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Review

A Comparison of Irrigation-Water Containment Methods and Management Strategies between Two Ornamental Production Systems to Minimize Water Security Threats

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Abstract: Water security in ornamental plant production systems is vital for maintaining profitability. Expensive, complicated, or potentially dangerous treatment systems, together with skilled labor, is often necessary to ensure water quality and plant health. Two contrasting commercial ornamental crop production systems in a mesic region are compared, providing insight into the various strategies employed using irrigation-water containment and treatment systems. The first is a greenhouse/outdoor container operation which grows annual ornamental plants throughout the year using irrigation booms, drip emitters, and/or ebb and flow systems depending on the crop, container size, and/or stage of growth. The operation contains and recycles 50–75% of applied water through a system of underground cisterns, using a recycling reservoir and a newly constructed 0.25 ha slow-sand filtration (SSF) unit. Groundwater provides additional water when needed. Water quantity is not a problem in this operation, but disease and water quality issues, including agrochemicals, are of potential concern. The second is a perennial-plant nursery which propagates cuttings and produces field-grown trees and containerized plants. It has a series of containment/recycling reservoirs that capture rainwater and irrigation return water, together with wells of limited output. Water quantity is a more important issue for this nursery, but poor water quality has had some negative economic effects. Irrigation return water is filtered and sanitized with chlorine gas before being applied to plants via overhead and micro-irrigation systems. The agrochemical paclobutrazol was monitored for one year in the first operation and plant pathogens were qualified and quantified over two seasons for both production systems. The two operations employ very different water treatment systems based on their access to water, growing methods, land topography, and capital investment. Each operation has experienced different water quantity and quality vulnerabilities, and has addressed these threats using a variety of technologies and management techniques to reduce their impacts.

Keywords: container production; propagation; in-ground production; water quality; disease management; irrigation return water; reservoir

1. Introduction—Framing the Issues

Ornamental production systems are typically very intensive, with high plant densities and fast growth rates, which typically require high inputs of resources, time, and labor [1,2]. Access to reliable sources of good quality water is a principal requirement for most of these ornamental operations, and is essential for container production in greenhouses and nurseries. This is especially true where daily application of irrigation is required, even when supplemented by rainfall. The locations of plant production systems are often initially chosen because of access to good water resources and adequate rainfall. However, with periodic droughts, urbanization, and increasing restrictions on water use, producers are faced with increasing water security issues, even in "water-rich" mesic regions.

The United States (U.S.) nursery industry consolidated slightly between 2008 and 2013, with 2% fewer operations on 13% fewer acres, most likely due to the economic downturn during those years. Overall water use by the nursery industry remained the same, but 12% more of that water came from groundwater resources [3]. Lea-Cox [4] calculated from the 2013 Farm and Ranch Irrigation Survey [5] that 40% of total U.S. irrigated horticulture (214,780 ha) was in protected and open production of nursery crops, while an additional 8.9% of this acreage was devoted to floriculture and bedding crop production. Of this total acreage, 68.1% of irrigated horticultural crops was overhead irrigated, and 25.1% was irrigated with low-volume or sub-irrigation systems, while 1.4% was hand-watered.

White et al. [6] conducted a national survey and round-table discussions with commercial growers to understand the barriers, issues, and concerns associated with the use of irrigation return water for ornamental production in the U.S. Of the 174 survey respondents, 63% identified their operation as having a portion devoted to greenhouse production, 55% as container production, and 39% growing field crops, using an average of 19,200 m^3, 150,200 m^3, and 61,300 m^3 of water per annum, respectively. The primary source of water for the surveyed operations was shallow well (<30 m) water (40%), deep well (>30 m) water (67%), surface water (45%), and/or collected rainfall or retention pond water (43%). Nearly half (49%) of the respondents identified state government agencies as controlling access or use of water, while 20–29% indicated that a county or local water authority maintained this control. Of the operations surveyed, 71% indicated that they did not collect irrigation return flow for day-to-day irrigation, but operational water restrictions did result in inadequate daily pumping capacity, requiring additional storage capacity. Respondents stored water in reservoirs (68%) or storage tanks (40%), and stored water was primarily used to extend water quantity when primary extraction was limiting (60%) or to blend water from different sources to ensure desired water quality (40%). Irrigation return water and rainfall runoff collected from greenhouse and nursery operations was primarily utilized to irrigate container production. The use of alternative (off-site) water was typically cost prohibitive, or municipal water use was restricted. Notably, nearly half of respondents stated the irrigation might not always be applied as needed, due to limited capacity on hot days or during drought periods. To overcome water shortage issues, growers indicated that they would firstly change production practices to adjust to water shortages, followed by increasing on-farm water storage capacity by collecting and recycling water captured from rainfall, irrigation return flow, and stormwater runoff [6].

The dominant water "challenges" identified by growers were future water availability (due to both drought and permitting and other regulatory issues), pathogen issues, and the environmental implications of containing water runoff from production facilities. Growers identified cost-savings and having increased water capacity as primary reasons to increase efficiency of water use by conserving or collecting irrigation runoff and/or stormwater. Research priorities identified by White et al. [6] were for better information on: (1) Recycled water infrastructure and management; (2) recycled water contaminants; (3) plant health and water quality; (4) water treatment technologies; (5) competing and complementary water uses; and (6) a better understanding of the societal perception of agricultural water use.

2. Recycling Water—Real and Perceived Challenges

Given this national survey information, it is clear that water supply is the primary consideration for growers to ensure water security, followed by water quality (contaminant) issues. More pervasive drought conditions in the southwestern and western United States have had major economic impacts in the past decade, where water conservation and recycling has become a standard practice. However, there are many locations in the mesic "water-rich" southern and eastern U.S. where access to ground water is dependent on well output, water rights and local environmental regulations. Many ornamental operations therefore use precision irrigation systems, including low-volume application (micro-irrigation) or moisture sensor networks to only apply water when and where necessary [4]. For growers using overhead irrigation, the capture and recycling of irrigation and stormwater runoff is also more prevalent. However, this is a major capital investment in terms of production area lost, along with the engineering, permitting, pumping, and treatment systems involved in containing and recycling water [3,4].

Substrates: Increasing substrate water-holding capacity (while maintaining porosity) and water application efficiency to plants are sometimes more cost-effective primary water-saving strategies for growers. Soilless substrate mixes used in container production are varied and diverse (e.g., peat, perlite, coconut fiber, pine, and other bark materials), but all typically have high porosities, to ensure adequate drainage and reduce the risk of root pathogen infestations. High substrate porosity and smaller container (rooting) volumes, however, can constrain plant-available water. Frequent (and precise) irrigation events are therefore necessary to maintain adequate water supply to prevent water stress and loss of growth potential without over-applying and leaching nutrients. Small container volumes can also amplify problems associated with poor water quality. For instance, carbonate accumulation from high water alkalinity can have a dramatic effect on micronutrient availability in small containers.

Water Application: Most commercial nursery and greenhouse producers face the conundrum of applying water precisely but economically to plants, while also minimizing agrochemical runoff and environmental issues. Fulcher et al. [3] noted that there are few economic alternatives to using overhead irrigation for container sizes less than 19-L capacity. And yet, floriculture and herbaceous perennial growers are increasingly using drip irrigation systems for 3.9–7.5 L containers. This is driven by perceived reductions in disease pressure, consumer intolerance for foliar residues, together with decreasing production inputs for low-margin crops [3]. Pot-in-pot woody perennial nurseries are also realizing the additional economic benefits of precisely irrigating medium size (11–19 L) container sizes, including the ability to precisely apply soluble fertilizers in low concentrations to match specific plant growth rates. Labor availability and timeliness of irrigation/fertilizer applications are often over-riding factors for optimizing plant growth rates while reducing labor costs and environmental impacts.

Agrochemical Runoff: The use of agrochemicals compounds the effects of irrigation runoff in ornamental production [6]. Since nursery and greenhouse production systems are input-intensive and water is an effective transport mechanism, they have the potential to contribute agrochemical loading to the surrounding environment if appropriate management and water control structures are not in place. Quantifying the range of agrochemical and irrigation application rates used by the ornamental nursery and greenhouse industry is challenging because of the variety of species, production systems, and cultural management techniques employed [7].

Agrochemicals and other contaminants in recycled return water can also have a detrimental effect on plant production. For example, plant growth regulators (PGRs) being recirculated in water-reuse systems can have negative effects on growth in some ornamental plant species. Million et al. [8] found that paclobutrazol at concentrations as low as 5 μg/l were enough to cause growth reduction in sensitive species. Concentrations of above 5 μg/l paclobutrazol have been found in various locations within water recirculation systems in one of the operations we studied.

Water Runoff and Capture: Majsztrik et al. [9] defined runoff from specialty crop container operations as coming from two sources: Fresh water sources and operational (irrigation return) water. Fresh water from rainfall or groundwater sources that have not previously come into contact with production areas should not have any significant contaminant load (nutrients, pesticides, pathogens, etc.) above background levels. As such, it should not require any treatment prior to leaving an operation or mixing with operational water to supplement the irrigation water supply. An example of this would be runoff from a greenhouse roof or well water. Operational water is defined as any water that flows from, through, or around a production area. As a result of contact with soils, agrichemicals, and phytopathogens, this water may have elevated concentrations of contaminants, and may require treatment before reuse or release, depending on operational needs and local regulations.

Ideally, both operational water and uncontaminated water should be captured, treated, and reused by ornamental production operations, but this is not always possible for a number of reasons. Given the widespread use of overhead irrigation in nurseries, the capture and recycling of irrigation runoff (i.e., the "first flush" of runoff) from containment ponds remains the most viable economic alternative to using fresh potable water, especially for production of small container crops [4]. This requires that the growing operation has the available space for these structures, which should be specifically designed and engineered for this purpose [10]. Oftentimes, however, operations have geographic or topographical limitations that constrain their capacity to capture runoff. Rainfall events in some regions of the U.S. are intense over short durations, resulting in runoff volumes that exceed the capacity of existing containment infrastructure. In some parts of the country, a high water table can limit feasibility to capture or treat runoff water. Saltwater intrusion and storm surges are also major concerns, particularly in coastal areas [11]. Some operations, especially smaller or more urban operations, may be land-limited, so there may not be sufficient area to store water for treatment or reuse. Other areas may not be able to store water due to high water table or soil type (i.e., rock, sand). These limitations must be considered when developing regulations and implementing best management practices (BMPs) for a particular area or operation [12].

The capture of stormwater to supplement water supply (in addition to production runoff) is limited by the climate, topography, and the regulation of waterways. In California, state regulations require growers to capture and retain water on site if it does not meet water quality standards for discharge. However, discharge can occur if runoff treatment and remediation is performed to prevent water body impairment [13]. If growers are going to invest in the infrastructure required for remediation and treatment, it is logical to reuse this return water for irrigation to reduce cost and reduce the need for other water sources, particularly in a dry climate [14]. The authors noted from their comprehensive cost analysis that capital costs associated with construction of recycled water systems were high, but were offset by rebates from the water provider and a grant from the National Resource Conservation Service (NRCS), in this specific case. However, subsequent operational costs (e.g., electricity for pumping) are low, which reduces the marginal cost of recycled water in future years [14]. Moreover, this strategy insulates the operation from reduced water availability and/or future price escalations, increasing overall water security. The need to increase water recycling and effectively capture greater proportions of rain events will be essential for nurseries in regions that will experience increasing droughts as a result of increasing climatic variability.

Disease Management Issues**:** For production operations that recycle and reuse water, pathogens are of particular concern. While water recycling systems provide the environmental benefit of water conservation, they also pose an increased risk of plant disease problems [15]. Monitoring to assess disease risk and large investments in water disinfestation systems are necessary to avoid and minimize loss. Waterborne fungal diseases caused by *Phytophthora* and *Pythium* species are among the most damaging to greenhouse and nursery-grown horticultural crops [16,17]. These pathogens cause various damping-off and root-rot diseases, as well as stem cankers, shoot dieback, and foliar blight of annuals, herbaceous perennials, and woody plants. While *Phytophthora* includes soilborne and aerial species [18], they are all water molds, meaning they require water to complete their life cycles. Sporangia are formed during moist conditions, releasing zoospores that swim through water to infect plant roots, stems, and leaves. *Phytophthora* and other plant pathogenic oomycetes, including *Phytopythium* and *Pythium,* are common contaminants of greenhouse and nursery irrigation systems [19]. Bienapfl and Balci [20] identified 18 different *Phytophthora* species in Maryland ornamental nurseries and many of these were present in the recirculated irrigation water system. This is not an issue isolated in Maryland, nor the U.S. for that matter. From studies performed between 1972 and 2013, Jung et. al. [21] reported infestations of *Phytophthora* species in nurseries throughout Europe, with several species being previously unreported. As in Maryland nurseries, many of the infected plants were symptomless, creating the concern for spreading the pathogens into landscaping and natural environments.

Phytopathogen contamination can create economic and ecosystem stressors, leading to disease within both the operation and the surrounding ecosystem via runoff [22]. Economic analyses of production losses attributed to phytopathogens in container-grown specialty crops are not widely available, making it difficult to calculate the impact on grower profits and the surrounding environment. Specialty crop production losses to pathogen infection have been estimated to range from 5 to 30% for some crop taxa, but losses are likely to be crop-specific and fluctuate annually based on environmental and production conditions [23–25]. Nursery plant distribution systems are effective at moving pathogens [26,27], as infected plants may not show symptoms [28]. In addition, some of the most widely used oomycete-specific pesticides, such as mefenoxam and fosetyl-Al, are fungistatic rather than fungicidal. Application of these materials can delay the development of symptoms and prevent pathogen detection until after plants are shipped. Resistance to mefenoxam has also developed in many nurseries [29]. Ecosystems may be negatively impacted by the discharge of pathogens from crop production facilities via plant transport from nurseries and eventual pathogen escape into the environment, as illustrated by the pathogen causing sudden oak death, *Phytophthora ramorum* Werres, De Cock & Man in 't Veld [30,31].

3. Effective Measures for Remediation of Recycled Water

Agrochemical load reduction and sanitation: Remediation can be defined as the process of removing chemicals, pathogens, and other constituents of concern to reduce loads of harmful substances to a water system [32]. The type of contaminant, the required load reduction, and the economics and efficacy of treatment technologies depend on various factors specific to each operation. Majsztrik et al. [9] provide a comprehensive evaluation of various treatment technologies, including the relative cost (initial and continuing), the contaminants managed, scalability, and relative efficacy of the technology. Although specific treatment technologies can reduce specific contaminants, oftentimes synergistic gains can be realized via pairing two or more types of treatment systems in series or in other combinations (i.e., treatment train approach such as filtration and sanitation). This coupling is often most effective when targeting different types of physical, chemical, and biological contaminants (e.g., agrichemicals and pathogens, or pathogens and sediment), since there is no single treatment system that will effectively manage all types of contaminants [32–36].

Disease Management Solutions: Parke et al. [37] describe how they applied a systems-type hazard analysis to identify sources of contamination for *Phytophthora* species in three container nurseries in Oregon, California, and South Carolina. Their procedure [37] is a modification of the hazard analysis of critical control points (HACCP) approach designed to ensure food safety in food processing facilities. Critical control points are defined as the best stages in a production process, where significant hazards of pathogen contamination can be prevented or reduced. In a nursery, critical control points commonly include plants brought in from other production facilities, potting media or components, cull piles that are used for making potting media, recycled containers, the soil or gravel under the containers, and untreated irrigation water. Once the source(s) of contamination are known, nursery growers can eliminate or reduce the risk of disease by implementing a specific management strategy that targets the contamination source [38–40].

Parke et al. [37] noted that surface water sources and recaptured runoff water were contaminated with plant pathogenic species at all three nurseries, but one nursery implemented an effective disinfestation treatment for recycled irrigation water. Other sources of contamination included cull piles and compost that were incorporated into potting media, infested soil and gravel beds, used containers, and plant returns. Management recommendations include preventing contact between containers and contaminated ground, improving drainage, pasteurizing potting media ingredients, steaming used containers, and quarantine and testing of incoming plants for *Phytophthora* species. The case studies reported below illustrate how recycled irrigation water can contribute to the spread of waterborne pathogens and highlight the need to implement best management practices to reduce disease risk.

4. Maryland Case Studies

Maryland had 12,140 ha in ornamental production in 2012, which included 200 ha of covered greenhouse production [41]. Wholesale and retail sales generated $773 million from woody plants (45.7%; $357M); annuals (22.8%; $178M); herbaceous perennials (22%; $171M); specialty greenhouse products (5.5%; $43M); Christmas trees (0.7%; $6M); aquatics (0.5%; $4M); and other products (2.9%; $22M). Container-grown products (including all greenhouse production) accounted for 71% of sales ($550M), whereas sales of field-grown products totaled 28% ($216M) of total sales.

Maryland is a relatively water-rich state, but even so, many operations are limited by well capacity, permitting of aquifer water use (by Maryland Department of Environment), and periodic droughts which can occur throughout the year. We document and discuss the water management strategies of two contrasting ornamental production systems. Both operations have water security issues and recycle water for irrigation and nutrient reuse, but employ different technologies and strategies to effectively reduce any water-related threats.

4.1. Case Study A

This is a large greenhouse and outdoor operation (totaling 10.9 ha of production area) that specializes in year-round containerized plant production, including two cycles of spring annuals, one cycle of summer annuals, one cycle of fall chrysanthemums, and one cycle of winter-holiday poinsettias (Figure 1).

Water Supply and Treatment: Irrigation is via drip emitters, boom spraying, or subsurface ebb and flow (flood) floors. The operation utilizes a recirculatory system from large underground cisterns and a catchment pond. In the past, about 75% of their operational irrigation water was captured, recycled, and blended with supplemental water derived from two relatively low-capacity wells (combined volume of 300 L per minute = 432 m^3/day). Previously, the operation tried several water sanitation methods, including chlorine gas, copper pass-through, ozone, and ultra-violet light systems. In 2017, they commissioned an 800 m^2 slow-sand filtration (SSF) facility. Since then, approximately 95% of their yearly irrigation is from recycled containment pond water with supplemental water provided from the two wells.

Water use in 2015 and 2016 was 88,876 m^3 and 85,921 m^3 of well water, respectively. In both years, about 31,822 m^3 of captured irrigation and rainfall runoff water was also used (not metered) during the summer and fall months, mostly for container-grown Chrysanthemum grown in outdoor production areas on drip irrigation. Since February 2017, this reservoir return water has been used almost exclusively for the entire operation, with only 2860 m^3 of well water used during 2017. As an additional 2 ha of outdoor production acreage was added in Fall 2017, the operation likely used at least the same volume (122,744 m^3), but probably more water than in 2015 and 2016. Before the SSF was installed, the operation used well water for most of the crops grown, with supplemental reservoir water being used from July–September for outdoor Chrysanthemum production when demand exceeded well capacity. Well water alkalinity is about 125 mg L^{-1}, with a pH of 7.3 and EC of 0.4 dS cm^{-1}. There are no other specific water quality concerns, except for paclobutrazol, a water-soluble plant growth regulator in the return pond water (discussed below), which has a half-life of over 6 months in water [42].

Now that the operation uses recycled reservoir water filtered by the SSF, the intention is to use this as the primary water source, supplemented during the summer months with well water. Total current reservoir capacity is approximately 18,500 m^3. The operation typically receives about 1000 mm rainfall per year. The 6 ha greenhouse roof therefore supplies approximately 40,700 m^3 of direct clean water recharge to the containment pond annually, with additional runoff (not measured) being received from the outside production areas around the greenhouse. An additional containment reservoir of slightly larger capacity is currently being excavated, which would bring the total reservoir capacity close to 40,000 m^3.

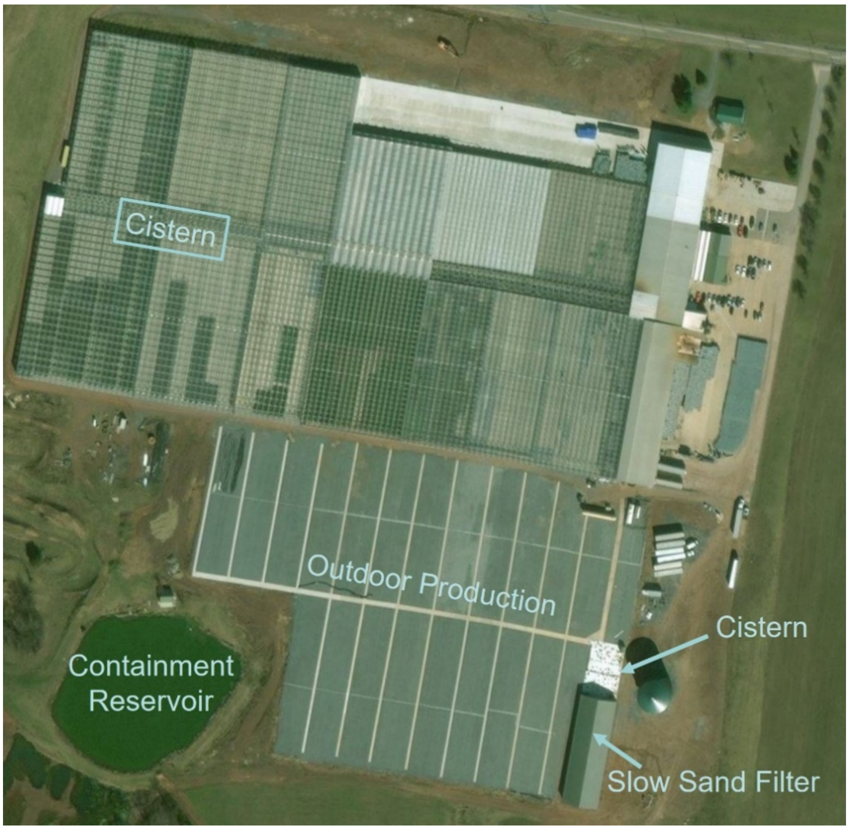

Figure 1. Aerial picture of case study A with 5.8 ha of indoor greenhouse growing area and 5.1 ha of outdoor growing area. Below-ground cisterns, water tank, and catchment reservoir allow this operation to now recycle up to 90% of its applied irrigation water.

Chlorine (liquid sodium hypochlorite) was used to sanitize reservoir water before the SSF system was installed. The reservoir water first passed through a coarse sand filter and then a glass bead filter prior to chlorine and sulfuric acid injection, in order to bring the pH down to 6.0 and make the chlorine more effective. However, now that the SSF is being used, chlorination has been eliminated to prevent disruption of the SSF "schmutzdecke" or biofilm. Once reservoir water has been filtered by the SSF, water is stored in a 2273 m^3 storage tank. This water is then pumped to the greenhouse or outdoor bed areas as needed for irrigation. Irrigation water runoff from the greenhouse floors is captured by the internal cistern for immediate reuse during periods where growth regulators are not used. During paclobutrazol application periods, the greenhouse runoff is diverted directly back to the catchment reservoir.

Threat Assessment**:** The most immediate threat to plant production and quality is to ensure adequate water quantity when demand is highest, between July and September. This is when outdoor chrysanthemums have peak water use, especially during dry years. The recycling pond and SSF filtration system is now functioning well, but malfunctioning irrigation solenoids can drain cisterns and leave minimal water capacity the next day. Water alkalinity is moderate to low and has not posed a problem with the relatively rapid growth cycles of container plant material.

The greatest water quality threat has been the contamination of irrigation water from use of paclobutrazol by the operation for spring bedding plant production. This growth regulator is known to affect sensitive species at concentrations as low as 5 μg L^{-1} [8]. We monitored paclobutrazol concentrations from the containment pond, and pre- and post-SSF in case study A during 2018 (Figure 2). Results show that recycled water exceeded these concentrations at times during the spring, by a factor of over 2. Notably, it appears that the SSF did not remove the paclobutrazol at this time, perhaps as the biofilm layer was disrupted during this period. Further SSF column studies are currently being performed by researchers at the University of California–Davis to determine the paclobutrazol loading and removal efficiency over time.

Various species of pathogens, including some highly pathogenic species of *Pythium* and *Phytophthora*, have been identified throughout the water system. Of these, *Pythium oopapillum* Bala, de Cock & Lévesque, *P. diclinum* Tokun., *P. cryptogea* Pethybr. & Laff., and *Phytopythium helicoides* Drechsler were all pathogenic (~90% damping off) in chrysanthemum seedling trials Beaulieu, J. (University of California, Davis, USA; Unpublished work, 2018). The SSF was relatively effective in reducing these pathogens. However, recovery of mostly non-pathogenic oomycetes and an isolate of *P. helicoides* was made after the filtration tank, past the SSF. This re-introduction or re-accumulation of pathogens illustrates the need to identify critical treatment points, especially after the SSF to improve pathogen management Beaulieu, J. (University of California, Davis, USA; Unpublished work, 2018).

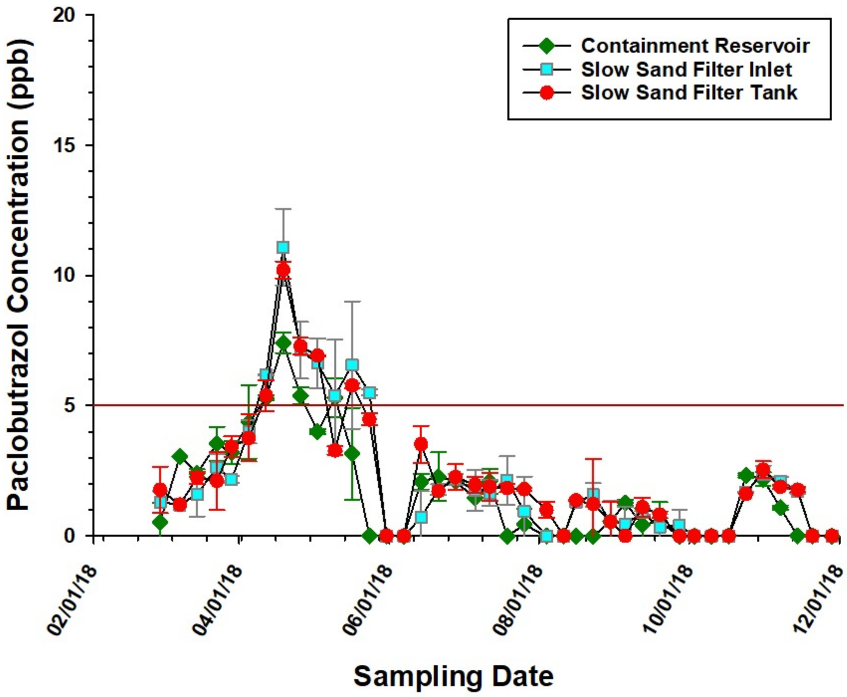

Figure 2. Paclobutrazol concentrations from the containment reservoir, pre- and post-SSF (slow sand filtration) in case study A. Lea-Cox et al. (University of Maryland, College Park, MD). Unpublished work, 2018.

4.2. Case Study B

This operation consists of 43 ha of field tree production and approximately 5 ha of container plants of various sizes. Plants are bought in from other (in- and out-of-state) nurseries, which are placed in a holding yard, and then re-sold to customers (Figure 3). This operation also propagates various species for their own use and sale, produced in plastic-covered Quonset houses.

Water Supply and Treatment: The operation recycles water from a system of four containment reservoirs (approximately 2.7 ha in area) situated in the lower half of the property (Figure 3), with a total capacity of 140,000 m^3. These reservoirs collect runoff from both irrigation and rainfall, and at least one pond is also spring-fed from groundwater in above-normal rainfall years. Reservoir 3 (Figure 3) is used for irrigation with recharge from rainfall, surface runoff, and groundwater recharge, while the first two reservoirs serve as settling basins for sediment and pathogen management [15,43]. The fourth reservoir is a reserve structure that was installed after a major drought in 2002, when purchased water was trucked at great expense. There are three wells on the property, from 100 to 300 m in depth. None are used for irrigation as all yield less than 40 L/min. After irrigation water is pumped from reservoir 3, it is filtered through sand and disc filters and chlorinated with chlorine gas before use. The operation converted to using sodium hypochlorite tablets for sanitation in 2019.

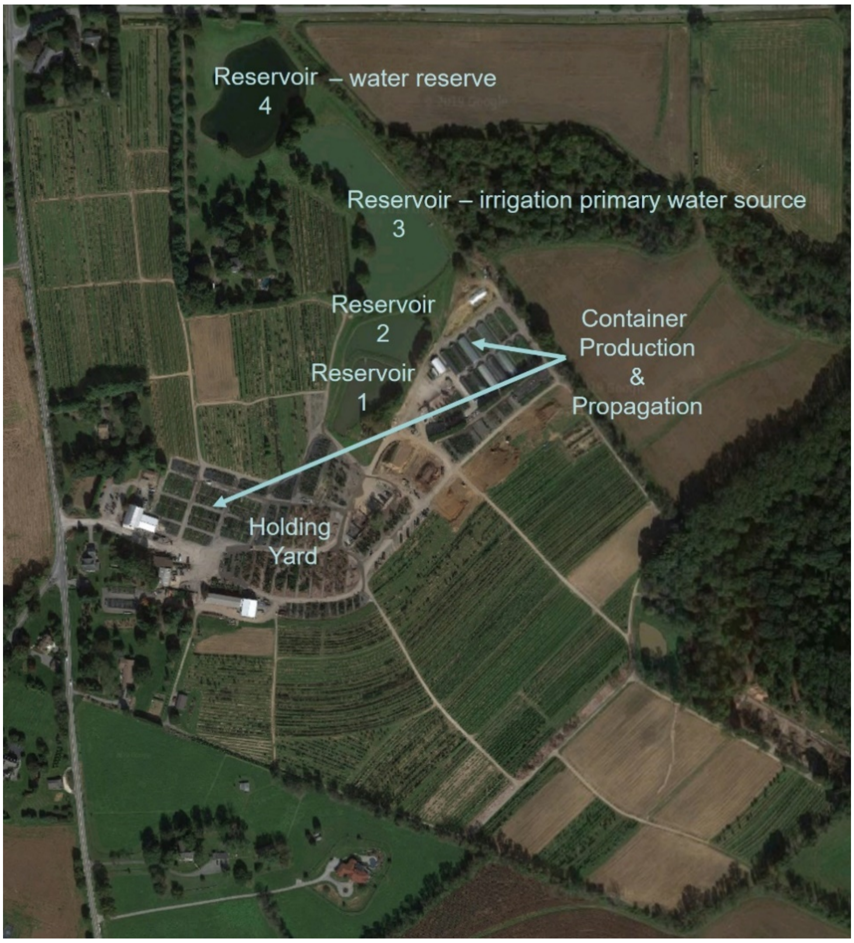

Figure 3. Aerial picture of case study B with 43 ha of in-ground plant production and 5 ha of container plant production. Catchment and recycling reservoirs serve to provide the nursery with 100% of daily irrigation requirements throughout the year.

Field trees are irrigated via drip emitters, while holding area containers (including ball and burlapped plant material) are irrigated daily during spring, summer, and fall. Before 2017, irrigation of the holding yards was done with large-volume overhead sprinklers. Since 2018, low-volume sprinklers have been used in this area, which allow for greater irrigation precision and a large reduction in daily runoff from this area. The operation uses approximately 136,400 m^3 of irrigation water annually, with the holding yard historically consuming the most water; that is, until the installation of low-volume emitters. Recent irrigation water analyses indicated a pH between 6.2 and 7.2 with alkalinity ($CaCO_3$) between 88 and 120 $mg \cdot L^{-1}$. Even though calcium levels are normal (between 40 and 75 $mg \cdot L^{-1}$), return irrigation water tends to stain leaves and equipment with a calcium precipitate. Sulfuric acid injection into the return water has reduced this problem.

Threat Assessment

The primary threat, due to the geographic layout of the operation, is disease re-introduction into the irrigation reservoirs from runoff. Runoff from the holding yard area (containing imported plant with potential root disease issues), which flows back into the reservoir system, is a particular concern. A reduction in the volume of irrigation water applied to plants in the holding yard (and hence irrigation runoff) by retrofitting low-volume irrigation systems has helped reduce this threat, but large-volume runoff from storm events is still an issue. The primary settling structure (Reservoir 1, Figure 3) helps to drop sediment and the chance of pathogen zoospore contamination [44,45], and prevents any direct runoff from entering the third pond, from which irrigation water is pumped (Figure 3).

Various species of *Pythium*, *Phytopythium* and *Phytophthora* were identified from monitoring the ponds, drainage channels, and greenhouses during 2017 and 2018 Beaulieu, J. (University of California, Davis, USA). Unpublished work, 2018. The pathogen disinfestation system (chlorine and filters) functions in reducing pathogen (based on bait monitoring) by 66%, but does not prevent all potential pathogens species from reaching plant in the return irrigation water.

5. Discussion—Economic Strategies to Increase Water Security

Water supply for ornamental operations in Maryland is generally not limiting, except during long-term droughts which can cause severe economic losses. Some ornamental operations in Maryland have well capacities greater than 2800 L/min. In certain areas with high populations and limited aquifer supply or recharge, groundwater regulations have placed strict limitations on well water withdrawals by growers, requiring the purchase of neighboring water rights. In many western areas of the state, well capacities are very low. As a result, many ornamental production operations in these areas have taken steps to conserve water through increased irrigation application efficiency by adopting various irrigation best management practices, including performing irrigation system audits [12,46,47], changing irrigation management practices (i.e., cyclic irrigation), or by monitoring substrate moisture using sensor networks [7,48]. Managing and conserving water also reduces leaching and runoff of nutrients and agrochemicals, but caution must be taken with some water-sensitive species.

Ingram et al. [49] provided a life-cycle analysis for poinsettia using data from case study A to illustrate the water and energy footprints of this popular ornamental crop. They documented that each poinsettia plant, produced in a highly water-efficient greenhouse, used 121 L over 16 weeks. Del Castillo Múnera et al. [48] investigated how reducing water use would impact plant growth and disease infection risk, using plant and substrate material from case study A in a controlled greenhouse study. They demonstrated that by using decision (sensor-based) irrigation, as well as precision drip irrigation, an additional 23.2% of irrigation water can be saved without compromising the growth, quality, or health of the plant. However, poinsettias grown in peat/perlite substrate were more prone to root infections at soil moisture contents below 25% volumetric water content, after inoculation of *P. aphanidermatum* (Edson) Fitzp. (1923) [48].

Chlorination is the most widely used method for nursery irrigation water sanitation and disinfestation [50] because of its ease of use, low cost, and relative safety. However, its efficacy varies widely based on dose, time, water chemistry (pH), and target organisms [51–53]. A concentration of between 0.5 and 2.0 mg/L free chlorine is typically recommended. This dose range seems to be the maximum to prevent phytotoxic damage to sensitive plants, but many pathogens and their life stages are resistant to these lower chlorine concentrations [15]. Other technologies include chemicals besides chlorine such as copper, silver, ozone, and peroxides, yet little information about effective doses exists [51]. Non-chemical options include filtration, heat and ultraviolet radiation, and ecological methods such as constructed wetlands or fast and slow sand filtration [51].

Slow sand filters have been shown to provide some pathogen management capabilities. Oki et al. [54] found SSF capable of removing *P. capsici* Leonian and tobacco mosaic virus within two weeks, but not *Fusarium oxysporum* Schltdl, Fr. after 7 weeks. Beaulieu (University of California, Davis, USA). Unpublished work, 2018 found that the SSF system employed by case study A was relatively effective in reducing the pathogen loads from pond water, but some recovery of non-pathogenic oomycetes and an isolate of *P. helicoides* were found after the filtration tank. It is clear from the monitoring of both Maryland ornamental operations that the potential reintroduction threat of plant pathogens illustrates the need to identify and continuously monitor critical points along the treatment train [40].

Agrochemical runoff also poses a threat for ornamental operations that recycle water from containment ponds [55]. Pesticide movement in runoff water can occur with the pesticide either dissolved in water or adsorbed to and transported by soil particles or organic matter [54]. Abdi and Fernandez [56] noted that water is the main mechanism for pesticide movement after application. Time is a critical factor in reducing pesticide movement, which allows for adsorption and degradative processes to occur. Practices that reduce the amount of water applied and delay irrigation after pesticide application can reduce pesticide movement. Best management practices for irrigation and agrochemical application can be used to reduce chemical- and nutrient-laden runoff. These practices, combined with supplementary treatment systems, can further reduce agrochemicals from reaching surface waters, groundwater, or the catchment basins for water recycling [56].

6. Conclusions

Ornamental operations share many similar production problems, but because of climate topography and site-specific systems, most day-to-day operational water management decisions are unique. Nevertheless, it is apparent that threats faced by many ornamental operations in recycling water are common throughout the United States. Decreasing reliance on groundwater and enabling the capture and recycling of scarce water resources, even in relatively water-rich areas, are helping ornamental operations become significantly more sustainable in their overall water use. Water supply issues are of common concern, but water quality and treatment issues tend to be site-specific, as are the strategies to ensure an adequate supply of clean recycled water. For operations that recycle water, plant pathogens and agricultural chemicals appear to be the most common threats, but many technologies and strategies for treating and sanitizing return irrigation water are available that can significantly reduce these threats.

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