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Water Use and Water Footprint in Container-grown Nursery and Greenhouse Crops

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Most freshwater use around the world occurs in agriculture. Approximately 80 percent of consumptive water use in the United States is for agriculture; however, if states are looked at individually, agricultural use accounts for 90 percent of all consumptive use for many Western states. Obviously, the production system determines the water consumption associated with a final consumer product. Regional markets and international trade in water-intensive goods (including agricultural products) means that areas with abundant water likely will transfer that water use to areas with less abundant water supply. Understanding the hidden water use behind products can assist in the understanding and management of worldwide freshwater resources. Also, knowing a product's real water cost can influence consumer attitudes in the market.

The objective of this publication is to define the analytical terms that characterize water management and present case studies to illustrate those terms. The comparison of water use and water footprint among specialty crop growers is not only affected by the production system (including species and management strategies) but by geography and season. This circular builds upon published models of representative plant production systems. These models include container production using recycled water in the Mid-Atlantic, Ohio Valley, southwest, and Pacific northwest regions of the United States and greenhouse production implementing rainfall capture and overhead and ebb/flood irrigation strategies in the southeast.

First, it is important in understanding and comparing water use in various systems that the terms describing various aspects of water terminology are understood. **Irrigation water applied** (IWA) is a term defining the volume of water applied through irrigation during crop production (Figure 1).

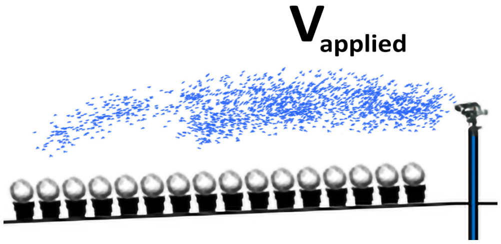

Figure 1. Illustration of irrigation water applied (IWA) as the volume (V) of water applied for irrigation.

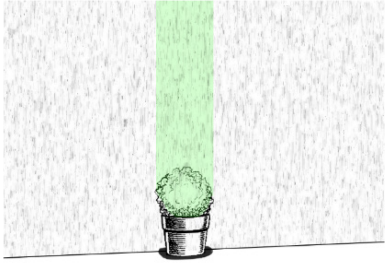

Figure 2. Illustration of green water concept: Green water is the water used directly during rainfall events. It can be measured by calculating the reduction in irrigation during and after rainfall events.

Green water refers to the volume of water used during production provided directly by rainfall (Figure 2). **Blue water** refers to the volume of water added to the system from streams, municipal sources, and underground stores as well as captured rainfall runoff. In the context of water footprint assessment, **grey water** is a measure of contaminants in water leaving the system expressed as the volume of water required to dilute any discharges to acceptable quality standards (Figure 3).

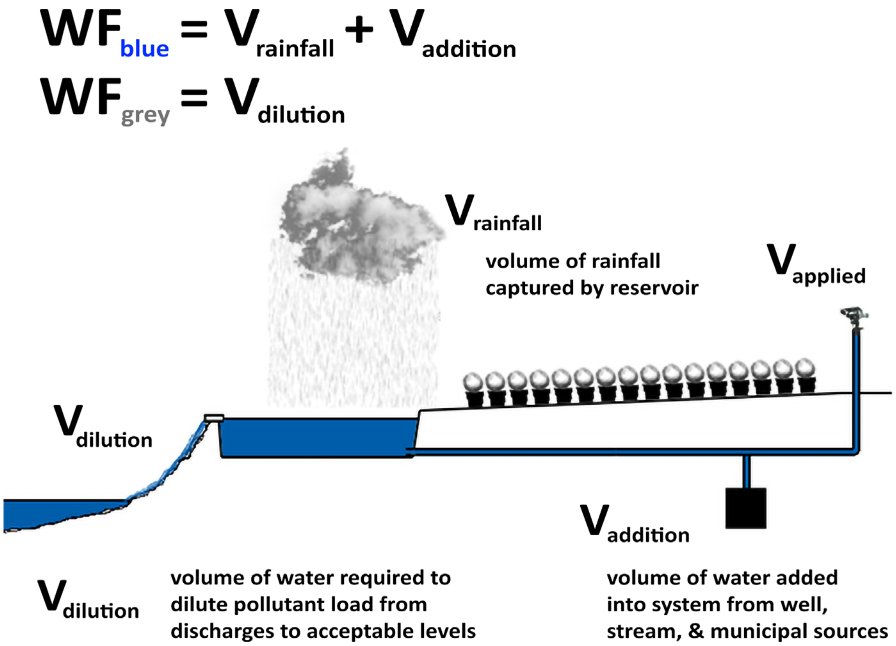

Figure 3. Illustration of blue water and grey water concepts in model nursery capturing rainfall and irrigation.

Total **consumptive water use** (CWU) is the volume of green, blue and grey water that has been used during plant production. Irrigation water applied does not take water recycling into account whereas CWU does. **Water footprint** (WF) is the volume of CWU multiplied by the corresponding watershed's scarcity index (in the month the water was used), as calculated by the **available water remaining** (AWARE) method. While water footprint may be considered a more scientific term with little impact on water management decisions by nursery and greenhouse growers, it is the international language that allows comparisons and marketing of products. The market might someday require the inclusion of WF information on product labels. As the consumer becomes more educated to what it is, they will ask those questions about nursery and floriculture products.

Components of Water Footprint

Consistent with the concept of WF, all components of a total WF are specified for location and time of year. WF is the total volumetric CWU required to produce a product weighted by location and time. This weighting process is characterized by the water scarcity indices for each month of water use in the watershed (Table 1). For the purposes of this publication, the authors are using the AWARE method, which assigns a number from 0.001 to 100 to every watershed on earth relative to global water scarcity.

A watershed with a water scarcity index of 1 under the AWARE method would represent the global average of water scarcity. A watershed with an index of 0.1 would have an abundance 10 times the global average. A watershed with an index of 10 would represent water being 10 times more scarce than the global average. WF is the sum of the four components: embodied water, green water, blue water, and grey water (Equation 1).

Equation 1.

$$WF_{Total} = WF_{Embodied} + WF_{Green} + WF_{Blue} + WF_{Grey}$$

Equation 2.

$$\text{Grey Water Volume} = \frac{\text{(Volume of Discharge) x (Desired Pollutant Load)}}{\text{(Recorded Pollutant Load)}}$$

$WF_{Embodied}$, sometimes referred to as "virtual water," is the weighted volume of water used to produce and deliver any components of production including pesticides, containers, herbicides, etc. WF_{Green} is the *unweighted* volume of water used, as direct precipitation, required to produce a product. This can be understood more easily as WF_{Green} is the volume of water that does *not* have to be supplied by irrigation. WF_{Blue} is the weighted volume of water used from ground, surface, and/or any municipal sources. Rainfall captured in a pond or artificial catchment contributes to WF_{Blue} because that water is not available for other uses. WF_{Blue} is first determined by calculating the total captured rainfall and added water in a production system each month for the length of production, then divided by the total number of plants. This yields an unweighted volume of consumptive blue water use. When this volume is weighted to reflect the scarcity of water based on local, specific conditions it results in WF_{Blue}. WF_{Grey} is the weighted volume of water required to dilute any discharges from the operation to meet local, regional, or national water quality standards. For example, there are discharge water standards for such water contaminants as nitrate-nitrogen (10 ppm) and phosphorus (10 to 40 ppb). See Equation 2.

In closed systems, such as greenhouses that do not discharge water or container nursery operations that collect all the runoff from the production area, there is no WF_{Grey}. However, growers must know what is in the water that is being recycled and reapplied as irrigation. WF_{Green} for covered greenhouse operations would be zero.

Captured Rainfall Runoff

Monthly rainfall amounts and intensities for these models were based on 30-year averages from 1981 to 2010 from the National Oceanic and Atmospheric Administration Climate Data Center. These data along with elevation data from Geographic Information System databases were used to define catchment areas for collecting irrigation and rainfall runoff.

Satellite imagery of the nursery surface was used to find infrastructure affecting water flow: reservoirs, impervious surfaces, and un-engineered areas. Un-engineered surfaces can be fields, woodlots, and generally refers to areas that have not been altered by structures, earthworks, drain tiles, gravel, and/or paving (Figures 4 and 5). These groups were further subdivided and assigned a runoff value based on what percentage of water would runoff and be captured by the reservoir after the first 0.5 inch of rainfall for engineered surfaces and 1 inch for un-engineered surfaces in a given 24-hour period.

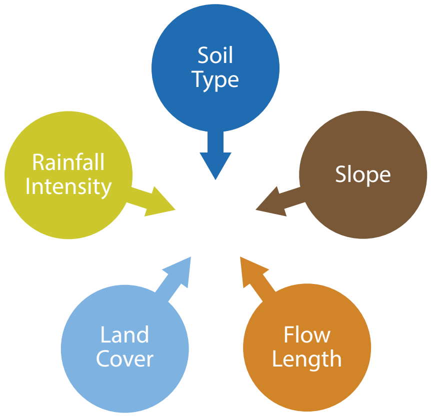

Figure 4. Factors influencing rainfall capture.

Table 1. Watershed water scarcity index by month.

Case Study	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Watershed
Mid-Atlantic	0.50	0.40	0.30	0.40	0.60	0.90	1.20	1.20	1.10	1.10	0.90	0.60	James River
Pacific Northwest	0.80	0.70	0.60	0.50	0.60	0.70	1.30	2.80	2.60	1.60	0.90	0.80	Columbia River
Southeast	1.20	1.30	1.10	1.20	1.40	1.30	1.30	1.20	1.20	1.20	1.30	1.20	St. Johns River
Southwest	1.00	0.60	0.80	1.50	2.00	2.10	2.90	10.4	7.90	4.80	3.40	2.80	Salinas
Ohio River Valley	0.40	0.40	0.30	0.40	0.50	0.70	0.90	1.20	1.30	1.20	0.90	0.50	Ohio River Valley

A water budget incorporating total water capacity and expected losses from the reservoir due to evaporation and infiltration was developed to estimate the potential for captured water during rainfall events. Water that is not captured by the catchment area but continues to flow downstream does not count towards WF$_{Blue}$.

Water Stress in Kentucky by Month

Water footprint reflects the volume of water consumed *and* the relative scarcity of the water being used, making it a measurement of impact. Scarcity is driven by overall availability and demand within a given watershed, both of which can change throughout the year. Whether it is due to demand or supply, a gallon of water consumed in spring has a different impact than a gallon of water consumed in fall. The World Resources Institute's Aqueduct project has modeled current seasonal water scarcity around the globe using total water availability and demand data from 1950-2010 to reduce the effect of multi-year climate cycles. Using these data, maps of Kentucky were generated to highlight the differences in water scarcity between spring (Figure 6) and fall (Figure 7).

Land Cover
- Reservoir Area 🟦
- Engineered Area 🟥
  - Nursery Pads
  - Gravel
  - Concrete
  - Plastic
  - Roof
- Permeable Area (Unengineered)
  - Wooded 🟩
  - Brush/Grass/Meadow 🟨

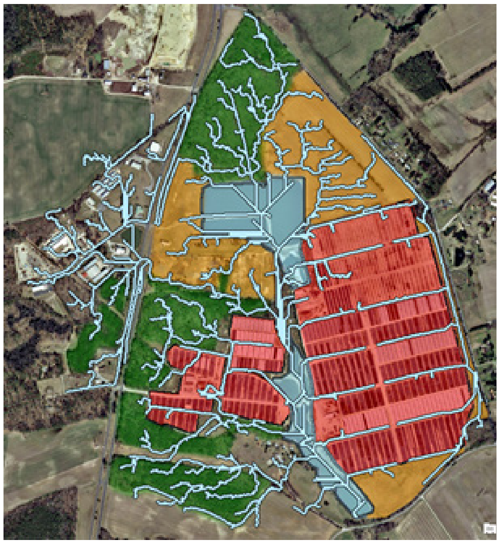

Figure 5. Satellite imagery of a mid-Atlantic nursery with surface and runoff analysis overlay.

Baseline Water Stress
- 🟥 Extremely High (>80%)
- 🟥 High (40-80%)
- 🟧 Medium-High (20-40%)
- 🟨 Low-Medium (10-20%)
- 🟨 Low (<10%)

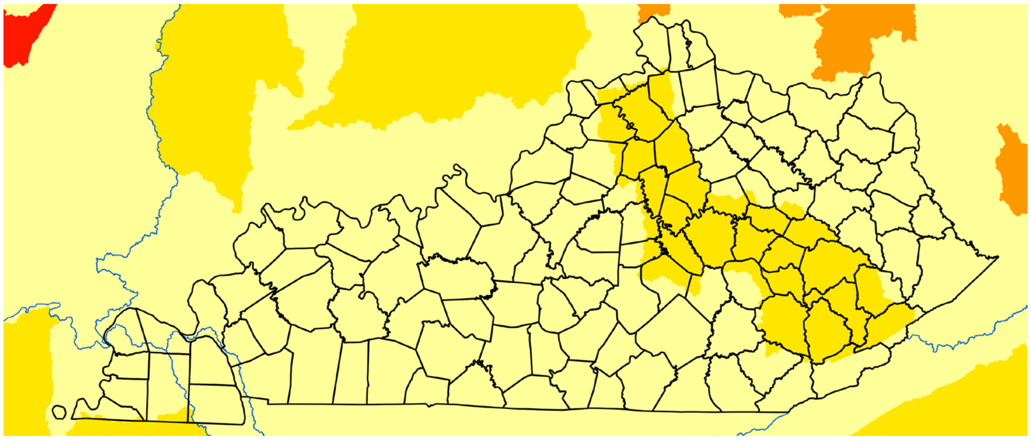

Figure 6. Projected water scarcity of Kentucky using baseline water stress (March). Baseline water stress measures total annual water withdrawals (municipal, industrial, and agricultural) expressed as a percent of the total annual available flow. Source: World Resources Institute Aqueduct project, 2019.

Baseline Water Stress
- 🟥 Extremely High (>80%)
- 🟥 High (40-80%)
- 🟧 Medium-High (20-40%)
- 🟨 Low-Medium (10-20%)
- 🟨 Low (<10%)

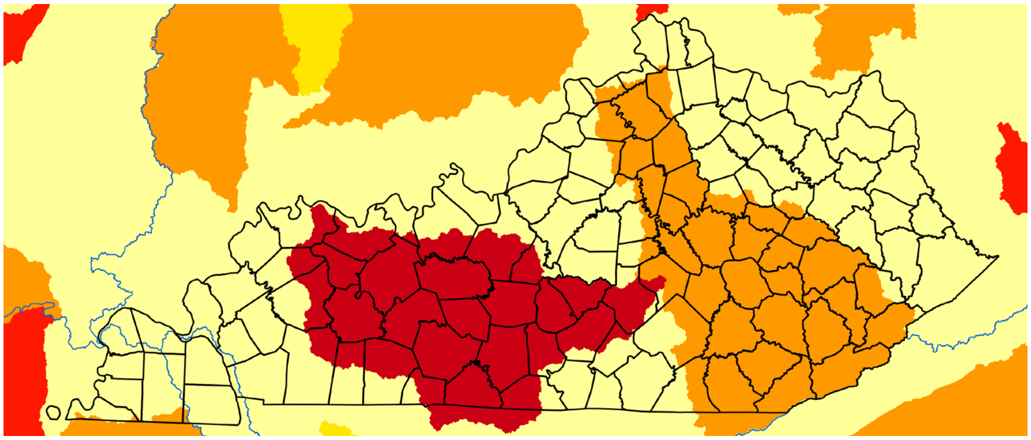

Figure 7. Projected water scarcity of Kentucky using baseline water stress (October). Baseline water stress measures total annual water withdrawals (municipal, industrial, and agricultural) expressed as a percent of the total annual available flow. Source: World Resources Institute Aqueduct project, 2019.

Comparison of Case Studies to Illustrate Water Use Terminology

To better understand the important aspects of water use, production system models were developed for: A) container production of a #3 (3.0 gal.) japanese holly (*Ilex crenata)* in the Mid-Atlantic U.S. with irrigation from surface water, B) container production of a #3 (3.0 gal.) japanese holly (*Ilex crenata)* in the Ohio Valley with irrigation from surface water, C) container production of a #3 japanese boxwood (*Buxus microphylla*) in the Pacific northwest U.S. with irrigation from surface water, D) greenhouse production of a 72-cell tray annual foliage using overhead irrigation sourced from well water in Central Florida, and E) greenhouse production of a 72-cell tray annual foliage using ebb and flood sourced from rainfall capture in Central Florida (Table 2).

These production system models were based on best management practices for their location and interviews conducted with nursery and greenhouse managers in the region to validate the cultural practices in the production system. Information was extracted from these published models listed in the additional resources, available geophysical water data, Geographical Information System spatial watershed analyses, and the latest 30-year climate normals from nearby monitoring stations for rainfall and rainfall intensity.

Outdoor Woody Plant Production Models

The case studies for outdoor production of woody plants in #3 containers were compared just for the #3 container production phase. It was assumed that 0.75 inches were applied each irrigation. Although plants can be grown with less water per irrigation, this amount of water is often applied due to a portion of the applied overhead irrigation being deflecting by the plant. Plants were grown on beds covered with either ground-cloth fabric or gravel. In all cases, runoff water was captured, treated and reused for irrigation. Information on treatment of captured irrigation water can be found at https://www.cleanwater3.org/. Regarding treatment technologies and the CleanWateR3 project, it is important to understand the three R's: Reduce, Recycle, and Remediate. "Reduce" refers to technology and practices which minimize the use of water in a greenhouse or nursery. "Recycle" refers to technology and practices which allow a greenhouse or nursery manager to re-use captured irrigation water, which contains nutrients but often needs to be treated for plant diseases and herbicides. "Remediate" refers to technology and practices which treat water to make it suitable for discharge back into the environment by removing herbicides, insecticides, plant growth regulators, and nutrients.

The length of time for the #3 phase differed between models on the Eastern and Western United States. The CWU in the #3 phase of japanese holly in the Mid-Atlantic and Ohio River Valley were 229 gallons and 106 gallons, respectively. CWU in the #3 phase in the Pacific Northwest was 108 gallons. The modeled production systems between the Eastern and Western United States allowed for a six-month shorter production cycle in the #3 phase for the Pacific Northwest.

CWU weighted by relative scarcity, gave a WF_{Blue} of 180 gal for the Mid-Atlantic model of #3 japanese holly and 75 gal for the Ohio Valley model. The #3 japanese boxwood produced on the Pacific Northwest yielded a WF_{Blue} of 140 gal (Table 3 and Figure 8).

Not taking scarcity into account, the production systems in the Mid-Atlantic region used 2.6 times more water than the production system of the Pacific Northwest production. Unweighted blue-water use represents the largest factor in the difference between the consumptive water use of each system, with blue water volume of #3 japanese holly on the Mid-Atlantic model using significantly more in the #3 japanese boxwood on the Pacific Northwest. However, it should be noted that the model systems assumed more efficient irrigation management in the Pacific Northwest model. Irrigation management alone can decrease the WF of container-grown plants.

Table 2. List of production systems modeled.

Letter	Plant	Location	Unit of Production	Irrigation Type
A	Japanese holly	Mid-Atlantic	#3 container	Overhead and recycled
B	Japanese holly	Ohio River Valley	#3 container	Overhead and recycled
C	Japanese boxwood	Pacific Northwest	#3 container	Overhead and recycled
D	Annual foliage	Central Florida	72-cell tray	Overhead
E	Annual foliage	Central Florida	72-cell tray	Ebb and flood and recycled

Table 3. Showing all modeled case studies calculating based on requirements for the entire #3 phase of production.

Case Study Attributes	Mid-Atlantic	Pacific Northwest	Ohio River Valley
Duration of #3 phase (months)	24	18	24
Irrigation water applied (gallons)	500	269	332
Consumptive water use (gallons)	229	108	106
Blue water footprint (gallons)	180	140	75

Weighting the differences by multiplying the CWU by the water scarcity indices calculated using the AWARE method according to geographic and temporal scarcity to generate WF_{Blue} for each production system brings the comparison closer in value. The water-rich #3 japanese holly production in Mid-Atlantic model having a WF_{Blue} 140 percent greater than the Ohio Valley model and 29 percent higher than the Pacific Northwest model.

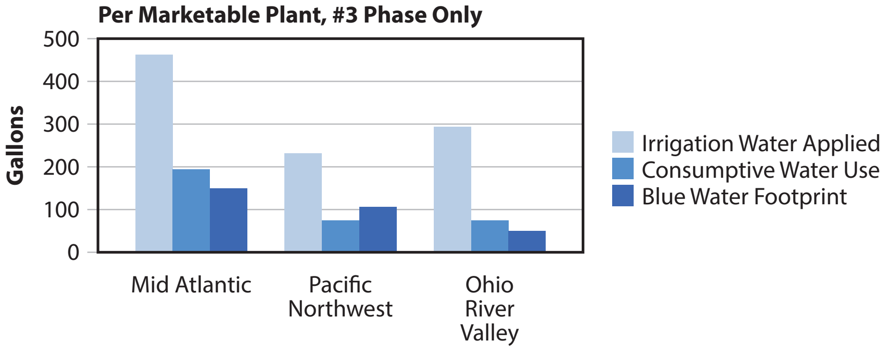

Figure 8. Comparison of case studies modeling water use and needs during the entire #3 phase of production.

Greenhouse Young Foliage Plant Production Comparisons

As both greenhouse production systems are closed, there is no green or grey water volume. The determination of water use was made for an eight-week production system for a 72-count flat of young plants. The older greenhouse with overhead irrigation used 131 gal of blue water per tray while the newer greenhouse with flood tables used 68 gal or 48 percent less (Table 4). When weighting for scarcity, the WF_{Blue} for the older greenhouse and new greenhouse were 48.4 gal and 38.0 gal, respectively.

Further analysis of the contribution revealed differences in water use by phase of production. The old and new greenhouses used 6.8 gal and 6.4 gal, respectively, of blue water for the four weeks of misting. Aside from this similarity, the production systems diverged during other phases and overall water use (Figures 9 and 10). The older greenhouse's eight-week overhead irrigation phase used 17.0 gal per tray while the newer greenhouse's eight-week ebb and flood system used 5.7 gal per tray, making this phase of production 204 percent more efficient with CWU. However, the fan and pad evaporative cooling system for the new greenhouse used 18.5 gal while the older greenhouse used 15.2 gal per tray. This difference is likely caused by the increased reliance on evaporative cooling for temperature reduction in the newer greenhouse and does not offset the water savings from increased greenhouse space efficiency and water recycling capacity of the ebb and flood system.

Table 4. Consumptive water use and water footprint by phase and use in two greenhouses located in the Southeastern United States.

Old Greenhouse	**CWU**	**WF**
Average blue water volume, 4 weeks misting	6.777	8.4144
Average blue water volume, 8 weeks overhead irrigation	17.047	21.1669
Average blue water volume, 12 weeks evaporative cooling	15.165	18.8305
Total	38.989	48.412
New Greenhouse	**CWU**	**WF**
Average blue water volume, 4 weeks misting	6.411	7.960
Average blue water volume, 8 weeks ebb and flood	5.719	7.102
Average blue water volume, 12 weeks evaporative cooling	18.519	22.994
Total	30.649	38.055

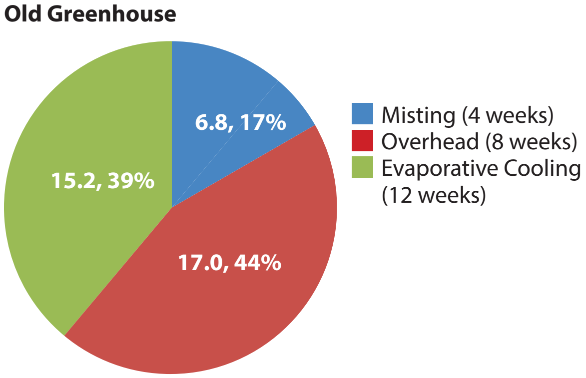

Figure 9. Pie chart showing consumptive water use by production phase or for cooling. All units in gallons.

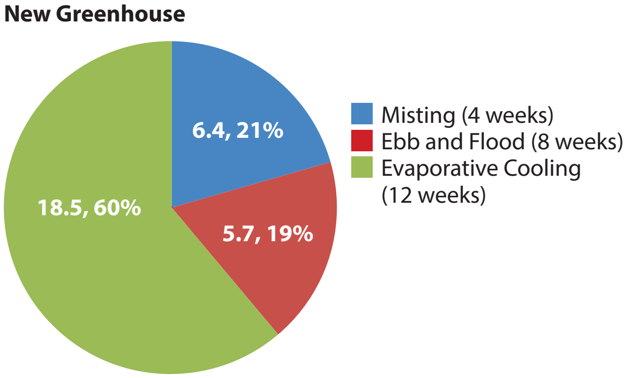

Figure 10. Pie chart showing consumptive water use by production phase or for cooling. All units in gallons.

Water Management and Performance Comparison of Case Studies

In order to compare production systems of a range of sizes and plant species in vastly different climates, their water use was compared on a acre-inches/acre basis instead of looking at individual plants as above. Irrigation water applied was 210 acre-inches/acre for the Mid-Atlantic case (among the container nurseries and overall), confirming its characterization as an abundant water user. All others were much lower, with 89 acre-inches/acre for the Southwest, 84 acre-inches/acre for the Pacific Northwest, 139 acre-inches/acre for the Ohio Valley model, 131 acre-inches/acre for the old greenhouse in the Southeast, and 109 acre-inches/acre for the new greenhouse in the Southeast.

Across all case studies, the highest blue CWU was found in the older greenhouse production system of the southeastern United States, with a total annual CWU of 131 acre-inches/acre of irrigated space. This is logical, because greenhouse environments are engaged in intensive production year-round, with this older greenhouse irrigating directly from a blue water source without recycling. The distinction between blue CWU and blue WF between the two greenhouse systems become clearer when volumes are compared on a monthly basis. The CWU in the older greenhouse would be consistent throughout the year if water use by the evaporative cooling system was excluded. Evaporative cooling accounted for 36.8 acre-inches/acre in the old greenhouse. The updated greenhouse in the same location, relying on captured rainfall runoff and using an ebb and flood recycling system reduces this total annual CWU to 68 acre-inches per acre of irrigated space with 23 acre-inches/acre of that total being used evaporative cooling.

Green CWU was above zero in only two case studies (meaning rainfall allowed for decreased irrigation events): Mid-Atlantic and Pacific Northwest where it amounted

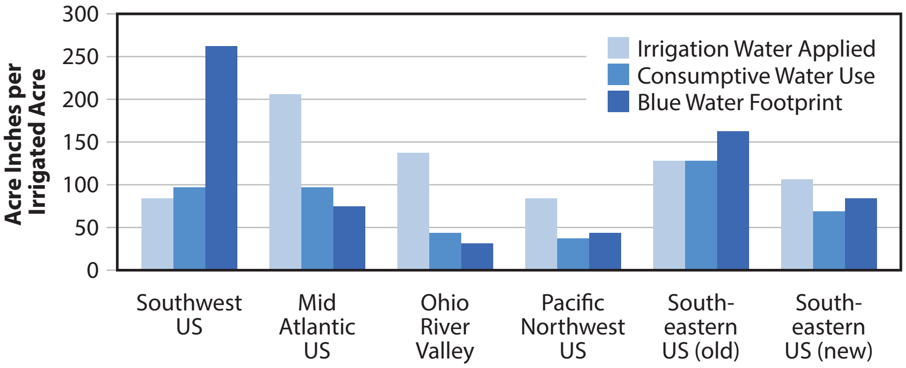

Figure 11. All case studies, calculated on a per year basis.

Table 5. All case studies. Units in acre-inches per acre of irrigated space per year.

Case Study	**Irrigation water applied**	**Consumptive water use**	**Blue water footprint**
Southwest	89	99	266
Mid-Atlantic	210	96	76
Ohio Valley	139	44	32
Pacific Northwest	84	37	46
Southeast (new)	109	68	85
Southeast (old)	131	131	163

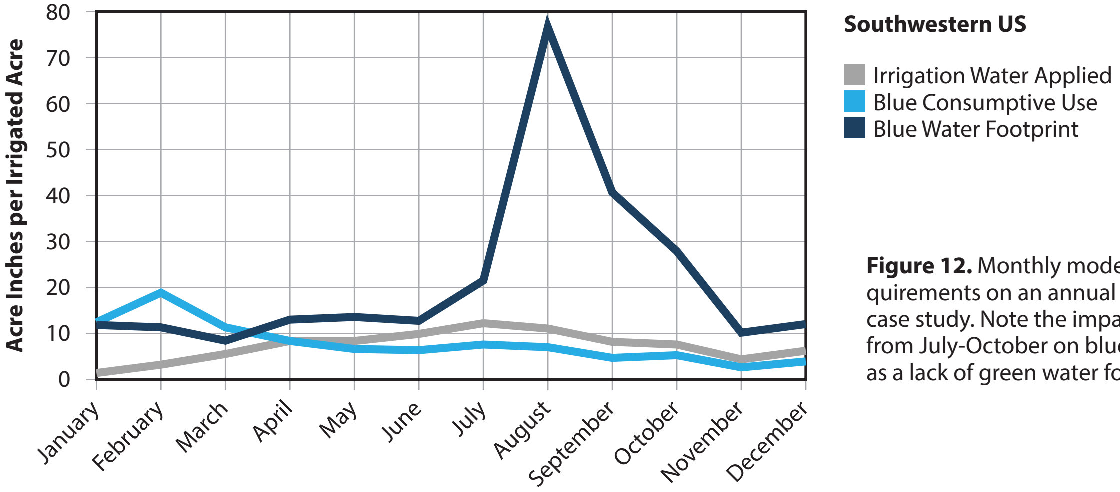

Figure 12. Monthly modeled water use and requirements on an annual basis in the Southwestern case study. Note the impact of extreme scarcity from July-October on blue water footprint as well as a lack of green water footprint.

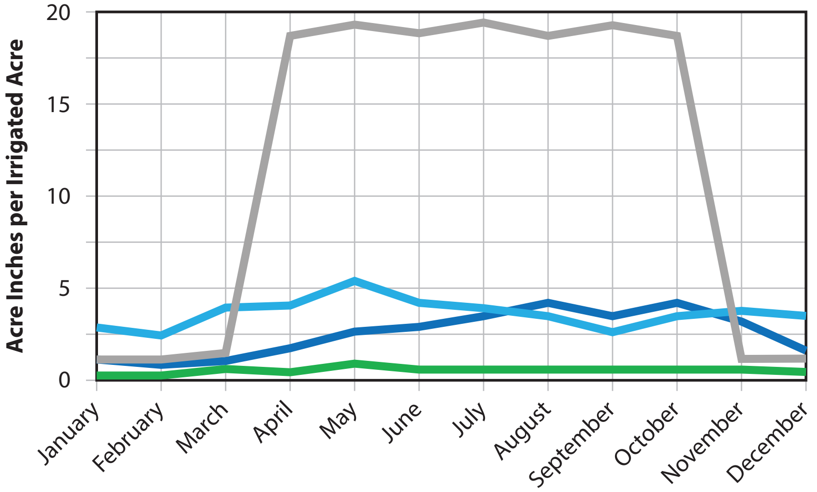

Figure 13. Monthly modeled water use and requirements on an annual basis in the Ohio River Valley case study, where water is relatively abundant year round.

to 8.9 and 4.6 acre-inches/acre, respectively.

The Pacific Northwest production system was the most efficient consumer of blue water across the case studies, using only 37 acre-inches/acre of irrigated space in a year, while the southwest and Mid-Atlantic locations used 99 and 96 acre-inches/acre, respectively (Table 5). When these CWU volumes are weighted according to the monthly water scarcity indices for each month the water was consumed to calculate an annual WF_{Blue} for each case study, the southwest United States production system had the greatest impact using 266 weighted acre-inches/irrigated acre while the Mid-Atlantic production system was reduced by weighting to 76 acre-inches/irrigated acre due to the higher relative availability of water (Figure 11). The timing of the scarcity impacts on WF_{Blue} is easily demonstrated by comparing the monthly breakdown of volumes for southwestern United States (Figure 12), Ohio River Valley (Figure 13), Pacific Northwest (Figure 14).

The distinction between CWU and WF_{Blue} is clearly observed during driest season from July through October in the southwest U.S. case study when water is least available.

Conclusions

The importance of water availability, also considered as water security, for plant production has become increasingly clear for growers in water-limited environments. Growers in areas where water availability is not currently scarce can benefit from considering conservation practices where water access is limited. The competition for available water between expanding residential demands as well as increased industrial water use will require all growers to understand their water use and water footprint and implement best water management practices. Being able to communicate this information to the public and local and state officials to avoid devastating policies for plant production is important and will become even more important to the green industry in the future.

Production systems using recycled water compare favorably in CWU to those that do not, regardless of the water source. Production systems in geographic locations with high water availability compare favorably to production systems in locations with high water scarcity in WF_{Blue}, but not necessarily CWU.

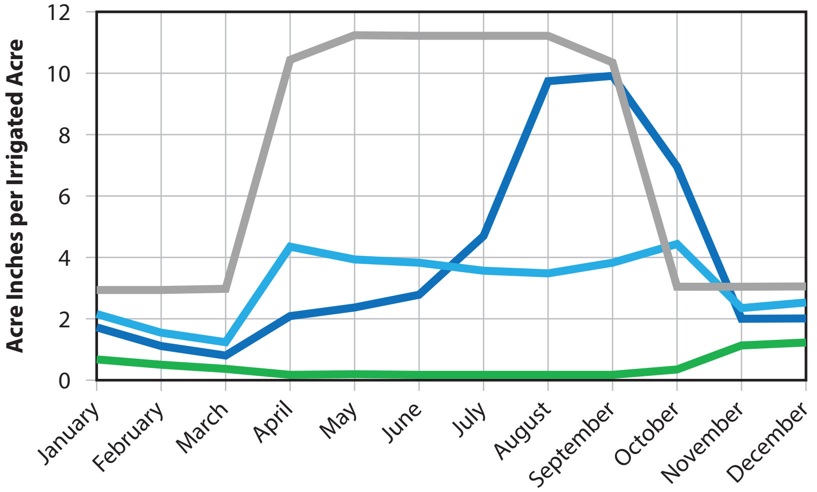

Figure 14. Monthly modeled water use and requirements on an annual basis in the Pacific Northwest case study where water is seasonally scarce.

While the reduced availability of water would increase the WF of a nursery or greenhouse operation, it is likely to create incentives for managers to reduce CWU leading to the adoption of innovative practices. Green industry managers at locations of water abundance can look at comparisons of CWU among nurseries and greenhouses to find and adopt these practices to improve their own water conservation practices.

From an Ohio River Valley container grower perspective, irrigation water availability throughout the year is a limited factor in selecting the location for production of container-grown plants. A minimum of 5 acre-inches per acre during the growing season is required. This of course assumes overhead irrigation to containers less than 3-gallon in size. More efficient irrigation such as low-volume irrigation suitable for larger containers would reduce the peak water requirement. Surface water storage in reservoirs designed to capture rainfall and irrigation runoff should be a part of the plan in this region. Deep reservoirs are more efficient in terms of evaporative loss from the water surface.

The evaporative loss from the same volume of water stored in a reservoir would be twice as much for a 10 ft. deep reservoir than a 20 ft. deep reservoir. If we assume the global average of 6.5 ft. of evaporation from a reservoir per year, that would be 0.65 vs 0.33 gallon of evaporation per gallon of water stored. This assumes the reservoir is full all the time. If not, then the evaporative loss per gallon of water stored would be higher. In most of Kentucky, a deeper reservoir is possible when compared to a coastal area with a higher water table or in flat terrain.

The pressures of sustainable water management are experienced differently by nursery and greenhouse growers, depending on the scarcity or abundance in their geographic location. Water use and water footprint analysis allows growers to account for these differences and evaluate a wide variety of water-saving strategies.

Additional Resources

Arguez, A., I. Durre, S. Applequist, M. Squires, R. Vose, X. Yin, and R. Bilotta. 2010. NOAA's US Climate normals (1981–2010). Natl. Oceanic Atmospheric Administration Natl. Ctr. Environ. Info. 10:V5PN93JP.

Boulay, A.M., J. Bare, L. Benini, M. Berger, M.J. Lathuillière, A. Manzardo, M. Margni, M. Motoshita, M. Núñez, A.V. Pastor, and B. Ridoutt. 2017 The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). Intl. J. Life Cycle Assessment. 23:368-378.

Cleanwater3.org. This website contains useful tools that were developed by a team of scientists federally funded by a Specialty Crops Research Initiative grant focused on research and outreach to help growers Reduce, Remediate and Recycle irrigation water. This project is focused on developing sustainable remediation technologies to encourage use of alternative water resources, especially recycled irrigation runoff, to decrease dependence on potable water, and enhance long-term economic viability. This is possible thanks to an award from the National Institute of Food and Agriculture Specialty Crop Research Initiative, and the involvement of 22 researchers at nine universities.

Knight, J., D.L. Ingram and C.R. Hall. 2019. Understanding irrigation water applied, consumptive water use, and water footprint using case studies for container nursery production and greenhouse crops. HortTechnology 29: https://doi.org/10.21273/HORTTECH04290-19

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