Simplified Water Requirement Calculators for Fruits and Vegetables

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SUMMARY. New users of drip irrigation in Myanmar had no idea how much water to apply to their crops with drip and could not afford tensiometers or other soil moisture monitoring tools. The concept of a simple paper calculator was born out of their need for an easy-to-use yet inexpensive tool to estimate horticultural crop water requirements. We used a generalized crop coefficient and growth stage approach together with average evapotranspiration (ET) for the vegetable crops “Water Wheel” calculator and a canopy cover approach for the tree fruit calculator. Differences among published crop coefficients are relatively small for a large number of vegetables and single coefficients were used for groups of crops without putting farmers’ crops at risk. Vegetable crops were divided into two groups based on whether water requirements during harvest remained the same as for the flowering and fruiting stage or were reduced for the harvest period. A simplified canopy cover approach was used to determine water requirements for perennial fruit, tree, and vine crops. Our faith in the ability of farmers to make their own adjustments gave us confidence to simplify ET-based water requirements and make them available in the form of simple rotating disc calculators printed in color on laminated card stock. The calculators were welcomed by our staff and enabled them to provide reasonably reliable recommendations for new users of drip irrigation. When surveyed, field staff responded that 74% of farmers they advised followed Water Wheel recommendations. Rough estimates of fruit and vegetable water requirements reached a large number of new drip users in a form they could easily understand, thereby lowering adoption barriers for an unfamiliar technology. This paper describes the Water Wheel concept and design so nonspecialists might develop their own calculators using local climatic data.

On-farm trials and demonstrations of low-cost drip irrigation systems for fruits, flowers, and vegetables were carried out with hundreds of farmer cooperators by the nonprofit organization Proximity Designs (Yangon, Myanmar) from 2007 to 2009 before launching the country’s first locally designed and manufactured drip system in Nov. 2009. Over 20,000 of these small farm systems had been sold by the end of the 2015 dry season (Rowell and Soe, 2015).

From the beginning of these demonstrations, we encountered farmer perceptions that limited adoption of drip. Myanmar farmers seeing—but not yet using—drip irrigation for the first time invariably commented that the system could not possibly supply enough water compared with traditional methods of sprinkler can

watering or furrow/flood irrigation. Most smallholder farmers trying drip for the first time could not believe that the relatively low water flow observed from emitters could supply needs of the crop.

Local farmers initially had no idea how much water should be applied through a drip system and could not afford simple tensiometers, much less more sophisticated soil moisture monitoring tools or computer software; none had access to personal computers or mobile phones at the time. On-farm demonstrations together with one-on-one discussions of crop water needs and drip application rates became important strategies to address

this issue. The idea of a simple paper calculator was born out of these discussions with farmers and their need for an easy-to-use yet inexpensive tool to estimate horticultural crop water requirements. This paper describes concepts and design of two different Water Wheel calculators in enough detail that nonspecialists might develop their own calculators using local climatic data. It is also hoped that this will stimulate further experimentation, discussion, and generate suggestions for improvement.

ET-based water requirements

Water requirements for various crops have long been estimated using local or regional meteorological records; the most common method uses calculated ET data. ET is defined as the amount of water or moisture that evaporates from the soil surface plus that which is lost through transpiration of the crop (Smajstrla et al., 1997). ET can be used to provide an estimate of the total amount of water needed to grow a crop for a given area. Weather stations commonly estimate water needs by measuring the amount of water evaporating from a wide, shallow pan of a standard size which is located within a well-watered grassy reference surface. Water levels in the pan are measured daily to determine the amount of water that has evaporated; this reference ET (ET_o) is expressed in millimeters or inches per day.

ET is affected by solar radiation, air temperature, wind speed, and relative humidity; historical weather records can be used to calculate estimates of ET_o (Allen et al., 1998). The Food and Agriculture Organization of the United Nations (FAO) has calculated ET_o for multiple weather stations in many different countries using the Penman–Monteith equation, which is considered the world standard (Allen et al., 1998); Penman–Monteith-calculated ET_o is commonly

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
0.4075	gal/100 ft ²	L·m ⁻²	2.4542
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
6.8948	psi	kPa	0.1450

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used to estimate water requirements for a wide range of horticultural and agronomic crops. To avoid confusion, we use ET throughout this paper to refer to calculated ET_o . ET data for Myanmar and most other countries are available from the ClimWat 2.0 climatic database (FAO, 2005), which is used by FAO's CropWat software (FAO, 2006, 2009).

Water Wheel concept

Although it was possible for a few of our senior technical staff to discuss water requirements with individual farmers in Myanmar, it became obvious that to scale up extension efforts, a simpler approach was needed. We needed an easy-to-use tool to help all of our 140 (nonspecialist) field workers quickly determine local water requirements for a variety of horticultural crops. A circular cardboard calculator was envisioned similar to one that had been developed by the Myanmar Agriculture Service to show the cultural requirements for home garden vegetable crops.

The purpose of what we dubbed the "Water Wheel" was to enable field staff to quickly and easily estimate water requirements for the most common fruits and vegetables grown in Myanmar. Field workers could discuss these requirements on the spot before or during installation of a new drip irrigation system, providing farmers with a reliable estimate or starting point to use with drip.

Unknown to us at the time, researchers at Wageningen University in the Netherlands had independently developed and tested a similar calculator based on local ET and crop growth stages; their calculator was tested from 2004 to 2007 on citrus crops (*Citrus* sp.) in Spain and achieved results comparable to those using more sophisticated tools such as FAO's CropWat software (Boesveld et al., 2011). Their Drip Planner Chart has some similarities (but also significant differences) with our Water Wheel and we have shared information and feedback regarding accuracy and ease of use of these tools since early 2009.

Using local climatic data

The first task for developing a simple calculator was to compile and transform local ET data. Fortunately, monthly average calculated ET values were available from 34

weather stations in Myanmar (FAO, 2005). These 30-year averages (1961–90) were exported to Excel® (Microsoft Corp., Redmond, WA) for development of the tables used in the calculators.

We first compared Myanmar weather station locations with the areas where our field staff were working at the time, the majority of whom were within one of three major physiographic regions of the country: 1) Lower Myanmar including states and divisions of the Ayeyrawaddy River delta with generally high humidity and rainfall, 2) Upper Myanmar encompassing the "Dry Zone," a region of high temperatures and low annual rainfall, and 3) higher elevations of Shan State with cooler temperatures throughout the year. On the basis of conversations with field staff, we selected from two (Shan State) to seven (Lower Myanmar) weather stations from each region, which were closest to where they were working and appeared to be most representative of the area. Monthly average ETs from these stations, within each region, were averaged to obtain an overall monthly average ET for the entire region. Only the 8 months of the dry season (October to May) were used, resulting in eight average ET values for each of the three regions. These monthly averages were in turn transformed to daily averages by dividing by the number of days of the month under consideration.

All ET data from ClimWat were converted to inches since only English units are widely understood in Myanmar. We assumed a water application efficiency of 80% recommended for drip irrigation in developing countries by Keller (2002). Daily ET values were divided by application efficiency and the resulting data used to determine water requirements as described below.

Vegetable crop growth stages and crop coefficients

Myanmar farmers are very much aware that plants require more water as they grow from seedlings to maturity and that some crops require more water than others. Using ET directly for determining water requirements would result in water wasted during earlier growth stages and underwatering

for later growth stages. For this reason, correction factors or crop coefficients (K_c) are used to adjust ET for a particular crop and its growth stage. Time-averaged K_c values have been reported for a wide range of horticultural crops and usually range from 0.4 to 1.2, depending on growth stage (Allen et al., 1998; Dittmar et al., 2015; Doorenbos and Pruitt, 1977; Grattan et al., 1998) (Table 1). Water requirements are estimated by multiplying daily ET by the crop coefficient (i.e., water requirement = $ET_o \times K_c$).

Growth stages

Since it is relatively easy to distinguish among major growth stages for most vegetable crops, we used this approach with crop coefficients rather than a canopy cover approach (used for fruit crops as discussed below). Our generic growth stages for vegetables were adapted from those published by FAO (Allen et al., 1998), Florida (Dittmar et al., 2015), and Australia (Qassim and Ashcroft, 2006). FAO and Australia use four stages, whereas Florida uses five stages for vegetable crops. We used only three or four growth stages in the Water Wheel for vegetables, depending on the crop. The fourth stage was used only for crops that benefit from a reduction in water application at harvest. Since drip irrigation was not likely to be used for emerging seedlings in Myanmar, we did not include the period from seeding to germination in our "very small plant" stage below.

Our growth stage names and descriptions were indicative of the crops' physiological state and easily recognized by local farmers and field staff. Growth stages were illustrated with tomato [*Solanum lycopersicum* (Fig. 1)] and described as follows:

1. Very small plants. Plants after emergence from direct seeding or transplants to $\approx 10\%$ of the final plant size is reached; plants cover 10% or less of the soil surface at this stage. This period lasts 2 to 3 weeks for most direct-seeded crops or until ≈ 1 to 2 weeks after transplanting. For vining crops, this stage lasts until the vines are ≈ 6 inches long.

2. Rapid growth. This is the period of the most rapid vegetative growth of the young plants. This stage includes plants that are small to medium sized before the full plant

Table 1. Single (time-averaged) initial, mid-, and late-season crop coefficients (K_c) for 25 vegetable crops in subhumid climates and their growth stage means, SD, and CV. Late-season coefficients include all 25 vegetables in the fifth column but only those without water reductions at harvest in the last column (adapted from Allen et al., 1998).

Crop	Scientific name	Initial	Midseason	Late season	
				All vegetables	No water reduction
				K _c	
Broccoli	<i>Brassica oleracea</i> var. <i>italica</i>	0.7	1.05	0.95	0.95
Brussels sprout	<i>B. oleracea</i> var. <i>gemmifera</i>	0.7	1.05	0.95	0.95
Cabbage	<i>B. oleracea</i> var. <i>capitata</i>	0.7	1.05	0.95	0.95
Carrot	<i>Daucus carota</i>	0.7	1.05	0.95	0.95
Cauliflower	<i>B. oleracea</i> var. <i>botrytis</i>	0.7	1.05	0.95	0.95
Celery	<i>Apium graveolens</i>	0.7	1.05	1	1
Garlic	<i>Allium sativum</i>	0.7	1	0.7	
Lettuce	<i>Lactuca sativa</i>	0.7	1	0.95	0.95
Onion (dry)	<i>Allium cepa</i>	0.7	1.05	0.75	
Onion (green)	<i>A. cepa</i>	0.7	1	1	1
Spinach	<i>Spinacia oleracea</i>	0.7	1	0.95	0.95
Radish	<i>Raphanus sativus</i>	0.7	0.9	0.85	
Eggplant	<i>Solanum melongena</i>	0.6	1.05	0.9	
Bell pepper	<i>Capsicum annuum</i>	0.6	1.05	0.9	0.9
Tomato	<i>Solanum lycopersicum</i>	0.6	1.15	0.8	
Muskmelon	<i>Cucumis melo</i>	0.5	0.85	0.6	
Cucumber	<i>Cucumis sativus</i>	0.6	1	0.75	
Pumpkin, winter squash	<i>Cucurbita pepo</i> , <i>Cucurbita maxima</i>	0.5	1	0.8	
Zucchini squash	<i>C. pepo</i>	0.5	0.95	0.75	
Sweet melon	<i>C. melo</i>	0.5	1.05	0.75	
Watermelon	<i>Citrullus lanatus</i>	0.4	1	0.75	
Table beet	<i>Beta vulgaris</i>	0.5	1.05	0.95	0.95
Potato	<i>Solanum tuberosum</i>	0.5	1.15	0.75	
Sweetpotato	<i>Ipomoea batatas</i>	0.5	1.15	0.65	
Green bean	<i>Phaseolus vulgaris</i>	0.5	1.05	0.9	0.9
Mean		0.61	1.03	0.85	0.95
SD		0.1	0.07	0.12	0.03
CV (%)		16.4	6.6	13.7	3.2

size is reached. It is the growth period before the first appearance of flowers for most vegetable crops or until the time of first fruit setting [melons (*Cucumis* sp., *Citrullus* sp.)]. From 10% to 70% of the soil surface is covered during this period.

3. Flowering and fruiting.

Plants are flowering and setting fruit and/or have grown to their full size. Fruit or pods are forming and enlarging. For vine crops, most of the ground is covered. This is a very critical period when yield is greatly affected by water available to the plants. This will be the longest and final stage for many crops.

4. End of season water reduction. Fruit ripening and harvest stage. This stage is used only with certain crops where product quality is improved by reducing water during crop maturity or fruit ripening. For tomato, this begins ≈ 7 to 10 d before harvests begin.

Crop coefficients

Crop coefficients for 25 vegetables used with FAO's initial, mid- and late-season growth stages are shown in Table 1. Lacking a computer or smartphone, these and similar lists are too long to include in a simple tool designed for small farmers in developing countries. Although CropWat generates multiple coefficients by linear interpolation between K_c values for each growth stage, this also results in too many data than can be used in a simple tool like the Water Wheel. CropWat in its present form is also not user friendly enough for use by most extension workers in developing countries.

FAO's "initial" growth stage (our very small plants stage above) coefficients range from 0.4 for watermelon (*Citrullus lanatus*) to 0.7 for a large group of nonfruiting crops referred to as "small vegetables"; the overall initial stage mean is 0.61

(Table 1) (Allen et al., 1998). These are relatively high coefficients for small plants and suggest they were developed for high soil surface evaporation, probably with frequent sprinkler irrigation. We chose a smaller single coefficient of 0.4 to use with drip-irrigated vegetable crops at this growth stage; smaller initial stage coefficients (0.2 to 0.4) are also recommended for unmulched vegetable crops in Florida (Dittmar et al., 2015).

Most FAO "midseason" (our flowering and fruiting) stage coefficients range from 1.00 to 1.05 with only a few significantly lower or higher: 0.85 for muskmelon (*Cucumis melo*) and 0.9 for radish (*Raphanus sativus*) on the low side and 1.15 for potato (*Solanum tuberosum*), and sweetpotato (*Ipomoea batatas*) on the high side. The mean coefficient for this entire group of crops is 1.03 with a CV of only 6.6% (Table 1). We chose a higher coefficient of 1.2, assuming

Fig. 1. Side 1 of the Water Wheel for vegetable crops for Upper Myanmar. The wheel consists of an inner stationary disc and outer rotating disc used to determine water requirements per 100 ft² (9.29 m²) based on average evapotranspiration (ET), growth stage, and crop coefficients. Colored boxes on the left side indicate crops with (A) and without (B) water reductions at harvest. The red arrow (C) is lined up with the appropriate month of the dry season to read the water requirement in gallons (D). Crops listed in box B also include betel vine (*Piper betle*), papaya (*Carica papaya*), and banana (*Musa* sp.); 1 gal/100 ft² = 0.4075 L·m⁻².

maximum canopy cover at this stage with many drip-irrigated vegetable crops grown in densely planted beds in Myanmar. Crops that grow to over 80% cover in California generally have peak K_c values between 1.0 and 1.2 (T. Trout, personal communication). We chose the higher coefficient

thinking that the risk of overwatering was preferable to underwatering for new growers unfamiliar with drip irrigation.

Allen et al. (1998) did not report average single coefficients for FAO's "crop development" stage (our rapid growth stage), but assumed a linear

relationship between the end of the initial and start of the midseason stage with K_c s ranging from 0.50 and 1.15, depending on the crop. Dittmar et al. (2015) also did not report single coefficients for this period except for vegetables grown using drip irrigation and plastic mulch, which range

from 0.4 for tomato to 0.6 for muskmelon. Amayreh and Al-Abed (2005) reported 0.65 for drip-irrigated tomato on black plastic for this stage. Other sources used a range between 0.6 and 0.8 (Qassim and Ashcroft, 2006). We chose a single coefficient of 0.8 for our rapid growth stage, erring on the high side at the beginning of this period.

We observed that differences among coefficients for some growth stages are relatively small for a large number of vegetable crops (Table 1) and that single coefficients could be used without putting farmers' crops at risk. In addition, the long list of vegetables could be subdivided into two groups based on whether their water requirement during harvest remained roughly the same as in the flowering and fruiting stage or was reduced for the harvest period. Although many vegetables have high water demands throughout harvest, it is best to reduce water for some crops to maintain high fruit or product quality. The latter group includes most fruiting vegetables like tomato, chili (*Capsicum annuum*), cucumber (*Cucumis sativus*), and melons together with root, bulb, and tuber crops like potato, sweetpotato, carrot (*Daucus carota*), radish, garlic (*Allium sativum*), and onion (*Allium cepa*) (Allen et al., 1998; Hartz, 1996).

FAO's late-season coefficients were more variable than midseason values because of the reduction in water needs during harvest for some vegetables as described above. Their overall late-season K_c mean was 0.85 with a cv of 13.7% (Table 1). However, when vegetables with late-season water reduction were excluded from this list, the mean coefficient becomes 0.95 (close to the midseason K_c of 1.03) with a cv of only 3.2% (Table 1).

On the basis of these observations, we considered it safe and reasonable to use single average crop coefficients for two large groups of vegetables: 1) those that received equal amounts of water during mid and late season, and 2) those for which water applications should be reduced during harvest. Erring on the side of overwatering, we used a higher coefficient for our flowering and fruiting stage; this same coefficient was used until the end of harvest for the group of vegetables without any end-of-season water

reduction. We used the average coefficients listed in Table 2 in the vegetable crops Water Wheel.

Fruit crop canopy cover estimates

The crop coefficient is dependent on crop growth, height, and architecture (Allen et al., 1998) and highly correlated with leaf area index and light interception/canopy shading by the crop (Williams and Ayars, 2005; Williams et al., 2003). Lysimeter studies have demonstrated that crop coefficients for grapevines (*Vitis* sp.) and fruit trees are closely related to midday light interception and canopy cover (Johnson et al., 2000; Williams and Ayars, 2005).

Using estimates of canopy cover is an altogether different approach to determine water requirements in place of growth stages and crop coefficients (Allen and Pereira, 2009; Grattan et al., 1998; Hartz, 1996; Trout and Gartung, 2006). This method relies on a visual estimate of the percentage of the ground shaded by crop foliage or canopy; i.e., the portion of the ground shaded with the sun directly overhead (Fig. 2A and B). We chose this approach to determine water requirements for perennial fruit, tree, and vine crops, thinking that farmers might find this method easier than crop coefficients and growth stages which can be difficult to differentiate for perennial crops.

To estimate canopy cover, extension workers or farmers make a visual estimate of the fraction or percentage of the field shaded from the sun at midday. This fraction then is multiplied by the average ET to determine the daily water requirement. Figure 2A is an illustration of canopy cover in plantings where canopies do not merge. Canopy cover can also be estimated by direct measurement for crops in which the foliage touches or merges within the rows by dividing the average width of foliage cover within a row (measure a few

representative plants) by the width between bed or row centers (Hartz, 1996; T. Trout, personal communication) (Fig. 2B).

Using the same averaged and efficiency-corrected ET dataset developed for vegetable crops, we constructed new tables using percent canopy cover as correction factors rather than growth stage-based crop coefficients. For the sake of simplicity, only four broad and nonoverlapping canopy cover ranges were used: 5% to 10%, 20% to 30%, 40% to 50%, and 60% to 100%. Since we wished to make liberal estimates of water requirements for first-time drip users, the upper limit of the range was used as the actual correction factor with the appropriate ET value. For example, 0.1 is multiplied by daily average ET for crop canopies within the 5% to 10% range, 0.3 for canopies in the 20% to 30% range, and so on (Table 3). Other researchers have suggested that canopy cover be estimated liberally since peak water demand may slightly exceed ET (Hartz, 1996); most agree that full ET (i.e., $K_c = 1$) can be assumed at 60% to 70% canopy cover (Smajstrla et al., 1997). We used a liberal correction factor of 1.2 for full cover within the 60% to 100% range.

Like the growth stage/crop coefficient method, this approach also has its gaps and simplifications with only four correction factors; however, we expected that growers would extrapolate within and among these ranges. For example, if a grower estimates canopy cover to be only 2% to 3%, she may decide to use an amount of water lower than the amount recommended for the 5% to 10% range. Similarly, if a grower estimates canopy cover to be 15%, he may decide on a water requirement between that indicated for the 5% to 10% range and the 20% to 30% range. Canopy cover ranges and correction factors

Table 2. Vegetable crop developmental stages used in the Water Wheel and corresponding stages used by FAO together with crop coefficients (K_c) used in the vegetable crops Water Wheel.

Water Wheel stage	FAO stage	Water Wheel K_c
1. Very small plants	Initial	0.4
2. Rapid growth	Crop-development	0.8
3. Flowering and fruiting	Midseason	1.2
4. End-of-season water reduction	Late season	0.8

FAO = Food and Agriculture Organization of the United Nations.

Fig. 2. Percentage of canopy cover for fruit crops can be estimated by visualizing the portion of the field that would be shaded at midday: (A) 20% cover for crops with canopies that do not merge; (B) percentage of canopy cover can be estimated by dividing the average canopy width by the row-to-row spacing in crops like grape where plants' foliage merges in the rows.

Table 3. Canopy cover ranges and correction factors used in the fruit crops Water Wheel.

Canopy cover range (%)	Correction factor
5–10	0.1
20–30	0.3
40–50	0.5
60–100	1.2

used in the fruit crops Water Wheel are listed in Table 3.

Construction and use

VEGETABLE CROPS WATER WHEEL. Crops were separated into two groups based on whether they benefited from reductions in water

applications during the harvest period. Crops with water reductions were listed in the yellow (upper) box with all others in the green (lower) box (Fig. 1A and B, respectively). Daily water requirements were expressed as gallons per 100 ft²; these numbers were the result from the appropriate average daily ET multiplied by its crop coefficient for a given growth stage. These numbers are the same for stages 3 and 4 for the green group, whereas stage 4 values are lower than stage 3 for the yellow group. The data table was reconstructed in circular form to make the inner stationary disc used on Side 1 of the Water Wheel. Separate Water Wheels were constructed and printed

for each of the three regions where we were working.

To estimate the daily water requirement, users first determine in which group the crop belongs and select the appropriate green or yellow half of the wheel's perimeter on Side 1 (Fig. 1). Users then point the red arrow at the top of the outer, rotating disc (Fig. 1C) to the appropriate month of the dry season on the perimeter of the inner disc. The water requirement in gallons per 100 ft² is read from within the cutout window opposite the appropriate growth stage (Fig. 1D).

After determining the water requirement in gallons per 100 ft², users then turn the disc over to Side 2 (Fig. 3) and point the red arrow at the top of the rotating outer disc (Fig. 3A) to the field size to be irrigated shown in square feet along the inner disc's perimeter (Fig. 3B). The result obtained from Side 1 (in gallons per 100 ft²) is then located within the column of red numbers to the left of the cutout window (Fig. 3C). The total water requirement in gallons per plot per day appears inside the window adjacent this number (Fig. 3D). The data table used for Side 2 was constructed using simple spreadsheet calculations and arranged in circular form (Fig. 4). Instructions for using the calculator were printed on sides 1 and 2 (Figs. 1 and 3). Fortunately, the Water Wheels are much easier to use than to explain.

FRUIT CROPS WATER WHEEL. Similar procedures were used to determine water requirements using the fruit crops Water Wheel; however, instead of separate wheels for each region, all three regions were combined on a single disc (Fig. 5). Color-coded sections at the top of the stationary inner disc represent the three regions in Myanmar where Proximity Designs was working. Each of these sections was subdivided into 8 months of the dry season. The result visible in the cutout on Side 1 is expressed as gallons per 100 ft² (Fig. 5A). To find the water requirement for a given field size, this number from Side 1 is located in one of the two columns adjacent to the cutout on Side 2 (Fig. 6A) and the water requirement per plot is read from within the cutout (Fig. 6B). Note that the numbers in these two columns are in descending order from

Fig. 3. Side 2 of the Water Wheel for vegetable crops for Upper Myanmar. The wheel consists of an inner stationary disc and outer rotating disc used to convert water requirements per 100 ft² to water requirements per plot. The red arrow (A) is aligned with the appropriate field size (B); the water requirement per 100 ft² from Side 1 is located in the column of red numbers (C) and the water requirement per plot is read in the cutout window (D); 1 ft² = 0.0929 m², 1 acre = 0.4047 ha, 1 gal/100 ft² = 0.4075 L·m⁻².

top to bottom; this was done so the larger water requirement numbers could be physically accommodated within wider spaces at the top of the cutout.

Instead of descriptions of growth stages, instructions and examples of percent canopy cover are illustrated on the outer rotating discs on both

sides of the fruit crops wheel (Figs. 5 and 6). Our extension staff was given a longer, more detailed publication that included good illustrations of canopy cover and discussions of water requirements for specific fruit crops (Rowell and Soe, 2010). This publication also included illustrations and simple instructions for determining

water requirements for crops like grape where canopies merge as in Fig. 2B.

An experienced technician at a local print shop developed the circular tables (Fig. 4) and disc layouts using Photoshop® (Adobe Systems, San Jose, CA) and our data tables. A few Burmese language prototypes printed

Fig. 4. Circular table of water requirements (gallons per plot) used as the stationary disc on Side 2 of the Water Wheel for vegetable crops for Myanmar; 1 ft² = 0.0929 m², 1 acre = 0.4047 ha, 1 gal = 3.785 L.

on ordinary paper were assembled and tested for ease of use among our field staff during an annual in-service training program; minor changes were made to the layout after these tests. All three regional versions of the vegetable crop discs and the fruit crop discs were printed in color on 8-inch diameter, 0.012-inch-thick card stock laminated for increased durability. In addition to printing, the shop arranged to make the tools required

to cut out the discs and rivet them together. Total costs for designing, printing, and assembling were \$1.00 per wheel.

English versions of the Water Wheels were never printed in quantity and are not commercially available. Water Wheel concepts and designs are not copyrighted or protected in any way so they can be used freely with local ET data in other countries. It is hoped that some of the concepts and

simplifications discussed here might be further developed into easy-to-use, farmer-friendly smartphone applications for determining horticultural crop water requirements.

Results and discussion

USER SATISFACTION. A Water Wheel user satisfaction survey was conducted in 2011 by Proximity Designs' impact team among 54 extension workers (from 54 townships)

Fig. 5. Side 1 of the Water Wheel for fruit crops for three regions in Myanmar. The wheel consists of an inner stationary disc and outer rotating disc used to determine evapotranspiration-based water requirements per 100 ft² (9.29 m²) corrected for percent canopy cover. Examples of 10% and 20% canopy cover are also illustrated. Water requirement is read in the cutout window (A); 1 gal/100 ft² = 0.4075 L·m⁻².

from all three regions. Staff reported on their experiences using Water Wheels that year in advising a total of 456 farmers with 763 new drip system installations. In answer to the question "How many farmers that you advised actually followed the Water Wheel recommendations?", 74% answered "almost all" or "almost all with adjustments according to

their experience." Eleven respondents or 20% reported that about half of the farmers they worked with followed recommendations, whereas only three (6%) reported that less than half of the farmers they worked with used Water Wheel recommendations.

When the same extension workers were asked if they thought Water Wheel recommendations were accurate, 91%

felt the recommended amounts were correct, whereas 5% and 4% thought the recommended amounts were excessive or insufficient, respectively. Lastly, when asked if the Water Wheels were helpful and useful for their work and program, 87% reported "very helpful and useful," whereas 13% reported "somewhat helpful and useful." None of the 54 responded

Fig. 6. Side 2 of the Water Wheel for fruit crops for three regions in Myanmar. The wheel consists of an inner stationary disc and outer rotating disc used to convert water requirements per 100 ft² to water requirements per plot. Examples of 40% and 60% canopy cover are also illustrated. The red arrow at the top of the cutout window is aligned with the appropriate field size; the water requirement per 100 ft² from Side 1 is located in one of the two columns of red numbers (A), and the water requirement per plot is read in one of the two columns in the cutout window (B); 1 ft² = 0.0929 m², 1 acre = 0.4047 ha, 1 gal/100 ft² = 0.4075 L·m⁻².

with the third choice, which was "not helpful or useful."

PRECISION VERSUS SIMPLICITY AND EASE OF USE. Although our Water Wheels have not been tested for accuracy against more precise water requirements generated by CropWat, we believe they provided reasonably

reliable recommendations for new drip irrigation users in Myanmar. The tool was welcomed by our field staff and gave them extra confidence in answering new drip users' first question: "How much water?" Fortunately, most of these farmers were also using Proximity Designs' 200-gal

collapsible "Water Basket" as a header tank (Fig. 7) which at a height of only 3 ft (equivalent to 1.3 psi water pressure) could irrigate a commercial vegetable plot of up to 0.25 acre (Rowell and Soe, 2015). Growers needed only know how many tanks were used per day to monitor the

Fig. 7. Proximity Designs' (Yangon, Myanmar) 200-gal (757.1 L) collapsible Water Basket and elevated treadle pump used for drip irrigating up to 0.25 acre (0.101 ha) of commercial vegetables in Myanmar in 2012.

amount of water being applied with drip.

The use of growth stages or selected ranges of canopy cover is of necessity an oversimplification of plant growth and therefore plant water requirements. Growth is more or less continuous, especially during the development or rapid growth stages when water demands are closely associated with the rapidly increasing total leaf surface area. Our simplifications undoubtedly resulted in some over- and under-watering, especially if they were followed too literally.

We justified using single crop coefficients for a large number of vegetables after observing only small differences among published coefficients for these crops and after reducing these differences by separating crops into two groups based on their water requirements at harvest. Other losses of precision occurred when fractional water requirements were rounded to whole numbers in the Water Wheel tables and when these were extrapolated for larger field sizes.

Sources of error also included the averaging of ET data as any given day or year can vary considerably from the average and ET at a given location is affected by local microclimate, groundcover, etc. The Water Wheel

also did not take into account the chance of dry-season rainfall or differing soil types. However, here again, for the sake of simplicity, we relied on the good judgment and experience of farmers to make adjustments for these variables. The bottom line is that a rough estimate of crop water requirements reached a large number of new drip irrigation users in a form that they could easily understand, thereby increasing their comfort level and lowering adoption barriers for a totally unfamiliar technology.

Most farmers in both developed and less developed countries know better than to blindly follow the recommendations of technical “experts.” Experienced farmers have a keen sense of the water needs of their crops regardless of their level of education and will adjust applications up or down until they are satisfied that the crop’s needs are being met. It is this faith in the ability of farmers to make their own adjustments that gave us confidence to simplify ET-based water requirements in the form of the Water Wheel calculators. With simplification, it is hoped that good information becomes more accessible to field workers and farmers with very limited or no technical background. We

believe that approximate recommendations are better than no recommendations at all.

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