Rainwater Harvesting with Solar and Gravity Powered Irrigation for High Tunnels

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HIGHLIGHTS

- Captured rainwater supplied nearly all the irrigation required for high tunnels in Tennessee.
- Solar pumping and/or gravity flow adequately supplied the pressure required for irrigation in high tunnels.
- Rainwater harvesting costs need to be reduced in order to be more competitive with alternate water sources.

Abstract. *High tunnels use clear plastic film over a large metal frame to trap solar radiation as heat in order to extend the crop growing season and reduce environmental stress. High tunnels differ from high tech greenhouses in that they use the natural soil as the growing media and use natural ventilation without fans or heaters to control the growing environment. High tunnels can provide some of the benefits of greenhouses at a much lower cost. However, the protective cover cuts-off rain water to the crop and significantly modifies the crop-water use environment.*

In order to reduce reliance on external sources of water, The University of Tennessee–Biosystems Engineering and Plant Science Departments implemented three types of rainwater harvesting (RWH) for high tunnels that did not require an external source of power for irrigation: gravity flow, solar battery-powered pumping, and solar transfer pumping. RWH by gravity-flow stored water captured off the high tunnels at a high enough elevation to deliver water for irrigation at very low pressure while solar battery-powered pumping delivered pressurized water directly to the irrigation system. Solar transfer pumping moved harvested rainwater to a higher elevation tank that used gravity flow to irrigate at intermediate pressures.

These RWH systems were designed to store 64 mm of rainfall from the high tunnel cover (6400 L per 100 m^2 of footprint area) and were able to provide 75% to 100% of the spring crop and 90% to 100% of the fall crop irrigation based on 16 experiments over six years. The RWH systems were ranked in order of increasing cost, maintenance, and complexity as follows: 1) gravity flow, 2) solar transfer pumping, and 3) solar battery-powered pumping. However, all RWH systems had high initial cost when compared to well and municipal water supplies, \$12,750 to \$15,950 for two 9.2- × 29-m high tunnels. Significantly lower cost rain gutters and water storage were identified but not yet tested for RWH in high tunnels.

Keywords. *Drip irrigation, Evapotranspiration, Gravity irrigation, Greenhouses, High tunnels, Microirrigation, Rainwater harvesting, Solar pumping.*

High tunnels are simple greenhouse-like structures that trap solar radiation raising the inside temperature and allowing crop growth during cold weather. In contrast with high-tech greenhouses, low-tech high tunnels use plastic films instead of rigid glazing, natural soils instead of container growth media, natural ventilation instead of fans, and solar radiation alone for warmth without supplemental heating. Of course, there is no clear delineation between greenhouses and high tunnels as the above production distinctions can be mixed in many configurations. The term greenhouse is more often used when referring to a protected agriculture structure with a mixture of practices. It is important to note that a simple high tunnel retains several of the benefits of an automated greenhouse at a fraction of the capital and operating costs. The fossil fuel and electricity required for heating and cooling greenhouses are a large production input (Vine, 2008);

Submitted for review in February 2020 as manuscript number NRES 13969; approved for publication as a Research Article part of the NIS Collection by the Natural Resources & Environmental Systems Community of ASABE in May 2020.

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for example, energy accounted for 60% to 80% of total production cost in Turkey (Ozgener and Hepbasli, 2006). High tunnels largely avoid these costs while providing substantial protection of fruits and vegetables from frost, hail, wind, pests, and disease; thus, allowing for increased crop quality and for the growing season to be extended beyond traditional periods when produce can be sold at higher prices (Lamont, 2009). Extension of the growing season at lower cost has facilitated the adoption of high tunnels.

Protected agriculture ranging from simple high tunnels to automated greenhouses has been widely adopted in China and is gaining popularity in the United States. There are approximately 410,000 ha of protected agriculture in China accounting for 86% of the protected agriculture in the world as of 2016 (Reddy, 2016; Tong et al., 2016). Protected agriculture also is the main source of fresh fruits and vegetables consumed in China during the winter months as compared with frozen and transported produce (Jiang et al., 2010; Xiang et al., 2014). In the U.S., the number of producers employing protected agriculture for food crops tripled from 1998 to 2018 (USDA-NASS, 2014; USDA-NASS, 2019). The average area placed under protection by a new producer was 0.1 ha, equivalent to three high tunnels (note that these survey responses include all types of protected agriculture, not just high tunnels). Much of the growth in protected agriculture has been fueled by the movement away from imported and long-distance transport of produce toward local and organic production. Even though the U.S. has sophisticated greenhouses, small-scale growers are installing simple high tunnels to supply the changing demand in local produce markets (Carey et al., 2009), and partly due to incentive programs like the Natural Resource Conservation Service Environmental Quality Incentives Program (NRCS EQIP) High Tunnel System Initiative (USDA-NRCS, 2020).

While high tunnels afford significant advantages for the producer, there are substantial inefficiencies in this production system. First, the soil is degraded by repetitive growth of the same high-value crops. The soils in Chinese structures are often degraded within 3 to 5 years such that a disease/salt tolerant cropping system needs to be adopted until the soil is remediated sufficiently to return to the same high value crop, or mobile high tunnels can be moved to a new location (Cao et al., 2012; Fu et al., 2017). Similarly, studies in the U.S. have documented a reduction in yield over time believed to be due to soil disease build-up (Janke et al., 2017; Zheng, 2017). Second, a significant portion of the solar radiation that is converted to heat during the day is not retained overnight. Studies in the U.S. have documented that over 65% of the solar radiation generated heat needs to be ventilated during the day while night time temperatures fall to within 1°C of outside temperature by morning in non-heated high tunnels (Zheng et al., 2017, 2019). Even Chinese solar greenhouses that are designed to take advantage of thermal mass in the north facing wall and are covered by insulation at night have been documented to only increase solar energy capture by 50% while nighttime temperatures can drop to 5°C in northern China (Tong and David, 2009; Xu et al., 2013; Fang et al., 2015). Third, natural rainfall is directed away from the interior soil by the protective cover; thus, an external source of water for high tunnel production is most often used, wasting 100% percent of the rainfall. Even though China has a long history and dependence on rain water harvesting (RWH), there has been limited application to protected agriculture structures (Huang et al., 2002; Zhang et al., 2007). In the U.S., there are a few demonstration sites and some Extension materials on RWH for high tunnels, but adoption appears limited since the Irrigation and Water Management Survey does not report RWH as a water source for protected horticultural crops (USDA-NASS, 2019).

This article focuses on methods to implement RWH in high tunnels along with the potential water conservation benefits. The problems of soil degradation and inefficient utilization of solar energy in high tunnels were mentioned because RWH can have a synergistic effect on soil and energy conservation. For instance, irrigation using rain water provides high-quality water that can help alleviate the build-up of salts in soil (Davies et al., 2011). Also, water can provide thermal mass that accumulates solar heat during the day and releases that heat at night (Bastien and Athienitis, 2017) when the harvested rainwater is stored inside the high tunnel. RWH is a solution that can benefit the whole production system and also fits the concept of high tunnels being a low-input, sustainable system. Since high tunnels are designed for low-energy consumption and are often placed in agricultural fields that do not have easy access to electrical power or pressurized municipal water, only RWH options were tested that did not require an external source of power or fossil fuel.

Background

General planning for RWH is described in a variety sources (Lawson et al., 2009; Texas Water Development Board, 2005; Waterfall, 2006). Resources specific to RWH for high tunnels are less available, but there are some "how to" installation guides (Naeve and Shouse, 2012) and studies that help verify the effectiveness of RWH planning methodologies in greenhouses (El-Behairy et al., 2000; Ji et al., 2010; Baytorun et al., 2019). While there are examples of greenhouses with solar-powered RWH, few published resources were found that integrate solar power for RWH in greenhouses (Leib et al., 2013) or document the effectiveness of a solar-powered approach to RWH in greenhouses.

RWH planning involves understanding water supply and water demand of a specific application in order to adequately size the storage capacity (Singh et al., 2019). The expected amount of water that can be harvested from high tunnels is based on the footprint area of the structure combined with the historic precipitation data, i.e., the frequency and amount of rainfall for a specific location (Verbist et al., 2009). The water demand from a RWH system is based on the high tunnel footprint area and the crop-water use rate. Crop-water use changes with crop type, crop development, and the growth environment inside the high tunnel that is affected by external weather conditions. Generally, RWH storage is sized to meet the water demand over a reasonable period of insufficient supply, i.e., a water balance of the amount of rain that can be captured related to irrigation requirements that can be sustained by the storage capacity over time. RWH can supplement or be supplemented by another source of water, which will also affect the storage required.

In a RWH system, water must move from the capture surface to the storage container and then from the storage container to the soil. Only gravity flow and solar-powered pumping options were considered for water transfer in order to maintain the low or no-power concept of high tunnels. Gravity flow criteria are described in hydraulic textbooks (Morris, 1963) and applied manuals (Jordan, 1980) while solar-powered pumping is most often described for remote cattle watering facilities (Morales and Busch, 2010). There is also a need to understand the hydraulic characteristics of irrigation equipment from manufacturer literature and product testing. This is especially import for gravity-powered systems that can provide pressures below the normal operating ranges of irrigation equipment.

The components required to assemble a solar or gravity-powered RWH system for a high tunnel are available from various suppliers (gutters, tanks, irrigation/pipes, solar energy pumping). The RWH equipment costs are high when compared to other more reliable sources of water. One study estimated the RWH cost for two small greenhouses to be $8,000 and noted that this amount may require cost-share assistance to promote adoption (Islam et al., 2013). There are companies that focus on RWH and other firms that have the capability to design and install RWH systems even though this is not their primary business. This type of integration for a turn-key product significantly adds to the cost of RWH.

Materials and Methods

In 2011, RWH systems were installed in three 9.2- × 14.6-m high tunnels located at the University of Tennessee's East Tennessee Research and Education Center-Organic Crops Unit, located on Government Farm Road in Rockford, Tennessee (lat. 35.88, long. 83.93, elevation 348 m) through an internally funded pilot project. One RWH system was completely gravity powered and provided water to a single high tunnel. The other RWH system was solar powered with a battery-operated pump that served two high tunnels. The project received USDA-NRCS Conservation Innovation Grant funding in 2013, and the original RWH systems were improved and made operational again. In 2014, three RWH systems were installed in commercial high tunnels in Blount (9.2 × 22.9 m), Rutherford (10.7 × 30.5 m), and Hawkins (9.2 × 22.9 m) counties of Tennessee. These RWH systems utilized solar transfer pumping, a hybrid between solar and gravity systems.

The storage container size was based on rainfall patterns. An examination of historic daily rainfall revealed that rainfall frequency was very high with most times between appreciable rainfall events being less than two weeks. Table 1 shows when dry periods of greater than two weeks occurred. Tennessee does have longer dry periods like those that occurred in 2007, but the increased cost of added storage to cover those infrequent events did not seem justifiable when supplemental water is available. Water use was based on spring tomato, a common high tunnel crop with high water requirements and a growing period that extends into summer. Since reference

Table 1. Analysis of rainfall from 2006 to 2010 at Tyson McGee Airport, Knoxville, Tenn.[a]

Year	Date Range	Dry Period	Rain Amount (mm)
2005		none	
2006	3 June to 24 June	22 days	2.5
2007	6 May to 2 June	28 days	9.1
2007	3 June to 17 June	15 days	11.7
2007	20 June to 5 July	16 days	7.4
2007	3 August to 28 August	26 days	2.8
2008	15 June to 4 July	18 days	10.9
2008	29 July to 25 August	28 days	9.7
2009		none	
2010	15 June to 8 July	24 days	9.9

[a] Time periods greater than two weeks with less than 12.5 mm of rain during the peak water use times of May through August.

evapotranspiration (ET) and crop coefficients were unknown for the high tunnels, open field reference ET based on the Turc method (Jensen et al., 1990) and single factor FAO crop coefficients (Allen et al., 1998) were used to estimate an average peak crop ET for summer at 38 mm week^{-1}. However, a design rate of 32 mm/week was used because high tunnels keep the soil surface very dry by blocking all rainfall while drip irrigation under plastic mulch also inhibits soil surface evaporation. Using these criteria, a two-week dry period would require 64 mm of water or 6400 L for every 100 m^2 of high tunnel footprint area. Different materials could have been used for RWH storage containers such as concrete, corrugated metal, and thick flexible membranes. However, polyethylene plastic tanks were used in all of these RWH systems.

In 2011, plastic-sectional gutters were used to collect water off the high tunnel roof surfaces. After 2013, galvanized steel sectional gutters replaced the plastic gutter and were used in the commercial high tunnels. This was done to ensure that snow loads could be removed from the high tunnels without damaging the gutters. All but one high tunnel was of the gothic style (vertical side-walls with a truss shaped roof-line from the peak to the side walls as shown in fig. 2b) which allowed the gutters to be installed at the top of the vertical side before the roof curvature at approximately 1.6 m above the ground (fig. 1a). This location was also above the roll-up sides and did not interfere with opening or closing them for ventilation. One high tunnel was a half-round hoop style house, and a 50- × 100-mm piece of lumber needed to be split diagonally and attached to the high tunnel in order to create a near vertical surface to attach the gutter as illustrated in Diagram 1 of Naeve and Shouse (2012). In all instances, the gap between the gutter and the high tunnel needed to be covered with repair tape to force all of the rain water into the gutter. Rectangular down spouts were adapted to the round air vent holes on the top of the tank lids allowing water to fall directly into the tanks after passing through a screen just under the tank lid.

The gravity RWH system limited tank size to around 2080 L (1.1 m high and 1.7 m diameter) because the tanks needed to be small enough to fit under the gutters and still be elevated off the ground surface by two layers of concrete blocks (about 0.45 m) to create the greatest possible gravity pressure (head) to operate the drip irrigation system (fig. 1). Still, the highest water pressure that could be developed was 14 kPa when the tank was full and less than 7 kPa when the tank was near empty. A typical low pressure for drip irrigation

(a) (b) (c) (d)

Figure 1. Rainwater harvesting by gravity flow, a) rain gutter attached to vertical side of Gothic style high tunnel, b) collection off high tunnel into storage tank, c) connection to irrigation from tank, d) irrigation monitoring and control with tank level sight-tube, screen filter, automated ball valve, and flow meter.

is around 55 kPa. Hydrogal drip tubing was used at UT's Organic Unit for the gravity system because it has been rated for very low-pressure operation, 14 kPa. Four of the lower-profile, 2080-L tanks were needed to meet the storage criteria of the 9.2- × 14.6-m high tunnel. Two of the tanks were placed at the downhill end of the high tunnel while the other two where place in the middle of the high tunnel in order preserve gravity pressure since irrigation needed to be delivered upslope from the tanks. Polyethylene header tubes with valves were connected at the bottom of each tanks to directly supply and control water to the drip tubing in small zones.

At UT's Organic Unit, the solar-powered RWH systems charged batteries to operate a direct current pump. Figure 2 shows pictures of the RWH components and table 2 lists the component specifications. This set-up only required two 4160 L tanks (1.3 m high and 2.2 m diameter) at the downhill side of the 9.2- × 14.6-m high tunnel. A charge controller managed the power from the solar panels to maintain two sets of parallel, 12-V, deep cycle batteries in series providing a 24-V output to a solar pump controller connected to a submersible solar pump located in the bottom of one 4160-L tank. The two tanks were hydraulically connected to each other through the ports located at the bottom of the tanks. The pump operated the irrigation system upon demand whenever a valve was opened because the pump controller was connected to a pressure switch and a pressure tank, much like a home well water supply system. The pressure switch set points were 138 and 276 kPa and a pressure regulator was used to deliver water to the 0.689 L s^{-1} m^{-1} of drip tape operated at 83 kPa.

The RWH systems at the commercial high tunnels utilized both solar pumping and gravity pressure, referred to as solar transfer pumping (fig. 3). Catch tanks were set-up at the downhill end of the high tunnel, and a solar-powered pump transferred water from the capture tanks to a delivery tank located at higher elevation. At commercial farm #1 with a 9.2- × 22-m high tunnel, the two capture tanks were 4160 L (1.3 m high and 2.2 m diameter), and the delivery tank was 2836 L (1.8 m high and 1.3 m diameter). At commercial farm #2 with an 11- × 29-m high tunnel, the two capture tanks were 8320 L (2.3 m high and 2.2 m diameter; dug 0.75 m into the ground to allow them to fit under the gutters), and the delivery tank was also 8320 L (2.3 m high and 2.2 m diameter; elevated 0.75 m on an earth mound and oversized to allow two more high tunnels to be eventually added to the system). The delivery tank supplied water to the irrigation system using gravity pressure. Since the delivery tanks elevation was not restricted by the height of the gutters, they developed higher pressure than the completely gravity pressure

Figure 2. Rainwater harvesting by solar battery-powered pumping: a) collection off high tunnel into storage tank, b) connection to irrigation and DC power with submersible pump in tank (gothic-style high tunnels noted by the vertical side-walls and the trussed roof), c) solar panel, d) batteries and charge controller, e) pump controller, f) irrigation monitoring and control with pressure tank, pressure switch, screen filter, automated ball valve, flow meter, and pressure regulators.

RWH system. The pump controller was wired to a float switch in the delivery tank and there were no charge controllers, batteries, pressure switches, or pressure tanks. The submersible pump and pump controller were the same type as used in the solar battery powered RWH system (table 1) and the float switch that interfaces with the pump controller was a normally open, mechanical float switch, Dayton (MFR#:6PNV7). When water was used from the delivery tank, the float switch dropped and signaled the pump controller to start the pump if there was enough sunlight for the solar panels to operate the pump. In essence, the system always transferred as much water as possible to the delivery tank leaving as much room as possible in the capture tanks to store water from rain events. On semi-cloudy days, the pump controller allowed the pump to operate at lower flow rates. While the pump was not able to operate on extremely overcast days, this did not cause a problem because there was already enough water in the delivery tank for gravity irrigation and irrigation is less necessary on cloudy days. Solar transfer pumping with gravity delivery provided 14 to 28 kPa of pressure while pumping to a higher elevation could have provided more pressure for irrigation. Water pressures of 55 to 100 kPa are normally recommended for drip tape but these pressures were notably higher than the gravity-alone RWH system.

Table 2. Components and specifications of the solar-powered RWH with battery to operate the direct current pump.

Component	Specifications	Quantity and Notes
Sun Pumps SDS-T-130	Solar submersible pump	Qty. of 1
Sun Pumps PCA-30M1D	Solar pump controller	Qty. of 1
Uni-Solar PVL-136	136-W photovoltaic panel	Qty. of 6 - Two sets of three connected in parallel
Xantrex C40	40-A photovoltaic charge controller	Qty. of 2 - Each set of three panels connected to a charge controller
Deep cycle battery	115 A-h	Qty. of 4 - Two sets in parallel connected to each charge controller. The sets were connected in series to provide 24-V output to the pump controller.
Bladder tank	115 L	Qty. of 1
ProSense PSD25-0P-0145H	Pressure switch	Qty. of 1
Banjo EV075	Automated ball valves	Qty. of 4

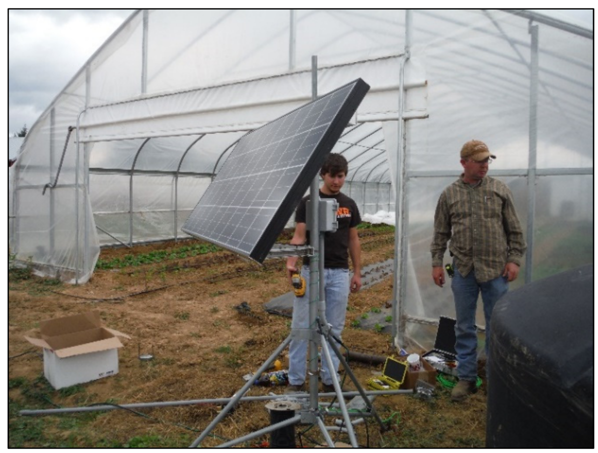
The major component costs of RWH systems for high tunnels are shown in table 3. All the RWH systems required gutters and tanks, which were high cost items, especially the tanks at $10,000. Gravity alone required the least cost to move water from the high tunnel surface to the plants inside while solar transfer pumping required more equipment and solar-powered battery pumping had the highest equipment cost.

As shown in tables 4 and 5, solar radiation, temperature, humidity, and windspeed were measured both inside and outside the high tunnels, while soil matric potential with soil temperature were measured inside, and rainfall, irrigation flow (UT only) and tank levels were measured outside. Only rain gauges, flow meters, and tank levels were used to evaluate the adequacy of the tank sizing. The logging system also allowed for real time management decisions because cell modems transferred the data to a web connected server several times per day.

Results and Discussion

The RWH systems were able to supply approximately 75% to 100% of the spring crop irrigation and nearly 100% of the fall crop irrigation based on 16 experiments over 6 years when RWH storage capacity was based on a volume of 64 mm of rainfall per high tunnel catchment area as shown in table 6. In early summer, when spring tomato and pepper

(a)



(b)

(c)

Figure 3. Rainwater harvesting by solar transfer pumping: a) collection off high tunnel into storage tank, b) water pumped from storage tank using solar panel, pump controller, and submersible solar-pump inside the storage tank, and c) water pumped to the higher elevation delivery tank that is controlled by a float switch inside the delivery tank before being gravity fed into high tunnel.

Table 3. Cost of three types of RWH systems based on two 9.2- × 29-m high tunnels: gravity flow (GF), solar transfer pumping (STP) and solar battery powered pumping (SBPP).

Item	RWH System Type	Description	Cost
Rain gutters	GF, STP, SBPP	122 m of installed aluminum or plastic. Material only for Galvanized	$2,000
Storage tanks	GF, STP, SBPP	33 kL water storage from rigid plastic tanks	$10,000
Elevate gravity tank	G	250 concrete blocks to create 0.45 m of lift	$400
Solar pumping	STP, SBPP	Solar panels, submersible 24-V solar pump, pump control, wire and conduit	$2000
Battery power	SBPP	4 deep cycle batteries, charge controller, pressure tank & switch, wire, conduit	$1200
Water conveyance	STP, SBPP	76 m of 25 mm PVC pipe with trenching	$750
Gravity-only		TOTAL	$12,750
Solar transfer		TOTAL	$14,750
Solar battery		TOTAL	$15,950

Table 4. Components and specifications of the data collection system to monitor and control RWH at the University of Tennessee – ETREC: Organic Unit.

Components	Specifications
Campbell Scientific CR1000	Datalogger
Campbell Scientific AM16/32	Multiplexers for soil temperature and watermark soil matric potential
Campbell Scientific SDM-SW8A	Switch closure modules for flow meters
Texas Electronics TE525	Rain gauge
Li-Cor LI-200R	Pyranometer
Vasaila HMP45C	Air temperature/humidity
R M Young 03001	Wind sentry set: Wind speed and direction
Thermocouple wire	T-type
Irrometer watermark sensors	Soil matric potential
Dwyer WMT2-A-C-01	Pulse output flow meter
Multi-Tech cellular modem HTC-H5-B01 controlled by a Multi-Tech MTS2SA serial-to-serial adapter	AT&T cellular data network

Table 5. Components and specifications of the data collection system to monitor RWH at the commercial sites.

Components	Specifications
Decagon/Meter Group EM-50G	Datalogger
Decagon/Meter Group ECRN-100	Rain gauge
Decagon/Meter Group PYR Sensor	Pyranometer
Decagon/Meter Group ATMOS-14	Air temperature/humidity
Davis Instruments 40030	Anemometer: wind speed and direction
Decagon/Meter Group MPS-2	Soil matric potential and soil temperature
Decagon/Meter Group HYDROS-21	Tank water level
Decagon/Meter Group CELL Modem	GSM cellular data network

Table 6. Percent of irrigation supplied by RWH at each site over six years when storage was based on 64 mm of rain per 100 m^2 of high tunnel footprint area.

	UT Organic Unit		Farmer 1		Farmer 2	
	Spring	Fall	Spring	Fall	Spring	Fall
2011	80%	100%				
2012						
2013	100%	100%				
2014	83%	100%	98%	100%		100%
2015	89%		100%	100%	87.5%	90%
2016			100%		75%[a]	

[a] Several occurrences of well water being added to the capture tank at the same time the crop was being irrigated effected the accuracy in determining irrigation amount from RWH.

crops had attained their largest canopy and ETr was at its highest, there were long-enough dry periods when an alternate water source was needed to supplement irrigation from the RWH systems. Predictably, there were differences in human perception of irrigation requirements and rainfall amounts among sites. The UT site used matric potential sensors with an attempt to keep these sensors in the 15 to 20 kPa range before adding municipal water to the RWH tanks, while commercial Farm 1 applied less irrigation and commercial Farm 2 applied more irrigation. During the driest period (2016) at commercial Farm 2, there were several instances of well water being added to the tanks at the same time crop irrigation occurred, making it difficult to get an accurate accounting of well water going into the tank. During these events, past rates of well inflow were used to estimate the amount of well water added to the tank; however, the cause of tank level change remained unknown since either well inflow or irrigation outflow could have changed. The design rule of 64 mm per high tunnel catchment area was adequate to provide a high proportion of irrigation in Tennessee. However, more storage capacity may be desirable if rain is the only water source. The longest drought in the last 20 years was a 9-week period in 2007 (beginning of May until the beginning of July) in which only 41 mm of rain occurred during peak water use. It does not seem feasible to triple the storage capacity for such infrequent events due to both size and cost of extra storage. It would be more reasonable to increase storage capacity by around 50% (three weeks of water storage instead of two would cover a majority of the dry periods in table 1), perform some deficit irrigation, remove some crops early and then transport water to the site when necessary. It should be noted that the rates of high tunnel water use have not been fully verified and it is possible that our design storage capacity could last longer than two weeks. Another possible benefit of RWH is the ability to use high quality water and thus reduce salt build-up and the leaching fraction in the drier environment created by high tunnels. Moreover, this project tested but was not able to document appreciable differences in soil salinity when using RWH, municipal, or well-water sources. High salinity soils and high salinity water are rare in Tennessee.

The gravity RWH system was the lowest initial cost with the lowest maintenance since there were no high-tech components to fix or replace. In fact, there were no leaks from the drip irrigation fittings under the low pressure on/off cycling compared to the higher-pressure systems. A gravity system can reduce leaks that could be very detrimental to the limited water storage capacity associated with RWH systems. However, there were some management challenges with gravity systems. Run times were based on tank water level drop and not fixed times since the pressure dropped as much as 50%. Also, several small tanks needed to be spaced along the sides of the high tunnel increasing the number of small irrigation zones that needed to be managed. Finally, a low-pressure gravity system can create irrigation uniformity issues on sloping sites where the higher elevation parts of the tunnel will not receive as much water as the lower elevation sections. Poor irrigation uniformity was not observed in the crop or the soil wetting patterns at this site.

The solar powered and battery pumped RWH system had the highest initial cost and the highest maintenance cost. Several electrical problems were encountered in this approach. Initially, the negative side batteries would not recharge using a single 24-V charge controller needed for the 24-V pump controller and solar pump. The solution chosen was to use two 12-V charge controllers to charge the negative and positive side batteries independently. While implementing this redesign, a wire was incorrectly connected in the system causing damage to a charge controller. In hind sight, it may have been better to have created a 12-V system from the beginning. Also, a nearby lightning strike created a large enough electrical surge to damage a charge controller and sensors that were attached to the metal frame of the high tunnel. In this repair, more lightning suppressors, ground rods and fuses were added to the system. Self-maintenance of a solar-battery powered RWH would be difficult without a good understanding of how the electrical components work together. This approach did provide on-demand watering that operated at the recommended pressures for drip systems. With proper placement of pressure regulators, the expected uniformity was high over the short lengths of dripline (less than 30 m), and run-times were easily calculated to apply the desired amount of water. Finally, the higher pressure on and off cycling caused some driplines to separate from the spin-lock connectors. This can cause a large leak that can flood sections of the high tunnels and waste a substantial portion of stored water in RWH systems if not detected early. Farm personnel need to check the entire system for leaks every time irrigation is turned on.

RWH by solar transfer pumping had less initial and ongoing cost, and it was easier to understand how the electrical components worked together. Two float switches did require replacement, but the system still pumped water in manual mode until repairs could be made. In automatic mode, the system maintained high water levels and operating pressure in the delivery tank while keeping the catch tanks as empty as possible to store water from rain events even though the pump could only operate with sufficient sunlight. The higher level of gravity pressures reduced the possibility of irrigation uniformity problems and reduced leaks caused by on/off cycling in high pressure systems. Solar transfer pumping was an on-demand system, by opening a valve, water flowed from the delivery tank to the dripline. This approach also had the ability to supply water to the entire high tunnel at one time to Farm #2 when a large enough delivery line (40-mm lay flat) was used. In contrast, the gravity system required opening several valves for each small tank in the high tunnel, and the solar battery powered system was limited by the low flow rate of the submersible pump. The characteristics of each RWH system are summarized in table 7.

Each RWH system had different strengths and weaknesses as shown in table 7; however, a shared weakness was the high cost as shown in table 3. The average cost of a home-sized well near Knoxville, Tennessee, that produces 0.6 L s^{-1} is around \$9,000 (personal communication, Corum Well Drilling and Pump Service, 2020). Therefore, the cost of a well would be less than RWH unless the well needed to be considerably deeper than the average depth of 100 m, was located a long distance from electrical power, and/or could not produce 0.1 L s^{-1} of flow. Also, a well would be a more reliable source of water during an extended dry spell. Municipal Water at the University of Tennessee's Organic Unit would be a \$1,200 initial fee for a 19 mm tap and \$1,200 per year to supply a 650 mm depth of water to two 9 m by 30 m high tunnels with no sewage charge (KC Utility District, 2020). Municipal water would be less expensive initially but cost more over time. This added cost could be acceptable for producing high-value crops in high tunnels because the water supply is a reliable, low maintenance, pressurized source of clean water. Much of the economics would depend on the price structure of and distance to municipal water. Some rural water districts have a more favorable price structure that accounts for agricultural uses. The ability to remove the sewer rate from municipal water charge would also be an important cost factor. RWH can be supplemented by existing home wells or municipal taps while reducing the continued competition with home water uses.

Rain water is generally a clean source of water with less minerals content than well or municipal water. Further, it can even have less biological contamination than surface water, but there is still the potential of bird waste being deposited on the capture surface (i.e., high tunnel film), and therefore experiencing possible contamination by Shiga-toxigenic producing *E. coli* and *Salmonella* spp. To minimize potential risk of foodborne illness, growers should consider agricultural water treatment with a UV light or an antimicrobial pesticide product, such as chlorine or peroxyacetic acid.

It is important to consider lower cost components in RWH systems for high tunnels. Water storage tanks made of rigid plastic cost over \$0.25 L^{-1} while water storage made of flexible thin-plastic could be incorporated into RWH at \$0.012 L^{-1}. Water stored in thin, flexible plastic would also

Table 7. Characteristics of three types of RWH systems based on: gravity flow (GF), solar transfer pumping (STP) and solar battery powered pumping (SBPP).

RWH	Initial	Repair		Irrigation				
System	Cost	Cost	Complexity	Pressure	Uniformity	Zone Size	Determine Set-time	Leaks
Gravity only	least	least	least	least	least	least	difficult	least
Solar transfer	---	---	---	---	---	most	difficult	---
Solar battery	most	most	most	most	most	---	easiest	most

be more adaptable inside the high tunnel to provide thermal mass for heat retention. Sectional gutters made of rigid plastic and galvanized steel have been used ranging in cost from \$12 to \$25 m^{-1} for material cost alone. In contrast, seamless aluminum gutters, that have less strength to withstand snow removal, could be adapted into RWH and cost \$11 m^{-1} installed and \$5 m^{-1} for materials if a seamless gutter machine can be rented or shared. The reliability and cold weather adaptability of these lower cost products still need to be tested.

Conclusions

Three RWH systems for high tunnels were developed and tested that did not require an external power source: 1) gravity flow, 2) solar transfer pumping, and 3) solar battery-powered pumping. The design criteria for RWH storage capacity was based on providing irrigation for a two-week period without rainfall during peak water use and the same storage criteria was applied to all RWH systems. The expected peak water use was 64 mm for a two-week period or the equivalent storage volume of 6400 L per 100 m^2 of high tunnel footprint. With this storage capacity, the RWH systems were able to provide around 75 to 100% of spring irrigation and 90% to 100% of fall irrigation for 16 experiments over 6 years. The tested design criteria for storage capacity was reasonable for a humid region like Tennessee with well distributed annual rainfall of over 1200 mm. Less storage capacity could be recommended if a supplemental source of water were available or more capacity could be recommended if precipitation was the only source of water for the high tunnels. Also, crop water use and RWH water balance studies are needed to improve irrigation and verify storage capacity requirements for RWH in high tunnels.

The estimated cost of each RWH type was \$12,750 for gravity flow, \$14,750 for solar transfer pumping, and \$15,950 for solar battery powered pumping based on suppling irrigation to two 9.2- × 29-m high tunnels. Corresponding with increased initial cost of RWH systems was increased maintenance and increased complexity. The solar battery powered pumping system had more components that were more expensive to replace. Also, the complexity of this system made trouble shooting difficult since a very good understanding of how all the components work together is required to make repairs. In addition, the higher irrigation water pressure of solar battery-powered pumping caused more drip irrigation fittings to separate with potentially large leaks that could have wasted significant amounts of water from the limited storage capacity. These factors alone would seem to suggest that gravity flow is the best approach to RWH in high tunnels, but the gravity flow system required setting-up several small tanks and each tank would only irrigate a small zone within each high tunnel. There was also the potential for poor irrigation uniformity on sloping ground when water pressure never exceeded 14 kPa at the tanks and irrigation needs to be delivered up slope from the tanks. Solar transfer pumping seemed to provide a better balance of cost, complexity, and operational characteristics.

One critical drawback with RWH for high tunnels is high capital cost since a home well system could also supply two large high tunnels at less cost, depending on well depth and distance from electrical power. Also, municipal water from a home-sized tap would most likely have a lower initial cost if a long pipeline were not required, and the on-going water cost could be justifiable depending on the price structure of the municipal supply. In addition, both private wells and municipal utilities are more reliable sources of water during extended dry periods than harvested rainwater. Rainwater will have lower soluble solids than well and municipal water, but harvested rainwater can develop biological contamination that may require remediation. This project has identified aluminum gutters and flexible thin-plastic water containers that could reduce RWH cost in high tunnels by 75%. Cost reducing components like flexible plastic containers could also be placed inside a high tunnel providing thermal mass to better control the high tunnel growth environment. However, these lower cost components need to be tested under commercial high tunnel conditions.

Acknowledgements

We would like to thank the University of Tennessee Institute of Agriculture for funding a pilot project that enabled the start of this work and for the USDA-NRCS Conservation Innovation Grant that further funded this effort. Also, we appreciate the staff at the University of Tennessee, East Tennessee Research & Education Center–Organic Unit for maintaining the high tunnels and assisting with the implementation of this research and outreach effort.

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