans is to conserve subirrigation water during the vegetative growth stage for later use in the period covering late flowering and pod development. Water that is left over can then be applied during pod fill.

Even the largest soybean growth stage k_y values are relatively modest compared to the k_y values for corn during flowering, indicating that soybean yields are less sensitive to water deficits. This fact has two important implications. One involves the case where the WRSIS water supply available is not sufficient to completely meet the late flowering and pod development needs of the total soybean crop. Unlike corn, Doorenbos et al. (1979) suggests that limited subirrigation should be provided to the whole acreage planted rather than fully irrigating only a portion of the soybean cropland. The second implication regards the case where both corn and soybeans are grown concurrently within the same WRSIS. Here, the high sensitivity of corn yield to a water deficit during flowering would seem to take priority. Dry season subirrigation efforts in this instance are focused on supplying the complete needs of corn during flowering. Any additional water available is then applied to the soybeans, particularly in the late flowering and pod development period. However, before this operational strategy is adopted, the economic value of the soybean and corn crop must be addressed, so that both yield and monetary benefits are in line.

A subirrigation strategy for soybeans containing components of the ones just discussed was applied successfully in 1999 and 2001 at the Van Wert County WRSIS site. Again, the 1999 growing season was dry overall, and the marginally wet 2001 growing season had a relatively dry period from mid–June through mid–July. As stated previously, in 1999, the total subirrigated corn crop was fully watered through flowering (31 July), after which the supply was shut off. Soybeans in 1999 were fully watered until 31 July, then subirrigated during the morning and afternoon hours, 12 instead of the usual 24 hours per day, through the middle of August, when the available water supply completely ran out. The 1999 soybean yield within the subirrigated plot at the Van Wert County WRSIS site averaged 3506 kg/ha (52 bu/acre), which was 863 kg/ha (13 bu/acre) greater than that obtained from the subsurface drainage only control plot. In 2001, the subirrigated soybeans, as with the subirrigated corn, were fully watered through 24 July and afterwards water was supplied only in the evening, night, and early morning hours (5:00 P.M. to 7:00 A.M.). Partial subirrigation of soybeans continued through 28 September as opposed to 20 August with corn. The subirrigated field soybean yield for 2001 averaged 3634 kg/ha (54 bu/acre), or 26 kg/ha (0.4 bu/acre) greater than that obtained from the subsurface drainage only control plot. It should be noted that the 2001 soybean yields at the Van Wert County site were probably affected by flooding from heavy rains early in the growing season that necessitated replanting within portions of both the subirrigated field and control plot. Once more, additional data will be needed to sufficiently assess the effectiveness of partial subirrigation in regard to crop yields.

Although confirmation is needed, it is believed that partial subirrigation is best done during times in the evening, night, and early morning if water is to be supplied in only 12 out of every 24 h. Subirrigated crops often appear taller directly over the drain lines, suggesting that transpiration is greatest over the drain lines and less between them. Given this to be true, during the daylight hours in which almost all transpiration occurs, the subirrigated field hydraulic gradients between drain lines and midpoints half the spacing distance away will be suppressed. Thus, when transpiration increases in late morning and afternoon, the flow of water getting to locations between drain lines is reduced. However, if subirrigation is done in the evening, night, and early morning hours when transpiration is least, hydraulic head differences between drain lines and points between them should be greater, in turn allowing water to be more effectively distributed into the soil. Proving this to be the case at the Van Wert County site will require installation of new observation wells containing pressure transducers for continuous water level measurement.

A third alternative for WRSIS operation during a growing season drought is to slowly lower the water table once the corn and soybean root systems becomes firmly established during the vegetative stage. Beginning in the middle of June, when the initial water table depth is 25 cm (10 in.) along drain lines, field ground water levels can be dropped gradually at a rate that allows downward root growth to keep pace. If this strategy can be implemented effectively, the deeper penetrating roots of both corn and soybeans are capable of supplying plant water needs given that there is a sufficient amount of moisture within the lower part of the soil profile (Larson and Hanway, 1977; Willatt and Taylor, 1977; Van Doren and Reicosky, 1987). Draining 46 cm (1.5 ft) of the soil profile from an initial saturated state down to field capacity could theoretically extract approximately 230 m^3 of water per hectare (25,000 gal of water per acre), which could then be reused when conditions warrant. This amount assumes, based on information from Todd (1980), that the drainable water between saturation and field capacity is 5% for a silty clay soil material typical of northwest Ohio. Whether lowering the water table by 46 cm (1.5 ft) results in a water recovery of this magnitude will depend on many factors, for one, the capillary fringe thickness.

Under normal operating procedures, soil surface over a drain is oftentimes moist, while between drains it is quite dry. This phenomena occurs because the water table over the drain is held at a position 25 cm (10 in.) beneath the surface, which is 20 to 25 cm (8 to 10 in.) higher than that found midway between drain lines. Given wet enough conditions with rough ground and turbulent air mixing, evaporation from moist soil can be very high, sometimes as much or even greater than that exhibited by a free–water surface (Tindall and Kunkel, 1999). Once the surface begins to dry out, the rate of direct evaporation from soil approaches a minimum value governed by shallow vapor state water transport processes (Jalota and Prihar, 1998). Consequently, lowering the water table by 46 cm (1.5 ft) would also reduce direct evaporation from soil over the drain lines, thereby further saving some of the subirrigation supply.

Finally, the goal of WRSIS has been to remove water as a yield–limiting factor over the entire growing season so as to maximize crop production. More research is therefore needed to establish water table management guidelines in drier years where the subirrigation supply is limited. In particular, comparison is needed between full season subirrigation and alternative partial season subirrigation strategies to identify a plan that will minimize the relative yield loss from providing crop water needs for only part of the growing season.

Non–Growing Season Procedures

All WRSIS water table management discussion up to this point has focused on the growing season. Typically, in the late fall, winter, and spring months (November through May), the subirrigated fields are kept in full drainage mode with flashboards removed from the hydraulic control structures and the water supply from the reservoir discontinued. These current non–growing season procedures are done in large part to help site trafficability during fall harvest and tillage along with spring planting and post emergence field operations. Even though water table management procedures have changed dramatically during the non–growing season, WRSIS continues to provide environmental benefits. Offsite discharge remains restricted during this period, and settlement processes in the wetland and reservoir still remove sediment and adsorbed phosphorous from water. Perhaps a better environmental alternative for the subirrigated fields is to re–insert the hydraulic control structure flashboards to let rainfall alone bring the water table close to the surface during the months of December, January, February, and March when trafficability is not a major concern. This form of water table management is called controlled drainage and would produce anaerobic soil conditions by which excess nitrate is removed through denitrification (Skaggs and Breve, 1995) and more carbon is sequestered due to reduced biodegradation (Lal et al., 1998). Fisher et al. (1999) describe the successful application of this water table management program (subirrigation in the growing season, conventional uncontrolled drainage during late fall and late spring, and controlled drainage in the winter and early spring). Because of the potential environmental benefits, this approach could be initiated at one or two WRSIS sites in the near future. Implementation will require monitoring to assure that salinity build–up in the soil does not become a problem.

Results and Discussion

Water Table Management Implications from Climate and Crop Data

The Defiance and Van Wert County sites have been in operation through five growing seasons (1997–2001), and the WRSIS site in Fulton County has experienced six (1996–2001). Climate and crop yield information from the WRSIS sites are compiled in tables 1, 2, 3, 4, and 5. The crop yield values that have been tabulated came from field averaging of yield monitor data at the Defiance County site and from weigh wagon measurements at the Fulton and Van Wert County sites. All reported crop yields have been adjusted to moisture contents of 15% for corn and 13% for soybeans.

Table 1 provides averages over the three WRSIS sites for the mean monthly growing season values of precipitation (Precip._M), potential corn evapotranspiration ($\text{PET}_{M:Corn}$), potential soybean evapotranspiration ($\text{PET}_{M:Soybeans}$), potential corn evapotranspiration subtracted from precipitation ($\text{Precip.}_M - \text{PET}_{M:Corn}$), and potential soybean evapotranspiration subtracted from precipitation ($\text{Precip.}_M - \text{PET}_{M:Soybeans}$). The monthly potential evapotranspiration values listed in table 1, which reflect crop water needs, were calculated using the following equation:

$$PET_{Crop} = k_C \, k_L \, PET_{Thornthwaite} \qquad (2)$$

where PET_{Crop} is the potential evapotranspiration of a particular crop such as corn or soybeans, k_C is a crop adjustment coefficient (Doorenbos et al., 1979), k_L is a latitude adjustment coefficient (Veihmeyer, 1964), and $PET_{Thornthwaite}$ is the potential evapotranspiration of grass based on Thornthwaite's method (Thornthwaite et al., 1944). The Thornthwaite method, devised for application in humid areas, is a simplified approach utilizing readily available temperature data. A summary of an investigation conducted in Coshocton, Ohio (Jensen et al., 1990) indicates that Thornthwaite's method can provide a reasonably accurate approximation for growing season evapotranspiration within the region where the WRSIS sites are located. Results of three years of research done in Coshocton, Ohio showed the Thornthwaite method to predict 95% of the actual March through November lysimeter measured evapotranspiration. Given the location, this method compares favorably to the Penman–Monteith and Jensen–Haise methods, which predicted 106 and 69%, respectively, of the actual lysimeter

Table 1. Mean monthly growing season climate data averaged over the WRSIS sites.

Month	$Precip._M$[a] (mm)	$PETM_{:Corn}$[b] (mm)	$PETM_{:Soybeans}$[b] (mm)	$Precip._M - PET_{M:Corn}$ (mm)	$Precip._M - ET_{M:Soybeans}$ (mm)
May	91	35	30	56	61
June	94	97	94	–3	0
July	92	149	141	–57	–49
August	78	122	115	–44	–37
September	81	61	52	20	29
Total	436	464	432	–28	4

[a] Data obtained from the NOAA – National Climate Data Center (NCDC, 2002).
[b] Value calculated using NOAA – National Climate Data Center temperature data (NCDC, 2002).

measured evapotranspiration. Table 1 shows that for an average growing season, the amount of overall precipitation essentially balances the total corn and soybean *PET* derived water needs. However, while there is excess rainfall in May and September, substantial precipitation deficits occur in July and August, when corn and soybean water requirements are critical. This highlights one important advantage of WRSIS, that being excess rainfall throughout the year can be stored to maintain water supply for when crops need it most, thereby improving yield, even in average or wetter growing seasons.

Tables 2, 3, and 4 when viewed together, provide some interesting insight with regard to the impact of WRSIS water table management. Average rainfall amounts from 1 May through 30 September for Defiance, Fulton, and Van Wert Counties are 434, 431, and 445 mm (17.08, 16.96, and 17.50 in.), respectively (NCDC, 2002). The following scale, based on deviation from average precipitation (DAP), was used as a gauge for overall growing season wetness/dryness:

extremely dry [DAP < –114 mm (–4.5 in.)]

dry [–114 mm (–4.5 in.) ≤ DAP < –76 mm (–3.0 in.)]

marginally dry [–76 mm (–3.0 in.) ≤ DAP < –38 mm (–1.5 in.)]

near average [–38 mm (–1.5 in.) ≤ DAP ≤ 38 mm(1.5 in.)]

marginally wet [38 mm (1.5 in.) < DAP ≤ 76 mm (3.0 in.)]

wet [76 mm (3.0 in.) < DAP ≤ 114 mm (4.5 in.)]

extremely wet [DAP > 114 mm (4.5 in.)]

Table 2 shows that 1996 was marginally dry in Fulton County. The 1999 growing season in the three counties ranged from marginally dry to extremely dry. All three locations were wet or extremely wet in 1997 and 2000, and either near average or marginally wet in 1998 and 2001. Table 2 also reveals, as one would expect, a strong positive correlation between DAP and the values of measured precipitation for a particular growing season minus the crop potential evapotranspiration for the same growing season calculated using equation 2 (r = 0.99 for DAP vs. Precip. – PET_{Corn} and r = 0.99 for DAP vs. Precip. – $PET_{Soybeans}$).

Compared with control plot results, tables 2, 3, and 4 indicate that subirrigation crop yield benefits can be quite substantial, particularly in growing seasons that are drier than average. The percent corn and soybean crop yield improvements due to subirrigation were respectively, 34.5 and 38.1% during drier growing seasons, 14.4 and 9.7% during near average to wetter growing seasons, and 19.6 and 17.4% overall. As shown in table 4, the subirrigated field minus control plot yield differences was significant at a level of 5% for both crops overall and during drier growing seasons, while for corn and soybeans in near average or wetter growing seasons the yield differences were significant at levels of 10 and 20%, respectively. Subirrigation during the two drier years of 1996 and 1999 improved mean corn and soybean yields by 2844 and 1039 kg/ha (45 and 15 bu/acre), respectively. Although near average and wetter growing seasons did not exhibit subirrigated field versus control plot crop yield improvements nearly as dramatic, on average, moderate increases of 1266 kg/ha (20 bu/acre) for corn and 286 kg/ha (4 bu/acre) for soybeans were still achieved.

During the extremely wet 1997 and moderately wet 1998 growing seasons at the Van Wert County site, subirrigation proved to be a minor disadvantage, and this result serves to emphasize a couple of important points. First, WRSIS water

Table 2. Total growing season (1 May – 30 Sept.) WRSIS climate data: 1996–2001.

County Location	Year	Deviation from Avg. Precip.[a] (mm)	Precip. – PET_{Corn}[b] (mm)	Precip. – $PET_{Soybeans}$[b] (mm)
Defiance (Weather station is in the city of Defiance, Ohio)	1997	250	234	265
	1998	3	–56	–21
	1999	–130	–195	–161
	2000	70[c]	32[c]	65[c]
	2001	2	–39	–6
Fulton (Weather station is in the city of Wauseon, Ohio)	1996	–45	–48	–18
	1997	213	219	247
	1998	63	39	71
	1999	–41	–79	–47
	2000	203	195	226
	2001	42	14	45
Van Wert (Weather station is in the city of Van Wert, Ohio)	1997	225	220	250
	1998	68	5	41
	1999	–108	–176	–141
	2000	174	147	179
	2001	59[c]	18[c]	51[c]

[a] Equals the growing season precipitation for a particular year minus the average growing season precipitation. Data obtained from the NOAA – National Climate Data Center (NCDC, 2002).
[b] Equals the growing season precipitation for a particular year minus that year's calculated growing season potential crop evapotranspiration. Data obtained from the NOAA – National Climate Data Center (NCDC, 2002).
[c] This value may be significantly underestimated due to missing data.

Table 3. Corn and soybean crop yields: 1996–2001.

WRSIS Site	Year	Corn (kg/ha) Subirrigated[a]	Corn (kg/ha) Control[b]	Corn (kg/ha) Difference[c]	Soybeans (kg/ha) Subirrigated[a]	Soybeans (kg/ha) Control[b]	Soybeans (kg/ha) Difference[c]
Defiance County	1997	9995	8360	1635	–	–	–
	1998	8172	–	–	3621	–	–
	1999	8738	7732	1006	2374	1497	877
	2000	4526	4526	0	526	681	–155
	2001	4803	5180	–377	1062	728	334
Fulton County	1996	11692	6852	4840	4552	3102	1450
	1997	11943	10686	1257	4248	4073	175
	1998	13201	11692	1509	4464	4248	216
	1999	12006	8549	3457	4639	3675	964
	2000	11378	10309	1069	3688	3378	310
	2001	12060	4570	7490	4902	3247	1655
Van Wert County	1997	9052	9322	–270	3129	3183	–54
	1998	9498	10171	–673	2765	2778	–13
	1999	11918	9844	2074	3506	2643	863
	2000	10912	9687	1225	3581	3216	365
	2001	12911	11855	1056	3634	3608	26

[a] Average subirrigated field crop yield.
[b] Average control plot crop yield.
[c] Difference equals subirrigated field crop yield minus control plot crop yield.

table management requires greater attention under wetter conditions in order to avoid difficulties associated with root zone flooding. Second, initial site design problems are often exacerbated during wetter than average growing seasons, especially with respect to low elevation areas prone to becoming waterlogged. This second point will be fully discussed in next section. The 2001 growing season at the Fulton County WRSIS site proved to be an interesting one. Although classified as marginally wet, subirrigated field minus control plot crop yield differences were substantial, 7490 kg/ha (119 bu/acre) for corn and 1655 kg/ha (25 bu/acre) for soybeans. May and June of 2001 were very wet, however July and August were very dry. The farm manager at the Fulton County WRSIS measured only 8 mm (0.3 in.) of rainfall from one storm event during the period between 24 June and 18 August. Consequently, having a subirrigated water supply for the crops during this crucial part of the growing season (flowering for corn and flowering followed by pod development for soybeans) was a great advantage. The Fulton County site in 2001 is a good example of an argument made previously, which is that WRSIS can provide yield benefits even in near average or wetter years through meeting the needs of crops caused by water deficits that commonly occur in July and August. The extremely low crop yields in 2000 and 2001 at the Defiance County WRSIS site are somewhat of an aberration because of a very wet spring in both years. Excessive rainfall in May and June, either prevented soybeans from being planted until 10 July in 2000 or necessitated their replanting on 15 June in 2001, and although corn was planted in early May of both years, side–dressed fertilizer could not be applied until mid–June.

Table 4. Statistics on crop yield differences (subirrigated field minus control plot) in relation to growing season wetness/dryness.

	–Corn– Near Average to Extremely Wet Growing Seasons	–Corn– Marginally Dry to Extremely Dry Growing Seasons	–Soybeans– Near Average to Extremely Wet Growing Seasons	–Soybeans– Marginally Dry to Extremely Dry Growing Seasons
Mean (kg/ha)	1266	2844	286	1039
Std. Dev. (kg/ha)	2223	1666	513	278
P[a]	P < 10%	P < 5%	P < 20%	P < 5%

	–Corn– All Growing Seasons Combined	–Soybeans– All Growing Seasons Combined
Mean (kg/ha)	1687	501
Std. Dev. (kg/ha)	2156	570
P[a]	P < 5%	P < 5%

[a] P equals the probability that the mean value is not significantly different than zero. In the case of the data presented in this table, a low P value of indicates a high likelihood that the mean value of the subirrigated field minus control plot crop yield difference is substantially greater than zero.

Table 5 compares subirrigated crop yields at the Defiance County WRSIS site between the 2.4– and 4.9– (8– and 16–ft) drain line spacings. Because subsurface drainage and subirrigation efficiency is expected to be better with a 2.4–m drain line spacing than a 4.9–m spacing, crop yields should also be improved with a 2.4–m drain line spacing compared to one with 4.9 m. This expectation is indeed the case with corn for every year at the Defiance County site, but for soybeans, the opposite is true, the 4.9–m drain line spacing working best each year except 2001. For soybeans, 2001 was somewhat anomalous because foraging groundhogs from the adjacent woodland (fig. 2), greatly reduced yields in the portion of the subirrigated field containing 4.9–m drain line spacings. This unanticipated overall behavior with regard to soybeans and drain line spacing is presently still being investigated. One possible explanation is that the lower average water table elevation found with the 4.9–m spacing is better for soybeans at this site than the higher average water

Table 5. Defiance County WRSIS site subirrigated crop yield comparison between 2.4– and 4.9–m drain line spacings.

Year	Corn (kg/ha) 2.4 m Spacing	Corn (kg/ha) 4.9 m Spacing	Corn (kg/ha) Difference[a]	Soybeans (kg/ha) 2.4 m Spacing	Soybeans (kg/ha) 4.9 m Spacing	Soybeans (kg/ha) Difference[a]
1997	10371	9555	816	–	–	–
1998	8423	7858	565	3466	3769	–303
1999	9177	8298	879	2158	2583	–425
2000	4752	4356	396	506	550	–44
2001	5205	4400	805	1281	843[b]	438

[a] Difference equals 2.4 m drain line spacing crop yield minus 4.9–m drain line spacing crop yield.
[b] Foraging groundhogs from adjacent woodland significantly reduced yield.

table produced by the 2.4–m spacing. [With the ground water level held at 25 cm (10 in.) beneath the surface along the drain itself, the drop–off in water table elevation at the midpoint between drain lines is less with a spacing of 2.4 than 4.9 m (8 than 16 ft)].

The WRSIS agricultural production goal in Ohio is to consistently achieve crop yields near 12,600 kg/ha (200 bu/acre) for corn and 4700 kg/ha (70 bu/acre) for soybeans, regardless of growing season rainfall amounts. These goals are based on experience gained in Ohio and represent what is possible to achieve in a typical farm field given good soil fertility and adequate amounts of rainfall distributed throughout the growing season. The biggest economic advantage from a crop productivity standpoint, of course, coming in the drier years, but moderate yield improvements are also likely in near average or wetter years. With a six–year subirrigated field average of 12,047 kg/ha (192 bu/acre) for corn and 4416kg/ha (65 bu/acre) for soybeans, the stated productivity goals are close to being achieved at the Fulton County location. The 1999 WRSIS design improvements put in place at the other two locations will undoubtedly improve their averages over time, however, at the Defiance County site, the 12,600–kg/ha (200–bu/acre) corn and 4700–kg/ha (70–bu/acre) soybean goals are probably somewhat unrealistic because the low permeability clay soils that are present inhibit water movement, thereby reducing the effectiveness of both subsurface drainage and subirrigation. Crop yields along with environmental benefits are to be improved further still at the three sites through optimization of WRSIS design, management, and operation. Fine–tuning the design, management, and operation of these systems will require the extensive data collection effort described previously, that includes not only crop yields but also environmental, hydrologic, and hydraulic measurements.

Design Modifications to Improve Water Table Management

Large depressions and low elevation areas within subirrigated fields can become waterlogged resulting in localized crop damage. Maintaining proper water table depths within the majority of the subirrigated field often results in raising ground water levels too high in regions with low surface elevation, which is especially a problem in wetter growing seasons. As shown in figure 7, this problem can be solved by installing an additional hydraulic control structure and separately managing the water table in the low elevation region of the field. A general rule for effective water table management is to partition subirrigation zones such that the maximum elevation difference over the zone, for the most part, does not exceed 0.3 m (1 ft). This practice was implemented initially at the Fulton County WRSIS and then later at both the Defiance and Van Wert County sites. A yield map from the marginally wet growing season of 1998 (fig. 8) illustrates the difficulty confronted at the Van Wert County location. As shown, high water table flooding injury substantially reduced corn and soybean yields in the north part of the east subirrigated field. This crop damage occurred because the surface elevation in the east subirrigated field decreases 0.55 m (1.8 ft) from south to north, with the steepest gradient being in the north end, thus making it virtually impossible to manage the water table in the field with only one hydraulic control structure. By adding a second hydraulic control structure in June 1999, the east subirrigated field was divided into north and south water table management zones. The crop yield map for 2000 (fig. 9), an extremely wet growing season which would tend to exacerbate any waterlogged low spot troubles, provides an indication, confirmed by site managers, that undertaking this measure has largely removed the high water table flooding problem along the field's north edge. The success with the additional hydraulic control structure can be further seen by a generalized comparison of the east subirrigated field corn yield map of 1998 to that of the same area in 2000.

Difficulties with high water table flooding problems were likewise encountered in the west subirrigated field at the Defiance County site. Again, the solution was to install a second hydraulic control structure in September of 1999, thus partitioning the field into two water table management zones. The severity of the problem is illustrated in figure 10, which depicts low corn yields in the northwest corner of the field resulting from waterlogged soils. (Note: The new zone was not added and made operational until late in the growing

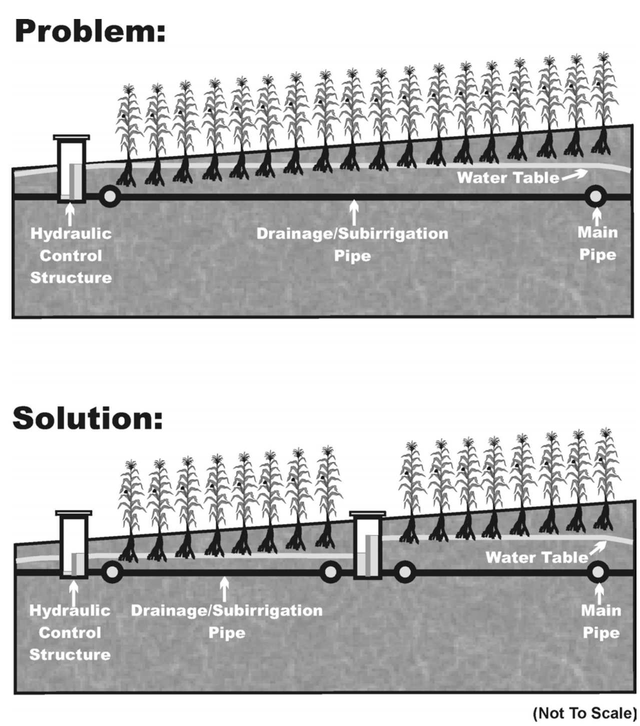

Figure 7. Root zone flooding problems can often be solved by installing additional hydraulic control structures to better manage the water table position in areas of low surface elevation.

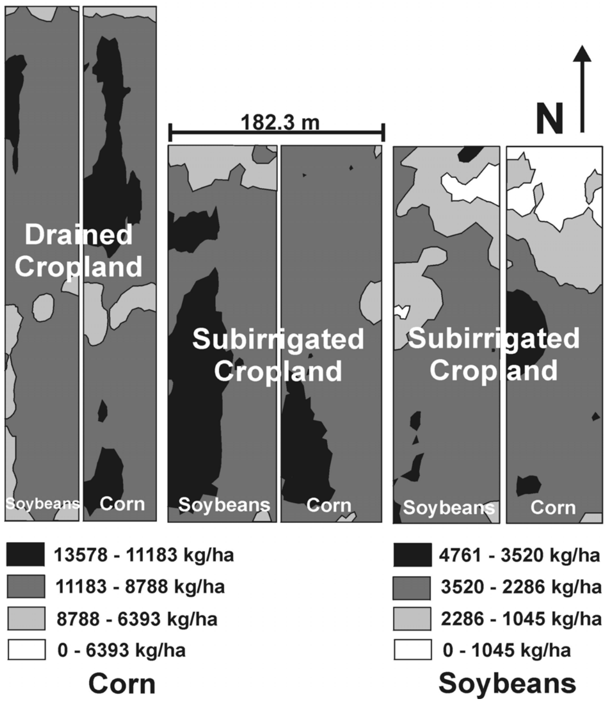

Figure 8. Corn (Beck's 5405, Pioneer 33G–26) and soybean (Charleston, Asgrow 3244) yield map for 1998 at the Van Wert County WRSIS site.

season.) The effectiveness of installing this additional hydraulic control structure will not be known until future yield maps are compiled at the Defiance County site for years unlike 2000 and 2001, where excessive rainfall hindered early growing season field operations. The lesson learned at both the Defiance and Van Wert County sites is that the initial WRSIS design may need to be modified by installing additional subirrigated field hydraulic control structures in order to better manage water table conditions in low spots.

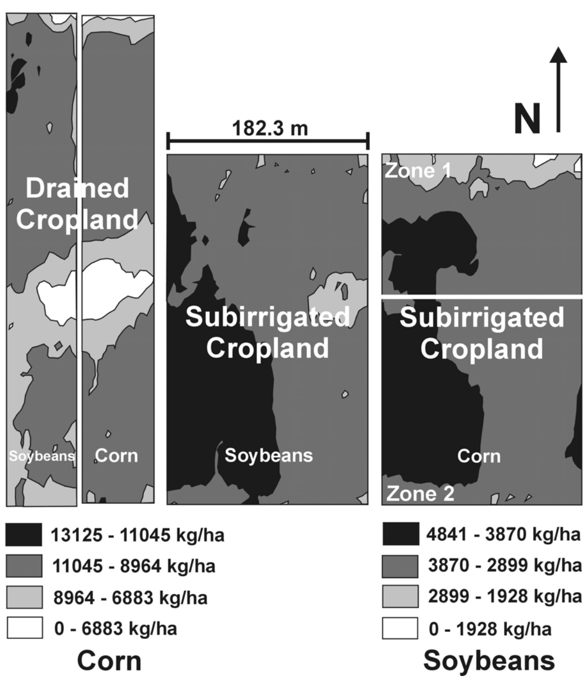

Figure 9. Corn (Beck's 5405, Agrigold A6469Bt) and soybean (Stout, Gries Seed 335) yield map for 2000 at the Van Wert County WRSIS site.

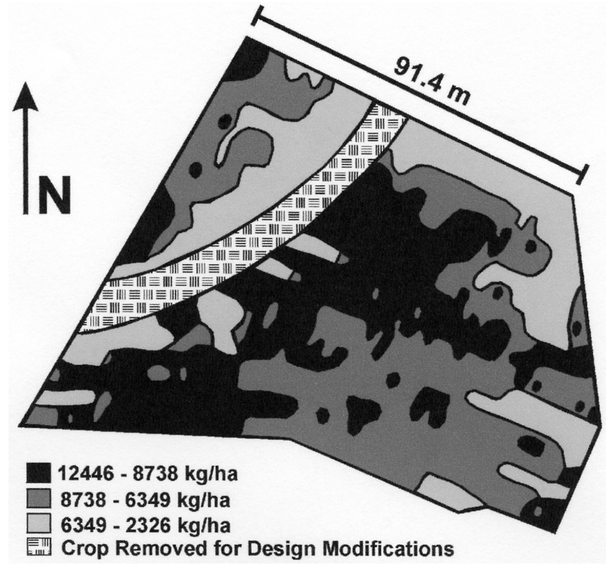

Figure 10. Corn (Beck's 5405) yield map of 1999 for the west subirrigated field at the Defiance County WRSIS site.

SUMMARY

Large–scale environmental benefits of WRSIS will not be achieved until farmers are convinced that these systems are capable of increasing crop yields significantly over time. Obtaining increased crop yields with WRSIS requires a proper water table management approach that includes a conscientious effort to follow suggested operational guidelines and a willingness to modify system infrastructure as warranted. Experience–based guidelines for WRSIS water table management were presented, and the operational practices outlined varied somewhat depending on whether wetter, near average, or drier conditions exist with respect to growing season rainfall. Near average and wetter growing seasons require adjustments to the subirrigation supply and hydraulic control structure weir height in order provide sufficient water to crops while preventing root zone flooding problems. For a drier year, three water conservation options were discussed. An important lesson learned at two of the three WRSIS sites is that infrastructure may require modification to better manage water table conditions. In particular, installing additional hydraulic control structures to partition a subirrigated field into separate water table management zones can often solve problems associated with flooded soils in lower elevation areas. The WRSIS water table management approach adopted has been successful. Compared to control plots, WRSIS subirrigated field crop yield increases for corn and soybeans, respectively, were 34.5 and 38.1% during drier growing seasons, 14.4 and 9.7% during near average or wetter growing seasons, and 19.6 and 17.4% overall. With more data collection and experience, further improvements in WRSIS crop yields are likely.

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References

Baker, J. L., and H. P. Johnson. 1977. Impact of subsurface drainage on water quality. In *Proc. of the ASAE 3rd National Drainage Symposium*, 91–98. St. Joseph, Mich.: ASAE.

Belcher, H. W., and L. J. Protasiewicz. 1995. Water quality impact of subirrigating maize, In *Subirrigation and Controlled Drainage*, eds. H. W. Belcher and F. M. D'Itri, 281–298. Boca Raton, Fla.: Lewis Publishers.

Beuerlein, J., D. Eckert, D. Jeffers, J. Johnson, P. Lipps, M. Loux, E. McCoy, W. Schmidt, M. Sulc, P. Sutton, P. Thomison, J. Undersood, M. Watson, and H. Wilson. 1996. Ohio Agronomy Guide. Ohio State University Extension Bulletin No. 472. Ohio State University. Columbus, Ohio.

Cervinka, V., C. Finch, G. Jorgensen, F. Karajeh, M. Martin, F. Menezes, and K. Tanji. 1995. Agroforestry as a method of salt and selenium management on irrigated land. In *Proc. of the Agroforestry and Sustainable Systems Symposium*, 103–114. Fort Collins, Colo.: USDA – Forsest Service.

Cooper, R. L. 1989. High–yield–system–in–place (HYSIP) concept for soybean production. *J. Prod. Agric*. 2(4): 321–324.

Cooper, R. L., N. R. Fausey, and J. G. Streeter. 1991. Yield potential of soybeans grown under a subirrigation/drainage water management system. *Agronomy J.* 83(5): 884–887.

Cooper, R. L., N. R. Fausey, and J. W. Johnson. 1999. Yield response of corn to a subirrigation/drainage management system in northern Ohio. *J. of Production Agriculture* 12(1): 74–77.

Doorenbos, J., A. H. Kassam, C. L. M. Bentvelsen, V. Branscheid, J. M. G. A. Plusje, M. Smith, G. O. Uittenbogaard, and H. K. Van der Wal. 1979. *Yield Response to Water.* FAO Irrigation and Drainage Paper 33. United Nations. Rome, Italy.

Fausey, N. R., L. C. Brown, H. W. Belcher, and R. S. Kanwar. 1995. Drainage and water quality in Great Lakes and Cornbelt states. *ASCE J. of Irrigation and Drainage Engineering* 121(4): 283–288.

Fausey, N. R., and R. L. Cooper. 1995. Subirrigation response of soybean growth with high yield potential management. In *Subirrigation and Controlled Drainage*, eds. H. W. Belcher and F. M. D'Itri, 225–230. Boca Raton, Fla.: Lewis Publishers.

Fausey, N. R., and L. C. Brown. 2000. Subirrigation water management guidelines. Exhibit H in marketing wetlands for profit: Final report. USEPA/GLNPO Contract #s GL995652–and GL995652–02–0. Compiled by Maumee Valley Resource, Conservation and Development. Defiance, Ohio.

Fisher, M. J., N. R. Fausey, S. E. Subler, L. C. Brown, and P. M. Bierman. 1999. Water table management, nitrogen dynamics, and yields of corn and soybean. *Soil Science Society of America J.* 63(6): 1786–1795.

Hershfield, D. M. 1961. Rainfall frequency atlas of the united states, for durations from 30 minutes to 24 hours and return periods from 1 to 100 years. Technical Report 40. U.S. Weather Bureau. Washington D.C.

Hillel, D. 1987. The efficient use of water in irrigation. World Bank Technical Paper No. 64. Washington D.C.

Jalota, S. K., and S. S. Prihar. 1998. *Reducing Soil Water Evaporation with Tillage and Straw Mulching.* Ames, Iowa: Iowa State University Press.

Jensen, M. E., R. D. Burman, and R. G. Allen. 1990. *Evapotranspiration and Irrigation Water Requirements.* New York: American Society of Civil Engineers.

Kirda, C., and R. Kanber. 1999. Water, no longer a plentiful resource, should be used sparingly in irrigated agriculture. In *Crop Yield Response to Deficit Irrigation*, eds. C. Kirda, P. Moutonnet, C. Hera, and D. R. Nielsen, 1–20. Dordrecht, Netherlands. Kluwer Academic Publishers.

Kovacic, D. A., M. B. David, L. E. Gentry, K. M. Starks, and R. A. Cooke. 2000. Effectiveness of constructed wetlands in reducing nitrogen and phosphorous export from agricultural tile drainage. *J. of Environmental Quality* 29(4): 1262–1274.

Lal, R., J. M. Kimble, R. F. Follett, and C. V. Cole. 1998. *The Potential of U.S. Cropland to Sequester Carbon andMitigate the Greenhouse Effect*. Chelsea, Mich.: Sleeping Bear Press, Inc.

Larson, W. E., and J. J. Hanway. 1977. Corn production. In *Corn and Corn Improvement*, ed. G. F. Sprague, 625–669. Madison, Wis.: American Society of Agronomy.

LeCureux, J. P. 1995. Profitability of a crop rotation utilizing subirrigation. In *Subirrigation and Controlled Drainage*, eds. H. W. Belcher and F. M. D'Itri, 193–205. Boca Raton, Fla.: Lewis Publishers.

Luckeydoo, L. M., N. R. Fausey, L. C. Brown, and C. B. Davis. 2002. Early development of vascular vegetation of constructed wetlands in northwest Ohio receiving agricultural waters. *Agricultural Ecosystems and Environment* 88: 89–94.

Merva, G. E. 1995. Horizontal hydraulic conductivity determination using the velocity permeater. In *Subirrigation and Controlled Drainage*, eds. H. W. Belcher and F. M. D'Itri, 151–167. Boca Raton, Fla.: Lewis Publishers.

Myers, M., B. Miller, M. Jacobs, N. M. N'Jie, A. Sobojeyo, and Larry Brown. 1998. Water column sampling system for the constructed wetland and water supply reservoir at the DARA WRSIS site. ASAE Paper No. 982094. St. Joseph, Mich.: ASAE.

National Climatic Data Center (NCDC). 2002. Online climate database – www.ncdc.noaa.gov. U. S. Dept. of Commerce – National Oceanic and Atmospheric Administration (NOAA) –NCDC. Asheville, N.C.

Oztekin, T., N. M. N'Jie, J. Hothem, L. Luckeydoo, L. C. Brown, N. R. Fausey, B. J. Czartoski, and C. Mills. 1998. Monitoring system for water quality and quantity, and ecological parameters at the DARA wetland–reservoir subirrigation system site. ASAE Paper No. 982110. St. Joseph, Mich.: ASAE.

Patrico, J. 2001. Into the dead zone. *Progressive Farmer* July Issue: 20–23.

Richards, S. T., M. T. Batte, L. C. Brown, B. J. Czartoski, N. R. Fausey, and H. W. Belcher. 1999. Farm level economic analysis of a wetland reservoir subirrigation system in northwest Ohio. *J. Prod. Agric.* 12(4): 588–596.

Schwab, G. O., N. R. Fausey, E. D. Desmond, and J. R. Holman. 1985. Tile and surface drainage of clay soils. Research Bulletin 1166. Ohio Agricultural Research and Development Center. The Ohio State University. Wooster, Ohio.

Skaggs, R. W. 1978. A water management model for shallow water table soils. Report No. 134. Water Resources Research Institute: Univ. North Carolina. Raleigh, N.C.

Skaggs, R. L., and M. A. Breve. 1995. Environmental impacts of water table control. In *Subirrigation and Controlled Drainage*, eds. H. W. Belcher and F. M. D'Itri, 247–267. Boca Raton, Fla.: Lewis Publishers.

Sohngen, B., and J. Rausch. 1998. Benefits of controlling soil erosion in the Maumee River Basin. Natural Resource and Environmental Economics Research News (Fact Sheet) – November Issue. Ohio State University Extension. Columbus, Ohio.

Stewart, J. I., R. H. Cuenca, W. O. Pruitt, R. M. Hagen, and J. Tosso. 1977. Determination and utilization of water production functions for principal California crops. W–67 Calif. Contributing Proj. Rep. University of California – Davis. Davis, Calif.

Sullivan, M., T., VanToai, N. Fausey, J. Beuerlein, R. Parkinson, and A. Soboyejo. 2001. Evaluating on–farm flooding impacts on soybean. *Crop Science* 41(1): 93–100.

Tanji, K. K., and F. F. Karajeh. 1993. Saline drain water reuse in agroforestry systems. *ASCE J. Irr. Drain. Res.* 119(1): 170–180.

Tindall, J. A., and J. R. Kunkel. 1999. *Unsaturated Zone Hydrology.* Upper Saddle River, N.J.: Prentice Hall.

Thornthwaite, C. W., H. G. Wilm, and others. 1944. Report of the committee on transpiration and evaporation, 1943–44. *Trans. Am. Geophys. Union* 23(5): 683–693.

Todd, D. K. 1980. *Groundwater Hydrology*, 2nd Ed. New York: John Wiley and Sons.

Van Doren Jr., D. M., and D. C. Reicosky. 1987. Tillage and irrigation, In *Soybeans: Improvement, Production, and Uses*, 2nd Ed., ed. J. R. Wilcox, 391–428. Madison, Wis.: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Veihmeyer, F. J. 1964. Evapotransiration, In *Handbook of Applied Hydrology*, ed. Ven Te Chow, 11.1–11.38. New York: McGraw–Hill Book Co.

Warner, K. L., and A. R. Schmidt. 1994. National Water–Quality Assessment Program – The Lower Illinois River. NAWQA FS 94–018. U. S. Geological Survey. Urbana, Ill.

Willatt, S. T., and H. M. Taylor. 1977. Water uptake by soya–bean roots as affected by their depth and by soil water content. *J. Agric. Sci., Camb.* 90: 205–213.

Zucker, L. A., and L. C. Brown (eds.) 1998. Agricultural Drainage: Water Quality Impacts and Subsurface Drainage Studies in the Midwest. Ohio State University Extension Bulletin 871. The Ohio State University. Columbus, Ohio.