Identifying Opportunities for Non-potable Water Reuse Based on Potential Supplies and Demands in the United States.

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Abstract

Water scarcity threatens the well-being of individuals, the natural environment, and economic systems that function within society. Faced with growing and evolving water supply concerns, many utilities and industries have relied on non-traditional water sources to mitigate severe shortages and combat water quality concerns. Treated municipal wastewater can serve as a reliable supply of water at a predictable quality and quantity, and is especially well-suited for non-potable end-uses. In this work, we identify areas within the contiguous United States where water reuse projects are possible based on existing supplies of treated wastewater at known qualities and quantities, estimated non-potable demands, and state-level policies that outline water quality requirements for reuse. We use publicly available data to develop a geographic information system-based supply-demand assessment that identifies spatial trends and areas of interest for locally-focused water reuse analysis. We find that the feasibility of water reuse is highly sensitive to existing state-level policies and the level of wastewater treatment currently in-place. Non-potable recycled water can potentially offset significant water withdrawals within communities where specific policy and technical criteria are met.

Keywords

water reuse, reclaimed water, environmental policy, geographic information systems

1 Synopsis

In conditions with appropriate existing wastewater treatment, suitable demands, and relevant regulations, there are great opportunities in the United States to offset local freshwater demands with non-potable reclaimed water.

2 Introduction

The United States faces a variety of challenges related to physical and economic water scarcity on state, regional, and local scales.[1,2] Water stress plays a crucial role in determining the locations where different aspects of the economy develop, and when severe water scarcity threatens those industries, they may relocate or consider using non-traditional water sources. Concerns over water supply reliability and sustainability have led many municipalities and water users to utilize non-traditional water sources by recycling municipal wastewater.[3–6] De facto reuse can also play a significant role in U.S. and global water supplies especially during periods of low streamflow.[7,8] Engineered water reuse provides an opportunity to capitalize on reuse processes that are already occurring and growing in quantity. Many existing wastewater treatment plants (WWTPs) can potentially provide reclaimed water for non-potable water users if certain criteria are met. Based on definitions affirmed by The WateReuse Association[9] and others,[10,11] the term "reclaimed water" refers to treated wastewater that is fit-for-purpose for certain end uses, but has not yet been reused, and the term "recycled water" refers to treated wastewater that has been put to use. Treated or "reclaimed" wastewater resources exist across the United States, but are largely discharged into natural bodies of water; the process of reusing or recycling this water involves consideration of many physical, administrative, and economic barriers.[10,11]

New water supply projects are motivated by existing and future demands that cannot reliably be met by current supplies. When considering which areas might benefit from reclaimed water supplies, a key step is identifying non-potable water demands near existing wastewater treatment plants. While demand for water resources might develop as additional supply becomes available, some degree of long-term demand must exist to motivate new infrastructure projects. If there are significant demands for water and an adequate supply of municipal wastewater, policies can inform whether or not the quality of water being discharged from a WWTP is sufficient for reuse for a specific end use. While the U.S. Environmental Protection Agency (EPA) has published guidelines for water reuse,[12] individual states are ultimately responsible for developing the legislative or policy framework to implement these projects. These criteria (supply, demand, and policy) are not exhaustive and do not comprehensively address the local factors that might contribute to or hinder the success of non-potable water reuse, but rather provide a foundation for more unique case-specific considerations.

This work presents a quantification of potential supplies and demands within the contiguous United States and determines where the quality of water supplied and demanded matches what is required by state water reuse policies. Publicly available data were used to develop a geographic information system (GIS) based analysis of existing supply and potential demand for reclaimed water that can serve as a decision support tool for future, locally-focused water reuse analysis. Our work reveals that water reuse is not an appropriate solution everywhere; rather, there are specific communities that meet these criteria such that water reuse could be a suitable solution for current and future water supply challenges.

In this study, we contribute to a broad body of literature examining reclaimed water use for cooling at power generation facilities, irrigating agriculture, and industry and manufacturing in the contiguous United States.[13–16] These water users make up 83% of water withdrawals in the United States[17] and generally have low water quality requirements compared to other end-uses. Thermoelectric power plants are typically located near a reliable source of cooling water like a lake, river, or aquifer and are susceptible to heat waves and droughts due to increased temperature of cooling water at intake, whereas fluctuations in reclaimed water temperature are much smaller.[18,19] Irrigated agriculture has developed around natural bodies of surface water or groundwater that may be over-allocated and potentially unable to support irrigated agriculture in the future.[20] Many of the most productive agricultural regions in the United States depend on conjunctive use to balance groundwater pumping with surface water withdrawals. A majority of U.S. industrial and manufacturing facilities use self-supplied water from nearby surface and ground water sources,[21] which can strain water supplies that support urban areas even if these water demands are primarily for withdrawal and not consumption.

The advancement of water reuse in the United States has been limited by a number of factors.[11] While opportunities for water reuse are broad, the volume of water available may be small compared to alternative water supply projects and water reuse may be less effective in communities that are generating less wastewater because of indoor water conservation measures. The benefits of water reuse largely depend on spatial considerations such as the location of water users relative to a WWTP. This work stands in the gap between studies that examine existing water reuse case studies,[22,23] reclaimed water policy and decision making,[24–26] water reuse within specific industries,[13,15] and reclaimed water technologies and supply infrastructure[27] with the goal of providing generalizable results than can complement and inform location-specific studies.

2.1 Current Water Reuse Practices and Considerations

Power plant cooling water withdrawals represent a large portion of water use in the United States,[17,28] and future demands for withdrawal and consumption are uncertain due to changing national climate policies and adoption of different technologies in the electricity sector.[29] During heat waves or periods of low streamflow, power plants perform less efficiently than under normal operating conditions and their generation may be curtailed due to thermal discharge regulations (Clean Water Act §316(a)).[30,31] For these reasons, a consistent, reliable supply of cooling water is essential for plant performance and balancing of electricity generation across the grid. Peer and Sanders[32] found that in 2014, over 60% of water withdrawn for power plant cooling came from fresh surface water sources and that natural gas and nuclear facilities are responsible for the highest median withdrawals across different cooling systems, revealing that the impacts of water withdrawal on freshwater sources are heterogenous and largely dependent on specific details of the cooling system and local water resources. Recycled water is best suited for recirculating cooling systems for a number of reasons. Facilities using recirculating cooling are generally newer and further from planned retirement and withdraw less, but consumer more, water per kilowatt-hour of electricity generated in comparison to once-through systems.[32–34] Many power plants in the United States are located sufficiently close to at least one municipal wastewater treatment facility, such that recycled water could be a viable source of cooling water,[34] although there may be other alternative water sources or retrofitting options that are more financially attractive.[35] This determination of suitability is highly dependent on the distance between the power plant intake and the WWTP and the cost of constructing new distribution infrastructure. One of the most well known examples of the use of reclaimed water for power plant cooling is the Palo Verde Nuclear Generating Station in Maricopa County, Arizona, which uses reclaimed water from the Phoenix metropolitan area, approximately 40 miles away.[36] Beyond the location and quantity of recycled water supply, water quality is also a consideration for power plants.[33,34] Water quality issues can lead to scaling, biofouling, and corrosion among other power plant operational challenges.[4] While water quality is an important consideration, these issues can be avoided by on-site treatment or sourcing from a wastewater treatment facility with sufficient treatment technologies already in place.

Irrigation is the largest consumer of water in the United States,[17] and is responsible for large virtual water exports from areas that face water scarcity.[37] "Virtual water exports" describe the volume of water that is consumed during the production of food crops that are then exported somewhere other than where the food was grown, resulting in the export of embedded water resources away from the original withdrawal.[38] The use of recycled water conjuctively with groundwater can potentially protect over-exploited aquifers while still providing comparable yields.[39] The quality of water required for irrigation depends largely on the crops being grown.[12,40] A number of studies have examined the human and environmental health benefits and risks of irrigating with treated wastewater. One such study found personal care product and endocrine distributor concentrations in leafy vegetables irrigated with reclaimed water their existence in these vegetables would likely have no impacts on health based on an average American diet[41] . In a case study examining the effects of long term irrigation with recycled water, researchers found that while treated wastewater may contain high concentrations of endocrine disruptors, percolation through the saturated and unsaturated zones above an aquifer can be sufficient in removing harmful pollutants so that groundwater quality is unaffected; however, these conclusions may not be true in areas where the water table is near the land surface.[42] Irrigation with recycled water can lead to the accumulation of salts, nutrients, and minerals in the soil; however, these issues can be avoided by adapting irrigation techniques and regular monitoring.[14,40] Additionally, farmers can offset their fertilizer needs by using reclaimed water that typically has a higher concentration of nitrogen than traditional water sources.[8,13,40] The use of reclaimed water for irrigation has proven effective in contexts like Bakersfield, California where an agreement between the North Of River Sanitation District and Sill Properties has been in place since 1990 to use secondary treated effluent for irrigation of fodder crops.[43,44]

Industry and manufacturing is responsible for approximately 5% of total U.S. water withdrawals,[17] but is largely regionalized and can be responsible for up to 75% of total withdrawals within some counties.[21] The United States has an extensive history of using recycled water for industry and manufacturing, including on-site and planned reuse from WWTPs.[16] Due to water quality requirement differences, there are only certain operations that can offset their water withdrawals by sourcing water from municipal wastewater treatment facilities without additional on-site treatment.[45] The three industrial sectors most heavily concentrated in water stressed regions of the United States are primary metals, transportation equipment, and fabricated metals, all of which have relatively low water quality requirements.[46] Industries like paper production[47] and data center cooling[48,49] have also been successful applications of water reuse from municipal sources.

2.2 Administrative and Policy Considerations

Regulatory challenges can create significant barriers to the development of water reuse projects.[11,15] The absence of clear enforceable guidelines leaves municipalities without explicit permission to reuse reclaimed water and even if utilities take the initiative to develop these resources, they may lack knowledge on the appropriate paring of reclaimed water sources with different end uses.[11,25,50] These issues are made more apparent as water reuse practices expand geographically and in diversity of end-uses.[24] The United States does not currently have federal legislation or explicit policies that directly govern water reuse. Legislation such as the Clean Water Act (33 U.S.C. §1251 et seq.) and Safe Drinking Water Act (42 U.S.C. §300f et seq.) regulate water quality in natural bodies of water and public water systems, respectively, and serve as a baseline for developing regulations for recycled water projects. In 1992, 2004, and 2012, the EPA published *Guidelines for Water Reuse* that serve as a set of suggestions from which individual states can develop specific laws or regulations. Many states have developed codified legislation outlining appropriate water reuse while other states have non-legislative departments that regulate water reuse.[25] The issue of advancing water reuse in the absence of clear policy is recognized by the EPA and is addressed by several actions in the ongoing Water Reuse Action Plan.[51] Other work by Hastie et al.[25] provides an analysis of patterns and trends in U.S. state water reuse policies and the results and underlying data from those analyses are used to inform this study.

3 Methods

3.1 Data Collection

The data used for this analysis were compiled from government agencies including the Environmental Protection Agency (EPA), Energy Information Administration (EIA), United States Department of Agriculture (USDA), and the United States Geological Survey (USGS) (Table S1). For each data source, we utilized the most recently published data except for irrigation data where we sought to maintain temporal uniformity between multiple data sets that were combined to determine our final irrigation estimates. Some value were reported in monthly or seasonal averages but we converted all values to uniform units of million gallons per day (MGD). Using discrete spatial data, we locate some water users and treatment facilities at their unique self-reported latitude/longitude while our industrial water withdrawal data are aggregated to a HUC-12 scale due to data limitations. The hydrologic unit code or "HUC" scale is a method of subdividing watersheds in the United States. The first division (HUC-2) delineates 21 regions in the United States with the HUC-12 scale represented by the 6th division.

Data relating to discharges of reclaimed water were gathered from the EPA's most recent Clean Watershed Needs Survey from 2012.[52] We also included data from the 2008 survey from South Carolina because their data were not included in the 2012 survey.[53] The Clean Watershed Needs Survey (CWA §516(b)(1)(B)) is mandated by the Clean Water Act

(33 U.S. Code §1375) as a means of assessing the financial cost of meeting the goals laid out in the Act. This survey includes data from publicly owned treatment works defined as "any devices and systems used in the storage, treatment, recycling, and reclamation of municipal sewage or industrial wastes of a liquid nature" (CWA §212(2)(A)). The information relevant to our study includes the locations of wastewater treatment facilities, effluent treatment levels, and annually averaged daily flow rate in units of MGD. We filtered these data to only include facilities designated as "treatment" and "wastewater" where location and flow rate data were available.

To examine power plant demand, we used self-reported data from the EIA that include power plant location, monthly withdrawal, and cooling system type. We used data from 2018 because those were the most recently available complete data at the time of analysis. We specifically used Form EIA-923 to find water withdrawals, cooling system type, and operating status.[54] Form EIA-860 was used for power plant location and water sources.[55] EIA-923 reports water withdrawals for individual cooling systems (for facilities with a nameplate capacity of 100 MW or greater) while EIA-860 reports for each generator at a facility (for facilities with a nameplate capacity of 1 MW or greater). When determining the cooling water demand at each facility, we used withdrawal values rather than consumption because these values more accurately represent the volume that must be delivered for the facility to operate. For facilities that report consumption but no withdrawal, we consider consumption equal to total demand. EIA-923 reports the type of cooling systems that exist at each facility, and our analysis only considers recirculating cooling systems.

We used the 2017 Cropland Data Layer,[56] the 2018 Irrigation and Water Management Survey,[57] the Moderate Resolution Imaging Spectroradiometer (MODIS) Irrigated Agriculture Dataset,[58] and work by Kukal and Irmak[59] to quantify potential demand for reclaimed water for agricultural irrigation. The Cropland Data Layer from 2017 is a raster file that identifies land cover in the contiguous United States at a 30-meter resolution and indicates 113 different landcover types, of which 106 indicate individual crops or crop combinations.

The 2018 Irrigation and Water Management Survey is a subset of the Census of Agriculture and reports state-averaged water application for a set of 22 different crop categories. The pairings we used to map the 22 categories from the Census of Agriculture to the 106 Cropland Data Layer categories can be found in Supporting Information Table S2. We used 2017 MODIS data to identify where irrigation occurs and exclude fully rain-fed crops and data from Kukal and Irmak[59] to determine the length of growing season for each state based on U.S. climate region. Combining these resources, we identify where particular crops are being grown, which crops are irrigated, and estimate their daily irrigation requirements during the growing season (Figure S1).

We used data from the EPA's EnviroAtlas database[60] to estimate potential demand for reclaimed water for industrial and manufacturing facilities. These are the only data we utilized in this analysis that are fully pre-processed by another agency, and we used these data directly as reported by the EPA. The EnviroAtlas Industrial Water Use layer reports self-supplied industrial water demand in the United States (excluding power generation) on a HUC-12 scale based on the 2010 Estimated Use of Water in the United States from the USGS.[60] The greatest limitations of this data set is that it only includes self-supplied water withdrawal and excludes industrial water provided by a utility, and does not provide specific latitude/longitude coordinates of withdrawal or any description of the types of facilities. These values are reported in units of million gallons per day, consistent with other data.

Analysis of state water reuse policies was performed based on previous work that developed a database of existing state-level policies in the United States.[25] States were categorized based on the level of treatment required for different end uses, and these treatment requirements were used to determine which watersheds contained at least one WWTP that could provide sufficient treatment for agricultural or industrial and power generation end uses. State policy requirements were categorized as requiring treatment levels of primary, secondary, secondary with disinfection, advanced, or advanced with disinfection. We define primary treatment based on National Pollutant Discharge Elimination System (NPDES)[61] definitions as physical treatment including processes like sedimentation, grit screening, etc. Secondary treatment is required for all point source discharges from publicly owned wastewater treatment plants by the Clean Water Act (33 U.S.C. §1251 et seq.). 40 CFR Part 133 - Secondary Treatment Regulation defines secondary treatment based on water quality indicators (monthly average B.O.D., suspended solids, and pH) and is associated with treatment technologies like activated sludge basins. In cases where states use the term "secondary treatment" or "activated sludge treatment" to describe their required treatment processes but outline water quality indicators mores stringent than 40 CFR Part 133, we classify that level of treatment as "advanced". In line with the EPA,[61] we categorize any treatment beyond secondary as "advanced" including processes such as nutrient removal or filtration. In cases of conflict between the state definition of treatment level and EPA definitions, we categorized based on EPA definitions. These state water reuse policies provide a feasibility filter from a governance perspective.

4 Results

4.1 Key Supplies and Demands

After cleaning and compiling data from the Clean Watershed Needs Surveys from 2012 and 2008, the data set for further analysis included 14,597 sites within the contiguous United States categorized as wastewater treatment plants (WWTPs) that employ at least secondary treatment processes as required by the Clean Water Act. Collectively these facilities generated 32.6×10^9 gallons per day (32.6 BGD) (123.23×10^6 m^3/d) of treated effluent with a median discharge of 0.19 MGD (700.3 m^3/d) per treatment facility. For this analysis, these values were aggregated to a HUC-12 scale with 11,817 watersheds reporting at least one centralized WWTP (Figure 1); 9,812 watersheds contain only one WWTP, 1,544 watersheds have exactly two WWTPs, and 462 watersheds have at least three WWTPs.

We found the median volume of reclaimed water generated at the HUC-12 scale to be 0.21 MGD (787.4 m^3/d). Geographically, supplies of reclaimed water are most heavily concentrated around large urban areas, especially those with combined sewer systems. More detailed descriptive statistics of the discharge from publicly-owned WWTPs on a HUC-12 scale are included in Supporting Information Figure S2.

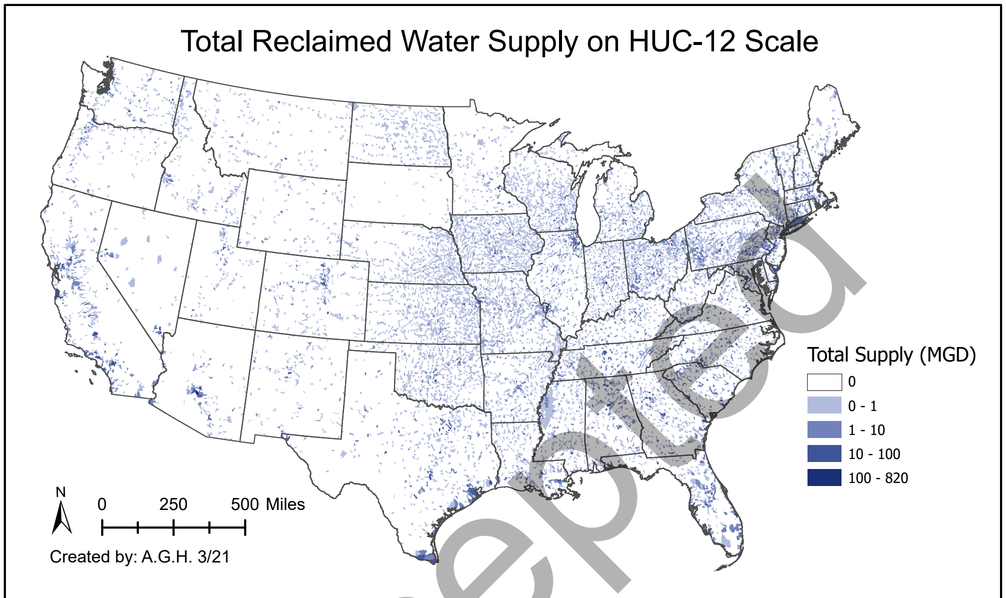

Figure 1: Total production of treated wastewater from publicly owned facilities on a HUC-12 scale. Corresponding to population distribution, there are many watersheds with small discharges of treated wastewater and fewer watersheds with large discharges.

The treatment level at these facilities also plays a key role in determining whether or not they are suitable for supplying water for different end uses. The level of treatment in place at each publicly-owned WWTP in the contiguous United States is influenced by local and regional water quality concerns and appears to be sorted across state boundaries by state-level policies (Figure S3).[25] 7,739 WWTPs only provide secondary treatment, 1,350 use secondary treatment and disinfection, 3,244 use advanced treatment methods, and 2,261 are using advanced treatment with disinfection. These different treatment categories inform which end users can receive effluent from these facilities. The level of wastewater treatment required before reuse for different end-uses based on state policies is reported in Supporting Information Figure S4 as recreated from Hastie et al.[25]

The 2018 Energy Information Administration (EIA) data reported 499 power plants in the contiguous United States with at least one operational recirculating cooling system that does not currently use recycled water. Examining water withdrawal at those facilities, 17 reported no water use in 2018 and were removed from consideration, bringing the final data set to 482 power plants. These power plants represent 675 individual cooling systems with 3 using forced draft cooling towers, 71 natural draft cooling systems, 83 using cooling ponds, and 518 use induced draft cooling systems. The total water withdrawal for these facilities was approximately 36.5 BGD (138.17×10^6 m^3/d). The distribution of these power plants is more heavily concentrated in the Midwest and Eastern United States (Figure S5). A more detailed description of the statistical properties of these data on a HUC-12 scale is included in Supporting Information Figure S6. On a watershed scale, the median demand is 3.7 MGD (13.9×10^3 m^3/d) distributed across 438 watersheds.

Data from the USDA and USGS reveal a total of 12.4 BGD (46.87×10^6 m^3/d) of water used for irrigation in the contiguous United States distributed across 38,601 HUC-12 watersheds (Figure S7, Figure S8). The estimated total area of irrigated cropland in the United States is 45,916,257 acres (18.6×10^6 ha). An average watershed contains 1,185 acres (480 ha) of irrigated cropland with an median demand of 0.02 MGD (77.1 m^3/d). Geographically, irrigation demand is heaviest in the regions overlaying the Ogallala, Central Valley, and Mississippi Aquifers. Irrigation in the Western United States is also densely clustered around river systems like the Snake and Columbia rivers.

Industrial self-supplied water withdrawal data from the U.S. EPA report total withdrawals of 20.8 BGD (78.62×10^6 m^3/d) distributed over 38,754 HUC-12 watersheds in the contiguous United States (Figure S9). While industrial facilities represent withdrawals at discrete locations, these data are reported by the EPA at a HUC-12 scale and do not include information on the type of industrial users that exist in which areas. The median industrial water use on the HUC-12 scale is 0.04 MGD (144.3 m^3/d). Geographically, the watersheds with the greatest demand for industrial water are located in major cities, and more heavily concentrated in the eastern United States. Supporting Information Figure S10 includes a more detailed statistical description of these data.

After estimating total non-potable water demand for power generation, irrigation, and self-supplied industry, these values were aggregated on a HUC-12 scale. These demands are distributed across 54,062 watersheds, with a median watershed demand of 0.064 MGD (243.5 m^3/d) (Figure 2, Figure S11). In total, 29,492 watersheds have industrial water use as their greatest demand, 24,217 are dominated by irrigation, and 353 watersheds are dominated by demand for power generation (Figure S12). Examining these data spatially, demands tends to be largest around large urban areas or in regions with irrigated agriculture, near either critical aquifers or river systems. The watershed with the greatest total demand has an average daily withdrawal of 2.9 BGD (10.96×10^6 m^3/d) for the Comanche Peak Nuclear Power Facility in Texas. The 20 watersheds with the greatest demand for non-potable water are all characterized by high demand for thermoelectric power plant cooling, but power generation as a whole represents a relatively small number of discrete demands compared to irrigation and industry.

4.2 Watersheds Matching all Criteria

Within the twenty-three states that allow the use of recycled water in an industrial context, including for power plant cooling, there are 999 watersheds that have at least one WWTP that is currently discharging water at a level of treatment that matches the quality required for demands within the same watershed (Figure 3). If all supplies are allocated to industrial demands within the same HUC-12 watershed, a total of 760 million gallons per day (2.9×10^6 m^3/d) of non-potable freshwater demands can be replaced by reclaimed water, which equates to a median demand offset of 0.15 MGD (568 m^3/d) in each watershed with a potential industrial or power generation reuse project (Figure S13).

Within the thirty-five states in the contiguous United States with policies addressing irrigating with recycled water, there are 2,408 watersheds with matching supply and

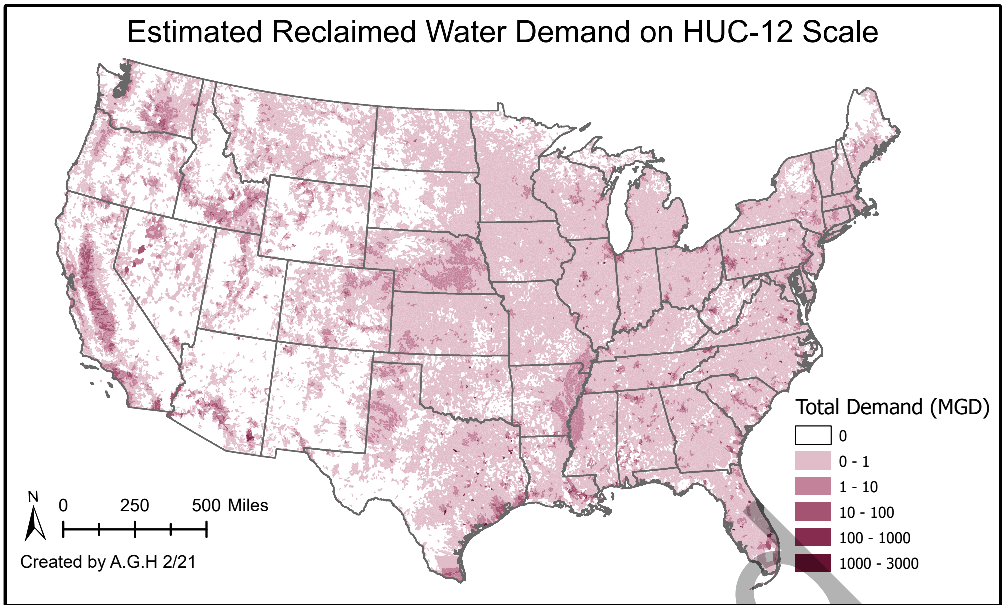

Figure 2: Estimated total non-potable water demand from power generation, irrigated agriculture, and self-supplied industry and manufacturing across the contiguous United States. There are few watersheds with very large demands and many watersheds with relatively little demand.

demand water qualities based on the current level of treatment in place at WWTPs (Figure 3). Appropriate water quality was determined based on state policies for non-food crops because they are less stringent and a more exhaustive collection of possible water reuse opportunities (Figure SI 4). If all supplies are allocated to agricultural demands within the same watershed, a total of 189 million gallons per day (715 $\times 10^3$ m^3/d) of traditional water resource demands can be offset by reclaimed water (Figure S13). On a watershed HUC-12 scale, this offset equates to a median decrease in traditional water withdrawal of 11,227 gallons per day (42.5 m^3/d).

4.3 Data Challenges and Uncertainty

As with any data-driven methodology, this work includes a number of uncertainties that could affect the final numerical results. For each analysis, the most reliable publicly available data were used. The greatest source of potential error comes from combining data from multiple sources, different reporting years, monitoring and collection methods,

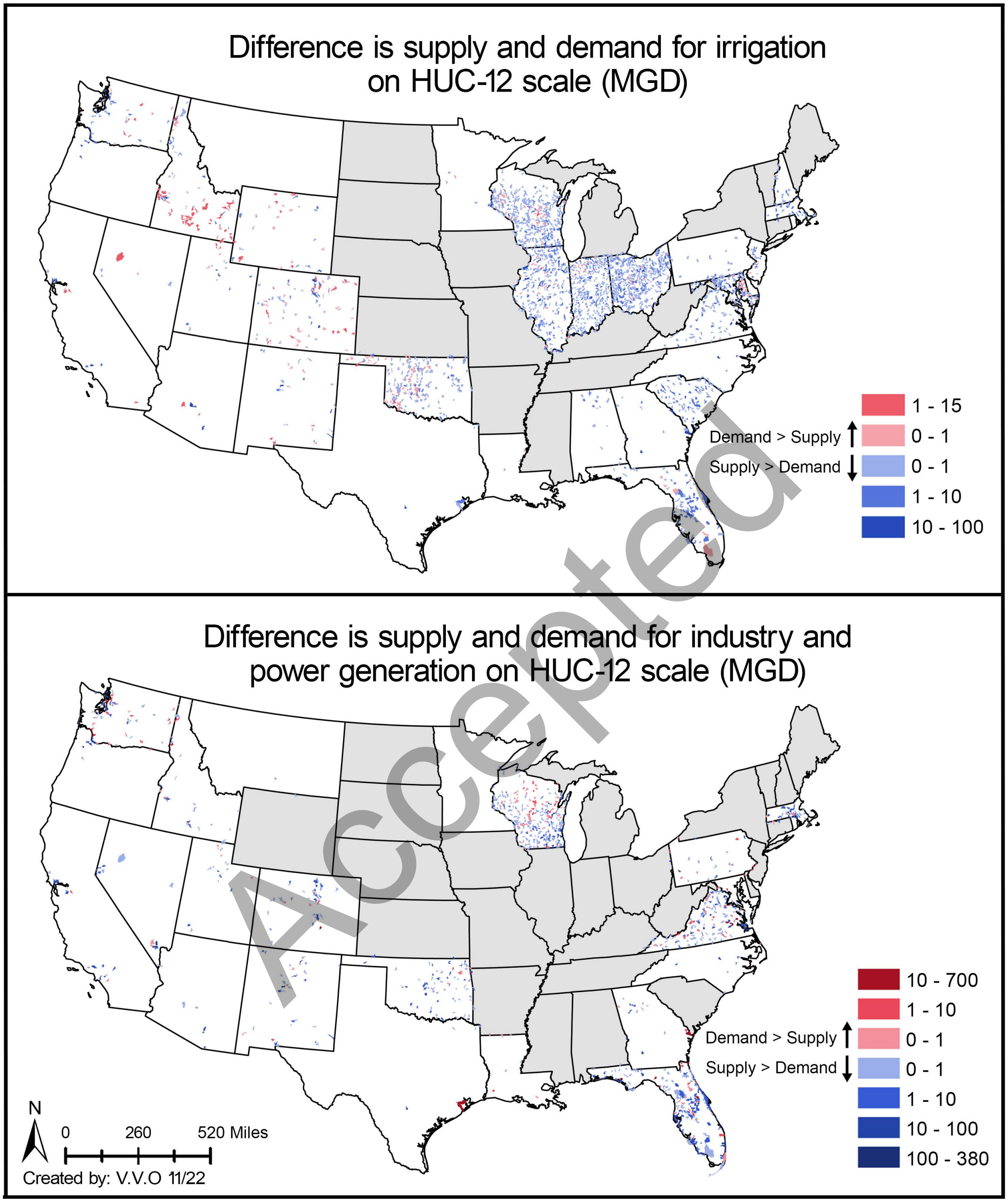

Figure 3: The difference in potential supply of reclaimed water and non-potable demand in HUC-12 watersheds where both supply and demand exist at an appropriate water quality based on state policies. States lacking clear non-potable water reuse policies are shaded gray.

and different spatial and temporal scales, which are prevalent problems across state and national water use databases.[62]

A HUC-12 scale is suitable for this analysis given data accessibility constraints, but water resource decisions are often made on a municipal or county scale where reclaimed water can be shared across watersheds. Using a hydrologic division may exclude opportunities for reuse between WWTPs in one watershed with water users in a neighboring watershed; this boundary problem occurs broadly in spatial analysis and could be potentially solved using finer resolution location-specific data on water users.

The Clean Watershed Needs Survey, which provides data on reclaimed water flow rates and location, only reports data from publicly-owned facilities, so this analysis excludes potential recycled water supplies from privately-owned wastewater treatment plants. Additionally, this analysis relies on the CWNS's classification of facilities as "treatment" and "wastewater". Upon examination, some very small facilities that fall within these categories were found to be miscategorized or were so small that they would likely not provide treated wastewater at a flow rate that is economically feasible. These very small facilities are still included in our data set and final analysis, but are not considered to be highly feasible options for water reuse.

EIA forms 860 and 923 have been used in a number of publications studying water withdrawals for power, but have also come under scrutiny for certain inaccuracies.[63,64] One source of uncertainty is that these EIA data are self-reported and in some cases are inconsistent between forms. These self-reported data are not collected using a uniform method and in cases where actual data are not available, estimates are used.[65] EIA and USGS estimates of national water withdrawals for power generation have been compared to water withdrawal coefficients based on power plants attributes, with variation in the results of these different methods showing some reported EIA withdrawal and consumption data falling outside of thermodynamically plausible bounds.[64,65]

To estimate irrigation demand, spatial and tabular data from three different sources were combined. The Cropland Data Layer describes where different crops are grown in the United States and has historically underestimated total cropland in the United States compared to other similar data sets.[66] One factor that likely contributes to this underestimation is the fact that direct pixel counting is used to develop this data set, which can misclassify pixels or be misaligned with other spatial data.[66] Boryan et al. describes in detail the purpose and methods behind the Cropland Data Layer project and how its methodology has changed over time.[67]

Crop irrigation data from the 2018 Irrigation and Water Management Survey also introduces error because it reports uniform irrigation practices across an entire state and uses self-reported data from a sample set of irrigators to determine these state-level averages. This dataset was used rather than evapotranspiration estimates to determine the volume of water applied to crops, including runoff. Appendix A of the survey provides a detailed description of the statistical methods used to develop this data set.[68] To maintain the anonymity of irrigators' water use, some states do not report irrigation for specific crops. For those values, we used estimated average irrigation across the Water Resource Region or nation as a whole. While the Cropland Data Layer reports land use for 106 different crop types, the Irrigation and Water Management Survey only provides irrigation values for 22 different crop types; Supporting Information Table S2 matches the 106 landcover categories to the 22 crop types in the survey. While the exact quantity of irrigation water applied has some degree of uncertainty and is notably smaller than other estimates,[17,63,69] the relative water intensity of different crops and different regions in the United States provides an acceptable spatial representation of irrigation water demand, for the purposes of this study.

The MODIS Irrigated Agriculture Dataset for the United States (MIrAD-US) identifies irrigated agriculture and is developed from three underlying data sets that each have some degree of uncertainty. Data from the USDA Census of Agriculture, the MODIS Normalized Difference Vegetation Index, and NLCD Landcover mask are all combined to generate the final product indicating where irrigation occurs in the United States. A major underlying assumption of these data is that the maximum normalized difference vegetation index (NDVI) is larger for irrigated crops than non-irrigated crops.[70] It should also be noted that the MODIS irrigated agriculture layer has a resolution of 250 meters compared to the Cropland Data Layer, which is reported at a resolution of 30 meters. MIrAD-US relies on survey and remote sensing data, which is among the best publicly available data sets of irrigated agriculture, but there are still unquantified uncertainties in these data.

Industrial water withdrawal data were taken as-is from the EPA's EnviroAtlas, which maps ecosystem services across the United States on a number of different spatial scales. The EnviroAtlas industrial water use layer is based on county level self-supplied water withdrawal from the USGS Estimated Use of Water in the United States from 2010 and information from an unidentified data set from Dun and Bradstreet containing the location of industrial facilities.[71] These data are ultimately reported on a HUC-12 scale. Other studies have recognized the challenge of finding and using facility-specific water withdrawal and discharge data.[72,73] Additionally, estimates show that 75% of industrial water withdrawal in the United States is self-supplied, so the demand values in this work are conservative and do not consider industrial water demands that are currently met by municipal sources.[21] This analysis could also be enriched with on-site industrial reuse data. Many facilities are required to treat wastewater on-site before discharge to comply with the Clean Water Act and given the right conditions, cost savings can be realized by incorporating additional treatment measures and reusing "waste" water on-site. As on-site reuse becomes more common in the United States we would expect total industrial water demands to decrease.

Many of the data sets that underlie these analysis are self-reported, which introduces inaccuracies due to non-uniform measurement methods, site-specific estimates, or missing data. For some of these data sets, the method used to estimate water withdrawal might change from year to year and grow in accuracy as new technologies are developed and permeate the industry. However, these data sets are the best publicly available spatio-temporal water supply and demand data. The final conclusions and discussion drawn from these data are representative, but these data uncertainties underscore the importance of continued and improved data collection in water-intensive end uses and the use of more detailed local data in the decision making process.

5 Conclusions

Given the widespread availability of reclaimed wastewater and significant nearby demands for non-potable water at a similar quality, there are diverse opportunities for water reuse in power generation, irrigation, and industry and manufacturing within the contiguous United States. We find that nationally, industrial demands for non-potable water are widespread and large in quantity. Self-supplied industrial demand is larger than power and irrigation demand in 70% of the watersheds where both supply and demand exist (Fig. S10). These findings highlight a need for not only greater exploration of municipal wastewater reuse for industrial facilities, but also the need for greater site-specific data transparency in industrial water use.[72,73] A subset of industrial water use is the application of reclaimed water for cooling power generating facilities. One strong motivator of water reuse in power generation is that inconsistencies in water supply and ambient water temperature can have severe negative effects on the reliability of electricity supplied to the grid, which makes a consistent stream of cooling water increasingly valuable.[74,75] An important policy consideration is that the introduction of an additional water source for power plants may have unknown effects in lengthening the lifespan of inefficient power plants that are nearing retirement. Energy and water considerations must be examined together to avoid pursuing water efficiency and conservation to the deficit of climate goals. Within an agricultural context, the use of reclaimed water can help alleviate conflicts over irrigation water supplies and protect sensitive natural water resources. As states adapt their water rights systems and groundwater and surface water policies to combat growing water scarcity and climate change, water recycling can work as a pathway towards more sustainable water resource management. The application of reclaimed water for irrigation is unique in that it may represent a transfer of water from urban areas to outlying peri-urban or rural areas, which can provide relief from historic conflicts in water stressed regions.

Our analysis reveals that supply-demand suitability is heavily influenced by the quality of water treatment in place at existing WWTPs and whether or not state policies are more or less stringent than current treatment. States like Florida and Wisconsin stand out in Figure 3 because they have many WWTPs that use advanced treatment processes with disinfection. Alternatively, Colorado has relatively few wastewater treatment facilities that used advanced technologies, but their water reuse policies require less stringent treatment before recycling so there are more options for reclaimed water supplies. In western states, population is less dense and water quality concerns are not as heavily emphasized in water policy, so existing wastewater treatment processes tend to be less advanced, which can detract from water recycling opportunities. Over time as wastewater treatment technologies improve and saturate the industry, we anticipate a growth in water reuse opportunities, especially in states like Texas with large demands but limited reclaimed water resources at a sufficient quality for reuse. There are potential opportunities for water reuse in a number of states that do not currently have relevant legislation or policy but large existing demands for non-potable water. Advancement of water reuse in states without existing policy can progress in a number of ways through the advancement of data sharing, infrastructure improvements, and proven success through local projects potentially partnered with universities or large private water users.[25] Understanding the main users of non-potable water and the current condition of treatment infrastructure can help inform water reuse policies at the state level. Recycled water legislation in the United States has historically been reactive rather than proactive and many recycled water projects exist in states with no formal legislation but are driven by local initiatives. This nationwide policy discrepancy introduces the question of whether state water reuse polices should be developed in consideration of current wastewater treatment technologies or developed in such a way to promote the improvement of existing wastewater treatment plants.[25]

While this study helps identify general conclusions about current opportunities for water recycling, the advancement of water reuse in the United States must balance local, regional, and national considerations. Many water reuse studies have been performed at the regional or local level,[22,23] but the challenge still exists of integrating national-level conclusions with site-specific insights. While appropriate supply, demand, and policy are crucial criteria for implementation of projects, these factors do not ensure that water recycling is a suitable solution for the areas identified, nor do they exclude projects in areas not identified for potential success. There are a number of location-specific considerations that are not addressed in this work: water supply scarcity,[76] local financial considerations and decision making,[27] end users' willingness to pay,[77] or the public perception[78] that might enhance or detract from non-potable water reuse in the future. Potential water users may be unaware of the availability of reclaimed water or may be hesitant to engage in water recycling without clear guidelines and proven success. Water recycling can be effective for other non-potable end uses beyond those considered in this project, but in practice, these considered applications are relatively common and represent a majority of water withdrawals in the United States. As water scarcity threats continue to grow and expand, water reuse is likely to become a more attractive solution in many communities and we are currently in the position to proactively develop a more thorough understanding of best practices and interconnections between water reuse and related industries.

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Supporting Information Available

The following files are available free of charge.

- Supporting Information Figure S1-13 and Table S1-S3 as referenced in text with associated citations.
- Underlying data and code used for analysis can be found at: https://www.hydroshare.org/resource/4cc681c07f674d3db766efa1afd5625a/

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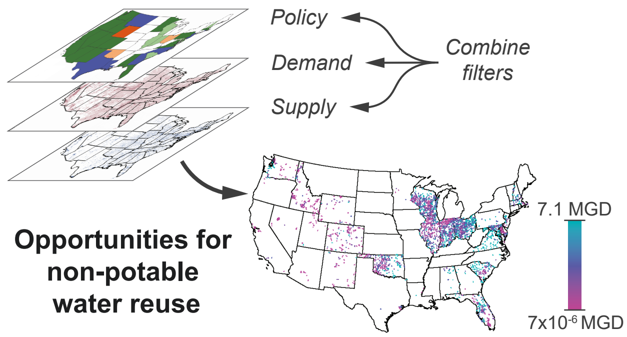
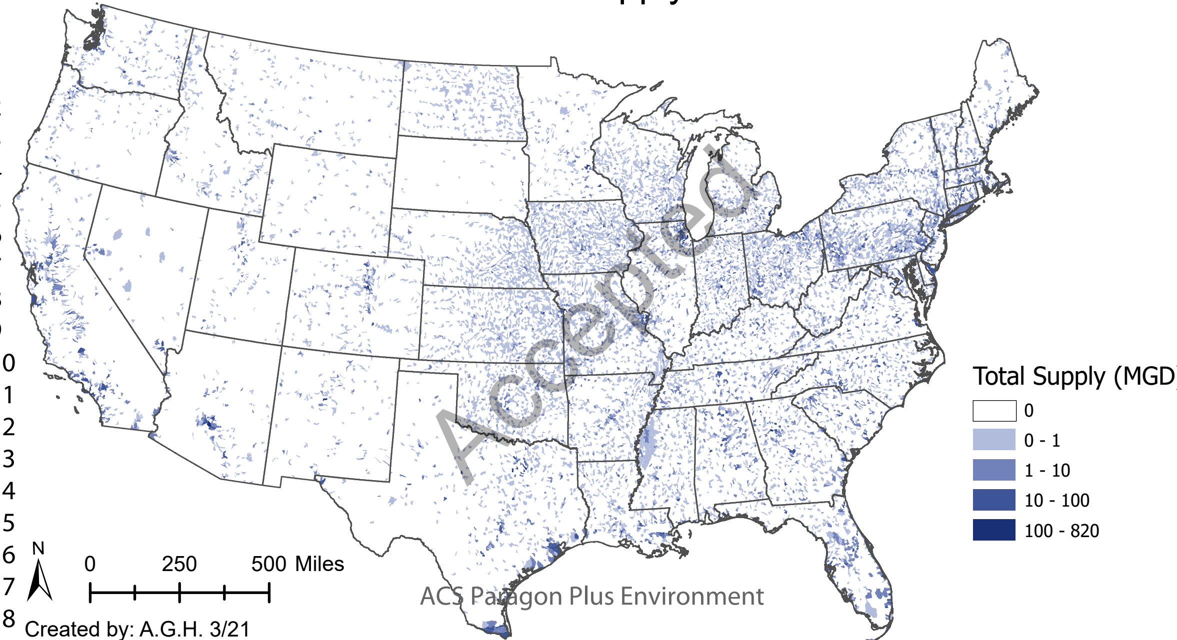
781 # TOC Graphic



Total Reclaimed Water Supply on HUC-12 Scale



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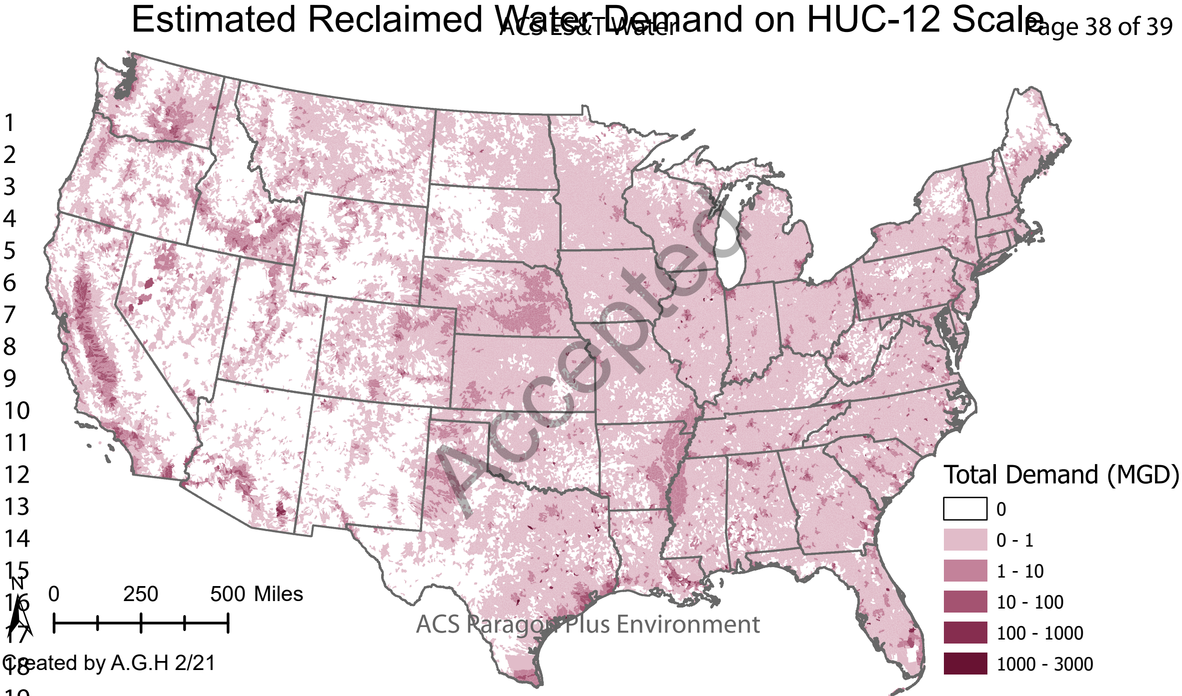
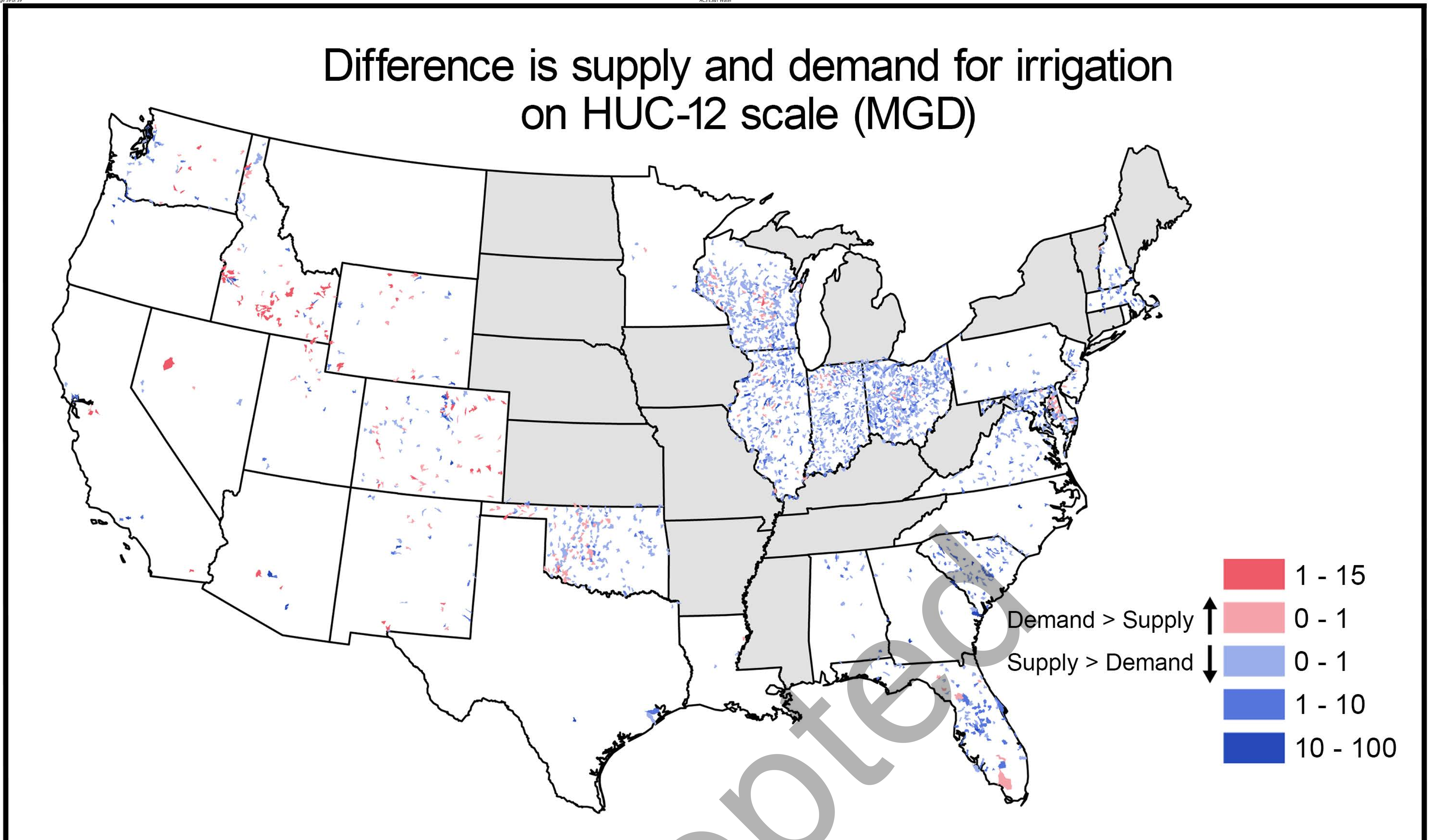
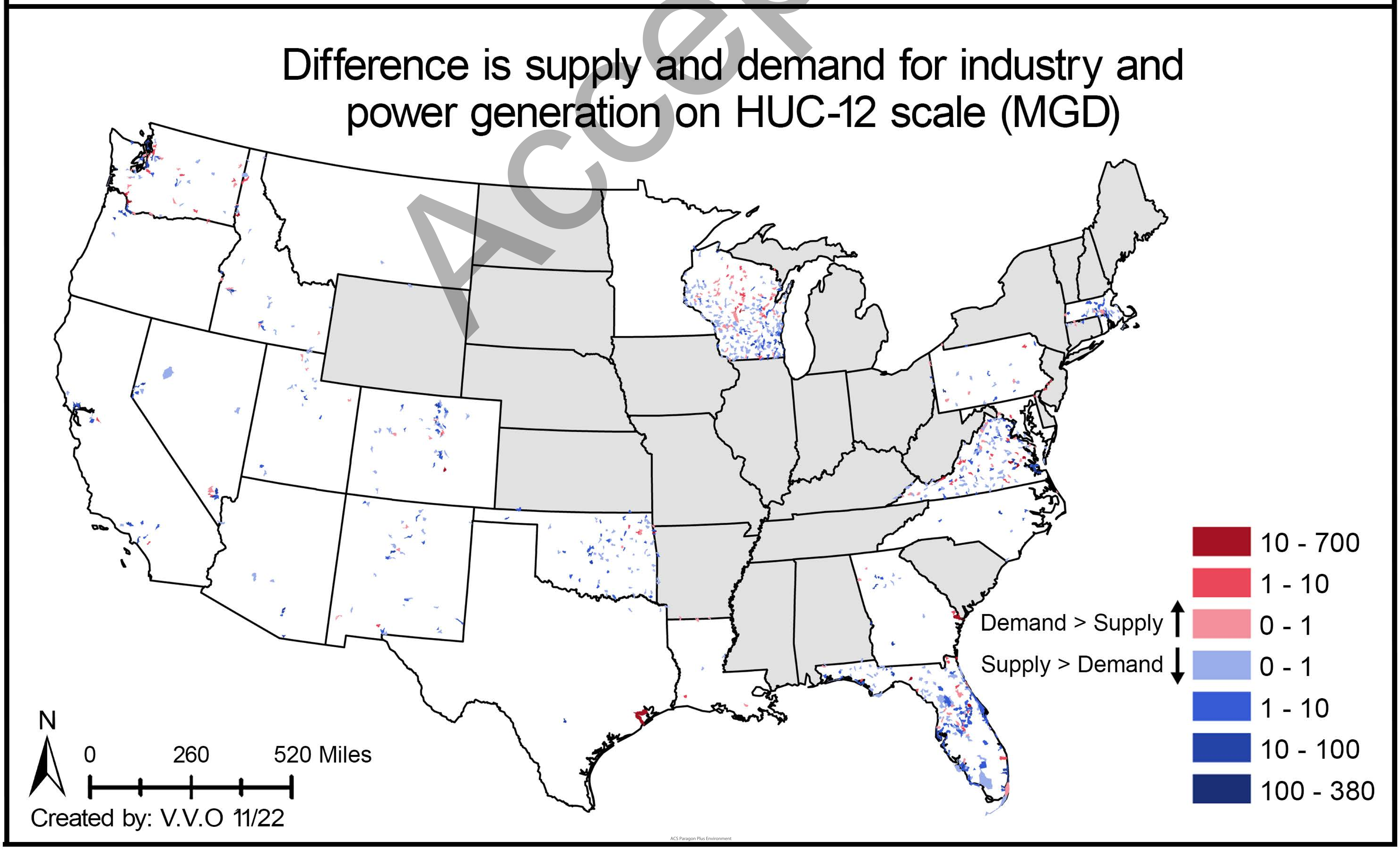



Difference is supply and demand for irrigation on HUC-12 scale (MGD)
Demand > Supply
Supply > Demand
1 - 15
0 - 1
0 - 1
1 - 10
10 - 100


Difference is supply and demand for industry and power generation on HUC-12 scale (MGD)
Demand > Supply
Supply > Demand
10 - 700
1 - 10
0 - 1
0 - 1
1 - 10
10 - 100
100 - 380
N
0
260
520 Miles
Created by: V.V.O 11/22