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## Evolving Roles of Blue, Green, and Gray Water in Agriculture

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## **Evolving Roles of Blue, Green, and Grey Water in Agriculture**

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# Advancing Agricultural Water Security and Resilience Under Nonstationarity and Uncertainty: Evolving Roles of Blue, Green, and Grey Water

Paula L.S. Rees

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With population expected to rise to close to 10 billion by the year 2050 (UN Department of Economic and Social Affairs 2017), the world faces an extraordinary agricultural and water management challenge. Food security, however, is a current as well as future problem. The World Health Organization estimates that today nearly 821 million people (~10.9%) are undernourished, and in Sub-Saharan Africa 29.5 to 48.5% of the population, depending on region, faced severe food insecurity from 2014-2017 (FAO et al. 2018). The most critical food shortages tend to correspond with areas under water stress, and the poor are most susceptible (FAO et al. 2018). Meeting the nutritional and caloric needs of the world population will require a combination of increased food production, food waste reduction, and improved food storage and delivery infrastructure systems. Effective management of water resources will be key to success.

In 2004, Falkenmark and Rockström introduced the green-blue water paradigm, which has since gained widespread acceptance in the international and U.S. water management communities. This framework has been expanded to include reclaimed and/or grey water (Dobrowolski et al. 2008; Waskom and Kallenger 2009). Blue water is the water storage in streams, lakes, wetlands, glaciers, snowpack, and saturated groundwater. Green water is soil moisture in the unsaturated zone. Grey water is classically defined as wastewater from domestic activities such as laundry, dishwashing, and bathing

which can be recycled and used, but of greater significance in terms of volume is reclaimed water from municipal wastewater. Reclaimed water is an important commodity in many areas of the world including areas of the U.S. The blue/green/grey framework has the potential to significantly improve water management within the agricultural domain.

With this in mind, in 2013, the United States Department of Agriculture (USDA) National Institute of Food and Agriculture (NIFA) issued a request for applications to “provide a global view of the challenges and the opportunities for future research, education and extension via presentation of a wide range of forward-looking perspectives on blue, green and grey water issues related to agriculture.” USDA award number 2013-51130-21485 supported a special track at the 2014 joint annual conference of the Universities Council on Water Resources (UCOWR), National Institutes for Water Resources (NIWR), and the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) entitled *Advancing agricultural water security and resilience under nonstationarity and uncertainty: Evolving roles of blue, green and grey water*. The conference track summarized the state of our knowledge and provided a global view of the challenges and the opportunities for future research, education, and extension via presentation of a wide range of forward-looking perspectives on blue, green, and grey water issues related to agriculture. Proceedings from the conference as well as abstracts

and videos of the presentations are available on the Massachusetts Water Resources Research website: <http://wrrc.umass.edu/events/blue-green-grey-water-agriculture>. A special session was subsequently held at the 2017 conference. This special issue of the Journal of Contemporary Water Research and Education (JCWRE) is the final deliverable of the USDA grant.

The issue begins with the paper *Blue, Green, and Grey Water Quantification Approaches: A Bibliometric and Literature Review* by Stanley Mubako, which provides an overview of methodologies for quantifying blue, green, and grey water in studies published from 2000 – 2018, including the most popular publications and most cited authors, an assessment of the spatial scale analyzed, and which components of the blue, green and grey paradigm were included in each study. Insight on approaches taken in the literature can lead to a better understanding of how production and consumption decisions impact freshwater resources.

In *Agricultural Use of Reclaimed Water in Florida: Food for Thought*, Lawrence Parsons examines the use of reclaimed water for agriculture irrigation in Florida over the last 50 years. Florida provides an example of how clear regulations and high quality research examining the impact of its use have enabled reclaimed water to become an important water source for agriculture. While agricultural producers and the public were initially opposed to its use, reclaimed water application to crops now has wide support and acceptance. Reclaimed water is currently utilized in 118 systems that irrigate agricultural crops, including 17 that irrigate edible crops. While reclaimed water supplies continue to grow in Florida, competition from public access and industrial users has increased and citrus production and acreage have declined, decreasing the percent of agricultural reuse. This may change if growers ask for a variance on the prohibition on direct contact of reclaimed water with crops eaten raw, as has been allowed in California for more than 30 years. Such a variance could reduce demand on groundwater for freeze protection of strawberries and blueberries.

In their paper entitled *Grey Water: Agricultural Use of Reclaimed Water in California*, Sheikh,

Nelson, Haddad and Thebo provide an overview of how impediments, incentives, and competing demands contribute to wide variability in agricultural water reuse practices across the U.S. and around the world using California as a case study. Drivers for and against water recycling can generally be classified into social, policy, technical, natural, and economic categories. While attitudes can be changed with proper outreach, demonstration, and education, most successful projects require “the persistence of a visionary champion” to bring stakeholders together in order to overcome barriers. Increased understanding of these factors will ideally lead to increased use of reclaimed water for agricultural production.

Effective nutrient management will be important for meeting global food needs, particularly in terms of protecting downstream ecosystems. In the paper *Water Chemistry During Base Flow Helps Inform Watershed Management: A Case Study of the Lake Wister Watershed, Oklahoma*, Austin, Patterson, and Haggard examine the effectiveness of a simple human development index as a framework for prioritizing installation of best management practices to reduce nonpoint sources of nutrients. Post-implementation monitoring must be conducted at the appropriate spatial and temporal scale to evaluate the effectiveness of management plans.

In his paper *Food Security as a Water Grand Challenge*, Courage Bangira describes the challenges posed by population growth, climate change, land degradation, and water stress on food security. Some experts suggest that by mid-century, food production must double to meet the caloric needs of the global population. However a large percent of current global food production is supported either by rain-fed agriculture or unsustainable water use, making water a limiting factor in agricultural production. In addition, food security is about more than just availability. Issues of access to a balanced and nutrient-rich diet and proper storage and preparation of food in its utilization must also be addressed. Investment in irrigation, resource-efficient agricultural technologies, development of new crop varieties, and the application of appropriate regional, national, and international policies will be necessary to meet global food security needs.



In *The Value of Green Water Management in Sub Saharan Africa: A Review*, Clever Mafuta discusses the importance of integrated soil and water management for meeting the food needs of Sub-Saharan Africa. In comparison to irrigation, which is costly in terms of infrastructure and requires access to water sources, green water management can benefit communities across Sub-Saharan Africa. Green water, or water available to the root zone of plants from precipitation, has historically not been included in water accounting and management decisions. This failure to account for an important component of the water footprint in sub-humid and semi-arid regions has perhaps limited management options for improving agricultural productivity. More productive use of green water for agriculture, however, may have unintended impacts to other ecosystems.

The journal concludes with a paper by Colby and Isaaks, *Water Trading: Innovations, Modeling Prices, Data Concerns*, which examines recent Colorado policy innovations related to water trading. Their study highlights the importance of transparent water trading information for making effective water management decisions in real-time as well as the development of economic models to improve evaluation of water trading and its effects. They also note the effectiveness of piloting new water transaction initiatives for shifting policy paradigms. Pilot programs, with their specific end date, can broaden support for permanent policy changes by reassuring those initially opposed, while providing sufficient time to evaluate effectiveness. This paper is of broader relevance for understanding the data and policy innovations that may help address water management challenges in other arid regions.

## Acknowledgments

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journal. This work was partially supported by USDA award number 2013-51130-21485.

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# Blue, Green, and Grey Water Quantification Approaches: A Bibliometric and Literature Review

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**Abstract:** An array of methodologies to quantify blue, green, and grey water have emerged in recent years and are still evolving rapidly, as are efforts to come up with reliable indicators of human appropriation of freshwater resources. This study provides an overview of recent blue, green, and grey water quantification approaches by analyzing publications extracted from the Web of Science database utilizing the Network Analysis Interface for Literature Studies (NAIS) bibliometric analysis tool, covering the period 2000-2018. A steep increase in the number of blue, green, and grey water publications was observed from the year 2009, with the United States and China among the top contributing nations. Blue, green, and grey water quantification approaches used in the analyzed publications were broadly categorized into Water Footprint Assessment, Life Cycle Assessment, and Hybrid methodologies. The Water Footprint Network was the most influential hub in terms of providing the most productive and cited authors. “Water footprint” and “virtual water” were unsurprisingly the trendiest and most cited keywords associated with the sample of analyzed publications. The study provides important insights that are helpful in understanding the diversity of techniques that have been applied to quantify blue, green, and grey water in recent assessment studies.

**Keywords:** *virtual water, water footprint, water scarcity, bibliometric analysis*

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Water is a critical input to most human economic activities. Growing human populations and increasing economic production and consumption activities call for comprehensive freshwater analytical frameworks that cover all water resource components, including water stored in the soil that limits food production potential (green water), surface and groundwater resources (blue water), and freshwater used to assimilate waste (grey water) (Postel et al. 1996; Falkenmark 2000; Falkenmark and Rockström 2006; Hoekstra 2011). Closely related to blue, green, and grey water components are the concepts of “virtual water” and “water footprint.” Virtual water refers to water used for the production of a commodity (Allan 2003), whereas water footprint is a measure of consumptive and degradative freshwater water use associated with all goods and services consumed by one person or the whole

population of a country (Hoekstra 2003; Hoekstra and Chapagain 2008). Thus, whereas virtual water refers only to the volume of water embodied in a commodity, the water footprint indicator broadens the scope of this definition by including spatio-temporal aspects: where and when the embodied water is being used (Hoekstra et al. 2011). Allan (2011) also used the term “virtual water trade” to refer to the amount of water embedded in traded commodities. A key distinction is that virtual water focuses primarily on blue and green water quantity, but water footprint goes a step further to highlight environmental impacts of water use (grey water footprints), in addition to blue and green water footprints (Ridoutt and Pfister 2013). A comprehensive water footprint therefore not only assesses a nation’s consumption of blue water (blue water footprint) and consumption of green water (green water footprint) (Hoekstra 2017),

but also accounts for indirect water consumption through import of water intensive commodities produced in other geographic locations and imported through virtual water trade. Because of this interrelatedness, blue, green, and grey water components are often quantified as part of water accounting approaches that assess virtual water content and water footprints.

## Water Accounting Approaches

Analytical frameworks that quantify blue, green, and grey water are evolving with the emergence of water footprint assessment as a new research field (Hoekstra 2017). In certain studies, these frameworks have been classified into two broad categories of Water Footprint Assessment (WFA) methodologies, and Life Cycle Assessment (LCA) methodologies (Jefferies et al. 2012; Vanham and Bidoglio 2013). WFA is a volumetric approach developed by the Water Footprint Network, but the LCA approach owes its origin to the LCA community (Hoekstra et al. 2011; McGlade et al. 2012; Postle et al. 2012). A fundamental difference between the approaches is that LCA focusses on products, and water sustainability is just one area of focus among others. In contrast, WFA focusses on water management covering products and consumption patterns of individuals at different spatial scales (Jefferies et al. 2012; Boulay et al. 2013). For a more comprehensive assessment of

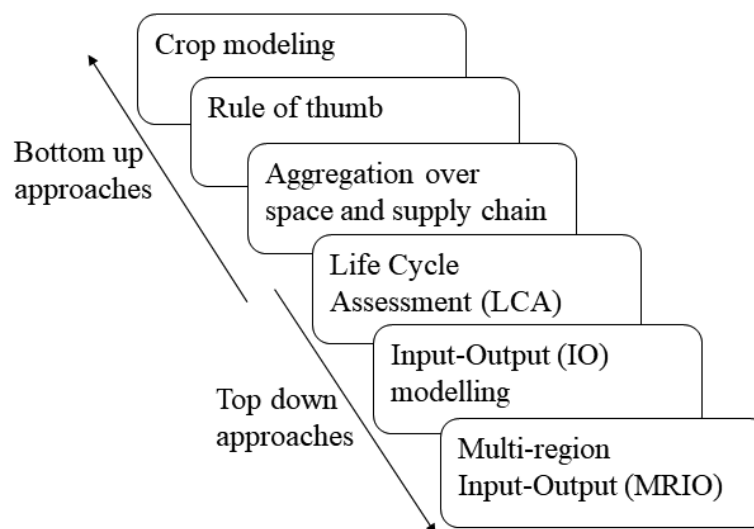
parallelisms, contrasts, and synergies between LCA and WFA, see Jefferies et al. (2012) and Boulay et al. (2013). Some schools of thought have broadly classified water accounting methods into the two general categories of bottom-up and top-down approaches, as shown in Figure 1 (Feng et al. 2011; Yang et al. 2013).

### WFA Approaches

Most WFA methods are indeed a mix of bottom-up and top-down techniques, encompassing methods such as modelling crop water requirements and aggregation of water requirements of various primary and secondary commodities over space and the supply chain (for example, Hoekstra and Hung 2002; Hoekstra and Chapagain 2007; Hoekstra and Chapagain 2008; Hoekstra et al. 2011). Further, WFA uses waste assimilated by freshwater to determine the grey water footprint, adds water volumes without weighting with water scarcity or pollution indicators, and is a geographically explicit indicator that shows location in addition to water use volume and pollution (Hoekstra 2009).

### LCA Approaches

LCA methods include a mix of largely bottom-up approaches used to assess environmental impacts of a product or service over its whole life cycle (Yang et al. 2013). In general, LCA involves an analysis stage such as setting goals and scope,



**Figure 1.** Water accounting methods and approaches. Adapted from Yang et al. (2013).



life cycle inventory, life cycle impact assessment, and interpretation (Vanham and Bidoglio 2013). Examples of LCA-based methods include relative blue water scarcity (Harris et al. 2017), and system-based tools (Al-Ansari et al. 2015). LCA-based methods have been used for applications ranging from assessing environmental impacts of food crops and livestock production, to dairy farming and energy use assessment (Vora et al. 2017).

### Other Major Water Accounting Approaches

Other major approaches that have been widely used to quantify human appropriation of freshwater are based on input-output (IO) modelling, where relationships are determined between direct and indirect water consumption by commodities. Contrary to WFA methods, the virtual water content of intermediate inputs in IO modelling is attributed to the virtual water content of the final product. IO techniques can be applied as individual tools of analysis or in the context of LCA, and have evolved into standalone research fields that have been used to analyze systems ranging from a small factory to the entire world economy and its supply chain effects (Ridoutt et al. 2009; Steen-Olsen et al. 2012; Boulay et al. 2013). Widely applied IO modelling techniques include multi-region input-output (MRIO) analysis and environmentally-extended input-output (EEIO) analysis. MRIO analysis uses a top-down approach to account for environmental pressures through complex supply chains (Steen-Olsen et al. 2012; Mubako et al. 2013; Huang et al. 2017), but the two major goals of EEIO, according to Kitzes (2013), are: 1) assessment of hidden or indirect environmental impacts of downstream consumption activities and, 2) quantification of environmental impacts associated with commodities traded between countries. The technique has been applied in impact evaluation studies that involve water, global carbon, and biodiversity, among other natural resource systems. For a comprehensive overview of the EEIO conceptual framework as well as an evaluation of the approach's strengths and limitations in environmental applications, readers are again referred to Kitzes (2013).

Great strides have been made in recent years to quantify virtual water and water footprints at various spatial scales. However, Yang et al. (2013)

claim that most of these assessments have focussed mainly on blue water, and there is a consequent weakness of conceptual frameworks that quantify green and grey water. The objective of this article therefore is to review blue, green, and grey water quantification approaches from recent years. First, blue, green, and grey water literature is identified through a database search. This is followed by a bibliometric analysis and structured review of water quantification approaches that have been applied in recent studies. The article ends by highlighting how an understanding of blue, green, and grey water quantification approaches could result in better comprehension of how production and consumption decisions impact freshwater resources.

### Methods

Blue, green, and grey water quantification approaches were assessed using bibliometric analysis, followed by a systematic literature review. Bibliometric analysis is a well-established meta-analytical technique that provides a rapid and quantitative way to handle large amounts of literature, and is a pathway to better understanding of research in any particular field of study (Kolle et al. 2015; Feng et al. 2017; Geissdoerfer et al. 2017).

A variety of data analysis tools and guidelines are available to conduct bibliometric analyses, for example Microsoft Excel, BibExcel, BibTex, and Pajek. However, even the most frequently followed guidelines are often not sufficient alone (Petersen et al. 2015), and there is always need to combine or update techniques. For this study, bibliometric analysis was performed using the Network Analysis Interface for Literature Studies (NAILS), an open source exploratory analysis software toolkit that provides a rapid visual overview and deep insight into any field of inquiry (Knutas et al. 2015). The NAILS toolkit uses literature records obtained from the Thomson Reuters Web of Science core collection, a comprehensive database containing high quality records (Gao and Guo 2014; Hajikhani 2017; Zhang et al. 2017). The records were uploaded to the analysis system via a web interface after typing in the keyword search terms "blue green grey water." A systematic literature review must be preceded by a predefined search

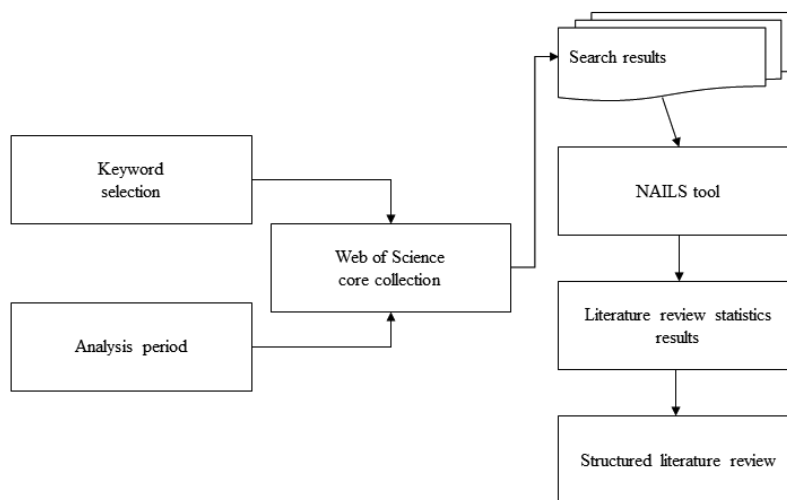
strategy for studies (Kitchenham 2004); keyword selection criteria, for example, the “Population, Intervention, Comparison, Outcomes, Context” (PICO and PICOC) frameworks (Kitchenham and Charters 2007; Moher et al. 2009; Petersen et al. 2015), in addition to inclusion and exclusion criteria for weeding out studies that are not applicable to the research questions (Petersen et al. 2008). For this bibliometric analysis however, the formulation of keywords and search for studies was straightforward and guided by the “blue, green, and grey water” focus of this special issue of the Journal of Contemporary Water Research and Education. Only a few records were retained from a preliminary search for the period prior to the year 1999, so the more recent period 2000–2018 was used as the analysis time frame in NAILS to get insight into the following key aspects in relation to literature on blue, green, and grey water quantification approaches: 1) type and geographic distribution of recent publications; 2) number of articles produced; 3) top 25 contributing authors; 4) 25 most popular and most cited journals; and 5) top 25 most popular and cited keywords. Detailed insights from this exploratory data analysis in NAILS were then used to prioritize blue, green, and grey water quantification literature for further structured review. This study differs from a bibliometric study on the water footprint by Zhang et al. (2017) in terms of the period of analysis, keywords, and the analytical tools used. For a comprehensive overview of literature

review methods focusing on other specific areas of expertise, readers can visit Budgen et al. (2008) for mapping studies in software engineering, Arksey and O’Malley (2005) for scoping studies and their rigor, transparency, and applicability in mapping areas of research in social policy and social work, and Grant and Booth (2009) as well as Levac et al. (2010) for scoping studies in healthcare research. The literature analysis workflow used in this study is provided in Figure 2.

## Results and Discussion

### Type of Publications and Geographic Distribution of Blue, Green, and Grey Water Literature Analyzed

The study period yielded 167 journal articles, 22 proceedings papers, 5 reviews, 2 editorial materials, and 1 letter from the Web of Science core collection. After removal of duplicate records, a total of 192 publications from 59 countries were analyzed. The word cloud in Figure 3 shows that the majority of publications were contributed by the United States and China. These two countries had a share of 15% and 13% of the total number of relevant publications, respectively. Figure 3 also reveals that the contributing countries are a mix of developed and developing countries from all world regions, indicating that blue, green, and grey water issues are globally important. The more prominent contributing countries, mapped in larger letters in the word cloud are to a large extent part



**Figure 2.** Workflow for bibliometric analysis of blue, green, and grey water quantification literature.

of developed or more industrialized countries. This unsurprising result is in agreement with findings of recent bibliographic studies in other academic fields of inquiry (for example Kolle et al. 2015; Kolle and Thyavanahalli 2016; Chen et al. 2017; Feng et al. 2017; Geissdoerfer et al. 2017; Hajikhani 2017; Zhang et al. 2017) where most publications tend to originate from more developed countries due to better access to more research resources.

### Number of Articles Produced

Figure 4 shows the number of recent blue, green, and grey water articles published each year during the analysis period 2000-2018. The general trend shows a steep increase in the volume of publications from 2009 onwards, with the greatest number of publications in 2017. The increasing trend of publications relating to blue, green, and grey water quantification from the Web of Science database indicates that this is still a growing field of inquiry.

### Top Contributing Authors

Figure 5 provides details for the top 25 contributing authors (Figure 5a) and the most cited authors (b) in the field of blue, green, and grey water literature for the analysis period. The

results are listed by lead author only. The top two most productive authors from the Web of Science database for the 2000-2018 analysis period were Mekonnen M. and Herath I., while Mekonnen M. and Hoekstra A. were the most important authors in terms of number of citations (Figure 5b). Most cited authors in the top 25 rank, for example Mekonnen, Hoekstra, Chapagain, and Aldaya have current or previous associations with the Water Footprint Network ([waterfootprint.org/](http://waterfootprint.org/)), indicating that this is one of the most important hubs conducting research related to blue, green, and grey water quantification work in recent years through water footprint assessments.

### Most Popular and Most Cited Journals

In Figure 6 the 25 most important journals are sorted by number of published articles and the number of citations. The top two most important publications were “Journal of Cleaner Production” and “Ecological Indicators” (Figure 6a), but the top two most cited publications were “Hydrology and Earth System Sciences” and “Proceedings of the National Academy of Sciences” (Figure 6b). These results provide insight into the top journal publication counts in terms of importance to blue, green, and grey water literature.



Figure 3. Word cloud of blue, green, and grey water literature contribution by country.

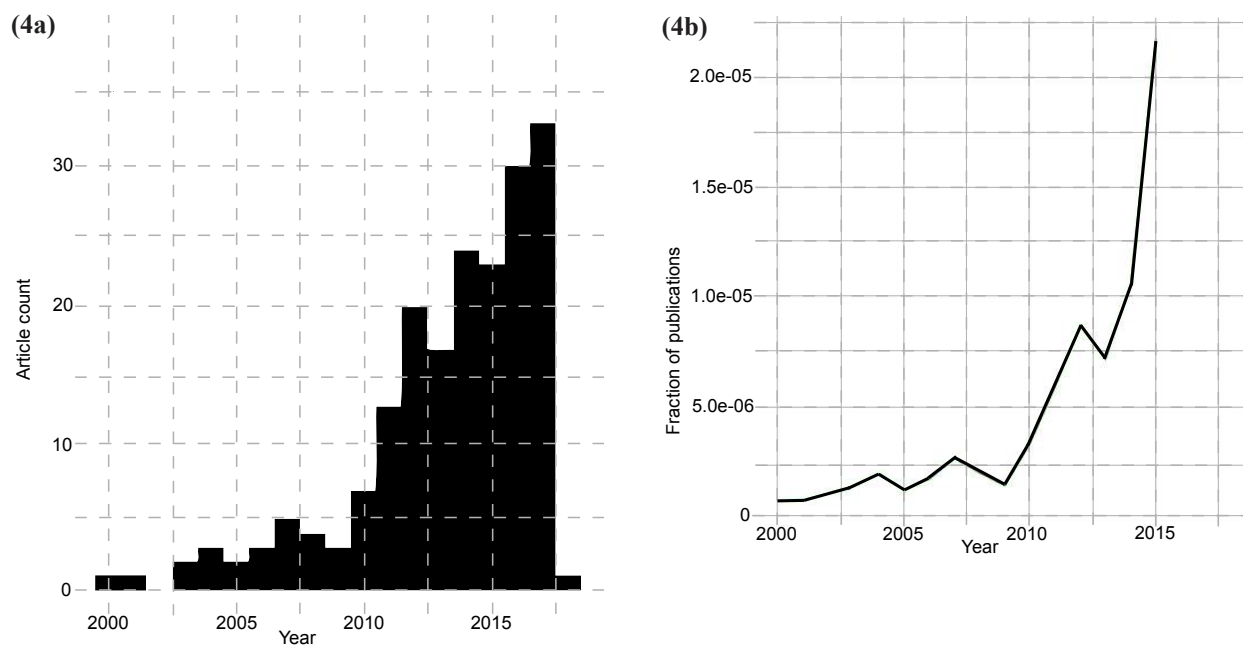


Figure 4. (a) Article citation count by year published, and (b) relative volume of publications.

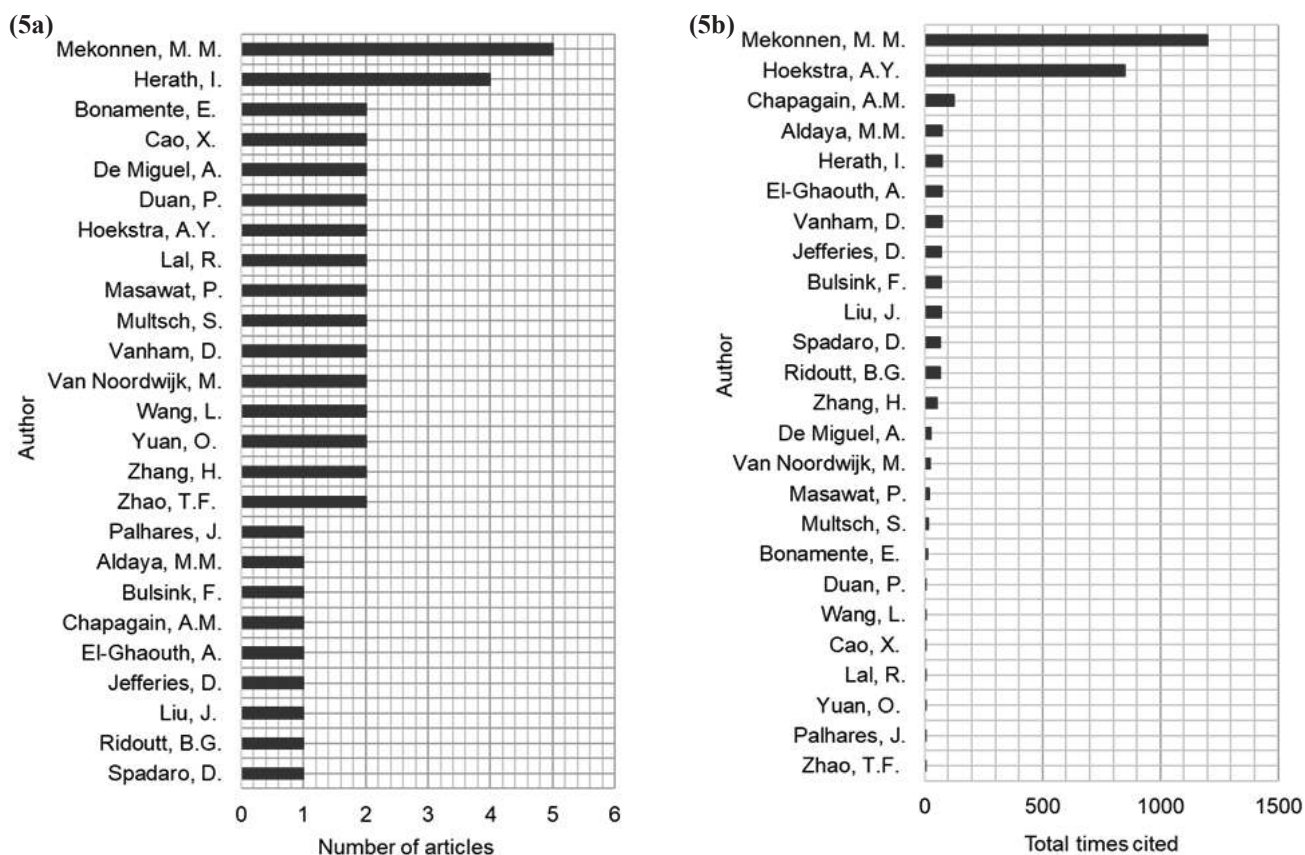
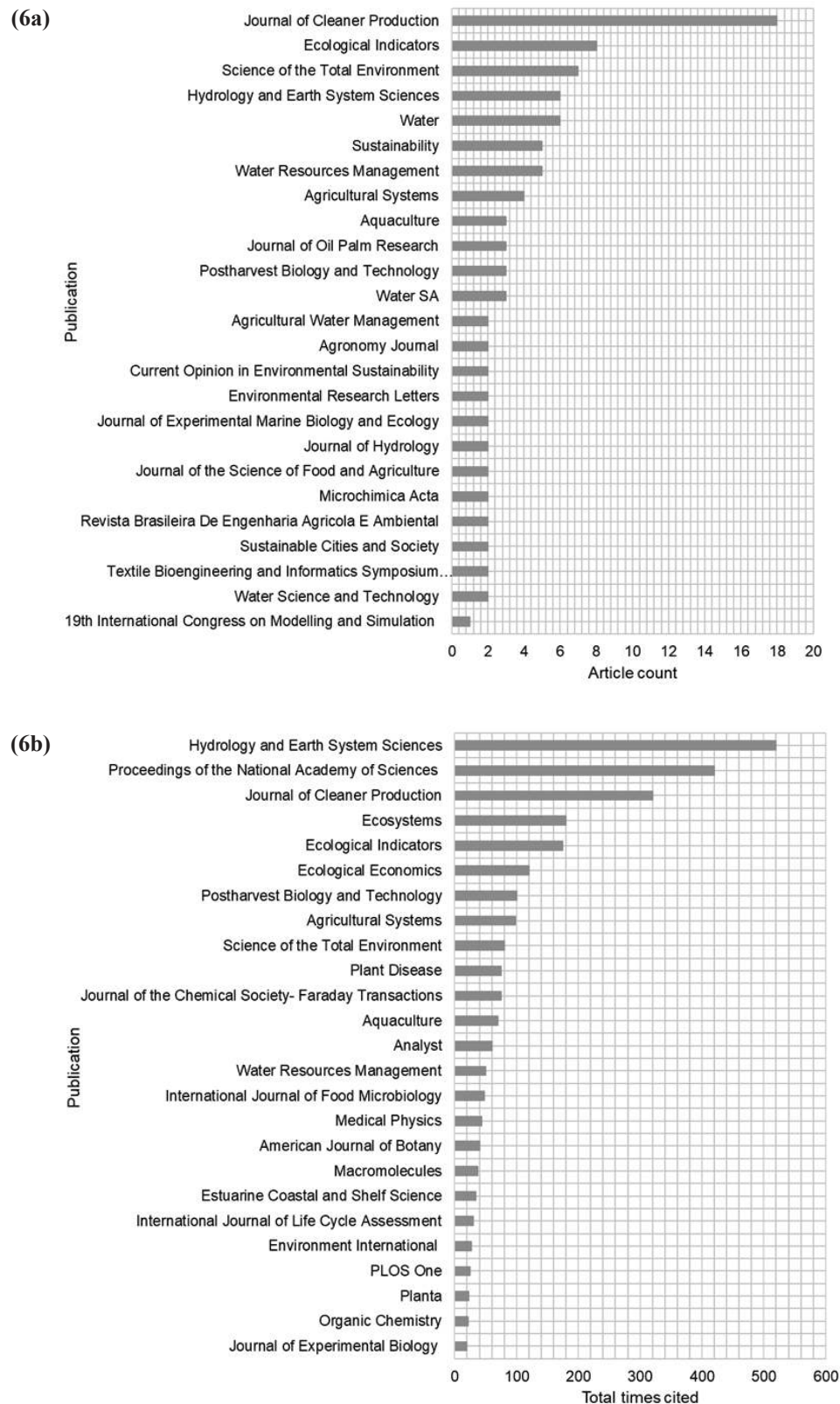


Figure 5. (a) Productive authors according to their blue, green, and grey water publication count, and (b) most cited authors in the field.





**Figure 6. (a)** Most popular publications by article count, and **(b)** most cited publications in relation to their activity in publishing blue, green, and grey water relevant articles.

### Most Popular and Cited Keywords

Figure 7 provides a list of the most popular and most cited keywords in relation to analyzed blue, green, and grey water literature, sorted by the number of articles where the keyword is mentioned, and by the total number of citations for the keyword (Knutas et al. 2015). “Water footprint” is the most popular keyword associated with blue, green, and grey water for the analysis time frame 2000-2018, followed by “virtual water,” “water scarcity,” and “sustainability” (Figure 7a). “Water footprint” is also the most cited keyword, followed by “water pollution,” “sustainable consumption,” and “virtual water trade” (Figure 7b). These keywords provide major insights into the combination of words and “hot topics” that are associated with blue, green, and grey water, and were instrumental in guiding the prioritization of the original 192 Web of Science publications in NAILS to a trimmed list of top 25 publications that were then used for further literature review (Table 1).

### Approaches for Blue, Green, and Grey Water Quantification

Figure 8 highlights the ranking results for the major blue, green, and grey water assessment frameworks associated with the final 25 publications reviewed in this study, as well as the scale of analysis. The summary is for the most important 25 out of the 192 records downloaded from the Web of Science core collection for the 2000-2018 analysis period. The publications are ranked using importance criteria that include in-degree, total citation count, and page rank scores (Knutas et al. 2015).

Among the broad assessment frameworks used to quantify blue, green, and grey water, the WFA methodology is the most popular framework applied, accounting for 16 out of 25, or 64% of the top 25 publications, followed by LCA (24% of the top 25 publications) (Figure 8). The remaining 12% of publications were grouped into a broad category called “Hybrid,” which included a combination of WFA and LCA, and other

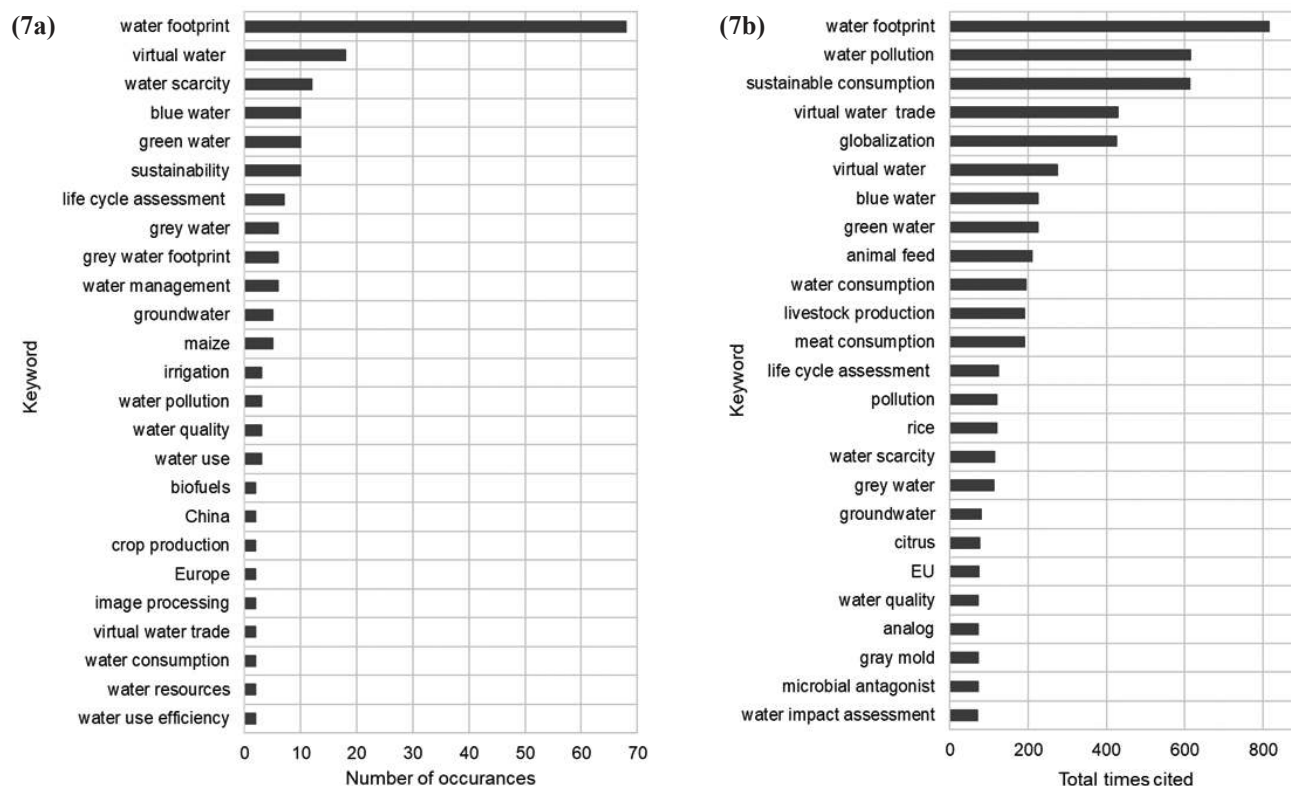


Figure 7. (a) Most popular, and (b) most cited keywords from the analyzed blue, green, and grey water publications.

**Table 1.** The 25 most important papers included in the 192 records downloaded from the Web of Science ranked using the NAILS toolkit.\*

Rank	Year	Study Region / Country	Scale / Location	Focus: Blue, Green, or Grey Water	Broad Study Approach / Assessment Framework	Specific Techniques Used	Reference
1	2011	Global	Global	Blue, Green, Grey	Water Footprint Assessment	Grid-based dynamic water balance model, CROPWAT model	Mekonnen and Hoekstra (2011)
2	2011	Global	Global	Blue, Green, Grey	Water Footprint Assessment	International trade, spatially explicit domestic production	Chapagain and Hoekstra (2011)
3	2010	Global	Global	Blue, Green, Grey	Water Footprint Assessment	Spatially explicit, production & consumption perspective	Mekonnen and Hoekstra (2010)
4	2012	Global	Global	Blue, Green, Grey	Water Footprint Assessment	International trade, production & consumption perspective, spatially explicit	Hoekstra and Mekonnen (2012)
5	2012	Global	Global	Blue, Grey	Water Footprint Assessment	Production systems, feed composition	Mekonnen and Hoekstra (2012)
6	2013	New Zealand	Local/ Marlborough, Gisborne	Blue, Green, Grey	Life Cycle Assessment	Water balance, hydrological perspective	Herath et al. (2013a)
7	2012	India, Ukraine	Local/ Coonoor, Zaporizhia	Blue, Green	Water Footprint Assessment, Life Cycle Assessment	Water accounting, environmental impact assessment	Jefferies et al. (2012)
8	2010	Italy	Local/ Puglia, Sicily, Emilia-Romagna	Blue, Grey	Water Footprint Assessment	Consumption perspective	Aldaya and Hoekstra (2010)
9	2013	China	Local/ Beijing	Blue, Green, Grey	Water Footprint Assessment	Interannual variability	Sun et al. (2013)
10	2013	European Union	Region/ European Union	Blue, Green, Grey	Water Footprint Assessment	Consumption perspective	Vanham et al. (2013)
11	2010	Australia	Region/ Australia	Blue, Green, Grey	Water Footprint Assessment, Life Cycle Assessment	Consumption perspective	Ridoutt et al. (2010)
12	2012	New Zealand	Local/ Waikato, Canterbury	Blue, Green, Grey	Water Footprint Assessment, Stress-weighted Water Footprint, Life Cycle Assessment	Catchment-specific characterization, sustainable aquifer yield, environmental impact assessment	Zonderland-Thomassen and Ledgard (2012)

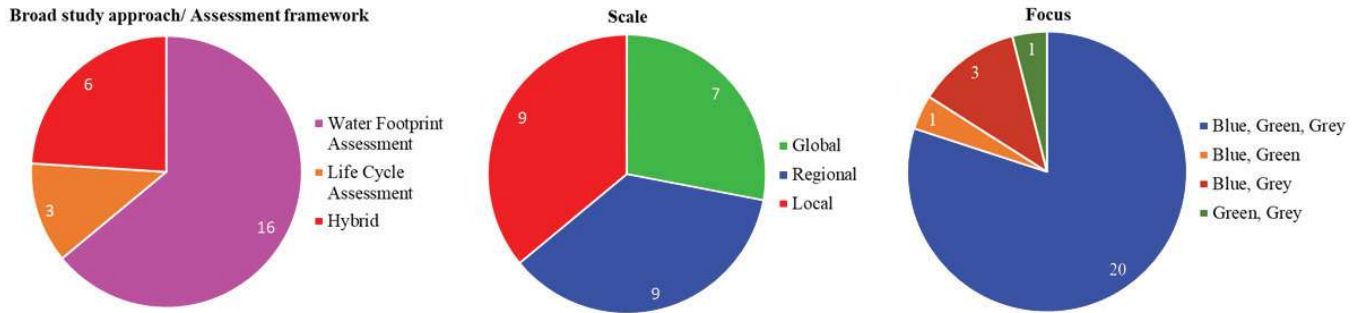
\*The 25 most important papers is an analysis of records downloaded from the Web of Science. The analysis identifies the 25 most important authors, journals, and keywords in the dataset based on the number of occurrences and citation counts. A citation network of the provided records is created and used to identify the important papers according to their in-degree, total citation count, and page rank scores according to the procedure described in Knutas et al. (2015).

**Table 1.** The 25 most important papers included in the 192 records downloaded from the Web of Science ranked using the NAILS toolkit.\*

Rank	Year	Study Region / Country	Scale / Location	Focus: Blue, Green, or Grey Water	Broad Study Approach / Assessment Framework	Specific Techniques Used	Reference
13	2014	Italy	Local/Sicily	Green, Grey	Water Footprint Assessment, VIVA methodology	Production perspective, Tier III approach for grey water footprint	Lamastra et al. (2014)
14	2015	Spain	Region/Spain	Blue, Green, Grey	Water Footprint Assessment	Production systems, feed composition	de Miguel et al. (2015)
15	2012	Global	Global	Blue, Green, Grey	Water Footprint Assessment	Production perspective	Gerbens-Leenes and Hoekstra (2012)
16	2011	New Zealand	Region/ New Zealand	Blue, Green, Grey	Water Footprint Assessment, Hydrological water balance method	Production perspective, water balance	Deurer et al. (2011)
17	2013	Romania	Region/ Romaina	Blue, Green, Grey	Life Cycle Assessment	Production chain analysis	Ene et al. (2013)
18	2014	Morocco	Region/ Morocco	Blue, Green, Grey	Water Footprint Assessment	Grid-based, spatially explicit	Schyns and Hoekstra (2014)
19	2015	China	Local/ Beijing	Blue, Green, Grey	Water Footprint Assessment	Logarithmic mean Divisia index (LMDI) decomposition method	Xu et al. (2015)
20	2013	Nepal	Local/ Districts	Blue, Green, Grey	Water Footprint Assessment	Water balance model, nitrate pollution dilution	Shrestha et al. (2013)
21	2013	Netherlands	Local/ Noord-Brabant	Blue, Green, Grey	Life Cycle Assessment	Environmental impact assessment, model irrigation requirements	De Boer et al. (2013)
22	2015	Global	Global	Blue, Green, Grey	Water Footprint Assessment	Production weighted average	Pahlow et al. (2015)
23	2013	New Zealand	Region/New Zealand	Blue, Green, Grey	Water Footprint Assessment, Life Cycle Assessment Hydrological water balance method	Consumption perspective, freshwater ecosystem impact method, freshwater depletion method	Herath et al. (2013b)
24	2015	South Africa	Region/South Africa	Blue, Grey	Water Footprint Assessment	Direct water footprint	Haggard et al. (2015)
25	2010	Indonesia	Region/ Indonesia	Blue, Green, Grey	Water Footprint Assessment	National water-use accounting	Bulsink et al. (2010)

\*The 25 most important papers is an analysis of records downloaded from the Web of Science. The analysis identifies the 25 most important authors, journals, and keywords in the dataset based on the number of occurrences and citation counts. A citation network of the provided records is created and used to identify the important papers according to their in-degree, total citation count, and page rank scores according to the procedure described in Knutas et al. (2015).





**Figure 8.** Summary of blue, green, and grey water quantification approaches based on the top 25 publications from the Web of Science core collection, 2000-2018.

frameworks such as stress-weighted WFA, the hydrological water balance method, and VIVA methodology (see Table 1).

In terms of spatial scale, 36% of the top 25 publications were conducted at regional level, defined in this study as national boundary or river basin, and a further 36% were at the local level, defined as any spatial scale below the river basin level, such as cities. The remaining 28% were global level studies in scope (Figure 8). This almost evenly distributed spatial scope indicates the applicability of current blue, green, and grey water methodologies across different spatial scales from global to local level.

Figure 8 also reveals that approaches used in 80% of the 25 top studies quantified all of blue, green, and grey water components within the same study, 3 out of 25 (12%) quantified both blue and grey water, and an equal proportion of 4% quantified a combination of blue/green and green/grey water, respectively. These results indicate the importance attached to partitioning blue, green, and grey water components by research communities who use the different assessment frameworks. A possible explanation behind this partitioning is the need to distinguish between the different opportunity costs and environmental impacts associated with each of the blue, green, and grey water components.

### Overview of Specific Blue, Green, and Grey Water Quantification Techniques Used

The outcome of this bibliometric analysis revealed a broad range of specific techniques used to quantify blue, green, and grey water. Examples of such unique techniques include crop water

requirement computations using the CROPWAT model (Mekonnen and Hoekstra 2011); use of international trade data to assess virtual water flows (Chapagain and Hoekstra 2011; Hoekstra and Mekonnen 2012); use of spatially explicit grid-based dynamic water balance models (Mekonnen and Hoekstra 2010; Schyns and Hoekstra 2014); environmental impact assessment (Jefferies et al. 2012; Zonderland-Thomassen and Ledgard 2012; De Boer et al. 2013); livestock production systems and feed composition (Mekonnen and Hoekstra 2012; de Miguel et al. 2015); hydrological water balance techniques (Herath et al. 2013a); water footprint assessment from production perspectives (Deurer et al. 2011; Gerbens-Leenes and Hoekstra 2012) and consumption perspectives (Aldaya and Hoekstra 2010; Ridoutt et al. 2010; Vanham et al. 2013); interannual variability assessment (Sun et al. 2013); catchment specific aquifer characterization (Zonderland-Thomassen and Ledgard 2012); tier III approach for grey water footprint assessment (Lamastra et al. 2014); nitrate pollution dilution (Shrestha et al. 2013); index decomposition method (Xu et al. 2015); production weighted average (Pahlow et al. 2015); and national water use accounting (Bulsink et al. 2010).

### Scale and Scope of Commodities and Industries Assessed

Global level studies focused on commodities that ranged from major crops (Mekonnen and Hoekstra 2010, 2011; Chapagain and Hoekstra 2011); animal products (Mekonnen and Hoekstra 2012); energy crops (Gerbens-Leenes and Hoekstra 2012); and aquaculture (Pahlow et al. 2015), to

the water footprint of humanity (Hoekstra and Mekonnen 2012). All these studies are associated with the WFA framework (Table 1).

The top ranked regional studies in Table 1 also covered a wide range of commodities and topics, including European diets (Vanham et al. 2013); fresh mango fruit in Australia (Ridoutt et al. 2010); kiwifruit in New Zealand (Deurer et al. 2011); wine production in Romania (Ene et al. 2013) and New Zealand (Herath et al. 2013b); various economic activities in Morocco river basins (Schyns and Hoekstra 2014); mining industry in South Africa (Haggard et al. 2015); and crop products in Indonesia (Bulsink et al. 2010).

Blue, green, and grey water quantification studies at the local level tracked the life cycle grape-wine production in New Zealand locations (Herath et al. 2013a); tea and margarine production in India and Ukraine (Jefferies et al. 2012); pasta and pizza margherita diets in Italian cities (Aldaya and Hoekstra 2010); crop production in Beijing (Sun et al. 2013; Xu et al. 2015); comparison of irrigated and non-irrigated dairy farming in climatically different New Zealand farming regions (Zonderland-Thomassen and Ledgard 2012); water use impacts of wine production in Italy (Lamastra et al. 2014); the pig sector in Spain (de Miguel et al. 2015); production of major primary crops in Nepal districts (Shrestha et al. 2013); and milk production in a Dutch province (De Boer et al. 2013).

The results in Table 1 demonstrate the utility of the NAILS bibliometric toolkit in providing a rapid but detailed analysis of freshwater literature, including the range of commodities and industries that are impacting freshwater resources in terms of blue and green water consumption, and grey water generation. These insights into blue, green, and grey water can improve the understanding of human appropriation of freshwater resources, and guide the implementation of the most appropriate water management measures as water consuming economic activities increase.

## Conclusion

This bibliometric and literature review study provided an overview of current approaches that have been used to quantify blue, green, and grey

water for the period 2000-2018. The scales of assessment are evenly distributed between global level focused studies, intermediate national and river basin levels, and the microscale level, focused approaches used to assess urban areas, individual economic sectors, and dietary styles. The spatial scope and diversity of commodities and industries assessed varies widely, indicating that blue, green, and grey water quantification approaches are still evolving. The study found that the WFA methodology is the most influential approach that has been applied in recent studies to quantify blue, green, and grey water. This study also highlighted the close association between blue, green, grey, virtual water, and water footprint assessments. It is therefore clear that most virtual water and water footprint assessment frameworks also quantify blue, green, and grey water. The results also show that there is an array of rapidly evolving approaches that can be broadly categorized into WFA, LCA, and other Hybrid approaches that include a mix of other major approaches that are standalone research areas. Each major approach tends to employ one or more specific analysis techniques, such as the more spatially and temporally explicit water accounting methods. The United States and China were found to be the leading contributors of blue, green, and grey water publications. Global distribution of publications highlighted the obvious worldwide importance of blue, green, and grey water issues. The growing body of knowledge on blue, green, and grey water issues was demonstrated by the exponential increase of publications during the studied period, particularly from the year 2009 onwards. The Water Footprint Network is one of the most important hubs in blue, green, and grey water assessments, contributing the greatest number of most cited and most productive authors. The most prominent journals in terms of importance to blue, green, and grey water literature were the *Journal of Cleaner Production* and *Ecological Indicators*, while “water footprint” and “virtual water” were unsurprisingly the most popular and cited keywords associated with blue, green, and grey water. The bibliometric indicators in this study have been calculated using only research papers extracted from the Web of Science database. Although this is a major research database, it should be noted that there are other often most

cited papers that were not accessible through the NAILS-Web of Science toolkit coupling that was used. Nevertheless, the use of a rapid bibliometric analysis toolkit still provided important insights to help better understand the diversity of techniques that have been applied in blue, green, and grey water quantification approaches in recent years.

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# Agricultural Use of Reclaimed Water in Florida: Food for Thought

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**Abstract:** Florida has successfully irrigated agricultural crops with reclaimed water (RW) for more than 50 years. Florida and California are the two largest producers and users of RW in the U.S. To allay early fears about RW, Florida regulatory agencies established rules in the 1980s that prohibited direct contact of RW with crops that are not processed but eaten raw. This means that RW cannot be used for direct contact irrigation or frost protection of crops such as strawberries or blueberries. Other states do not have such limitations on RW use. Reclaimed water has an excellent safety record, and no health problems have occurred from its use. The main edible crop that uses RW in Florida is citrus. Reclaimed water contains some macro- and micronutrients, but can provide only a small amount of nitrogen (N) to citrus. Some RW sources can provide adequate N to turf grass. Reclaimed water production has increased dramatically in the past 20 years, and much of the increased flow has gone to public access irrigation. While still important, agricultural use of RW as a percentage of total flow may continue to decrease, but the supply of RW continues to grow as Florida's population increases.

**Keywords:** *recycled water, water reuse, wastewater treatment facility, WWTF*

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Which state in the U.S. is the largest producer and user of reclaimed water (RW) or recycled wastewater? A logical answer would be one of the arid western states such as Arizona or a state with a large population. Surprisingly, the answer is Florida. Even though Florida has an average annual rainfall of 54.5 inches (1385 mm) and ranks fifth in the nation in precipitation (Current Results 2017), it still leads the nation in RW production. Table 1 shows reported reuse and reuse per capita for several states (WateReuse National Water Reuse Database 2018) over the time period of 2009-2012. During this period, average RW daily use in Florida was an estimated 722.04 million gallons per day (mgd) (2733.2 thousand cubic meters per day or  $\text{tm}^3\text{d}$ ), while daily RW use in California was an estimated 597.38 mgd (2261.3  $\text{tm}^3\text{d}$ ). The other states were noticeably lower. Even though Florida has about half the population of California, it still produces more reuse water, and reuse per person per day in

Florida is more than twice that of California (Table 1). The purpose of this paper is to discuss RW use in Florida with emphasis on edible crops.

## Florida Experience with Reclaimed Water

The reasons for Florida being a leader in recycling wastewater are varied, but many of the earlier RW projects were related to improving surface water quality. Initially, some projects were designed as ways to manage and dispose of wastewater. Later projects were set up to be sources of irrigation water (Parsons et al. 2010; Toor and Rainey 2017). To meet demand, arid western states have been able to use several water sources such as the Colorado River, along with dams and reservoirs, to capture snow melt from mountains. Recent western droughts, however, have forced them to reconsider RW as a potential water source. Florida has few dams and reservoirs

and essentially no snow melt. Much of Florida's drinking water comes from the Floridan aquifer, but droughts have also increased interest in RW as a supplementary water source.

The Florida Department of Environmental Protection (FDEP) defines RW as "water that has received at least secondary treatment and basic disinfection and is reused after flowing out of a domestic wastewater treatment facility." Reuse refers to "the deliberate application of reclaimed water for a beneficial purpose" (FDEP 2017c).

By state statute, Florida encourages water recycling. Florida Statute 373.250 encourages the "promotion of water conservation and reuse of reclaimed water" and indicates that these "are state objectives and considered to be in the public interest." It also states that RW produced by a permitted domestic wastewater treatment plant "is environmentally acceptable and not a threat to public health and safety" (Online Sunshine 2018).

Reuse flow in Florida has increased more than 3.6 times (from 206 to 760 mgd or 779.8 to 2876.9  $\text{tm}^3\text{d}$ ) between 1986 and 2016 (FDEP 2017a). Reuse flow from 1998 to 2016 is shown in Figure 1. In 1990, reuse flow was 322 mgd (1218.9  $\text{tm}^3\text{d}$ ). At 90 mgd (340.7  $\text{tm}^3\text{d}$ ), agricultural irrigation accounted for 28%, and public access systems at 99 mgd (374.8  $\text{tm}^3\text{d}$ ) accounted for 31% of the reuse flow. Since then, public access and landscape irrigation increased more than four-fold to 438.9 mgd (1661.4  $\text{tm}^3\text{d}$ ), while agricultural irrigation

declined to 64.8 mgd (245.3  $\text{tm}^3\text{d}$ ). While total RW flow has increased, public access now accounts for 58% of the total flow, and agriculture accounts for only 8% of total flow (Figure 2) (FDEP 2017a).

There are currently 118 systems that irrigate agricultural crops, and 17 are those that irrigate edible crops (FDEP 2017a). One of the premier agricultural and public access projects is Water Conserv II, west of Orlando, FL (Water Conserv II 2018). The background of Conserv II is instructive because this project went through a history that other RW projects have often repeated. In the mid-1980s, the city of Orlando and Orange County were told that they could no longer dispose of their treated wastewater into Lake Toho, a good bass fishing lake, and would have to find an alternate disposal place. When city and county officials approached growers with the proposal of providing free RW that could be used to irrigate their citrus groves, the growers initially rejected the idea. Even though the city and county would provide the water free and nearly eliminate pumping costs, growers were wary of this "unknown" water. There were concerns about heavy metals, salinity, disease organisms, or flooding from excessive water (Parsons et al. 2001a). After much negotiation, nearly all of the grower demands were satisfied. Dr. Robert Koo of the University of Florida established water quality standards that met most drinking water standards. Parsons et al. (1981) had recently demonstrated that microsprinkler irrigation could

**Table 1.** Water reuse in different states estimated between 2009 and 2012. Reuse per Capita is based on 2010 population estimate.

State (year of report)	Population <sup>1</sup> (2010 est)	RW Daily Avg Use <sup>2</sup> (mgd)	Reuse per Capita (gal/person/day)	Rank (per Capita reuse)
Florida (2011)	18,846,461	722.04	38.31	1
California (2009)	37,327,690	597.38	16.00	2
Nevada (2011)	2,702,797	18.92	7.00	3
Texas (2010)	25,241,648	46.02	1.82	4
Arizona (2012)	6,407,002	10.04	1.57	5
Colorado (2011)	5,048,029	1.25	0.25	6

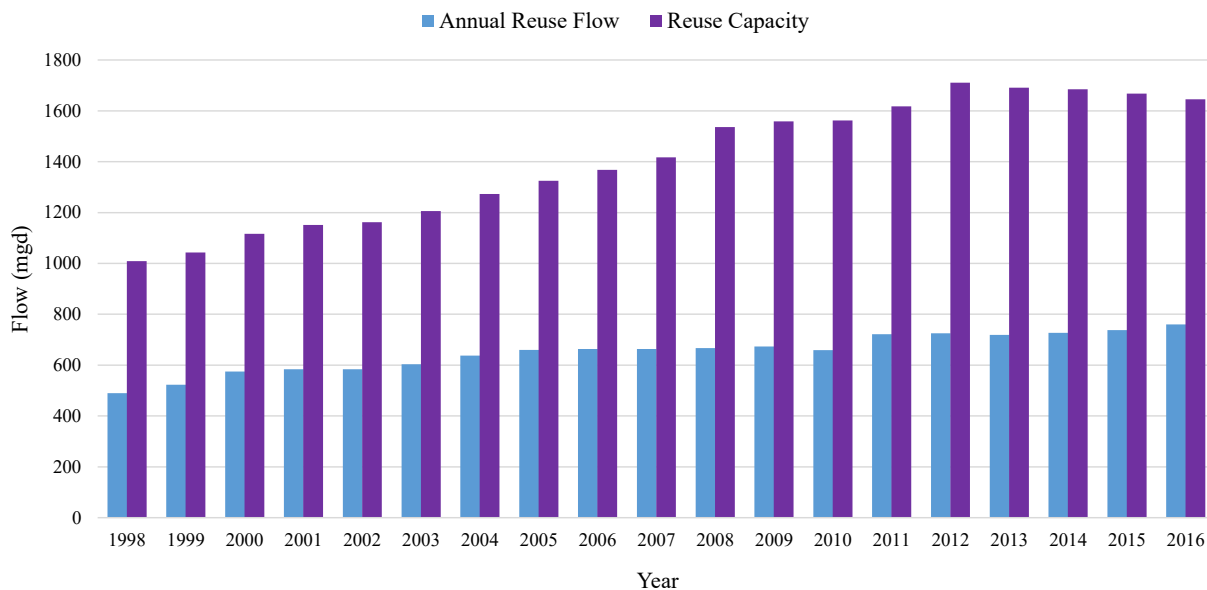
<sup>1</sup>Population estimate for July 1, 2010. (United States Census Bureau 2018)

<sup>2</sup>Reclaimed Water Daily Average Use from WaterReuse Foundation National Water Reuse Database (2018). "Daily Reclaimed Water End Use Pattern (mgd)."

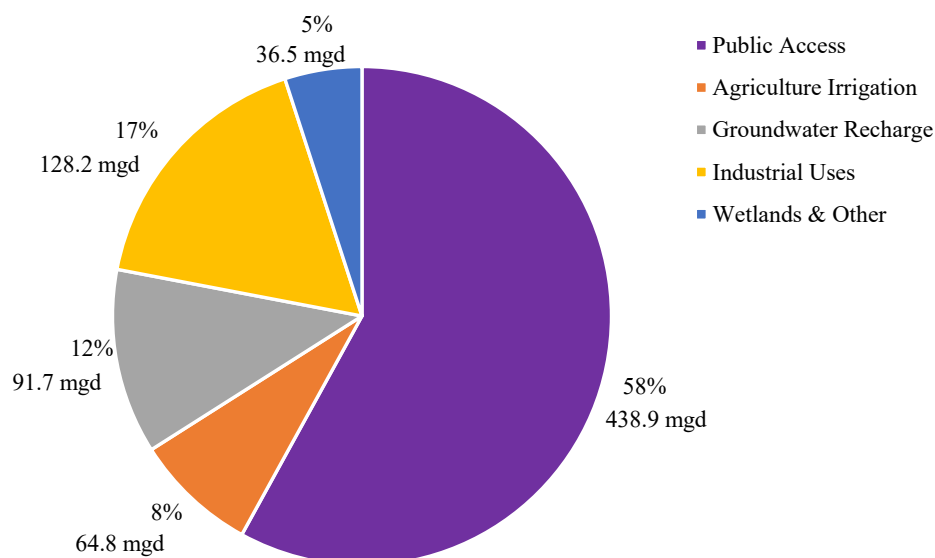


provide some frost protection, and the RW would provide additional water on freeze nights. The frost protection advantage convinced some growers to start using the water, and eventually, other growers accepted the water. Because there have been no major problems and the treatment facilities have consistently met water quality standards, most growers in the area now understand that this is a good quality resource for year-round use.

Growers in the Conserv II area requested that University of Florida scientists carry out research on this RW (Parsons et al. 2001a) to make sure it was not damaging their trees. Since the city and county were more concerned with wastewater disposal at the time, purposely-high irrigation rates of 100 in/yr (~2500 mm/yr) were applied. On these well-drained sandy soils, tree canopy growth and fruit production were greater at the high irrigation



**Figure 1.** Growth of water reuse (Florida Department of Environmental Protection 2017b).



**Figure 2.** Reclaimed water utilization (Florida Department of Environmental Protection 2017b). Note: Agriculture irrigation includes edible crops (e.g., citrus) as well as feed and fodder crops (e.g., spray fields).

rate than at lower rates because the trees suffered essentially no water stress. The 100 in/yr rate reduced the concentration of juice soluble solids, but the greater fruit production significantly increased the total soluble solids per hectare (the basis on which growers are paid) (Parsons et al. 2001b). Disease was not a problem at the high rate. Now, most growers who were initially skeptical have become enthusiastic supporters of this water. Public acceptance has increased also because RW use has fewer pumping restrictions during droughts than potable water.

Nevertheless, the pattern of initial rejection of RW because of the perceived “yuck factor” is commonly repeated in other locations. In the 1980s, growers in Florida’s east coast Indian River area rejected a proposal to bring RW to groves there. This area is noted for producing high quality grapefruit. Much of this Indian River grapefruit is marketed in Europe and Japan. Growers feared that, because of perception issues, marketers in these countries would not accept grapefruit that was irrigated with RW. However, recent work has shown that RW from treatment plants on the east coast can be lower in salinity and bicarbonates than existing well water (R. Adair, pers. comm. 2017). Thus, RW can be a better irrigation source than existing wells. Some growers in the region are now starting to get interested in irrigating with RW.

Approximately 79% of the agricultural reuse flow in Florida goes to irrigation of citrus. However, citrus production and acreage have declined in the past 20 years because of hurricanes, real estate development, and diseases. Two major bacterial diseases, citrus canker and greening, have caused major decreases in citrus acreage. Part of the reason for the decline in agricultural RW use is a disease called citrus greening that came into Florida in 2005. Greening, or huanglongbing, which is spread by an insect called a psyllid, causes trees to decline and eventually die, and is currently devastating the Florida citrus industry. The 2017-2018 production of Florida oranges was 44.95 million boxes, which is only ~18.4% of the 244 million-box production of the 1997-1998 season (USDA 1998, 2018). Because greening has caused major tree and production loss, some growers have abandoned their groves. In 2016,

there were an estimated 130,684 acres of citrus groves abandoned (USDA 2016).

## Safety of Reclaimed Water

Safety of RW has always been a major concern. Because RW comes from sewage or wastewater treatment facilities (WWTFs), public perception has often been an issue. The public outcry of “toilet to tap” has delayed or cancelled some RW projects. However, the safety record of RW is excellent. Florida has been using RW for more than 50 years, and there are no documented reports of people becoming sick from exposure to RW (SWFWMD 2017). Part of the reason for this excellent safety record is the water quality regulations established by governmental bodies. York et al. (2003) also stated “Reuse and the Absence of Disease. It must be noted that there is no evidence or documentation of any disease associated with water reuse systems in the United States or in other countries that have reasonable standards for reuse. This is true for protozoan, viral, helminthic, and bacterial pathogens.”

Several organizations have established recommended microbiological quality guidelines for agricultural use of wastewater. One common way to determine water quality is to measure coliform or fecal coliform bacteria. Water quality standards and measurements are complicated and involved, and we will only discuss the main features of the water quality standards used.

The World Health Organization (WHO 1989) recommended that for “irrigation of crops likely to be eaten uncooked, sports fields, and public parks” the geometric mean number of fecal coliforms be less than or equal to 1000 per 100 ml. In Florida, the FDEP requires RW to have basic disinfection. “Basic disinfection” means that the arithmetic mean of the fecal coliform values shall not exceed 200 per 100 ml. For public access areas, FDEP requires high-level disinfection. This level of disinfection is the most stringent. It requires that over a monthly period, 75% of the fecal coliform values must be below the detection limits and “any one sample shall not exceed 25 fecal coliform values per 100 ml of sample” (Florida Department of State 2016. Rule: 62-600.440). Because 58% of reuse flow is for public access (Figure 2), this

means that at least 58% of Florida's RW receives high-level disinfection.

In an effort to encourage water reuse and reduce public perception of what has been called the "yuck" factor, Florida statutes were written that prohibited direct contact of RW with crops unless they were "peeled, skinned, cooked, or thermally processed before consumption" (Florida Department of State 1999. Rule: 62-610.475). This prohibition on direct contact of RW with crops eaten raw (e.g., salad crops) was done without scientific study, but remains in effect. This means that Florida has more severe restrictions on crop application than California. This is significant, because this Florida prohibition prevents the use of RW for frost protection using overhead irrigation on crops such as strawberries and blueberries. This is unfortunate because pumping of well water during some freezes to protect strawberries has caused sinkholes to develop due to water table drawdown.

California has allowed direct contact of RW on vegetable crops eaten raw for more than 30 years. A Monterey wastewater reclamation study for agriculture was carried out in the Salinas Valley of California (Engineering-Science 1987). This study showed that irrigation of vegetable crops (eaten raw) with RW was as safe as irrigation with well water. No virus was found on crops grown with RW. In addition, "levels of naturally-occurring bacteria on samples of effluent-irrigated crops were equivalent to those found on well-watered irrigated crop tissue samples." No health problems have occurred with California vegetables irrigated with RW.

Interestingly, in 2016, a variance to Rule 62-610.475 was granted to the City of Pompano Beach, FL to allow homeowners to irrigate their gardens with RW. The petition for the variance showed that the RW met all potable water standards except for chloride, sodium, and total dissolved solids. It also pointed out that a) water reuse was a state objective, b) other states allowed direct contact with crops eaten raw, and c) this would cause a substantial economic hardship. The final order found that "this economic hardship was unnecessary because the Petitioner could use reclaimed water to meet the demand for residential irrigation" (Florida Department of State 1999). It will be interesting to

see if other Florida cities request a variance from the direct contact rule similar to the one granted to Pompano Beach.

## Nutrients in Reclaimed Water

Reclaimed water contains several mineral elements, some of which are beneficial for plant nutrition. Elements of particular interest are nitrogen (N), phosphorus (P), and several micronutrients such as boron (B). While RW can provide some plant nutrition, the benefit depends on the level of treatment and the crop itself. Florida requires that all WWTfs producing RW for reuse must provide secondary treatment and disinfection. Treatment plants discharging into Tampa Bay and surface waters in the Southwest Florida Water Management District (SWFWMD) must meet the more rigorous N and P standards of advanced wastewater treatment (AWT). AWT standards are 5/5/3/1 (5 mg/L of CBOD<sub>5</sub>, 5 mg/L of total suspended solids, 3 mg/L of total N, and 1 mg/L of total P).

Levels of N and P in RW are relatively low. Typical levels of total Kjeldahl N (which consists of organic N and ammonia N) are 13.9 ppm (mg/L) in secondary treated wastewater and 0.9 ppm in AWT water (Toor and Lusk 2017). Nitrate N levels are 1.4 ppm and 0.7 ppm, respectively. Jacangelo et al. (2012) reported that a "survey revealed that 40% of the sampled reuse facilities in Florida had total N concentrations less than 5 mg N/L, and 70% had total N concentrations less than 10 mg N/L. The higher total N levels were primarily from facilities with limited nitrification and, as such, they contained much higher levels of ammonium... Regarding total P concentrations, 40% of the 40 sampled facilities were below 1 mg P/L, and 90% had levels below 5 mg P/L."

In the Water Conserv II location near Orlando, FL, growers initially received the RW for free and used it at high rates to dispose of it. Trees grew well with the high irrigation rates and produced more fruit and total orange soluble solids than trees irrigated at lower rates (Parsons et al. 2001b). Zekri and Koo (1993) compared citrus trees irrigated with RW or well water and found higher levels of sodium (Na), chloride (Cl), and B in leaves of trees irrigated with RW. Because of the higher irrigation

rates, groves irrigated with RW also had a denser canopy, better leaf color, heavier fruit crop, and more weed growth. In a related later study, Morgan et al. (2008) found higher leaf B and magnesium (Mg) levels in trees irrigated with RW. As in previous studies, they also found that RW irrigation increased soil P and calcium (Ca) and reduced soil potassium (K). Hence, it may not be necessary to lime Florida soils irrigated with RW. Scholberg et al. (2002) carried out N studies on young citrus seedlings with emphasis on N concentration, application frequency, and residence time in the soil. They compared application frequencies of three 500-mL applications/week of 7 mg N/L (simulating RW) with one 150-mL application/week of 70 mg N/L. Increasing application frequency and residence times from two to eight hours increased nitrogen uptake efficiency (NUE). High irrigation application rates displaced RW below the main root zone and reduced NUE.

Both Zekri and Koo (1993) and Morgan et al. (2008) did not find increases in leaf N in trees irrigated with RW. This is probably because of limited N uptake, due to short residence time in the soil from high application rates, and low N concentration (typically < 7 mg/L). Maurer and Davies (1993) found that RW did not provide adequate nutrition for young trees and indicated that supplemental fertilization was necessary.

Reclaimed water may not play a large role in providing N for citrus trees. In a normal Florida rainfall year, citrus needs around 15 inches of irrigation water to supplement the rainfall. With RW of 7 mg N/L, 15 inches of RW would supply 23.8 lb/acre. Depending on tree size, tree age, planting density, and crop yield, the annual N fertilization rate for oranges should range from 140 to 250 lb/acre (Obreza et al. 2017). Hence, if the tree roots could extract all of the N out of the RW, the RW would supply only 9.5 to 17% of the total N requirement. If the RW met AWT standards of 3 mg N/L, 15 inches would supply only 10.2 lb of N, or less than 7.3% of the N needed.

Turf grass may respond better to RW. Pinellas County developed a map that shows that RW can supply N so that less fertilizer is needed in the landscape. Because WWTFs produce RW with different concentrations of N, the RW from some facilities can provide the entire N amount

needed. For example, the St. Petersburg facility can provide sufficient N to meet the N requirement of several turf grass varieties (Pinellas County National Resources 2017). These varieties need no additional N fertilizer.

## Conclusions

Reclaimed water use in Florida has increased greatly in the past 20 years, and much of the increase in RW flow has gone to public access irrigation. Because of diseases and real estate development, agriculture is changing in Florida. Nevertheless, agriculture is an important part of the Florida economy, and RW is a useful resource that helps keep agriculture productive. The common way to move RW from the WWTFs to the place of use is to pump the RW through a network of pipes (commonly colored purple). Instead of installing more purple pipelines, other methods of distribution, such as groundwater recharge and aquifer conveyance may be used in the future as a more economical way to bring RW from treatment plants to agricultural operations and other areas where it is used. With continued population growth in Florida, RW total flow will continue to increase.

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Center, University of Florida/IFAS, 700 Experiment Station Road, Lake Alfred, FL 33850.

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# Grey Water: Agricultural Use of Reclaimed Water in California

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**Abstract:** Potential for use of recycled water<sup>1</sup> is great, especially for agricultural irrigation, which comprises by far the highest percentage of water taken from developed sources in the arid and semi-arid regions of the world. In California, 80% of developed water is used for agriculture, and the same pattern prevails throughout the western United States. The potential for recycled water use in agriculture remains under-realized because of numerous impediments. Understanding how the incentives and impediments to agricultural reuse vary based on local context is critical to understanding the tradeoffs and technology requirements for different end uses of recycled water. Public perceptions about the safety of reclaimed water (from human waste) were a major impediment to water recycling until recent years. Several pioneers of water recycling have demonstrated—as specialists in the field of social psychology have hypothesized—that these attitudes are ephemeral and can be changed with proper outreach, demonstration, and education. Another impediment is the regulatory structure in some states. Water rights issues are another impediment specific to some western states in the United States. Cost differences for delivered water from traditional sources versus recycled water can be another challenge potentially requiring financial incentives in the interest of the greater good. One other impediment to the use of recycled water for agricultural irrigation is competition with other demands for the same water—landscape, golf course, industrial, and potable reuse. Potential for increased use of recycled water is great if impediments are removed and incentives are provided at the local, state, and/or federal levels to close the gaps (geographic and otherwise) between the utilities and the farmers.

**Keywords:** *agricultural reuse, recycled water, reclaimed water, water reuse, California agriculture*

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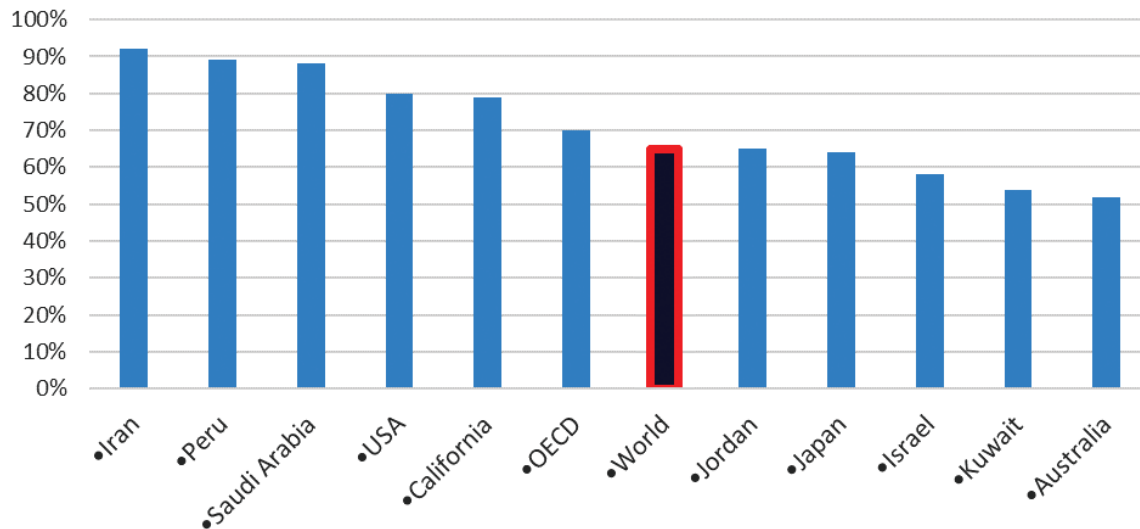
<sup>1</sup> As used in this paper, “recycled water” and “reclaimed water” are synonymous and interchangeable. In California and some other states, “recycled water” is consistently employed, while in Florida and some other states “reclaimed water” is the term of art.

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This paper is a high-level overview of the use of recycled water (treated municipal wastewater) for agricultural irrigation for crop production. The majority of the world’s food supply comes from agriculture which is dependent on water, whether from rain, irrigation, or a combination. In the arid and semi-arid regions of the world irrigation is essential for nearly all crop production. In these regions, the vast majority of developed water is dedicated to agriculture. As shown in Figure 1, the world-wide percentage of

water used for agriculture is more than 60%, with the USA (and California) percentages hovering around 80%.

This work is based in part on the results of research supported by the Water Environment and Reuse Foundation (WE&RF) (Sheikh et al. 2018). The WE&RF research project is titled “State of Irrigated Agricultural Water Reuse — Impediments and Incentives.” This paper presents highlights from a comprehensive literature review, interviews with farmers and utilities, and case



**Figure 1.** Proportion of developed water used for agricultural irrigation in various world regions. Sources: United Nations Food and Agriculture Organization (UN FAO 2010); California Department of Water Resources (Pezzetti and Balgobin 2016); Organization for Economic Co-operation and Development (OECD 2018); Snapshot of Australian Agriculture (ABARES 2018).

studies of specific projects. A team of scientists from the United States, Australia, Japan, Spain, and the Middle East contributed to the project. Another source of data is the recently completed 2015 survey of recycled water use in California, conducted by the California State Water Resources Control Board in collaboration with the California Department of Water Resources (DWR) (Pezzetti and Balgobin 2016).

### From Wastewater Use to Water Recycling

Agricultural water reuse practices vary significantly around the world, ranging from the use of untreated wastewater in regions where wastewater treatment is limited, through the use of highly treated recycled water in the more developed regions. In either case, both food and non-food crops are commonly irrigated. Across all contexts, water scarcity is the common motivation for agricultural reuse.

### Methods

While “Grey Water” in this special journal issue refers to recycled water, graywater per se is defined as untreated wastewater that excludes wastewater from toilets and, in most states that have graywater regulations, wastewater from

kitchen sinks and dishwashers. While this type of graywater can be a significant source of irrigation water for landscaping under certain circumstances for individual residences and businesses, it is estimated to comprise a very small fraction (by volume) of the total water recycling in California. For these reasons, the discussion that follows is confined to reclamation of municipal wastewater and recycling the reclaimed water for agricultural irrigation. In the context of this special issue, “Grey Water” encompasses non-conventional sources of water derived predominantly from domestic wastewater, including the following:

**Recycled Water**, also called “**reclaimed water**” is a regulated, treated water suitable for specifically allowed classes of uses. **Graywater** is untreated wastewater from domestic sources (except toilet/urinal wastes, kitchen sink, and dishwasher) and allowed to be used with specific regulatory restrictions.

In order to provide a general overview of the subject, the authors drew upon summaries of literature reviews, results of recent research, outcome of recent surveys, and professional knowledge of the field collected over several decades of work in the field of water reuse in the United States and abroad, with some emphasis on California conditions.



## Results

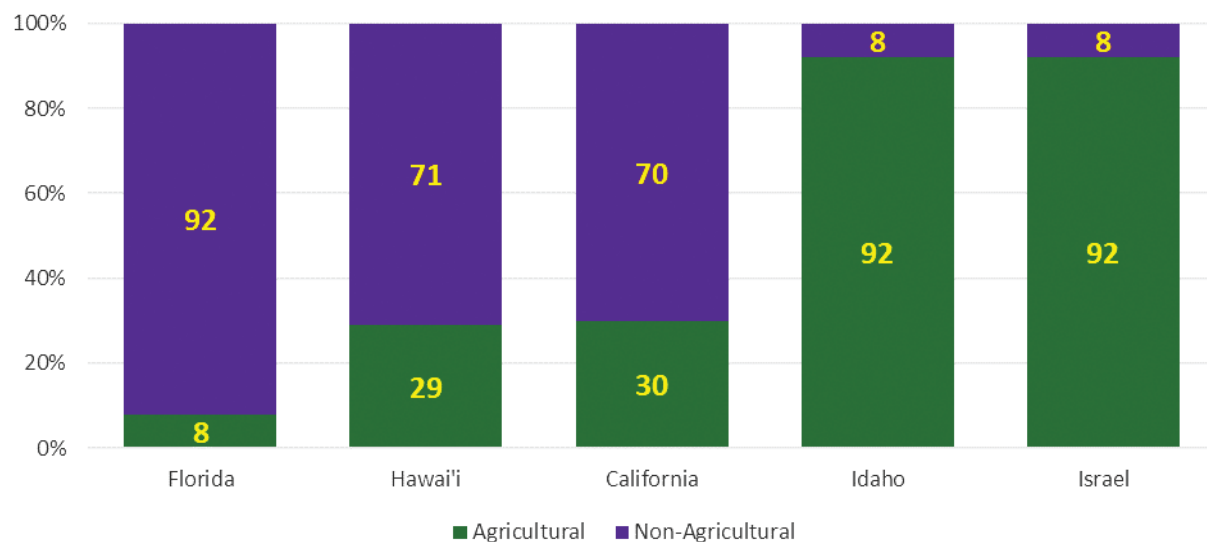
### Use of Water in Agriculture

The predominance of water utilization for agriculture emphasizes the importance of the nexus between water and food production, essential for human life and the economic health of nations. In addition to food, agriculture provides many other products necessary for economic development in the built environment, including construction materials, textiles, and medicines.

Agricultural use of water resources accounts for the largest demand on water by far, while use of recycled water in agriculture, in most regions, accounts for a much smaller proportion of the overall recycled water use. Agricultural percentage of use of recycled water in California is illustrated in Figure 2, and contrasted with corresponding percentages in Florida, Hawai'i, Idaho, and Israel. While the percentages in Idaho and Israel reflect the general pattern of water use in agriculture (shown in Figure 1), California's lower percentage of recycled water use shows a sharply different picture, possibly due to the more aggressive urban uses of recycled water, where non-agricultural customers are at closer proximity to the sources of water.

The contrast between California, Florida, and Hawai'i on the one hand, and Idaho and Israel on

the other, is striking. This contrast may well be an illustration of the effect of impediments to the use of recycled water for agriculture in some regions in contrast to the relative lack of impediments in Idaho and strong incentives in Israel. While impediments play a large part in the differences noted in Figure 2, there is also simply more urban demand for recycled water in California and Florida for such applications as landscape irrigation, industrial uses, and increasingly, for potable reuse. The coastal urban utilities in California are generally better resourced than their interior counterparts and thus are better able to provide funding for urban recycled water projects. Increased urban uses of recycled water may have contributed to the declining proportion of recycled water used in agriculture in California since the previous survey in 2009 (the volume of recycled water used in agriculture stayed about the same while overall recycled water use increased). Likewise, in Florida, the use of recycled water for urban and industrial uses is actively incentivized via larger potable water offset credits (Florida DEP 2016). In some regions, such as in southern California, urban reuse can make more economic sense due to long distances to agricultural lands, pumping costs, vulnerability, and increasing costs of imported water supplies.



**Figure 2.** Proportion of recycled water used for agriculture in various regions. Sources: Hawaii 2013; Florida DEP 2016; Pezzetti and Balgobin 2016; Nichols 2017 (personal communication on March 7, 2017 with the Idaho State regulator for uses of recycled water); Sheikh et al. 2018.

### Use of Recycled Water in Agriculture

The state of Florida ranks first among U.S. states in total annual water reuse, followed closely by California. The aggregated total water reuse by all the other states is much less than that in either Florida or California. Table 1 illustrates these standings in total water reuse.

Of the totals presented in Table 1, a fraction is used for agriculture, as illustrated in Figure 2. In California, that fraction is currently 30%, as estimated in a 2015 survey of water reuse throughout California by the California DWR (Pezzetti and Balgobin 2016). A historical depiction of trends in use of recycled water in the various hydrologic regions of California, based on the 1970-2015 survey results, is presented in Figure 3.

The rate of increase of water reuse in California declined since the most recent (2009) survey. The reasons for this decline are attributed in part to the recession of 2008, which caused lower water sales and limited capital investments in water reuse infrastructure. The recession was followed closely by a prolonged drought from 2011 to the end of

2015, causing water rate hikes, potable water supply issues, mandatory conservation, and less wastewater generation (resulting in some projects recycling less water) with higher salt content. However, the drought appears to have motivated planning for numerous water reuse projects into the coming years, incentivized by state and federal grants and loans.

The DWR 2015 survey (Pezzetti and Balgobin 2016) revealed the following breakdown of recycled water among various categories of applications, shown in Figure 4.

An interesting water quality aspect of use of recycled water in agriculture is that for most crops it is not necessary to use a highly treated recycled water. As shown in Figure 5, undisinfected secondary recycled water accounts for the largest volume of water reuse in agriculture with disinfected tertiary treated recycled water (the highest non-potable grade) in second place.

In California, disinfected tertiary recycled water is allowed for unrestricted irrigation of all food crops, including root crops. Use of undisinfected secondary effluent is allowed for surface irrigation

**Table 1.** Water reuse flow rates for nine states reporting data in 2015.

State	Population	Reported Water Reuse, MGD*	Reported Water Reuse, m3/d**
Florida	18,019,093	663.0	2,500,000
California	36,121,296	580.0	2,200,000
Texas	23,367,534	31.4	120,000
Virginia	7,628,347	11.2	42,000
Arizona	6,178,251	8.2	31,000
Colorado	4,751,474	5.2	20,000
Nevada	2,484,196	2.6	10,000
Idaho	1,461,183	0.7	3,000
Washington	6,360,529	0.1	400

\* MGD = million gallons per day

\*\* m3/d = cubic meters per day (rounded to two significant digits)

Source: Adapted from Florida 2015 Reuse Inventory, with credit to WaterReuse Foundation National Database of Water Reuse Facilities and California State Water Resources Control Board, from its previous survey results (Florida DEP 2016).

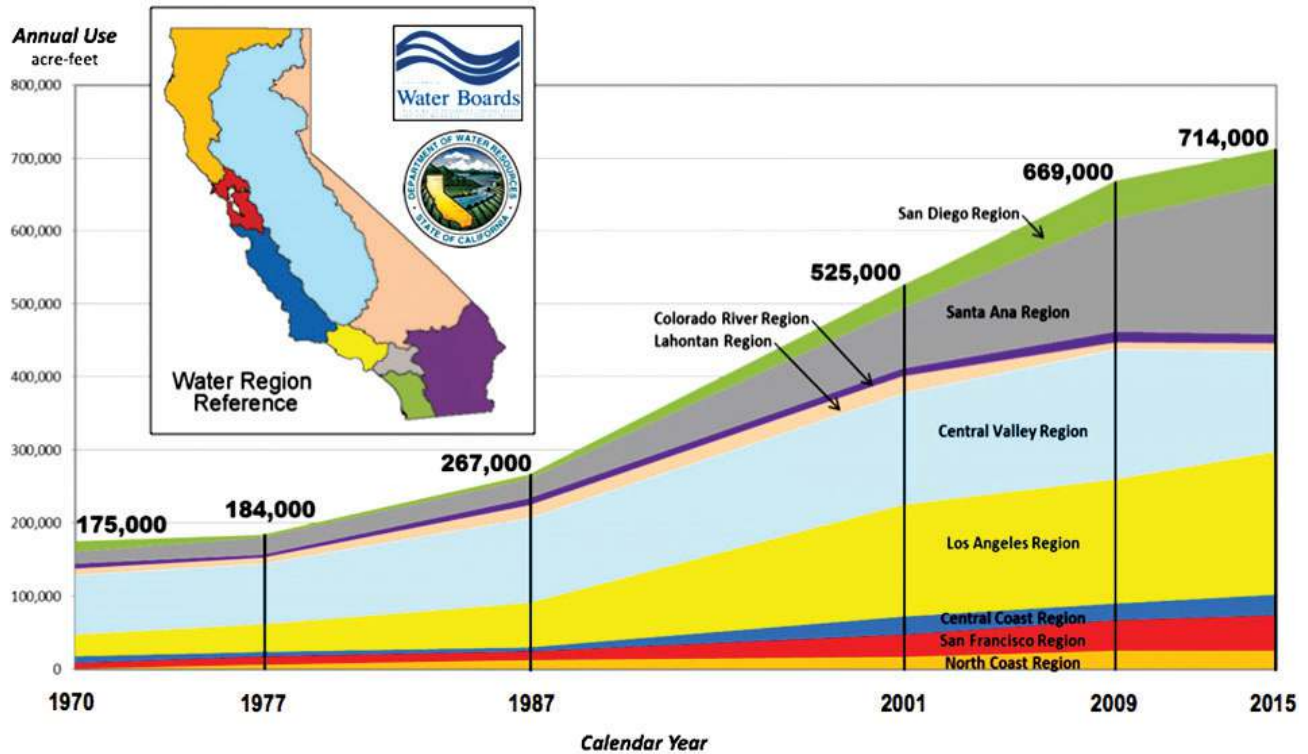


Figure 3. Historical growth of water recycling in California, from 1970 to 2015. Source: Pezzetti and Balgobin 2016.

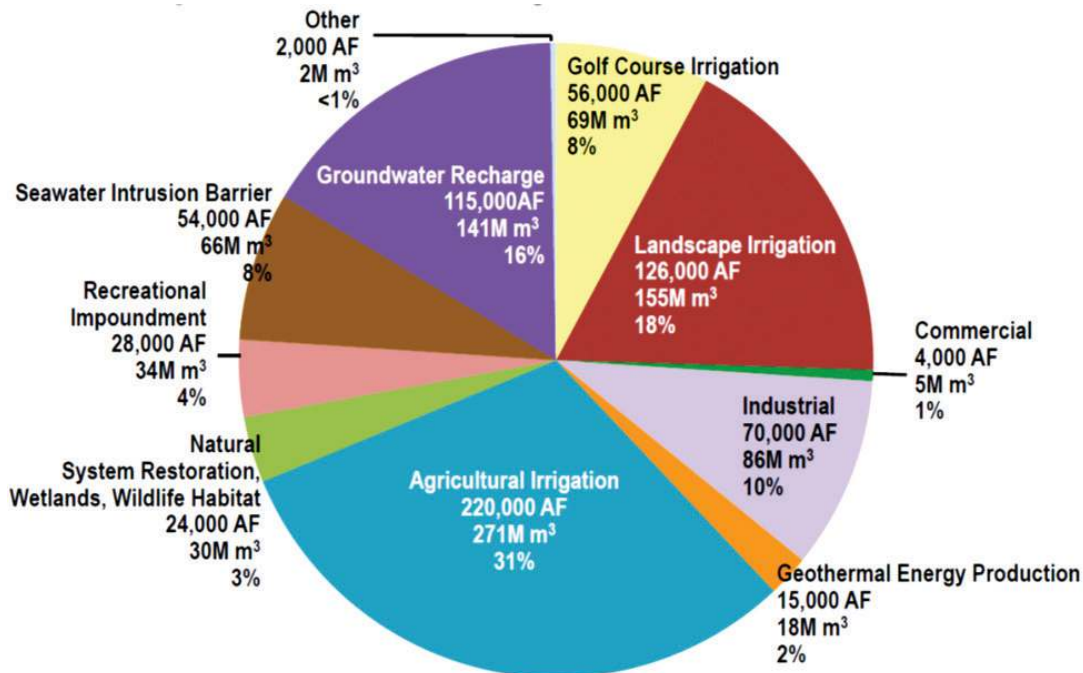
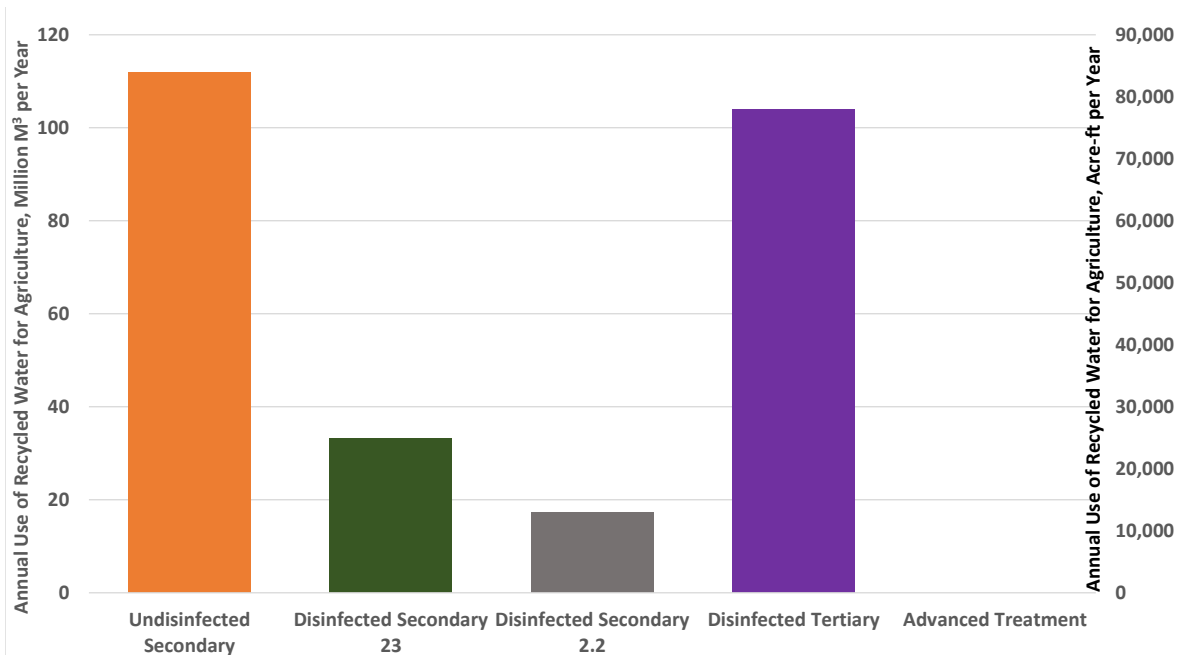


Figure 4. Distribution of California water reuse among application categories – from the 2015 DWR Survey. Source: Pezzetti and Balgobin 2016.



**Figure 5.** Level of treatment for agricultural uses of recycled water in California. Source: Pezzetti and Balgobin 2016 (DWR 2015 Water Resuse Survey); re-plotted for greater clarity.

of orchards and vineyards where the edible portion is produced above ground and not contacted by the recycled water. In addition, secondary effluent is allowed for irrigation of non-food bearing trees including Christmas trees, fodder and fiber crops, pasture for non-milk animals, seed crops, food crops undergoing commercial pathogen-destroying processes, ornamental nursery stock, and sod farms. For a complete list of allowed uses of recycled water in California, under four different treatment levels, refer to Title 22, Division 4, Section 60304 (Use of Recycled Water for Irrigation) of the California Code of Regulations. The allowed uses of recycled water in California are summarized at <https://www.sdcwa.org/sites/default/files/files/water-management/recycled/uses-of-recycled-water-new.pdf>.

### Drivers for Use of Recycled Water for Agriculture

A broad variety of drivers motivate for switching from conventional water sources to recycled water for irrigation. Kunz et al. (2016) conducted a detailed literature review of drivers for and against water recycling. They generally classified these drivers into social, policy, technical, natural, and

economic categories and noted the importance of scale in driver applicability. A condensed summary of their findings is presented in Appendix A.

In California, nearly all of these drivers were observed to be at work, depending on locality, state of drought, and the persistence of a visionary champion capable of removing impediments and bringing together stakeholders that individually would not have had the motivation to spearhead a water recycling project. This has been most evident in southern California where water agencies and wastewater utilities have collaborated to implement some of the largest water recycling projects, usually led by a tenacious champion unwilling to accept “no” for an answer. In the central coastal region of California, agricultural use of recycled water has been successfully implemented in Monterey and Watsonville over the past 20 years. The long-running success of these projects is credited with motivating other agricultural reuse projects in other parts of the world.

### Impediments to Use of Recycled Water in Agriculture

**Water Quality Impediments.** Water quality-related impediments to agricultural use of recycled water



may include salt concentrations, pathogenic microorganisms, chemical contaminants, and water quality variability. Water quality can influence both the process of agricultural production and the end-product's quality. Salinity, sodium, and boron in higher concentration can impact the productivity of irrigated fields. The more water conservation is practiced in prior uses, the higher the salt concentration of wastewater will be. The type of irrigation (sprinkler, drip emitters, subsurface drip) and local soil characteristics influences the degree of salt impact.

#### ***Risk Evaluation and Management.***

Microorganisms are found in nearly all waters and are prevalent in urban wastewaters. Risks can be associated with both agricultural products and production processes. Multiple opportunities exist to reduce microbial risk along the food production supply chain. The first begins at the wastewater treatment plant during advanced treatment stages. Proper operation can reduce the microbial load of recycled waters to below ambient surface water levels. Then, on the farm, recycled water can be used for non-edible agricultural products and irrigation methods that avoid contact between irrigation water and edible portions can be used. It should be noted, however, that the most stringent category of recycled water regulated for agricultural irrigation reduces risk to acceptable levels even when spray irrigation of edible crops is practiced. At the processing stage, edible portions can be rinsed or outer leaves removed. At the retail, institutional use, and consumption stages, edible portions can be further rinsed before consumption; however, this stage should not be relied upon and edible produce must arrive at the consumption stage free of pathogens.

Risk identification, characterization, tracking, avoidance, and mitigation are part of a sound food safety strategy. The Hazard Analysis and Critical Control Point (HACCP) process has well-established procedures for risk management in the food industry. HACCP provides useful principles for thinking about one aspect of the use of recycled water for agricultural irrigation: product contamination risk.

Also, based on plant physiology, root systems and xylem cells serve as filters making it very unlikely that pathogens will enter edible portions of

crops from root uptake. The more likely pathway of contamination for edible plants (food products) is through spray irrigation of edible portions depositing pathogens on the surface of the plant.

***Perceived Risks As Impediments.*** With respect to perceived risk, in the highly competitive global markets for agricultural products, fear of food contamination can influence a buying decision even if the fear is not consistent with results of a hazard analysis. In the early years of irrigation with recycled water this was a concern of growers who were either considering or using recycled water. Growers were concerned about both wholesale buyer reaction and end-user reaction, and even were concerned that rivals growing the same crop without recycled water would raise the issue to influence market outcomes. As the years of incident-free irrigation with recycled water grow, farmer and market concerns have reduced.

***Public and Farmer Acceptance Impediments.*** Use of recycled water has not emerged as a product perception issue in the agricultural irrigation sphere, and market participants rarely know or care about the origins of their food's irrigation water. Non-food agricultural markets have shown even less concern. Public attitudes about use of recycled water have improved in California over the last several decades, especially for non-potable water reuse. Several longitudinal surveys have shown these positive trends for different communities in the United States and Australia (Sheikh and Crook 2014). In Israel, the public has completely accepted the practice of water recycling for agriculture. In the United States, potential customers, farmers, utilities, and some regulators with little or no knowledge of (or experience with) water recycling exhibit a skeptical or negative initial reaction.

***Technological Impediments.*** The technology of water treatment is well established. An impediment for growers involved in high-end production that demands exact growing conditions is the variability of recycled water's chemistry. Recycled water treatment facilities focus on carrying out required treatment processes and meeting public and environmental health goals for recycled water quality. The targets in terms of concentrations of constituents in the water are regulatory, not market driven. In some instances, such as Watsonville,

California, the treatment facility intermittently blends its advanced recycled water with well water to meet non-regulatory salinity goals required by farmers.

Two areas of impediments potentially exist. One is availability of recycled water storage so near-constant flows of urban water can be applied when farmers actually irrigate. Wastewater flows regularly out of cities 24 hours per day. Farmers primarily irrigate during or close to daylight hours. Without sufficient storage, reclaimed water resulting from nighttime wastewater flows would not be available to farmers.

The next technological impediment involves the extent to which farmers know what quality water they are receiving. Recycled water meets minimum health standards but varies in salinity, nutrient levels, and other measures. Treatment plants already monitor nearly every quality measure of concern to farmers. Therefore, it is necessary to communicate water quality mitigation measures to farmers in time for farmer to take the necessary on-farm management decisions to optimize their irrigation practices.

***Regulatory Impediments and Institutional Settings.*** In the early stages of agricultural use of recycled water, stakeholders felt that the lack of regulatory roadmaps to permitting and operation of facilities was a significant barrier to new projects. Colorado and six other states specifically prohibit use of any recycled water for irrigation of edible crops including fruits and nuts. Regulations are evolving across the U.S. that increasingly allow for agricultural use of recycled water, although they differ in their thrust and details, ranging from prohibitive to permissive. The challenge to regulators and legislators is to base regulations on science and on the success story of ongoing agricultural enterprises using recycled water, while also recognizing that recycled water is an underutilized beneficial resource.

***Economic and Financial Impediments.*** In stakeholder interviews, economic risks were raised as the most important impediment to recycling projects for agricultural use. Cost impediments were especially emphasized in the case of smaller municipal utilities. Economically, the least-cost approach to water supply is to take water that is

naturally stored in aquifers or winter snowpack and delivered by rivers. In most parts of the world, the low-cost, low-hanging fruit of water supply has been claimed. The unique characteristics of recycled water start with its non-seasonality. Cities, even those dependent on rainfall-supplied surface waters, generate a fairly constant flow of wastewater regardless of season, hence a consistent supply of recycled water. Agricultural regions rarely enjoy an equivalent engineered storage system and therefore experience the risk of extended drought periods. The flow reliability of recycled water is a recognized benefit to farmers.

***Supply/Demand Imbalance Impediments.*** The consistent diurnal and year-round flows from urban recycled water that serve farming regions may require additional storage to meet two imbalances related to agricultural irrigation. The first challenge is due to the general lack of agricultural irrigation in the middle of the night. The second is related to the lack of demand for irrigation water during the rainy season. Additional storage can help address these problems but require significant capital expenditures. Of the two challenges, the more serious imbalance relates to lack of farmer demand for recycled water during the rainy season. Storage is a potential solution to this problem, but the scale of required seasonal storage is much larger than the diurnal need for storage. Groundwater aquifers can serve as storage reservoirs, where geological formations are suitable for the purpose. During non-irrigation periods, the reclaimed water could be used for other beneficial purposes or discharged to surface waters in compliance with state/federal regulations.

***Coordination Impediments.*** In California, as in many other states, different utilities are charged with the responsibility to manage different parts of the water cycle (raw water, bulk water, potable water, stormwater, floodwater, agricultural water, urban wastewater, retail sale of water to the end user, etc.). Implementation of a newly conceived recycled water project usually involves coordination among two or more of these utilities—sometimes a formidable challenge. The earliest and most successful water reuse projects, especially for agriculture, were those involving one agency handling both potable water and wastewater management responsibilities.

## Case Studies

In Table 2, several case studies are summarized, illustrating the specific drivers, impediments, incentives, and other details about each case in which impediments were successfully overcome and the project was ultimately implemented successfully. The Monterey case is described in more detail below.

### Monterey County, California

The federal Clean Water Act of 1972 provided substantial subsidies to utilities across the United States to upgrade wastewater treatment in their

regions so as to eliminate discharges of pollutants to the nation's receiving waters. Supported by the Clean Water Act subsidies, a basin planning program for the central coastal region of California recommended a regional wastewater collection and treatment system for northern Monterey County. The U.S. Environmental Protection Agency agreed to provide funding for this regional plant on the condition that the effluent from the treatment plant would be reclaimed and reused for agriculture, in part to relieve demand on the over-drafted aquifers and the consequent seawater intrusion. Farmers were highly skeptical about using recycled water and demanded proof-of-concept with a

**Table 2.** Summary of drivers, impediments, and incentives for selected case studies.

Case Study	Drivers	Impediments	Incentives	Treatment, Reuse	Crops Irrigated
Monterey, CA	<ul style="list-style-type: none"> <li>Overdrafted groundwater</li> <li>Seawater intrusion</li> <li>Saline groundwater</li> </ul>	<ul style="list-style-type: none"> <li>Safety concerns,</li> <li>Soils impact from salt</li> <li>Sales impact from customer acceptance issues</li> </ul>	<ul style="list-style-type: none"> <li>11-year pilot project</li> <li>Clean Water Act grants and loans</li> </ul>	Disinfected tertiary, pressure-pipe distribution	Cauliflower, broccoli, lettuce, celery, artichokes, strawberries, etc.
Modesto, CA	Nitrogen discharge limit to river	Farmers' senior water rights	State grant, loan	MBR*, UV*, Delta-Mendota conveyance	Nuts, stone fruit, citrus
Hayden, ID	<ul style="list-style-type: none"> <li>Discharge limits to Spokane River</li> <li>Nitrate pollution of groundwater</li> </ul>	Separate permits for reuse	Farmer pays \$55/acre	Oxidation ditch, BNR, ultrafiltration, chlorination, irrigation on city-owned farmland	Alfalfa, poplar trees
Oxnard, CA	Reduce dependence on imported water	Farmer resistance	Lower salinity recycled water	MF*, RO*, AOP*, irrigation and groundwater recharge	Lettuce, broccoli, strawberries
Escondido, CA	<ul style="list-style-type: none"> <li>\$0.5 billion cost of outfall</li> <li>Water scarcity</li> </ul>	Recycled water salt content and avocado salt sensitivity	\$0.25 billion cost savings	Reverse osmosis	Avocados
Virginia Pipeline, AU	<ul style="list-style-type: none"> <li>Algae blooms in Gulf St Vincent</li> <li>Groundwater overdraft</li> <li>Seawater intrusion</li> </ul>	<ul style="list-style-type: none"> <li>Private company risk aversion</li> <li>Cost to upgrade and distribute recycled water</li> </ul>	<ul style="list-style-type: none"> <li>\$1.0 billion government subsidy</li> <li>Monterey case as pioneer</li> </ul>	Disinfected tertiary + sidestream reverse osmosis	High-value raw-eaten vegetables

\* MBR = membrane bio-reactor; MF = microfiltration; UV = ultraviolet disinfection; BNR = biological nitrogen removal; RO = reverse osmosis; AOP = advanced oxidation processes.

pilot research and demonstration program. As a result, an eleven-year research effort, including a five-year field trial was undertaken (Sheikh et al. 1990). Locally produced vegetable crops (lettuce, broccoli, celery, cauliflower, and artichokes) were grown in 96 randomly selected plots each receiving one of three types of water (disinfected tertiary with coagulation and settling, disinfected tertiary with in-line coagulation, and locally available well water from a depth of about 200 m (600 ft)). Four fertilization regimes and four replications were also incorporated to account for the impact of nutrients in recycled water and to minimize the impacts of natural variations in the field.

Thousands of samples were collected from the edible tissues of crops at harvest and from the soils. Samples also were collected from the irrigation water, from the tailwater, and from the groundwater. Harvests were weighed and inspected for shelf-life appearance and other subjective qualities. Samples were subjected to microbiological and chemical analysis and the results were analyzed using Analysis of Variance (ANOVA) to evaluate for statistically significant differences between variables. (ANOVA is a powerful statistical tool for distinguishing real differences from random, natural variations.) The results of the pilot research and demonstration study are summarized below.

Both types of reclaimed water had higher levels of most chemicals, including metals, than the native local groundwater. Measurable levels of viruses were detected in 80% of secondary effluent. No naturally occurring viruses were detected in disinfected tertiary effluent from either pilot treatment train throughout the study, and no viruses were detected in any of the crop or soil samples. Indicator (coliform) organisms were occasionally found in all three types of irrigation water. None of the samples taken from the three water sources or the soil indicated the presence of *Salmonella*, *Shigella*, *Ascaris lumbricoides*, *Entamoeba histolytica*, or other pathogens. Pathogens were detected in plant tissues during the first year of the study, but there were no differences between the levels in reclaimed and well water. There was no significant difference in any of the nine heavy metals studied (cadmium, chromium, cobalt, copper, iron, lead, manganese, nickel, and zinc) among plots irrigated with the different water types. Heavy metal input from

commercial fertilizer impurities was far greater than from irrigation waters and accounted for the differences observed in soil samples throughout the five-year study period. Analyses of edible plant tissues indicated no consistent significant differences in heavy metal concentrations.

Crop yield for most of the vegetables grown during the study was slightly higher for crops irrigated with either of the two reclaimed waters than with well water. Field crop quality assessments, shelf life measurements, and visual inspection did not reveal any difference between produce irrigated with reclaimed water and produce irrigated with well water. A marketing firm was commissioned to identify the key issues associated with marketability of crops irrigated with reclaimed water. Interviews were conducted with individuals involved with produce distribution, such as wholesale-retail buyers, brokers, and store managers. Responses indicated that produce grown in reclaimed water would be accepted, and labeling would not be necessary.

Based on the results of the pilot study, in 1998 farmers finally agreed to switch from well water to recycled water for irrigation of their crops. Since then, nearly 5,000 hectares (12,000 acres) of raw-eaten vegetables and fruits (including strawberries) are irrigated with recycled water without any adverse incidents.

A recent study examined growers' attitudes toward water reuse practices in the Monterey region (Reed 2017). It identified growers' perceived need for water supply, how recycled water differs from existing alternatives in quality and reliability, how information is provided to farmers, and the level of trust or confidence growers have in the provider of reclaimed water as key determinants in the decision to use recycled water for crop irrigation. The level of trust is a most important criterion for farmer acceptance of recycled water, achieved in the Monterey region by involvement of farmer representatives in water supply decisions affecting their enterprise.

## Conclusions

### Water Quality and Quantity

In the arid regions of the world, such as western United States, shortages of surface or groundwater



are the most common reasons for inability to irrigate with surface and groundwater, possibly indicating that there is potential for recycled water to replace those water sources. Particularly in water-scarce regions, recycled water can help utilities and irrigation districts reduce their reliance on imported water or diminishing local resources.

### **Costs and Benefits**

The availability of funding to design, construct, and operate recycled water facilities is one of the most important incentives for initiating these projects. Water quality drivers for agricultural reuse are motivated by economics. In several instances, agricultural reuse helps facilities reduce their discharge of nutrients or high-temperature waters to sensitive receiving waters and, in so doing, helps them avert expensive facility upgrades. There is a large potential for agricultural reuse to help utilities facing more stringent nutrient discharge requirements avoid the installation of expensive and energy-intensive nutrient removal processes. Financial constraints are the most frequently cited impediments to initiating agricultural water reuse projects. Particularly in California, where significant funding for recycled water projects is included in state bond measures, timing and utility preparation play a major role in overcoming this impediment.

### **Emulating Successful Water Reuse Projects**

The successful implementation of agricultural reuse projects by peer utilities is frequently cited as an impetus for the initiation of new projects. The long-term, safe operation of older projects combined with previous work evaluating the health risks of agricultural reuse are cited as major factors in ameliorating any health-related concerns that arise during the planning process of recent projects.

### **Water Reuse Regulations and Treatment Technologies**

State regulations are the primary driver motivating the selection of treatment technologies for the production of recycled water. The main driver for what treatment technologies are used for producing recycled water for agricultural irrigation is compliance with state regulations. In most cases specific treatment technologies are mandated, although processes exist to demonstrate

equivalency of alternative technologies.

Some utilities adopt a higher level of treatment to better manage two common impediments of particular relevance to agricultural reuse—seasonal variation in irrigation demand and total dissolved solids (TDS) concentration in recycled water. In most of the world, demand for irrigation water is seasonal. However, utilizing a higher level of treatment can help utilities manage recycled water in conjunction with other local resources. More specifically, installing treatment technologies that produce water of adequate quality for indirect potable reuse can allow utilities to supply recycled water to agriculture during the irrigation season and recharge groundwater during the non-irrigation season. The second impediment, high TDS concentration in some recycled waters compared to surface and groundwater, is a major concern for many growers, but it can be ameliorated with higher levels of treatment and/or strategic blending with other water sources.

### **Potential to Increase Agricultural Reuse**

There are both compelling reasons and extensive potential for increasing agricultural reuse in many regions of the United States. Of all the treated effluent that is produced each day in the United States, only a small fraction is put to beneficial use. A substantial portion of the remainder is lost to ocean outfalls, surface evaporation, or other unproductive uses (e.g., over-spray on forests and pastureland.) This portion could be put to beneficial reuse in agriculture or other applications.

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## Appendix A

### Summary of Drivers For and Against Water Recycling (adapted from Kunz et al. 2016).

	For Water Recycling	Against Water Recycling
<b>Social Drivers</b>	Population pressures	Public opposition
	Community enthusiasm	Negative perceptions
	Changes in attitude	User rejection
	Community engagement	Preconceptions
	Psychological factors	Lack of public involvement
	Demonstration projects	Lack of cooperation among stakeholders
	Success of ongoing projects	Lack of cooperation among water utilities
	Influential stakeholders	Lack of trust and confidence in public institutions
	Organizational support for water reuse	
<b>Technical Drivers</b>	Ageing infrastructure	Water quality requirements (salinity issues)
	Technological advancements	Uncertainties around water quality
	Research and technology development	Availability of recovery technologies
		Technological challenges

## Appendix A Continued.

	For Water Recycling	Against Water Recycling
<b>Policy Drivers</b>	Reforms for improvement of receiving waters	Prohibitive or restrictive regulations
	Wastewater discharge regulation	Protective legislation for water utilities' service territories
	Environmental protection laws	Lack of adequate guidelines
	Discharge regulations with tightened rules	Convoluting project approval paths
	Water recycling goals	Lack of standardization
	Subsidies with a reuse requirement	Lack of definition of responsibilities
	State government support	Uncertainties over future legislation
	Planning mechanisms with reuse agendas	Fragmented water institutions (silos)
	Advocacy by environmental groups	Too many utilities vs. "one water"
	Water recycling guidelines	
	Water reuse as a condition of project approvals	
	Integrated water management planning	
<b>Economic Drivers</b>	Price security for users of recycled water	Higher cost of recycled water
	Federal government grants and loans	Low (subsidized) cost of conventional water
	State government subsidies	Economic/financial disincentives
	Economic/financial subsidies	High up-front infrastructure costs
	Recognition of value of recycled water	Economies of scale—decentralized reuse
	Restrictions on potable water supply	Relatively low cost for wastewater disposal
	Corporate sustainability focus	Farmers' core business focus
	Lower cost of (subsidized) recycled water	Distance from source to farm
	Higher cost (full-value) of potable water	Financial stability of water reuse projects
<b>Natural Drivers</b>	Drought and water scarcity	Water quality impacts
	Need for water supply security	Environmental concerns
	Ecological goals/requirements	Human health and safety concerns
	Limits on natural sources of water	Seasonality of demand for irrigation
	Environmental abatement	Lack of appreciation of the hydrologic cycle
	One-water approach to water management	
	Climate change	
	Geographic isolation	
	Awareness of environmental impacts of over-use of water drawn from natural systems	

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# Water Chemistry During Baseflow Helps Inform Watershed Management: A Case Study of the Lake Wister Watershed, Oklahoma

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**Abstract:** Nonpoint source (NPS) pollution from agricultural and urban development is a primary source of nutrients and decreased water quality in aquatic systems. Installation of best management practices (BMPs) within critical source areas of the watershed can be helpful at reducing the transport of nutrients to waterbodies; however, prioritizing these areas may be difficult. The objective of this study was to develop several potential frameworks for prioritizing subwatersheds using baseflow water chemistry data in relation to a simple human development index (HDI; total percent agriculture and urban development). At a monthly interval, samples were collected at 26 sites throughout the Oklahoma portion of the Lake Wister Watershed (LWW) and analyzed for total nitrogen, total phosphorus, total suspended solids, and chlorophyll *a*. Change point analysis for each parameter found significant thresholds for each of the parameters ranging from 20 to 30% HDI. Change point analysis summary statistics were used to develop prioritization frameworks for the LWW that could be used to target subwatersheds where BMP installation would have the greatest effect at improving water quality. Additionally, regression models developed from the relationships between water quality parameters and HDI values serve as realistic targets for improving water quality, with the modeled line representing the target concentration for a given HDI value. After BMPs have been implemented, baseflow monitoring should continue at the subwatershed scale to track changes in water quality. Focusing monitoring efforts at the subwatershed scale will provide an earlier indication of the effectiveness of BMPs, as it may take several decades to detect improvements in water quality at the larger watershed scale.

**Keywords:** *human development index, nonpoint source pollution, best management practices, change point analysis, regression analysis*

Accelerated eutrophication from excess nutrients entering aquatic systems is a global issue. Nutrients from the landscape associated with human activities [i.e., nonpoint sources (NPS)] are one of the leading causes of impairment to water ways in the United States (EPA 2000). Nutrient enrichment decreases water quality and water clarity through increased algal production (Smith et al. 1999). Increased algal production can form nuisance and or harmful algal blooms (HABs) (Heisler et al. 2008; Paerl et al. 2016) and increases prevalence of hypoxic

conditions in coastal waters (Rabalais et al. 2002), such as that in the Gulf of Mexico proximal to the inflow of the Mississippi River.

The Mississippi River Basin drains the heartland of agricultural production in the United States, where the nutrient cycle in agriculture, from a systems perspective, is broken. Nutrients (i.e., fertilizers) are input into the Midwest to grow crops (e.g., corn and soybeans) which are then used as feed in animal production (e.g., poultry production) outside the region. The feed grains are exported from row crop production areas

(e.g., Midwest) to animal production areas (e.g., Southeast), where food products are then exported globally but the manure remains locally (Sharpley and Withers 1994). The manure left behind is an excellent fertilizer, but it has an imbalance in terms of nitrogen (N) and phosphorus (P) in relation to plant needs (Eck and Stewart 1995). The manure was historically applied locally to pastures, which has led to P buildup in soils and P loss during rainfall and runoff (Sharpley et al. 1996).

The loss of nutrients from fields fertilized with manures is an overwhelming water quality concern, and it is important to understand that only a small fraction ( $< 10\%$ ) of the nutrients applied are lost in runoff annually. For example, plot studies have shown that only 4 and 2% of the N and P applied as manure was lost in surface runoff in Northwest Arkansas (Edwards and Daniel 1993), although these initial rates of loss may vary based on location, soil type, and slope. Interestingly, these percent losses from manure applied to the landscape can be scaled up to the large watershed scale; a mass balance often shows that nutrient loads from a watershed are small percentages of the total amount of manure produced and likely applied within the watershed (e.g., Haggard et al. 2003). The important point is that a large percent of the nutrients applied remain on the landscape within the watershed, i.e., legacy nutrients from past application and management.

Legacy nutrients in soils slowly move with water, either vertically with infiltration (Tesoriero et al. 2009, 2013; Puckett et al. 2011) or laterally with surface runoff (Gburek and Sharpley 1998; Tesoriero et al. 2009), with the rate at which legacy nutrients leave the landscape varying greatly between soil types (Sharpley 1985). The legacy nutrients moving along these surface and subsurface pathways may end up in nearby waterbodies (Basu et al. 2010). This nutrient source and the other sources (e.g., current fertilizer and manure applications) with transport potential result in increases in stream nutrient concentrations. This is why stream nutrient concentrations (from individual samples to annual means) are often positively correlated to the proportion of agricultural lands (sum of % crop, % pasture, and % grassland) and urban development (sum of % developed open-space, and % low, medium, and high intensity development) in the watershed. This relationship has been documented

across the nation (Byron and Goldman 1989; Jordan et al. 1997; Jones et al. 2001; Howarth et al. 2002; Haggard et al. 2003; Toland et al. 2012; Cox et al. 2013; Giovannetti et al. 2013).

Best management practices (BMPs) are often used to reduce nutrient and sediment loss from the landscape, which hopefully translates into improved water quality downstream. Buffer strips and riparian buffers can be installed along the edge of fields to slow overland flow and intercept nutrients and sediment in runoff (Schoumans et al. 2014). Conservation tillage practices (e.g., no-till, spring-till, and cover crops) reduce erosion in the field during the non-growing season (Tilman et al. 2002), decreasing the amount of nutrients and sediment lost from the landscape. Implementing these practices throughout the entire watershed would have the greatest effect at reducing NPS of nutrients and sediments. However, implementation of these BMPs [and others; see (Schoumans et al. 2014)] throughout the entire watershed may not be feasible due to low landowner participation, and limited funds and resources. Targeting critical source areas to implement these BMPs would optimize the benefit while reducing the cost (Sharpley et al. 2000; Niraula et al. 2013).

A variety of techniques have been used to identify priority locations for BMP implementation to improve water quality, including qualitative indices [e.g., P Index, (Lemunyon and Gilbert 1993; Sharpley et al. 2001)] and watershed modeling (Pai et al. 2011). Recent work suggests that water quality monitoring during baseflow conditions can be used to prioritize subwatersheds for BMP implementation (McCarty and Haggard 2016). The premise is that stream water quality during baseflow conditions reflects the influence of NPS pollution across the watershed. Thus, stream water quality can be related to human development (i.e., percent urban and agriculture land cover) across a target watershed and this relation can be used to suggest priority areas for BMP installation.

Here, we present a case study focusing on baseflow water quality monitoring within the Lake Wister Watershed (LWW), near Wister, Oklahoma. The primary goal of this monitoring was to assist the Poteau Valley Improvement Authority (PVIA) and other stakeholders in prioritizing subwatersheds for BMP implementation to help reduce sediment

and nutrient transport from the landscape. At the end of the case study we provide several potential methods for subwatershed prioritization and also a means for setting realistic targets for water quality improvement.

## Case Study

Lake Wister is on Oklahoma's 303(d) list for impaired water quality, including excessive algal biomass, pH, total phosphorus (TP), and turbidity (ODEQ 2016). To address these water quality issues, the PVIA released its "Strategic Plan to Improve Water Quality and Enhance the Lake Ecosystem" in 2009. The strategic plan divides the restoration efforts into three zones of action to focus on, including the watershed, the full lake, and Quarry Island Cove. The purpose of this project was to focus on the watershed by monitoring stream water quality during baseflow conditions at or near the outlets of the subwatersheds, in the Oklahoma portion of the LWW.

## Methods

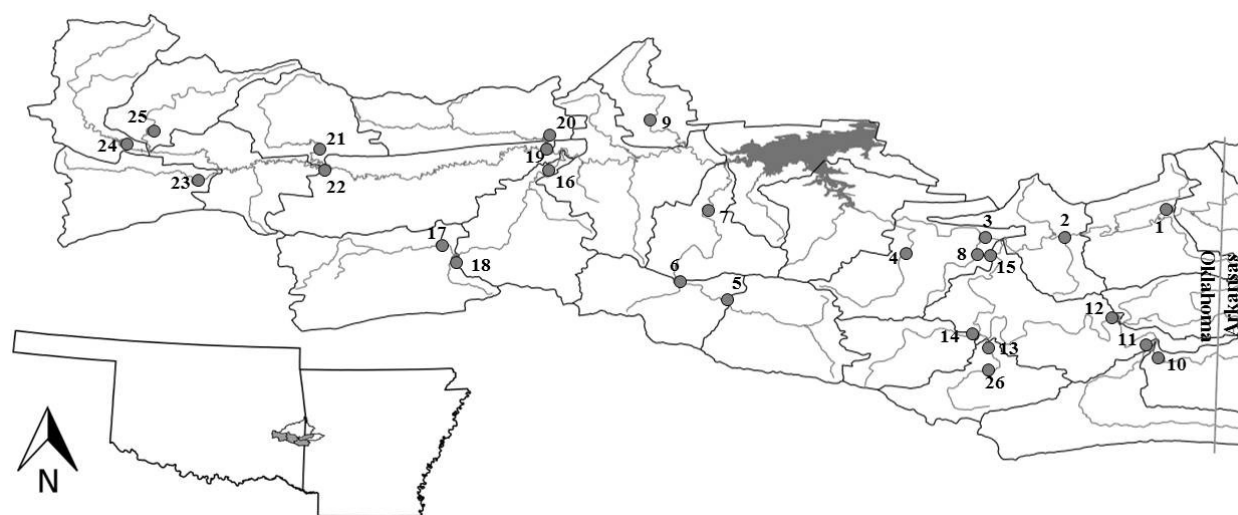
### Study Site Description

The LWW covers an area of 2,580 km<sup>2</sup> (~640,000 acres) and makes up the southern half (52%) of the entire Poteau River sub-basin (hydrologic unit code (HUC) 11110105; Figure 1). The primary land use

and land cover (LULC) across the Oklahoma portion of the LWW is 72% forest (sum of % deciduous, % evergreen, and % mixed forest), 19% agriculture, and 4% urban; the LULC for the 845 km<sup>2</sup> (~209,000 acres) portion of the LWW in Arkansas is similar with 71% forest, 20% agriculture, and 5% urban.

Within the Oklahoma portion of the LWW, there are 26 HUC 12 subwatersheds that range in size from 42 to 125 km<sup>2</sup> (10,300 to 30,800 acres). Forest is the dominant LULC across the HUC 12s, ranging from 45 to 95% of the watershed. The proportion of human development (i.e., agriculture plus urban) was less than half of the LULC across the stream sites (4 to 48%; Table 1). Additionally, across the LWW there are seven EPA national pollutant discharge elimination system (NPDES) permitted point sources, including wastewater treatment plants (WWTPs), sewage systems, and a poultry processing plant.

For this study, 26 sites were selected at bridge crossings near the outflow of 23 of the HUC 12's in the Oklahoma portion of the LWW shown in Figure 1. The LULC for the catchments upstream of the 26 sample sites ranged from 49 to 95% forest, < 1 to 37% agriculture, and < 1 to 10% urban. LULC data in Table 1 represent the land use for the entire catchment upstream of each sampling location.



**Figure 1.** Sample sites within the Lake Wister Watershed of Oklahoma. Site numbers on the figure correspond to site numbers in Table 1.

**Table 1.** Sample sites and land cover within the Lake Wister Watershed organized by hydrologic unit code (HUC) 10s. The number in the HUC 12 column is the final two digits associated with the HUC10 number listed at the top of each group of sites. Watershed area and land use and land cover values are representative of the full catchment upstream of the sites.

Site #	HUC 12	Stream Name	Area (Km <sup>2</sup> )	%F <sup>1</sup>	%AG <sup>2</sup>	%U <sup>3</sup>	% HDI <sup>4</sup>	Lat.	Long.
HUC10-1111010503: Upper Poteau River									
*1	03	Poteau River	694	66	25	5	30	34.8798	-94.4830
*2	04	Poteau River	768	66	25	5	30	34.8587	-94.5657
*3	05	Poteau River	1335	74	18	5	22	34.8584	-94.6292
HUC10-1111010505: Middle Poteau River									
4	02	Conser Creek	34	95	3	2	5	34.8671	-94.7039
5	04	Holson Creek	73	94	3	2	5	34.8069	-94.8376
6	05	Holson Creek	132	92	4	3	7	34.8227	-94.8765
7	06	Holson Creek	182	91	5	3	7	34.8795	-94.8533
8	02	Rock Creek	11	67	30	2	32	34.8431	-94.6357
9	03	Coal Creek	27	72	19	2	21	34.9514	-94.8900
HUC10-1111010502: Black Fork Poteau River									
10	02	Black Fork	122	88	6	2	9	34.7600	-94.4902
11	01	Big Creek	112	90	3	5	8	34.7692	-94.4987
12	03	Black Fork	323	89	5	3	8	34.7926	-94.5257
*13	04	Shawnee Creek	48	88	1	6	8	34.7679	-94.6276
14	05	Cedar Creek	48	95	1	4	4	34.7785	-94.6400
*15	06	Black Fork	509	88	6	4	9	34.8432	-94.6248
*26	04	Shawnee Creek	23	93	1	5	6	34.7894	-94.6279
HUC10-1111010504: Fourche Maline									
16	08	Long Creek	180	80	13	1	15	34.9084	-94.9803
17	07	Long Creek	77	83	12	1	13	34.8512	-95.0662
18	07	Long Creek tributary	20	87	8	3	12	34.8401	-95.0538
*19	09	Fourche Maline	417	63	28	4	32	34.9293	-94.9813
*20	06	Red Oak Creek	71	54	37	6	43	34.9360	-94.9809
21	04	Little Fourche Maline	55	70	23	3	26	34.9275	-95.1626
*22	05	Fourche Maline	313	67	26	4	30	34.9124	-95.1561
*23	03	Bandy Creek	59	49	37	10	47	34.9023	-95.2615
24	02	Fourche Maline	72	81	12	4	16	34.9325	-95.3195
25	01	Cunneo Creek	45	90	7	>1	7	34.9419	-95.2975

<sup>1</sup> % Forest, includes deciduous, evergreen, and mixed forest; <sup>2</sup> % Agriculture, includes crops, grassland, and pasture/hay; <sup>3</sup> % Urban, includes developed-open space, low, medium, and high intensity development; <sup>4</sup> % Human Development Index (HDI) is the sum of % agriculture and % urban; \* Sites downstream of EPA NPDES permitted point sources.

### Sample Collection and Analysis

Water samples were collected at the 26 sites at monthly intervals from July 2016 through July 2017 during baseflow conditions, as defined by no measurable precipitation seven days prior to sampling. Samples were not collected in October of 2016 due to abnormally dry conditions which resulted in no flow in several of the smaller streams, resulting in a total of 12 samples collected. Samples were collected from the vertical centroid of flow where the water is actively moving, either by hand or with an Alpha style horizontal sampler lowered from the bridge. Water samples were split, filtered, and acidified in the field based on the specific storage needs for each analyte. All samples were stored on ice until delivered to the Arkansas Water Resources Center certified Water Quality Lab (AWRC WQL).

All water samples were analyzed for total nitrogen (TN), TP, total suspended solids (TSS), and sestonic chlorophyll-*a* (chl-*a*) using standard methods that are available at <https://arkansas-water-center.uark.edu/water-quality-lab.php> (accessed 11/18/2018).

### Data Analysis

All LULC data for the LWV, HUC 12s within the LWV, and catchments upstream of each sampling location were compiled using GeodataCrawler (see <http://www.geodatacrawler.com/>; accessed 11/18/2018) and Model My Watershed (see <https://app.wikiwatershed.org/>; accessed 11/18/2018). LULC data were used to calculate a simple human development index (HDI) value as the total percent agriculture and urban land use for the catchment upstream of each sample site and for each subwatershed (Table 1).

All water quality data collected over the course of this study can be found in the data report “DR-WQ-MSC385” available at [https://arkansas-water-center.uark.edu/publications/DR-WQ-MSC385\\_Water-quality-monitoring-Poteau-Valley-Improvement-Authority.xlsx](https://arkansas-water-center.uark.edu/publications/DR-WQ-MSC385_Water-quality-monitoring-Poteau-Valley-Improvement-Authority.xlsx) (accessed 11/18/2018). The geometric mean of constituent concentrations at each site was used in the data analysis, because it is less sensitive to extreme low and high values than arithmetic means. The geometric mean is typically a good estimate of the central tendency or middle of the data.

Both seasonal and annual geometric means were calculated for the water quality parameters at each site. The geometric means of all the data from each site were related to HDI using simple linear regression. This statistical analysis shows how geometric mean constituent concentrations change across a gradient of HDI, or agriculture plus urban land use, in the drainage area.

Change point analysis is another way to examine how HDI might influence constituent concentrations in streams. Change point analysis looks for a threshold in the geometric mean concentration and HDI relation, where the mean and variability in the data changes. This statistical analysis is not dependent on data distributions, and it gives a threshold in HDI where the geometric mean concentrations likely increase.

## Results and Discussion

### Nitrogen

The majority of TN in the flowing waters was in the particulate form, where dissolved inorganic N (DIN:  $\text{NH}_3\text{-N}$  plus  $\text{NO}_3\text{-N}$ ) was typically less than 35% of the total. Annual geometric mean concentrations for TN ranged from 0.10 to 1.50  $\text{mg L}^{-1}$ . This range in TN is consistent across all four seasons, and there was no real seasonal pattern (Figure 2A). In roughly 60% of the samples, TN was within the range of the nutrient supply threshold needed to promote algal growth and cause shifts in algal community composition [0.27 to 1.50  $\text{mg L}^{-1}$ ; (Evans-White et al. 2013)] potentially creating nuisance algal conditions.

The geometric mean concentrations of the TN species varied across the LWV, reflecting changes in nutrient sources and land uses within the drainage areas. TN geometric means increased with the proportion of agriculture and urban development (Figure 3A), i.e., HDI values, in the watershed, explaining 78% of the variability in TN. This relationship with stream N concentrations and HDI has been observed across the region (e.g., see Haggard et al. 2003; Migliaccio and Srivastava 2007; Giovannetti et al. 2013). The regression lines provide a possible water-quality target to which TN concentrations might be reduced at a given HDI. The sites, or streams, with concentrations well above this line might be of specific interest for



management purposes, e.g., Site 23. Additionally, streams with greater HDI that fall below the line may also be of interest to determine why these stream reaches have low constituent concentrations despite having a higher HDI value (i.e., is it due to good riparian, implementation of BMPs, etc.).

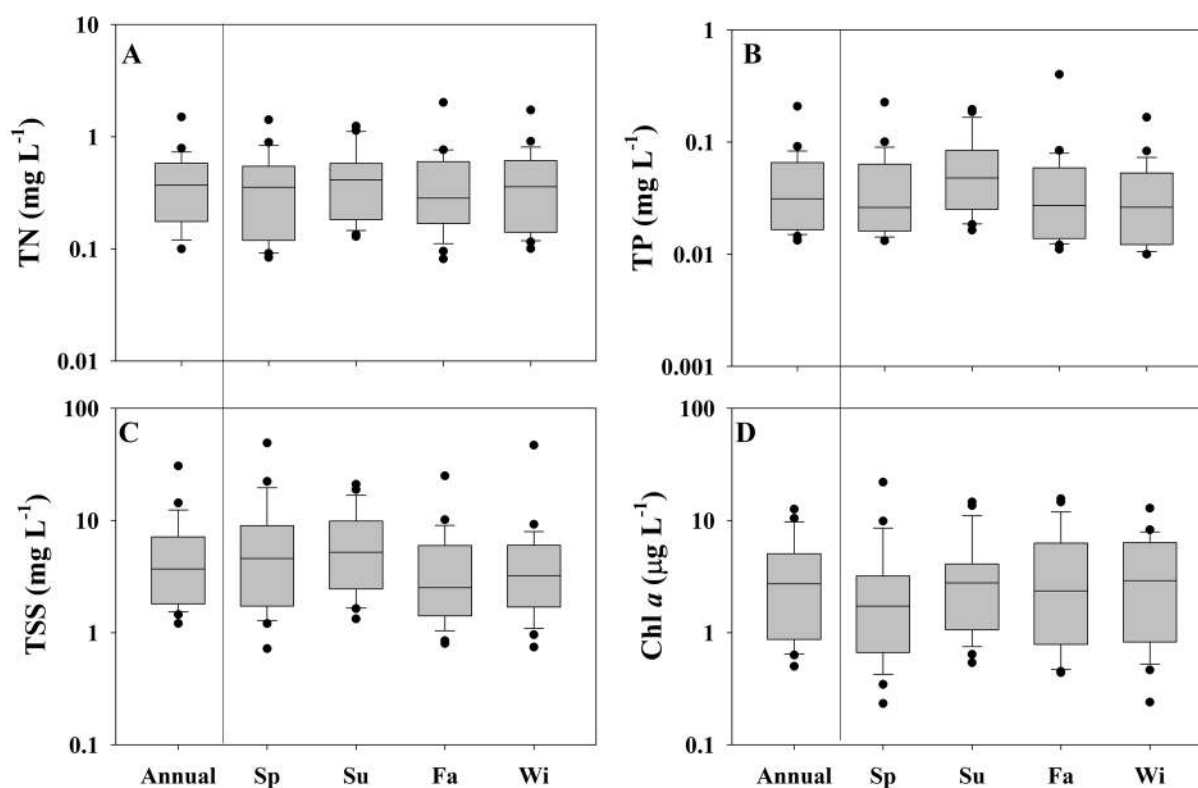
The geometric mean concentrations for TN also showed a changepoint response to increasing HDI; that is, the average and deviation of the geometric means increased above a HDI value of 28% (Figure 4A). The average of the data above the changepoint was generally two to three times greater than the data below that HDI value.

### Phosphorus

Geometric mean concentrations for TP ranged from 0.013 to 0.208 mg L<sup>-1</sup>; much of which was in the particulate form, where the dissolved form (SRP) typically made up less than 33% of the measured TP. This range was consistent across all of the seasons except for summer, when median

TP concentration was elevated relative to the other seasons and annual median (Figure 2B). The increase in TP across the streams during summer corresponded with slight increases in sediment and Chl-*a* in the water column (discussed later). In roughly 80% of the samples, TP was within the range of nutrient supply threshold needed to increase algal growth and drive shifts in algal community composition in streams [0.007 to 0.100 mg L<sup>-1</sup>; (Evans-White et al. 2013)] and potentially cause nuisance algal conditions. However, two sites with values much higher than this range were directly downstream of effluent discharges (Bandy Creek and Shawnee Creek at Hwy 59).

Geometric mean P concentrations varied across the streams draining the LWW, showing that 70% of the variability in P concentrations was explained by HDI (Figure 3B). These relationships between stream TP concentrations and HDI, like TN, have been observed across the region (e.g., see Haggard et al. 2003; Cox et al. 2013), reflecting potential TP



**Figure 2.** Box and whisker plots of constituents showing medians (horizontal line within each box), range (error bars show the 5<sup>th</sup> and 95<sup>th</sup> percentiles), and outliers (points above and below error bars) for each of the constituents analyzed at the Oklahoma sites in the Lake Wister Watershed. Annual data are to the left of the vertical line, while seasonal data are to the right. The abbreviations stand for: spring (Sp), summer (Su), fall (Fa), and winter (Wi).

sources such as poultry litter applied to pastures (DeLaune et al. 2004; Cox et al. 2013). The regression lines provide a realistic water quality target to which P concentrations might be reduced (without conversion to forest) and show sites that deviate greatly from concentrations at a given HDI.

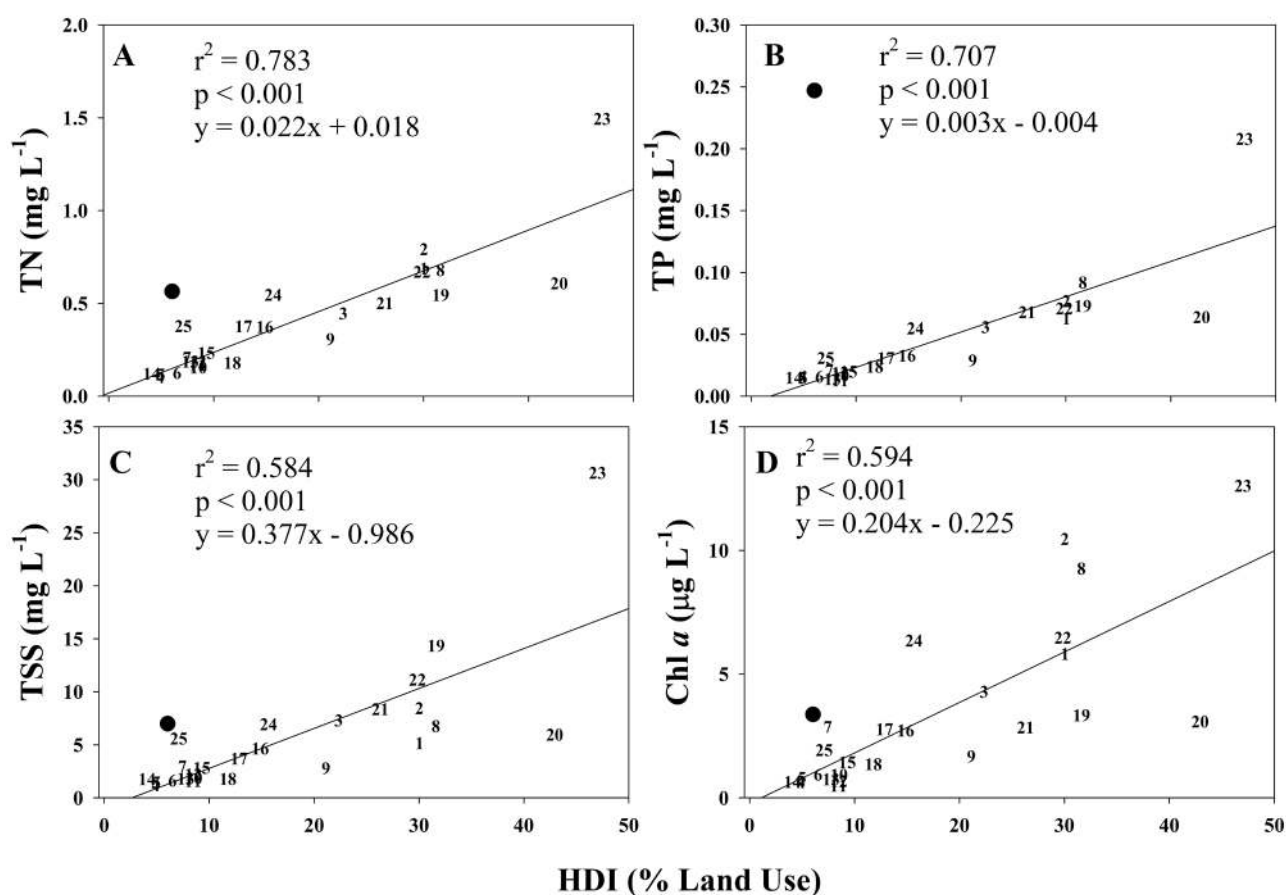
The geometric mean concentrations of TP showed changepoint responses to increasing HDI. The changepoint for TP was slightly lower than TN at 21% HDI. As with TN, mean TP values above the threshold were more than two times greater than the mean values below the threshold. Site 23 consistently shows elevated P and N concentrations relative to other sites across the LWW, suggesting nutrient sources upstream might need to be investigated (Figure 4B).

### Suspended Sediments

Annual geometric means for TSS ranged from 1

to 31 mg L<sup>-1</sup>. Geometric mean TSS concentrations were greater in the spring and summer than the fall and winter (Figure 2C). Low values in the fall may be explained by the drier conditions that began towards the end of summer through early winter 2016. The less frequent rainfall-runoff events reduce erosion from the landscape and within the stream channel, and the lower flows throughout this season have less power to erode the channel and suspend particulates in the water column (Morisawa 1968). The more frequent storms and elevated baseflow during spring and early summer likely kept TSS elevated in the streams (relative to fall) across the LWW. TSS was positively correlated to TP in streams of the LWW ( $r = 0.739$ ;  $p < 0.001$ ), which has been documented elsewhere (Stubblefield et al. 2007).

Many factors influence the amount of particulates in the water column of streams,



**Figure 3.** Simple linear regression of geometric mean constituent concentrations versus human development index (HDI) values for the Oklahoma portion of the Lake Wister Watershed. The site number in red is Shawnee Creek at highway 59, downstream of effluent discharge, thus it was not used in the statistical analysis.

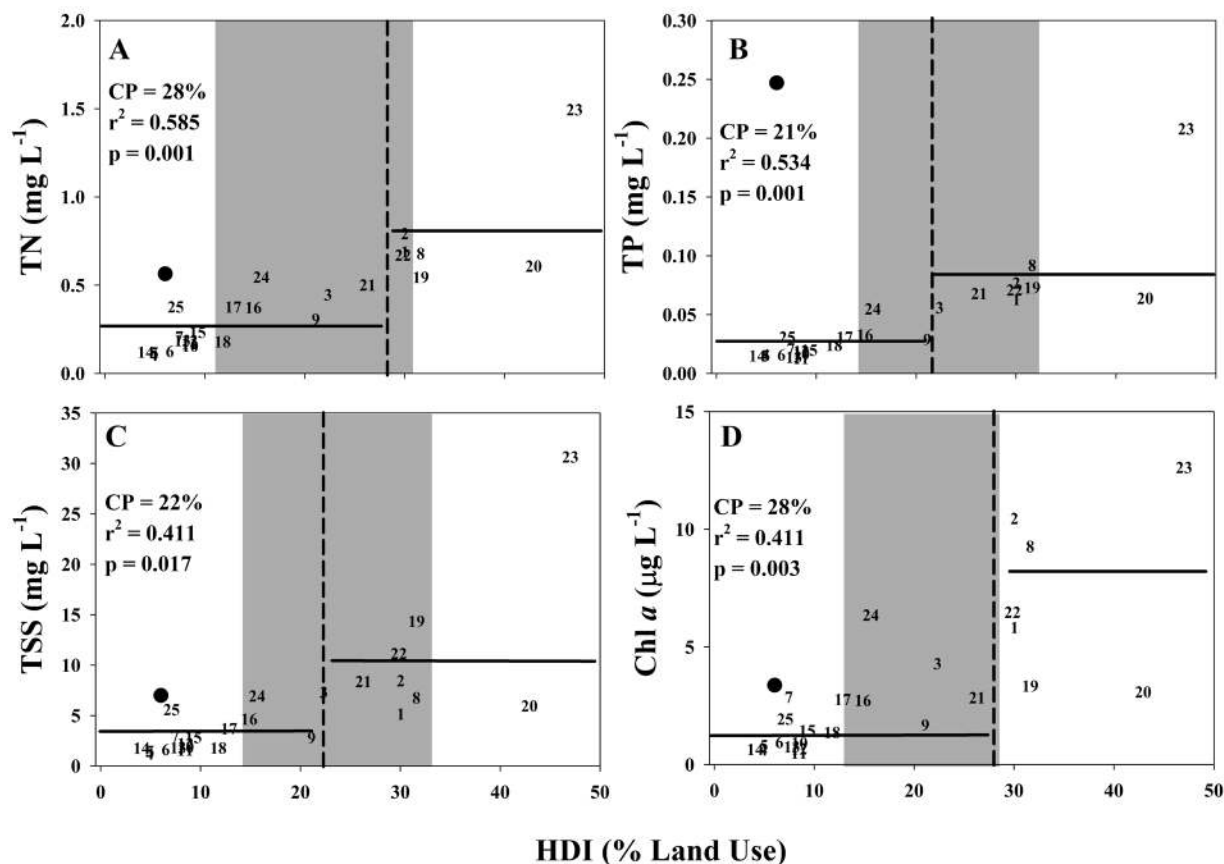
including rainfall-runoff, discharge, channel erodibility, and even algal growth. The myriad of factors that influence TSS in water are also influenced by human activities, which is likely why HDI explained more than half of the variability ( $R^2=0.584$ ;  $P<0.001$ ) in the geometric means of TSS across the streams of the LWW (Figure 3C). These relationships are not well defined regionally, but where data are available, similar observations have been made (Price and Leigh 2006). There was also a significant threshold response in TSS at 22% HDI (Figure 4C). It is interesting to note that while samples were collected at baseflow, TSS was still strongly correlated to HDI across these sites.

### Chlorophyll *a*

Annual geometric mean concentrations of sestonic Chl-*a* (algal biomass in the water

column) ranged from 0.5 to 12.6  $\mu\text{g L}^{-1}$  across the LWW. Geometric mean Chl-*a* concentrations were consistent throughout the year, without much variability between seasons (Figure 2D). Additionally, Chl-*a* concentrations across these sites were strongly (positively) related to total nutrient concentrations in the water column, where TP explained 78% on Chl-*a* variability ( $p < 0.001$ ), while TN explained 85% ( $p < 0.001$ ). This relationship between sestonic algae and total nutrients has been documented in other systems (Chambers et al. 2012; Haggard et al. 2013).

The geometric mean concentrations of Chl-*a* increased with the proportion of human development in the watershed (i.e., HDI values), where HDI explained 59% of the variability in sestonic Chl-*a* ( $p < 0.001$ ; Figure 3D). This strong relationship was surprising, because many physical,



**Figure 4.** Changepoint analysis of geometric mean concentrations versus human development index (HDI) value for sites in the Oklahoma portion of the Lake Wister Watershed. The vertical dashed line represents the changepoint values specific to each constituent. The gray box shows the 90% confidence interval about the changepoint. Horizontal bars represent the mean of the data points to the left and right of the change point. The site number in red is Shawnee Creek at highway 59, downstream of effluent discharge, thus it was not used in the statistical analysis.

chemical, and biological factors influence algal growth in streams (Evans-White et al. 2013). It is likely that this correlation is driven by the increased nutrient concentrations that are found at sites with higher HDI values. Additionally, hydrology [e.g., discharge and velocity (Honti et al. 2010)] may also be an important factor controlling sestonic algal growth, where slower velocities in low gradient streams might allow for greater growth than in high gradient streams, when nutrients are elevated. Interestingly, sestonic Chl-*a* still showed a threshold at a HDI value (28%) similar to that observed with the chemical concentrations (Figure 4D).

## Criteria for Prioritizing HUC 12s

Changepoint analysis is a powerful statistical tool, and one of its most useful aspects is that it gives a threshold, i.e., specific value on the X-axis. In this case, the changepoint is the HDI value where land use begins to have a significant influence on water quality, as seen by increasing constituent concentrations. Thus, this information can be used to help design a process for PVIA and its stakeholders to use in establishing which HUC 12s or smaller subwatersheds are priorities for NPS management. The following sections provide some guidance on how this might be done.

When water quality data at all subwatersheds are absent, constituent specific HDI thresholds can be used. The HUC 12s could be prioritized and separated into categories based on the example (Figure 5A). The hypothetical categories could include:

- Preservation: HDI < 15%; These subwatersheds would be background or reference sites, as established by the lower end of the 90<sup>th</sup> percentile confidence interval about the changepoint.
- Low priority: HDI from 15 to 25%; These subwatersheds would be a low priority for NPS management, as established by the lower end of the 90<sup>th</sup> percentile confidence interval about the changepoint and the changepoint.
- Medium priority: HDI from 25 to 30%; These subwatersheds would be a medium priority for NPS management, as established by the changepoint and the upper end of the

90<sup>th</sup> percentile confidence interval about the changepoint.

- High priority: HDI > 30%; These subwatersheds would be a high priority for NPS management, as established by the upper end of the 90<sup>th</sup> percentile confidence interval about the changepoint.

Based on the LWW stream data, sites with HDI values less than the lower 90<sup>th</sup> percentile confidence interval about the changepoint had low constituent concentrations (Figure 5A). The goal here would be to keep or preserve these HUC 12s to maintain existing water quality conditions. On the opposite end of the spectrum, streams with HDI values greater than the threshold, and even greater than the upper 90<sup>th</sup> percentile confidence interval around the changepoint, generally had greater constituent concentrations. Thus, PVIA and stakeholders might focus efforts on HUC 12s with HDI values above the threshold (i.e., medium and high priority) because these catchments likely have the greatest restoration potential. Using the LULC for each individual HUC 12 (Table 1), this classification scheme shows the HUC 12s along the Fourche Maline River and Poteau River in Oklahoma (Figure 6) as areas of priority. In the absence of water quality data, this option can be a good method for selecting HUC 12s when developing the watershed management plan.

When water quality data are available, thresholds can be used differently to select HUC 12s based on measured constituent concentrations, as opposed to predicted values based on human development (Figure 5B). This method focuses on the average constituent concentrations on either side of the threshold. The HUC 12s could be prioritized and separated into categories based on the example in Figure 5B, where the hypothetical categories would include:

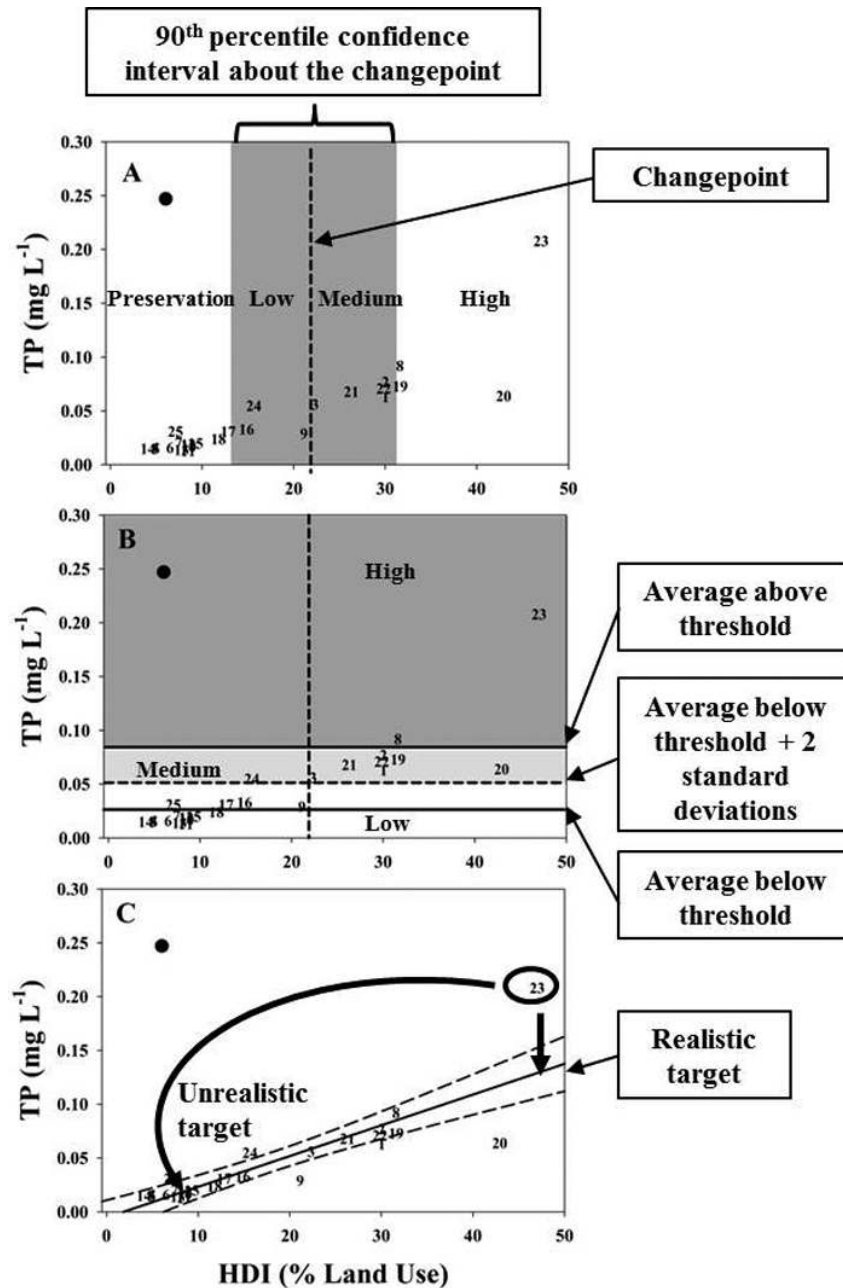
- Low priority: HUC 12s with constituent concentrations less than average constituent concentration below the threshold plus two standard deviations (horizontal dashed line or 0.05 mg L<sup>-1</sup> for TP; Figure 5B).
- Medium priority: HUC 12s with constituent concentrations greater than the horizontal dashed line but less than the average constituent concentration above the threshold (upper solid line or 0.08 mg L<sup>-1</sup> for

TP; Figure 5B).

- High Priority: HUC 12s with constituent concentrations greater than upper solid line or  $0.08 \text{ mg L}^{-1}$  (Figure 5B).

As stated earlier, constituent concentrations below the thresholds were generally low. The

horizontal dashed line (i.e., for TP  $0.05 \text{ mg L}^{-1}$ ) provides a realistic bench mark for separating low and medium priority watersheds, as it represents the upper limits of baseline conditions for the constituents analyzed in this study. This method could be conducted for each constituent of interest,



**Figure 5.** Potential methods using changepoints to identify watersheds for nonpoint source (NPS) management. Categorization of hydrologic unit code (HUC) 12s based on their human development index (HDI) value only (A); separation of HUC 12s based on measured water quality data (B). Linear models (regression line) represent realistic targets for improving water quality within a HUC 12 of a given HDI value (C).



resulting in the selection of constituent specific HUC 12s (Figure 7).

A weight of evidence approach may be used to combine HUC 12 priorities developed for individual constituents. Low, medium, and high priorities can be ranked 1, 2, and 3, respectively, for each constituent. Rankings for each constituent can then be added together to form a cumulative rank for each HUC 12. The cumulative ranks across all HUC 12s within the Oklahoma portion of the LWW were divided into five categories, where the subwatersheds shaded the darkest had the highest priority (Figure 7).

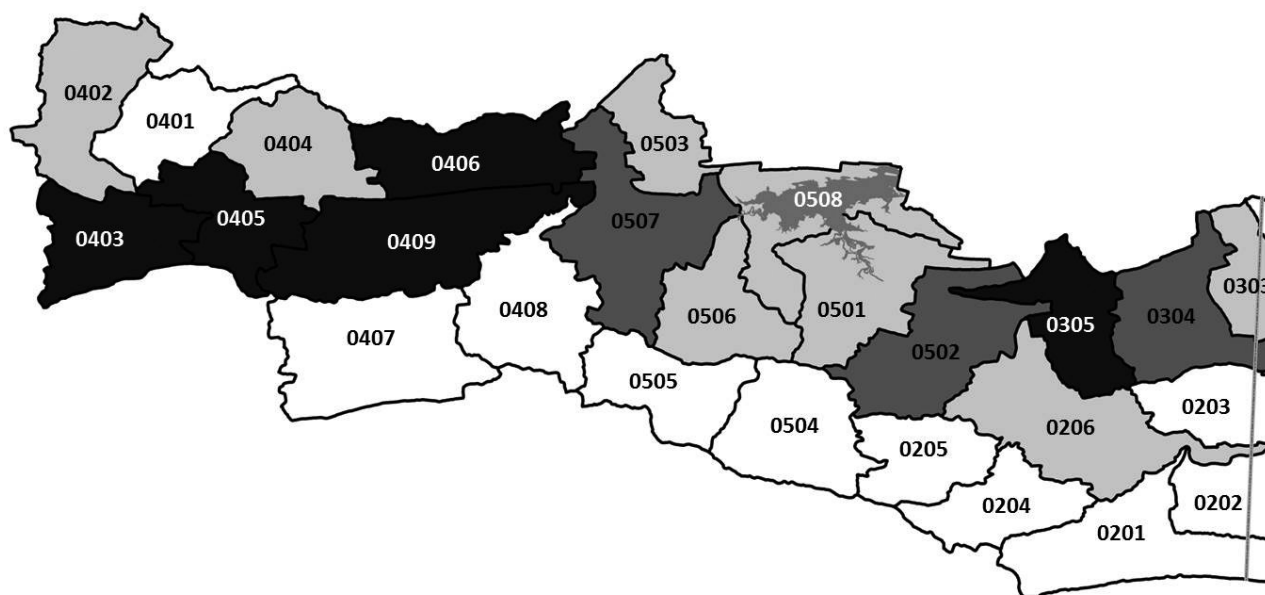
With this approach you must be mindful of the nested nature of the watershed, in that several subwatersheds are down river of one or more other subwatersheds. Water quality in an upstream subwatershed may result in higher than expected constituent concentrations, based on the level of human development. In such a case, it may be beneficial to compare subwatershed priorities identified by both methods.

Constituent concentrations change with land use, where the relation can often be described with a simple linear model (Figure 5C). Once subwatersheds have been prioritized, the goal

should be to move the higher priority HUC 12s below the linear regression, which represents the average conditions at a given HDI level. Continued routine monitoring methods, such as establishing an annual geometric mean concentration point by collecting and analyzing 12 monthly baseflow samples, can be used to track improvements within the watershed. The geometric mean data point should be plotted against the most current land use information available, to reflect the changing LULC and HDI gradient. Once the data point shifts from above the line to below the line, then this site has reached its target concentration as defined by the original regression. However, it would be wise to make sure the HUC 12s have consistently changed priority categories (e.g., moved from high to low) over multiple years before assuming the target has been met.

## Discussion

In addressing the issue of eutrophication, it is important to focus on both point and NPS of nutrients. Point sources, such as municipal WWTPs, can be a major component of a watershed's overall nutrient load, especially for P (Haggard



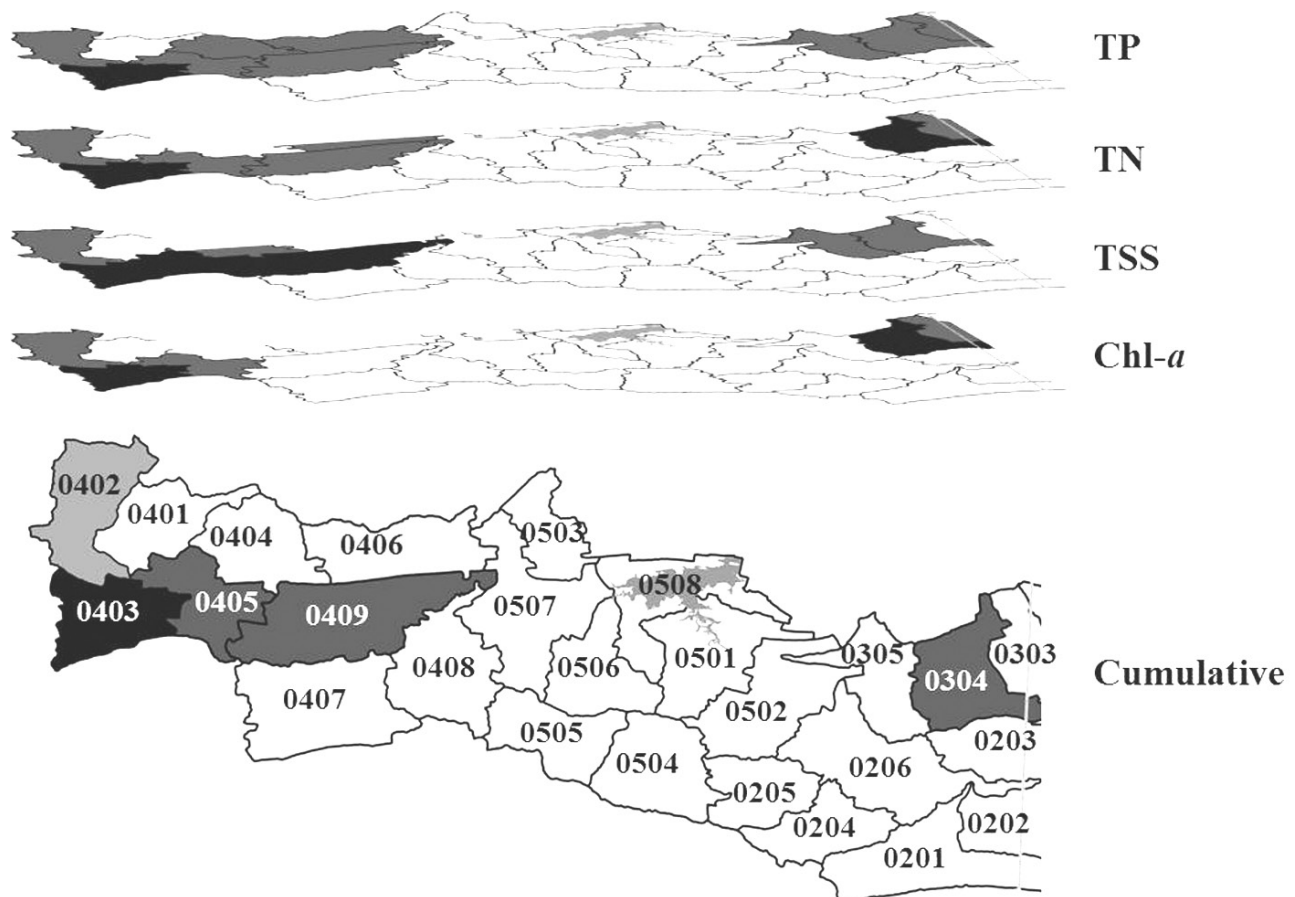
**Figure 6.** Potential prioritization of hydrologic unit code (HUC) 12 subwatersheds based on the threshold response of constituent concentration to the human development index (HDI); the priority for nonpoint source (NPS) management varies from lightest (preservation) to darkest (highest priority). HUC 12 subwatersheds are labeled with the last four digits of their HUC 12 code.

2010). However, improvements to these WWTPs have been successful in reducing the nutrient concentration in the effluent leaving treatment facilities and, as a result, reducing nutrient loads in receiving waters downstream of urban areas (Jaworski 1990; Haggard 2010; Scott et al. 2011). The contribution of nutrients to receiving waters from point sources is likely to continue to decrease as more stringent and widespread controls are put in place (Jarvie et al. 2013). However, decreasing nutrient inputs from point sources is only part of the solution.

Reducing nutrient loads associated with NPS pollution is often much more difficult than for point sources. In fact, over the past four decades, most NPS management plans have reported little

to no improvement in surface water quality, even with extensive BMP installation throughout their watersheds (Meals et al. 2010; Jarvie et al. 2013). Low landowner participation resulting in poor distribution of BMPs, poor site selection, and inappropriate BMP selection for NPS pollution type are just a few factors that contribute to the failure of NPS management plans (Meals et al. 2010). Identification of critical source areas in need of BMPs can increase the success of NPS management plans.

Both proposed methods in the case study suggest subwatersheds along the Fourche Maline and Poteau Rivers were priority areas in need of BMPs, which aligned well with target areas previously highlighted in the LWW using the Soil



**Figure 7.** Potential prioritization of hydrologic unit code (HUC) 12 subwatersheds when chemical concentrations are available in streams. Priorities for individual constituents can be used to meet specific management needs, or priorities can be added across multiple constituents to prioritize subwatersheds based on a cumulative approach. For each constituent shown and for the cumulative map, the priority for nonpoint source (NPS) management varies from lightest (low priority) to darkest (highest priority). Each subwatershed is labeled with the last four digits of its HUC 12 code.

Water Assessment Tool (SWAT) (Busteed et al. 2009). Although the Oklahoma NPS Management Program Plan suggests that monitoring and assessment at the HUC 12 scale is the most effective means to identify water quality problems associated with NPS pollution (OCC 2014), this scale is coarse when compared to the hydrologic response units (HRU's) used in SWAT models. However, these methods can be applied at a finer scale within the higher priority watersheds to further isolate the specific areas in need of BMPs.

Across the LWW of Oklahoma, there was a significant threshold at roughly 25% human development, with catchments above this threshold having nutrient and sediment concentrations greater than catchments below this threshold. However, in an analysis of Arkansas watersheds, the threshold HDI where nutrients and sediments began to increase was closer to 50% (McCarty et al. 2018), suggesting that these watersheds were more resilient to increasing land use. This suggests that, while there is variability between watersheds, this approach is applicable to other watersheds as long as there is a gradient in human development across the watershed. For instance, this method would likely not work in areas heavily developed for agriculture such as the Mississippi River Delta and areas in the Midwest with greater than 90% agriculture. Additionally, these methods require that baseflow constituent concentrations relate to human development in a predictable way, as seen in this case study and in other areas outside of Arkansas and Oklahoma (e.g., see Jones et al. 2001; Buck et al. 2004). Application of this method in other watersheds also requires that the threshold responses between constituent concentrations and HDI are developed for each specific watershed.

While these methods can assist watershed managers in identifying priority subwatersheds for the development of NPS management plans, determining the success or failure of these plans requires assessment at the appropriate spatial and temporal scales. Most often BMPs are installed at edge-of-field or small watershed scale, but then assessed for effectiveness at the sub-basin or larger watershed scale, resulting in difficulties in detecting BMP effectiveness (Mulla et al. 2008). Nutrient hot spots throughout larger watersheds that are responsible for the storage and eventual release

of nutrients from riparian buffers, wetlands, and stream and lake sediments, likely mask the effect of reduced nutrient export from the landscape following the implementation of BMPs (Haggard et al. 2005; Ekka et al. 2006; Jarvie et al. 2013). So, while improvements in water quality may result from BMP implementation, they may not be detected, especially if monitoring is occurring further down in the watershed than where the management practices are occurring.

The issue of eutrophication in streams and lakes arises over decades of intensive agricultural practices and increasing human development, and cannot be solved overnight. Nutrient management plans that reduce or eliminate fertilizer application to fields can take up to 50 years or more to cause reductions in  $\text{NO}_3^-$ , due to the long residence time of  $\text{NO}_3^-$  in groundwater (Bratton et al. 2004). While P is more likely to stay in the soil, it can take a decade or more to draw down soil P reserves through removal in crop biomass (Zhang et al. 2004; Hamilton 2012). Additionally, many BMPs require time to establish; for instance, it can take up to a decade for trees in riparian buffer strips to become fully established and start removing nutrients from subsurface flow (Newbold et al. 2010). Sediment-bound P in the fluvial channel is not mitigated by edge-of-field BMPs (Dunne et al. 2011), and can be a substantial source of P to the water column (Jarvie et al. 2005). Lag times associated with stream bed sediments are highly variable and depend on flow regime, hydromorphology, and sediment retention (Jarvie et al. 2006), but sediments can take 50 years or more to be flushed from larger watersheds (Clark and Wilcock 2000). These pools of N and P constitute legacy nutrients that can contribute to the system for decades after BMPs have been put in place.

Many of the issues associated with long lag times between BMP implementation and improvements to water quality at the larger watershed scale are reduced in smaller watersheds. In general, improvements to water quality should be detected in smaller watersheds (e.g.,  $< 15 \text{ km}^2$ ) faster than larger watersheds because monitoring efforts are likely closer to the source and the mitigation efforts (Meals et al. 2010). Additionally, water quality in smaller streams tends to respond more quickly and directly to watershed alterations

(Lowe and Likens 2005). Thus, targeting smaller watersheds for water quality monitoring following BMP installation should provide watershed managers a better indication of the effectiveness of implemented BMPs due to a shorter lag period between installation and observed changes in water quality.

## Conclusion

Managing NPS pollution can be difficult, and the results of such efforts may take several decades or longer to be fully realized at the larger watershed or basin scale. The first issue for watershed managers is to identify or prioritize the areas within the watershed in need of mitigation. In the case study of the LWW, we found that in lieu of generating calibration and validation data needed for watershed models, baseflow water quality monitoring at the subwatershed scale provided an effective way of identifying areas in need of BMPs, producing recommendations similar to those generated by SWAT models (Busteed et al. 2009). Once BMPs are implemented, the effects of legacy nutrients that have built up on the landscape and in the fluvial channel can mask the effects of improvements made in the watershed. However, focusing monitoring efforts at the subwatershed scale can provide an early assessment of the effectiveness of BMPs implemented.

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# Food Security as a Water Grand Challenge

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**Abstract:** Perhaps the biggest challenge the world faces is providing sufficient, nutritious, and safe food at the right time for its ever-increasing population. Considering current world population growth trends, it is estimated that the global population will be about 10 billion by the year 2050. Therefore, food production should at least double in the same period if food security is to be satisfied. Water and land resources play a pivotal role in agriculture and directly connect to food security. At the same time, the capacity to produce food is constrained by global climate changes and increased pressure on land resources. These challenges are more severe in Southern Asia, Sub-Saharan Africa, and East Asia, where conflict and lack of capacity to fund agricultural research and food production are common. Strategies that simultaneously increase food production and reduce threats to food security are therefore needed. The objectives of this paper are to review the grand challenges of global food security and to propose strategies for mitigating food insecurity, with an emphasis on the link between water resources and food production.

**Keywords:** *food security, water, land, food access*

The world's population is estimated at seven billion and it is expected to grow by another two billion people by 2050 (Barron 2009). This population growth demands that there be adequate, safe, and nutritious food at the right time and place. Food and nutrition security is a broad and complex issue that encompasses a number of dimensions. Food and nutrition security is defined as existing "when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life" (FAO 2009). Food security was defined by the Food and Agriculture Organization (FAO) (FAO 1996) as follows: "Food security, at the individual, household, national and regional levels exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (Hilderink et al. 2012). Three aspects are commonly addressed in food security studies, namely availability, access, and utilization (Hilderink et al. 2012). Availability addresses the supply side of food security and is determined by the level of domestic food production, stock levels, and net trade. Access to food is ensured when all households and individuals within those

households have sufficient resources for acquiring the appropriate foods that make up a nutritious diet. Whether this can be achieved depends on the level of household resources (capital, labor, and knowledge), food prices, and the presence of a social safety net. Under access to food is the ability of households to generate sufficient income which, together with own production, can be used for meeting their nutritional needs. Utilization of food has a socio-economic and biological aspect. If sufficient and nutritious food is available and accessible, households must decide which foods to consume and in what proportions. Appropriate food intake (balanced and nutrient-rich food) for young children and mothers is very important for nutritious status. This requires not only an adequate diet, but also a healthy physical environment, including safe drinking water and adequate sanitary facilities, as well as an understanding of proper health care, food preparation, and storage processes (Hilderink et al. 2012).

Globally, the number of chronically malnourished people is estimated to be 815 million (FAO 2017). Food insecurity is greatest in Sub-Saharan Africa (SSA) and Asia with about 239 and 578 million undernourished people, respectively.

Although the world has made significant progress in reducing the number of hungry people over the last several decades, individuals need more than calories for health and well-being; they also need a nutritious and balanced diet. Along these lines, many countries are facing the “triple burden of malnutrition”: insufficient intake of dietary energy (hunger), micronutrient deficiencies (hidden hunger), and excessive intake of dietary energy and nutrients (overweight and obesity) (Fan and Brzeska 2014).

## Food Availability

The availability of food is largely controlled by how much resource has been allocated to food production. Water is key to food production and agriculture is the largest economic sector, using about 70% of the freshwater worldwide (UN 2016). For example, about 3,000-5,000 liters of water are needed to produce a kilogram of rice and 2,000 liters of water for a kilogram of soya (UN 2016). Attempts to increase food security require a corresponding increase in water consumption. Agricultural water use is projected to increase by about 20% globally by 2050 (WWAP 2012). Most global food production is from rainfed agriculture, which accounts for 80% of the cultivated land and produces about 60% of the global crop output (FAO 2011). Africa contributes the largest proportion of rainfed agriculture, about 90% of its cultivated land (UN 2016). However, due to climate change that would potentially reduce the rainfall patterns in some parts of the world, intensification of irrigation agriculture and improvements in water-use efficiency are considered vital in addressing water demand and food security (UNEP 2011). However, the projected increase in demand for water for manufacturing (400% by 2050), energy, and domestic use will likely impact the availability of water for food production (OECD and FAO 2012). It is estimated that 52% of the world's population and 40% of grain production could be at risk due to water stress by 2050 (UN 2016).

## Food Access

Despite an overall improvement in the global availability of food, lack of nutrition has remained a serious problem. Over the period 1969-1971,

920 million people were undernourished globally. This was 35% of developing countries' population (McCalla 1999). From 1990-1992, 840 million people were undernourished throughout the world, amounting to 20% of developing countries' population (McCalla 1999).

Different rates of progress across regions have led to global and regional shifts in the distribution of undernourished populations. While a noteworthy reduction of absolute hunger in the world has occurred, roughly one out of eight people continues to be undernourished (Fan and Brzeska 2014). The overwhelming majority of these people (827 million) live in developing countries, where the prevalence of undernourishment has decreased from 23.6% to 14.3% (Fan and Brzeska 2014).

According to the FAO (FAO et al. 2013), most of the world's undernourished people are still found in Southern Asia, closely followed by SSA, and Eastern Asia (Belesky 2014). There are important trends within the distribution of undernourished peoples across Asian regions, with the regional share of undernourished people declining most in Eastern Asia and South-Eastern Asia, but increasing in Southern Asia, SSA, Western Asia, and Northern Africa (Belesky 2014).

The incidence of undernourishment in SSA has also fallen (from 32.7% to 24.8%) but remains the highest in the world (Fan and Brzeska 2014). A large part of the progress in reducing global hunger occurred in China, where the number of hungry people decreased from 272 million to 158 million between 2011-2013 (Fan and Brzeska 2014). In fact, two-thirds of the people who escaped hunger globally over the past two decades reside in China. Similarly, the prevalence of under-nutrition in China dropped from 22.9% to 11.4% over the same time period. However, China continues to be home to the second largest population of hungry people (19% of the world's hungry) after India (Fan and Brzeska 2014).

## Food Utilization

Over the period 1961-1990, close to one billion people suffered from deficiencies in one or more micronutrients (e.g., vitamin A, iron, iodine, zinc, and copper). During 1994-1996, 1.6 billion were at risk of iodine deficiency. Deficiencies in



important micronutrients such as vitamin A, iron, and zinc, known as hidden hunger, plague more than two billion people globally, again primarily in the developing world (Fan and Brzeska 2014). Significant numbers of children in developing countries suffer from micronutrient deficiencies, including anemia (52.4%), vitamin A deficiency (34%), and iodine deficiency (29.6%) (FAO et al. 2013). The inadequate intake of these essential micronutrients can potentially weaken the mental and physical development of children and adolescents and reduce the productivity of adults due to illness and reduced work capacity.

### **Food Security Threats and Challenges**

Food production systems need to feed a growing and increasingly wealthy population amidst emerging challenges that include a progressively more fragile natural resource base, climate change, and food safety (Fan and Brzeska 2014). Many systemic issues affect food production, including price surges (Brown 2012) and unpredictable crop growing conditions resulting from climate change events such as droughts, floods, and changes in rainfall. Other global socio-political, economic, and ecological issues influencing food production include rapid urbanization; competition for the use of declining arable land; and systemic soil degradation, water scarcity, and loss of biodiversity. Food production systems are also affected by decreased quality of river ecosystems; over-exploitation of fish stocks; increased diversion of food for animal feed; rising energy costs; diversion of food and animal feed for bio-fuel; global population growth; critical resource constraints; global food wastage; reduced agricultural research and development support; and decreasing world grain reserves. Additionally, there is a trend toward excessive financial speculation on agricultural derivatives, primarily through over the counter (OTC) commodity index funds (CIFs) (Cribb 2010; Dawe and Slayton 2010; Lawrence et al. 2010). These multi-faceted, transnational issues are contributing to ongoing food price volatility and global food insecurity. Such complex and interconnected issues cannot be adequately addressed solely at the local or national level, but instead require broader regional cooperation (Belesky 2014).

A growing and urbanizing global population will put enormous stress on global food and nutrition security going forward (Fan and Brzeska 2014). A significant portion of this growth is predicted to occur in urban areas in Asia and SSA, where urban populations will almost double and triple in size by 2050, respectively (Fan and Brzeska 2014).

### **Natural Resource Pressures**

Economic and population growth across the globe have come at a high environmental cost. Increasing natural resource constraints and degradation mean that the food demands of a growing and more affluent global population will have to be met with fewer resources (Fan and Brzeska 2014). Nearly a quarter of all global land has been affected by degradation, which equals a 1% loss in global land area annually – an area which could produce 20 million tons of grain per year (1% of global production) (IFPRI 2011; UN 2018).

### **Water Resources and Food Security**

In terms of water stress, about 36% of the global population lives in water scarce areas, while 22% of the world's gross domestic product (GDP) is derived from water stressed areas (Veolia Water 2011). Especially relevant for the discussion on food and nutrition security is the fact that currently, 39% of global grain stores are produced through unsustainable water use (Fan and Brzeska 2014). In fact, the continuation of current water management practices threatens to expose 52% of the global population to severe water scarcity by 2050 (Fan and Brzeska 2014). Food production systems are both a cause and casualty of increasing climate change (Fan and Brzeska 2014). Activities associated with the production of food are estimated to generate between a quarter and a third of global greenhouse gas emissions that are responsible for climate change, mainly from the clearing of land for agricultural cultivation, fertilizer use, and farm animal digestion and manure management (Beddington et al. 2012).

### **The Special Challenge of Sub-Saharan Africa**

Global models predict that SSA will have an



increasing food deficit due to low crop yields, largely attributable to low water use efficiency and minimal use of fertilizer and agrochemicals (Neumann et al. 2010; FAO 2011). Several studies (Mauser et al. 2015; Pradhan et al. 2015; Erb et al. 2016) have argued that SSA can meet its projected global food demand by narrowing the gap between actual and potential yield. Yield gap closure is only achievable by applying the correct quantities of plant nutrients, adopting best agronomic management practices (such as good pest and weed control), and soil water management. These authors have also underscored the need for investment in research and development and good policies by governments that promote increased crop production. Analysis of the capacity of ten selected SSA countries to feed themselves by 2050 has shown the need for increased crop intensity on the current land and expansion of area under irrigation, in addition to yield gap closure and accelerated crop growth rates (van Ittersum et al. 2016). The latter option calls for additional availability of water, which is projected to be between 23% and 42% above agricultural water availability in 2010 (Burek et al. 2016). In Africa, water availability for food production is further threatened by the pollution of water bodies that has been occurring over the last two decades (UN 2018). Lack of adequate soil moisture caused by periodic droughts and poor soil fertility will probably be the biggest challenges to closing yield gap. Despite allocating about 70% of its fresh water resources to agriculture, Southern African Development Community countries still face food insecurity (Malzbender and Earle 2009). Therefore, there is need to critically consider other factors that impact food security such as land tenure, availability of inputs, and medium- to long-term financial support for agriculture.

Sub-Saharan Africa has significantly less land area under irrigation with less than 4% of its total cultivated land and an estimated 20% of the potentially irrigable land being irrigated (Burney et al. 2013). These data are in sharp contrast to Asia that has about 40% of its land under irrigation. (UN 2016). Therefore, most crop production in SSA is rainfed which, for countries in the semi-arid regions, is erratic with more frequent occurrences of drought (Rockstrom et al. 2010; FAO 2011). Such climatic and weather patterns have significantly

contributed to crop and livestock failure and further worsened food security. For example, the drought of 2015-2016 agricultural season caused more than 40 million and 2.2 million people to be food insecure in southern African countries (SADC 2016) and Kenya (FAO 2017), respectively. During the dry seasons, dam water levels can decline by up to two meters (Swenson and Wahr 2009) and more than 90% of the water can be lost through evaporation (Mugabe et al. 2003).

Given that Africa alone has more than 90% of potentially irrigable land, this region offers opportunity for investment in water resources and irrigated agriculture. Although some countries in this region have policies that aim to boost crop productivity by expanding area under irrigation, water availability and accessibility will remain the limiting factors for improved crop and livestock productivity. Fereres et al. (2011) commented that future availability of water for food production using irrigation was more doubtful than the ability to produce sufficient food in the future. Indeed, with about 75% of the Southern African Development Community countries classified as water-scarce (Nhamo et al. 2018), it is unlikely that its population will be food-secure by 2050.

## **Strategies for Mitigating Food Insecurity in Sub-Saharan Africa**

Water is central to food security in SSA, and several strategies that make it more available, accessible, and improve its utilization efficiency are necessary. Allocation and distribution of water resources have always been a big challenge in SSA (Dos Santos et al. 2017). In order to promote water accessibility and availability for food production, there is need for policies and legislation that govern water resources. This is particularly important in view of the shared water resources worldwide. Sub-Saharan countries that lie in the arid and semi-arid regions have shown interests. There have been some interests in technologies and practices that save water and improve water-use efficiencies in agriculture. For example, about 4-6 million hectares and 20 million hectares of land use untreated wastewater for irrigation (Jimenez and Asano 2004; Keraita et al. 2008). Rainwater harvesting practices such as collecting water from rooftops

with corrugated iron sheets (Barron 2009), in-field water harvesting (Motsi et al. 2004; Munamati and Nyagumbo 2010), and the construction of sand dams (Nilsson 1988) have been widely promoted. In general, these strategies include investment and better management of water resources at farm, catchment, and regional scale. A summary of these strategies is shown in Table 1.

## Conclusion

Food security is not only about supply, but also access, which calls for generating employment and income. Water availability and access are central to agricultural production and food security. Satisfying food security for the ever-increasing global population requires the implementation of effective water policies and strategies. Globally, the long-term strategies to food security remain technology development, productivity improvement, and continued investment in agricultural research. Although expansion of arable

land has resulted in an increase in food production in SSA, developing more irrigation and intensifying crop productivity will likely be more sustainable strategies. These strategies will require additional exploitation of water resources and subsequent integrated water resources management. The availability and consumption of nutritious foods can be promoted through the development of high water-use, efficient, high yielding, and more nutritious crop varieties (for example, using biotechnology), public information campaigns, and pricing policies. The dwindling of arable land and water resources calls for the development of resource-efficient agricultural technologies and practices that enable the production of more food using less resources. Food security will also require sustainable intensification of complex production systems, and appropriate national and international policies. Policies and investments should promote food production systems that are adapted to the emerging climatic, natural resource, and nutrition challenges facing food security.

**Table 1.** Selected strategies for mitigating food insecurity in Sub-Saharan Africa.

Strategy	Implementation	Challenges	References
Increase Water Availability	<ul style="list-style-type: none"> <li>• Construct more water reservoirs</li> <li>• Adopt integrated water resources management</li> <li>• Use water harvesting technologies</li> <li>• Re-use and re-cycle water</li> </ul>	<ul style="list-style-type: none"> <li>• High initial cost of irrigation development</li> <li>• Some technologies are labor intensive</li> </ul>	FAO 2011 Keys and Falkenmark 2018 Motsi et al. 2004 Ngigi et al. 2005 Moges et al. 2011
Increase Water Productivity	<ul style="list-style-type: none"> <li>• Adopt soil and water conservation technologies</li> <li>• Use water harvesting technologies</li> </ul>	<ul style="list-style-type: none"> <li>• Some technologies are labor intensive</li> </ul>	Tilman et al. 2011 Keys and Falkenmark 2018 Dile et al. 2013
Expand Irrigated Agriculture	<ul style="list-style-type: none"> <li>• Open up new area</li> <li>• Rehabilitate irrigation</li> <li>• Use water saving irrigation technologies</li> </ul>	<ul style="list-style-type: none"> <li>• High initial cost of irrigation development</li> <li>• Threats of salinization of soil and reduced groundwater quality</li> </ul>	Fereres et al. 2011 Nakawuka et al. 2018 van Ittersum et al. 2016
Research and Development	<ul style="list-style-type: none"> <li>• Breeding for drought tolerant and early maturing crop varieties</li> <li>• Precise application of water to plants</li> </ul>	<ul style="list-style-type: none"> <li>• Requires longer time for positive results</li> </ul>	Hadebe et al. 2017

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# The Value of Green Water Management in Sub-Saharan Africa: A Review

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**Abstract:** Due to its multiple uses, water is a highly competed-for resource. While the competition is mainly in the use of the resource, contestation over water resources is also demonstrated through how the resource is defined and described. Terms such as water stress and water scarcity are commonly used in literature, and so are various colors that define water quality, including white, grey, yellow, and black water. Water that is useful for agriculture is distinctly known as blue or green water, with the latter increasingly gaining prominence in water planning for improved agricultural productivity. Proper management of green water has been shown to improve grain yields in Sub-Saharan Africa by as much as 2.5 – 6 times. The arid nature of Sub-Saharan Africa, coupled with the high evapotranspiration rates, calls for improved management of green water, including reducing evaporation losses, reducing seepage, and increasing the water holding capacity of soils. The value of green water management in Sub-Saharan Africa is further enhanced by its low-cost nature when compared to irrigation, which is an area that Sub-Saharan Africa has also been focusing on as part of the solutions to the increasing food needs of its growing population. Infrastructure for irrigation is costly and not affordable to the majority in Africa. In addition, irrigation can only benefit those communities near the water sources, whereas proper green water management can have benefits to all communities, including those far from a water source.

**Keywords:** *agricultural drought, meteorological drought, green water, blue water, green water grabbing, water scarcity, water stress*

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Falkenmark (1995, 2008) introduced the term green water to describe the often unaccounted-for precipitation that goes into the root zone of plants. Green water is much needed in sub-humid and semi-arid regions where evapotranspiration rates are high and rainfall is generally low. As it is found buried in the soil, green water is also described as invisible water, while the visible flowing water is classified as blue water (Sood et al. 2014). Earlier definitions of green water continue to be refined; van der Zaag et al. (2002) define green water as rainfall that infiltrates the root zone and is used by plants for biomass production through transpiration, and Mekonnen and Hoekstra (2011) define it as rainwater that is consumed. Green water is also rainfall that infiltrates the soil and is picked up by roots before returning to the

atmosphere as evapotranspiration (Falkenmark 2012). Hoekstra et al. (2011) added another layer to the definition of green water, referring to it as “water that is temporarily stored in the soil and on top of vegetation and returns to the atmosphere as evaporation instead of running off.” Green water is useful for the sustenance of grazing pastures, forestry and other terrestrial ecosystems, and for crop production (Savenije 2000; Gerten et al. 2005).

The inclusion of green and blue water into the water mix is partly meant to improve water accounting and management, especially for water-scarce and water-stressed countries. In the semi-arid and sub-humid regions of Africa, the inclusion of green water brings a completely different picture to the region’s water balance. Based on studies from Kenya, Falkenmark (2012) noted that

blue water accounts for only five percent of the country's water balance while green water, which forms the bulk 95 percent, is often not included in the country's water balance.

Unlike the temperate regions where annual evaporation rates are in the range of 100 – 500 mm, sub-tropical regions such as the savannas that make up much of Sub-Saharan Africa's sub-humid and semi-arid zones have annual evaporation rates as high as 2,000 mm, while as little as 100 mm is retained as blue water (Falkenmark 2012). The high evaporation rates in the sub-humid and semi-arid regions of the tropics imply that little of the received rainfall is available for crops and other terrestrial vegetation in the form of green water. Also, of the little rainfall that ends up as blue water, much of it flows out into surface water bodies including large rivers such as the Nile, Congo, Volta, and Zambezi Rivers, and lakes such as Victoria and Malawi. Africa has 64 large transboundary and lake basins (UNEP 2010).

In acknowledging the value of green water, countries are better placed to find ways of improving agricultural productivity, especially in sub-humid and semi-arid regions (Sood et al. 2014) like Sub-Saharan Africa's savannas. Referring to studies by the Stockholm International Water Institute, Falkenmark (2012) revealed the low agricultural productivity of green water in Sub-Saharan Africa. Based on farm field studies in semi-arid Nigeria, the Stockholm International Water Institute noted that as much as 90 percent of farm water needs came from rainfall, out of which only 12 percent was used by crops. As much as 70 percent of green water that could potentially reach the root system of crops evaporated from wet surfaces. The effect of the low uptake of water by crops through their roots was a reduction in potential grain yield from as high as seven tons per hectare to one ton per hectare. According to the study, a third of the 90 percent share of water received through rainfall was lost to runoff (Falkenmark 2012).

Falkenmark and Rockström (2006) observed that agricultural policies tend to focus on irrigated agriculture which uses only 25 percent of the global water. In their pioneering work on green water, Falkenmark and Rockström (2006) estimated that 5,000 km<sup>3</sup>/year of water out of 6,800 km<sup>3</sup>/year consumed in food production came from green

water, implying a contribution of around 73.5 percent to the overall water budget. The balance came from irrigation. Unfortunately, Africa does not derive much benefit from irrigation due to low investment in the sector, while also suffering low uptake of green water as the farm studies from Nigeria by Falkenmark (2012) demonstrated.

This paper reaffirms that the generally arid conditions in Africa, coupled with the low capacity for further intensification of food production for a growing population, as well as low investment in infrastructure for irrigated agriculture, call for improved ways of managing and accounting for water. In addition, Sub-Saharan Africa's efforts for improved productivity of green water must adjust to the changing climate, as well as improve water use efficiency. The acknowledgement and proper management of green water is presented as one of the means for better water accounting and improved agricultural productivity. However, the paper also acknowledges the possible negative impacts of the horizontal expansion in the use of green water for agriculture through grabbing water from other ecosystems. Overall, the paper calls for the need to fully acknowledge green water as a valuable part in Sub-Saharan Africa's water mix.

## Methods

This paper is largely based on the review of literature, with the intention of drawing answers to the meaning of green water and its role and value in water accounting and management in Sub-Saharan Africa. The paper also explains the role of green water in agricultural productivity in arid and semi-arid regions of Sub-Saharan Africa. The key question that the literature review seeks to address is, "What difference does green water make to agricultural productivity, especially in semi-arid and arid regions of Sub-Saharan Africa?"

## Literature Review

With a total landmass of about 30 million square kilometers, Africa is the second largest continent in the world after Asia (UNEP 2016). There are 54 countries on the continent, with all but six located within the Sub-Saharan region. The six countries that are not in Sub-Saharan Africa are wholly or

partly in the Sahara Desert, and they are Algeria, Egypt, Libya, Morocco, Sudan, and Tunisia (Ekwe-Ekwe 2012). The Sahara Desert is the world's largest hot desert covering an area of 9.4 million square kilometres (Zimmermann 2012), translating to 31 percent of Africa's landmass. Other prominent deserts in Africa are the Kalahari and Namib Deserts, both located in the southern part of the continent. The large area covered by deserts in Africa, is partly the result of the dry conditions on the continent. According to the United Nations Environment Programme (UNEP 2010), Africa is the second driest continent in the world, with nine percent of global renewable water resources. The UNEP report also notes the uneven distribution of water in Africa, with as much as 50 percent of the internal renewable water resources being concentrated around the equatorial belt of the continent.

According to the United Nations Department of Economic and Social Affairs (UNDESA 2016), 66 percent of Africa is arid or semi-arid, and out of an estimated 1 billion people in Sub-Saharan Africa, close to 40 percent live in water-scarce environments where they live on less than 1,000 m<sup>3</sup> of water per capita per year. However, the use of water withdrawals upon which water scarcity has previously been defined is contested with scholars looking for a more comprehensive definition. For example, Hoekstra et al. (2012) suggested a measure of water use that includes consumptive use of both ground and surface water flows. This expanded definition of water scarcity would partly justify the need to acknowledge green water as this may correctly represent water availability, and in so doing allow for proper and more productive use of water.

### **Green Water and Agricultural Productivity in Sub-Saharan Africa**

Green water is valuable for agricultural productivity, and therefore needs proper management, especially in arid and semi-arid regions. A United Nations Development Programme (UNDP) working paper (Chauvin et al. 2012) points to inadequate water and poor soil fertility as the main reasons for Africa's poor agricultural performance. Sub-Saharan Africa suffers chronic water stress, partly due to high

population growth rates and urbanisation, as well as due to lack of infrastructure, especially for water harvesting. For example, out of the 980 large dams in Sub-Saharan Africa, 589 are in South Africa alone while Tanzania, which is of comparable size to South Africa, has only two large dams (Tatlock 2006). Very little of the continent's groundwater is tapped even though its quality is generally viewed to be good, however, little is known of the quantity (Pavelic et al. 2012). This implies that much of Africa relies on green water for its agriculture.

Throughout Sub-Saharan Africa, agriculture is a significant contributor to national economies. Agriculture's contribution to national gross domestic product (GDP) ranges from 3 percent in Botswana and South Africa to more than 50 percent in Chad (OECD and FAO 2016), while employing from low ratios of 5 – 10 percent in Angola, South Africa, and Mauritius to as much as 80 percent of total labor in Burundi, Burkina Faso, and Madagascar (Brookings Institute 2017). For the majority of countries in Sub-Saharan Africa, agriculture is the main source of exports. As a result, despite its supposedly water-stressed situation, Africa is a major exporter of virtual water, including Ghana's exports that are estimated at 12,151 Mm<sup>3</sup>/year (Water Footprint Network 2016a) and Rwanda's virtual water exports of 233 Mm<sup>3</sup>/year (Water Footprint Network 2016b).

Despite the significant socio-economic contribution of the agricultural sector, current efforts to increase productivity may not keep pace with the demands of a growing population which are not helped by the low investment in irrigation and the changing climate.

### **Growing Population**

Africa's population is estimated at 1.27 billion, with Sub-Saharan Africa's share of the population pegged at 1.014 billion (Worldometer 2017). Sub-Saharan Africa has the world's fastest growing population which is expected to double by 2050, having increased from 507 million in 1990 to 936 million in 2013 (FAO 2015). The region is at the same time home to the largest proportion of food insecure people in the world, numbering 233 million people and representing one in every four persons said be undernourished (FAO 2014, 2016, 2017).

The growing population in Sub-Saharan Africa is part of the reason for the expansion of land under agriculture. Since 1995, the global cropland is estimated to have expanded by 68 million hectares, with Africa's share of the expansion estimated at 47 million hectares (FAO 2016). At that scale, Africa contributed almost 70 percent of the amount of new land that was brought into agriculture, with significant impacts on forests and biodiversity. The horizontal expansion of land under agriculture has meant a greater use of green water by farming at the expense of other ecosystems, a development called green water grabbing.

The growing population places increased demands for food, and this places further strain on water, including both green and blue water. Other socio-economic needs, such as energy, also exert pressure on water even though the water use by the energy sector is non-consumptive. According to Falkenmark and Rockström (2006), population growth places a significant increase in water requirements estimated at an additional 1,300 m<sup>3</sup> for every additional person per year. Part of this water is needed for food production.

Africa's growing middle class and its taste for diversified agricultural products such as vegetables, fruits, dairy, meat, and fish (NEPAD 2013) places greater demand on water and land, further straining the continent's water resources, including green water. According to Deloitte and Touche (2012), Africa's middle-class population increased from 111 million in 1980 to 313 million in 2010, representing a change in the ratio to total population of 26 percent in 1980 to 34 percent in 2010.

The implications of Africa's growing population, an expanding middle-class against a finite land resource, and the arid and sub-humid conditions, demand that the continent produces more food per unit area, and this includes the need to improve on green water productivity.

### **Investment in Irrigation**

In 2006 Africa had 13.6 million hectares of irrigated land, an amount that had almost doubled from 7.4 million hectares over a period of close to 50 years (Lebdi 2016). Despite the expansion, the figure represented about 5.4 percent of Africa's arable land, and about 32 percent of the region's

irrigated land potential of 42.5 million hectares (Lebdi 2016). The quoted figures indicate that Africa has close to 70 percent under-utilized potential for irrigated agriculture.

The biggest challenge to investment in irrigated agriculture is the high cost that is involved. Using year 2000 estimates, Lebdi (2016) noted that it costs Sub-Saharan Africa more than \$8,000 in investment for one hectare of irrigated land where water is already available. Where a new water source is to be constructed (such as a dam) the unit cost per hectare is more than \$14,000 and these high costs are prohibitive of large irrigation projects. Lebdi (2016) further observed that irrigated farming requires lots of water, with an area of 1,000 hectares having water requirements that are equal to the basic needs of two to three million people. Besides the high costs, Africa has never prioritized irrigation, but rather safe drinking water and sanitation (African Ministerial Conference on Water 2018).

The return on investment for irrigation is also considered low and not worthwhile for many initiatives in Africa where agriculture is largely for subsistence purposes. Drawing on studies from Kenya, Lebdi (2016) noted that the majority of small holder irrigation schemes in Sub-Saharan Africa are based on political rather than economic decisions. As such, some irrigation schemes are often not profitable, with only one in six assessed schemes in Kenya returning a net profit. While this conclusion could be confined to Kenya, it is worth noting that there are also expansive irrigation schemes across Africa, with the majority being for high value crops and are being run successfully by commercial enterprises. It is also worth noting that there are several small to medium scale irrigation schemes run by families and communities, with most of these being non-profitable (Barghouti and Moigne 1990).

The low investment in irrigated farming means a strong reliance on rain-fed agriculture in Sub-Saharan Africa, hence the importance of green water in food production in the region.

### **Changing Climate**

The Intergovernmental Panel on Climate Change (IPCC 2014) identifies Africa as one of the most vulnerable regions in the world to the



impacts of the changing climate. Both the low and high emission scenarios project a warming Africa, and a decrease in rainfall in much of the continent with the exception of East Africa where rainfall is projected to increase (Serdeczny et al. 2015). Both climate change scenarios also project a more arid southern and southwestern Africa due to a decline in rainfall, while in parts of Somalia and Ethiopia wetter conditions are expected (Serdeczny et al. 2015).

The projected arid conditions across much of Africa may imply less reliance on rain-fed agriculture, but the continent's strong dependence on agriculture may call for more innovative ways of managing the scarce water resources, as well as on improving water productivity, including that of green water.

### Water Use Efficiency

It is often argued that current agricultural practices, especially irrigated agriculture, are not efficient. Water use efficiency in irrigated agriculture is as low as 30 percent (Falkenmark and Rockström 2006). The situation is not different for rain-fed agriculture whereby 10 – 30 percent of seasonal rainfall is productively used as green water flow (Falkenmark and Rockström 2006), with as much as 50 percent being lost as non-productive evaporation, and 30 percent lost to runoff and ending up as blue water, while another portion is lost as deep percolation.

The level of water use efficiency is said to be lowest in the tropical rain-fed agricultural systems, with the largest of such inefficiencies being in the semi-arid and dry sub-humid zones or areas that are commonly known as savanna agro-ecosystems. According to Falkenmark and Rockström (2006), rain-fed agriculture in the savanna agro-ecosystems of Sub-Saharan Africa consumes between 2,000 – 3,000 m<sup>3</sup> of water on average for every ton of grain compared to the global average of 1,000 – 1,500 m<sup>3</sup>/ton. The low water use efficiency in the savanna agro-ecosystems is due to low yields and high evaporation.

Water use efficiency, where green water is concerned, can be improved through better soil fertility management, soil tillage that allows for greater water filtration, and water harvesting. Pretty and Hine (2001) noted the possibility of

doubling crop yields through improved methods of soil, crop, and water management, while Falkenmark and Rockström (2006) observed that integrated soil and water management has the potential to improve productivity in the savanna agro-ecosystems from the high of 3,000 m<sup>3</sup> per ton to 1,500 m<sup>3</sup> per ton.

### Discussion and Conclusions

Green water, if properly accounted for and used in agriculture, is part of the long-term solutions to Africa's food security. The low average cereal yields of 1.6 ton per hectare compared to world averages of 3.9 tons per hectare (Tadele 2017) are partly blamed on poor management practices, including that of soil moisture and ultimately green water. The low yields are exacerbated by agricultural drought, which occurs when soil moisture is too low to sustain crop production and growth (Maracchi 2000). With better management and efficient use of green water, some high crop yields can be achieved. Management techniques that ensure proper retention of water will result in not only more productive use of green water, but also increased crop yields. The results below by Kauffman et al. (undated) followed some studies conducted in Africa:

- Mulching can reduce runoff by 72 percent, and this can increase rain water use efficiency by 20 percent;
- Good tillage practices can reduce runoff by 60 percent, and can increase rain water use efficiency by 58 percent; and
- Water conservation techniques can reduce runoff by 66 percent, resulting in as much as a three-fold increase in crop production.

The low rainfall amounts received in much of Sub-Saharan Africa, along with poor irrigation practices, call for improved management of green water. Proper management of green water will not only harvest as much rainfall as possible, but also ensure water conservation, limit evaporation losses, reduce seepage losses, improve efficiency in water use, and allow for the use of high water tables for farming purposes. With better management practices, inclusive of improved productivity of green water, average grain yields in Zambia were shown to increase from 1.3 tons per hectare to



4.5 tons per hectare (Mati and Hatibu undated). Such increases in the magnitude of 250 percent as recorded in Zambia and 600 percent in Nigeria make a good case for better understanding and use of green water in as far as this can significantly improve agricultural productivity. Additionally, the proper management of green water will not only cause higher crop yields, but also free up blue water for other uses, including hydropower generation, fisheries, and recreation. This is significant given that water is a much competed-for resource on the continent by domestic, industrial, and agricultural sectors.

In calling for improved management of green water, this paper also makes a case against expansion of land for agriculture. The common practice of horizontally expanding land for crop production not only causes loss of forests through land clearance, but also taps into green water for other terrestrial plant needs. Woodhouse (2012) warned that any rights to land also provide prior rights to water, implying that agricultural expansion is not just for the investments that are made on land, but also for all forms of expansion of agricultural land into natural forests. The horizontal expansion of crop fields not only means the substitution of the forest with crops, but also the grabbing of water by the newly crop-colonised land and from the replaced forest. In recent times Africa has become the priority region for large-scale land investments. While many scholars and policy makers have rightly described the investments as land grabs or land deals (African Union et al. 2013; Conigliani et al. 2016), water has often been the missing link. Even more misleading has been the narrow look at only blue water because it is harvestable and can be conveyed to places where it can be used. Much of the expansions and investments in large-scale land deals have also benefited from green water.

Large-scale investments in agriculture in Africa have emerged as a big business for the production of food, fuel, and fiber, as well as for conservation efforts. A report by UNEP (2016) shows that the continent has 60 percent of the world's unconverted arable land, indicating not only a great potential for local and external investment in food production on a massive scale, but also showing Africa's potential to become a major player in the global export of food, biofuels, and fiber. The importance

of access to water in large-scale land investments is often underplayed and not recognized, although it is becoming clearer that water resources are a major attraction for such investments (Williams et al. 2012; Breu et al. 2016). Matavel et al. (2011) noted how sugar cane farming is linked to both land and water grabbing. While sugar production in Sub-Saharan Africa accounts for four percent of world production, there is huge potential for expansion of the crop area due to production potential, low cost of production, and nearness to the European markets (Tyler 2008). Due to the fact that new land may need to be opened up for sugar cane production, water will be grabbed from the replaced vegetation types and from the soil in general.

As green water is not included among the traditional water indicators, it is not surprising that it is often under-valued. This results in countries that are not water poor being classified as such, with implications for investment in agriculture and local food production. By stressing the importance of green water, this paper calls for not only the proper management and use of the resource, but also for the recognition of green water in water accounting.

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# Water Trading: Innovations, Modeling Prices, Data Concerns

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**Abstract:** This article examines policy innovations and data concerns related to water trading in Colorado, and develops econometric models of transactions occurring over two distinct time periods. The Punctuated Equilibrium Theory (PET) of policy adaptation is used to examine shifts in Colorado water trading policy paradigms. Creating better policy frameworks for water trading is a key concern for agricultural, urban, and environmental water interests, given hotter temperatures and more variable precipitation patterns in the western U.S. Contractual arrangements of varying types are being used to engage farmers in providing reliable water supplies for ecosystem and urban needs through changes in farm water use practices. While various pieces of information about changes in water use can be gleaned from public databases, transaction price information is notably lacking. Recent Colorado policy innovations related to water trading emphasize reducing on-farm consumptive use and making water available for other purposes without permanently drying up irrigated cropland. The use of econometric models analyzing water rights transactions provides insight into how changes in key external factors affect transaction prices. The econometric models developed here focus upon Colorado's urbanizing Front Range and examine the effect of demographics, housing prices, drought indicators, and agricultural profitability on prices at which water is traded. Volume traded, drought measures, housing prices, alfalfa prices, and water source characteristics are statistically significant in these models. The article concludes by discussing factors that contribute to water trading policy innovations and the broader relevance of Colorado's innovative trading arrangements to water management challenges in arid regions.

**Keywords:** *water transactions, trading, risk*

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Water trading policies and water-management agreements have become more complex as timing and volume of supplies are made more uncertain by climate change (Jones and Colby 2010). Transaction programs in many regions have matured from local water trusts conducting one-on-one negotiations with farmers, to strategic regional water-sharing agreements involving agricultural, municipal, industrial, energy, and environmental sectors. Economic impetus for water trading among different water users grows when water shortages threaten to impose high costs. When policies that enable water trading are lacking, the threat of shortage costs spurs innovations to accommodate creative water trading

approaches and work around existing impediments. Identifying ideal policies to enable trading has deservedly been a classic emphasis over 40 years of research on water markets. However, this has tended to overlook valuable innovations that occur despite institutional obstacles and lack of enabling conditions. This article examines such innovations in Colorado, uses econometric modeling to analyze patterns in water trading over two distinct time periods, and concludes with broader implications for water management and policy.

Colorado provides an ideal setting in which to examine changes in water transaction activity over time. It is unique among the U.S. states in its reliance on a specialized judicial system (Water



Court) to oversee its formal water right transfer process. Its vibrant economy provides impetus for water trading among active agricultural regions, mining and other large industrial water users, growing municipalities, and public agencies and Non-governmental organizations (NGOs) seeking water to support stream flows and habitat.

Colorado also stands out in high costs and delay associated with its formal change of water right process. While there are no recent quantitative studies of transaction costs (TC) for trading water in Colorado, previous studies indicate that Colorado TC far exceed those of neighboring states. Colby (1990) found, for instance, that TC were about 12% of prices paid in Colorado compared to 6% in Utah and New Mexico. MacDonnell, Howe, and Rice (1990) found similar patterns. Time delays to achieve formal approval of a water right transfer also are much higher than in neighboring states (Colby 1990; MacDonnell, Howe, and Rice 1990). These costs and delays create economic impetus to stimulate water transfers across use sectors and locations and to consider mechanisms to facilitate a more cost-effective process for trading water.

The evolution of water transactions in Colorado usefully illustrates a process of water policy change in response to economic impetus. Transaction activities in Colorado have moved well beyond the customary transaction of the 1960s - 1990s; permanent changes in the place and purpose of use of a water right. More complex arrangements are occurring to simultaneously meet demands of agricultural and municipal users as well as the environment (Aylward et al. 2016). Many transactions of the “low-hanging fruit” variety already have been realized, those cases where simple outright purchases benefit both parties and impose minimal third-party effects. Thus, more complex transactions are becoming the norm as large municipal and industrial users seek to secure a reliable water supply while complying with Colorado’s labyrinthine water laws. The Colorado innovations discussed here spring from state legislative and administrative policies, water court officials, and federal-state collaborations.

Examples include Colorado’s Alternative Agricultural Transfer Mechanisms Grant Program (ATM Program), the interstate System Conservation Pilot Program (SCPP), Substitute

Water Supply Plans (SWSPs), and other programs that pay farmers to implement deficit irrigation and on-farm management practices that provide water for urban and environmental uses.

## Related Literature

Literature comparing water markets and transactions across time periods and regions typically considers more conventional type of transactions, leases, and sales that change the place and purpose of use of a water right. These have been the dominant type of transaction for many decades, and state water agencies maintain some publically available data on these changes in water right processes. However, pressures of climate change and values for preserving agricultural economies spur a need to consider a much wider range of transactions.

A number of recent publications examine water trading programs. Aylward et al. (2016) developed a framework for considering cost-effectiveness in Environmental Water Transaction (EWT) programs. Stanford’s Woods Institute Water in the West program issued a draft report and score card on EWTs for the seven Colorado River Basin (CRB) states (Stanford 2017). A Science for Nature and People Partnership (SNAPP) project directed by The Nature Conservancy has developed a framework for assessing EWT programs, focusing on small basins needing seasonal improvements in streamflow regimes (Kendy et al. 2018).

In this article, we use the term water transactions to encompass a wide range of voluntary agreements to reduce water consumption, application, or diversion in order to make water available for a different location and/or use. Transactions encompass traditional water-right sales and leases, irrigation forbearance agreements, dry-year options, deficit irrigation contracts, agreements to shift crop mix to reduce consumptive use, split-season leases, groundwater banking, and switching to alternative water sources.

## Colorado Water Trading Innovations

The forms in which water trading occurs is a dynamic mix which varies over time as public policies governing trades adapt to accommodate

new concerns. Colorado's experience exemplifies this, in the four programs briefly summarized here. SWSPs provide an interim means by which water use moves out of crop irrigation. The ATM and Instream Flow (ISF) Acquisition Programs are other examples of innovative activities administered through the State of Colorado. Development of these mechanisms has been stimulated by costs and delays in the formal change of water right process, as well as by special considerations for EWTs. The CRB SCPP is an example of an interstate program, with NGO, municipal, state, and federal partners, that alters agricultural water use to make water available for other purposes.

### Conventional Trading: Change in Water Right

Changes in use of a water right from irrigated agricultural use to other uses occur through the Colorado Division of Water Resources (CDWR) and Water Court process (see Table 1). This category of transaction has been the dominant means to transfer water from agricultural uses in Colorado. The CDWR maintains a Water Transactions Database that can be analyzed to identify changes in water rights that move water from irrigated agriculture to other uses. The CDWR Water Transactions Database includes *many other* types of water rights changes, not relevant to this evaluation project, and multiple layers of data analysis are necessary to identify relevant transactions. Water right changes typically involve multiple ditch rights. However, they are tracked by the CDWR (and in this publication) under a unifying case number.

In 2007 the Colorado Supreme Court responded to requests voiced in various public processes for expediting the change of water right process.

Many commentators criticized the costly length of delays between filing and final approval for changes in water rights. Following a lengthy study and public comment period, the Colorado Supreme Court in 2009 adopted rule changes that included specific timelines and created a clear and more coordinated path to timely decisions. Under the revised rules, judicial officers are active case managers from the outset of every water court filing and CDWR engineers coordinate with the water judges. The rule changes have had a positive, measurable impact in reducing unnecessary delay and uncertainty (Hobbs 2014).

### Substitute Water Supply Plans (SWSPs)

SWSPs provide temporary administrative approval of plans for changing location, use, and/or timing of a water right (and for water augmentation plans) without first having to obtain a Water Court decree. Legislation in 2002-03 gave the Colorado State Engineer authority to approve SWSPs, an important innovation in Colorado transaction opportunities.

SWSPs are utilized to quickly accomplish a change in place/use/timing of a water right for a duration of less than five years. The Colorado State Engineer verifies that the proposed change will not cause injury to other water rights, typically limiting water quantity in the new use to the 'historical consumptive use' of the water right. The CDWR maintains a public database containing the most recent 20-24 months of currently active SWSPs. Statewide there are several hundred SWSPs active at a given point in time, concentrated in the eastern portions of Colorado. Some water users file for both a traditional transfer through water court, and file for a SWSP (Colorado Department of

**Table 1.** Changes in water rights from crop irrigation to other use, 2010-2017. Number of transactions and volumes by year decree entered.

	2010	2011	2012	2013	2014	2015	2016	2017	Total
Transactions	0	3	4	14	11	22	18	3	75
Volume (AF)	0	508	417	4,177	16,891	34,199	30,966	26,241	113,397

Source: Colorado Information Marketplace 2017b

Notes: "Transactions" is the number of unique case numbers that decreed/settled in the respective years. Three transactions did not have a quantity measure noted in the CDWR database. For these, CDWR documents were reviewed to produce a volume estimate.

Natural Resources n.d. (a); Colorado Information Marketplace 2017a). In this case, the SWSP allows the water to be utilized for its new use immediately, while the traditional, slower water right transfer works its way through the Water Court process.

### **ATM Grant Program Projects**

Colorado implemented the Alternative Agricultural Water Transfer Methods Grants Program to develop alternatives to “buy and dry” transfers of agricultural water. Funded projects vary from actually implementing an ATM to analyzing different ATM methods. Since its inception, the grant program has funded many studies of ATMs and pilot implementation projects.

The number of ATM projects that move water from crop irrigation to another use is relatively small, two to five projects of this type funded per year over 2013-16. Typically, ATMs are temporary or intermittent, and leave the ownership of the water right with agricultural interests.

Despite their small numbers, ATM projects are essential for showcasing promising approaches. An ATM consists of several features: a) a method to reduce agricultural water consumption (such as fallowing, deficit irrigation, crop switching); b) a mechanism to make that water available to another user (such as a lease or Interruptible Water Supply Agreement (IWSA)); and c) financial compensation to the agricultural water users for reducing their use. Over the period 2013-16, annually there were an average of three active ATM projects that reduce water consumption in irrigated agriculture to be available to other uses. The volume of water made available is not readily obtainable. ATMs have the potential to provide municipalities, habitat protection programs, and industrial operations with water, without permanently drying up farmland. While permanent changes in water rights still are the dominant type of transfer in Colorado, ATMs are now an ongoing part of Colorado transaction activity (Colorado Department of Natural Resources n.d (b); WestWater Research 2016).

ATMs include the following strategies to make irrigation water available for another use:

- Fallowing: farmer stops irrigation for all or part of the irrigation season.
- Deficit Irrigation: farmer applies less water than usual.

- Crop Switching: farmer grows less water-intensive crop mix available for another use.
- Infrastructure Agreements: an outside party finances an infrastructure project beneficial for the farmer’s operation, in exchange for use of a portion of the farmer’s water rights.

Some common mechanisms of transferring the water made available include: IWSAs under which water right is used for agriculture in normal conditions, but transferred if certain shortage circumstances arise; and regular leases in which a farmer leases a portion of now unused water to a new use in exchange for payment. In some cases, a SWSP has been utilized as part of an ATM, such as to allow a long-term transfer to proceed while waiting for Water Court approval, and for ATM leasing agreements lasting fewer than five years.

### **Colorado Water Conservation Board Instream Flow (CWCB ISF) Acquisitions**

The CWCB ISF program is responsible for appropriation, acquisition, and protection of instream flow water rights and acquires water through direct purchase, donation, lease, exchange, and other transaction types. CWCB acquisitions provide more senior ISF water rights than those coming from the appropriations process. The CWCB conducts hydrologic modelling for each water right acquired to determine historic consumptive use of the right and identify potential issues arising from a proposed change to ISF use. Over 2013-16, the annual average number of new stream segments protected varied from one to seven. Despite the small annual numbers, CWCB ISF acquisitions are an important feature of Colorado water transaction activity. Counting stream segments is not ideal for representing achievements of the ISF acquisition program. Yet these indicators are more readily available than more sophisticated measures that would account for ecological improvements and seasonal flow considerations.

### **System Conservation Pilot Program (SCPP)**

The SCPP was developed in response to long-term reservoir declines. The SCPP was initiated in the summer of 2014 through an agreement between the Bureau of Reclamation (BOR) and four major southwest U.S. urban water suppliers (Central

Arizona Water Conservation District, Metropolitan Water District of Southern California, Southern Nevada Water Authority, and Denver Water). SSCP projects active in 2015-17 encompass a variety of conservation techniques, including fallowing (both full and partial season), deficit irrigation, and crop switching. The SSCP is an important innovation to reduce water consumption in irrigated agriculture to make water available for other purposes.

Initiated in the summer of 2014 through an agreement between the BOR and four major urban water suppliers, the parties committed to funding pilot projects. Pilot projects have been implemented in the upper basin (2014-17). Over 2014-17, several dozen projects were active in Colorado, New Mexico, Utah, and Wyoming with annual water savings of 2,500 – 11,500 acre-feet (AF).

Ranching and farming water users demonstrated increased interest through a steady increase in applications to participate. Some participating Colorado farms and ranches used program payments to fund a transition to organic farming, helping cover the loss of income from the required three-year hiatus from pesticide spraying (Tory 2017). The SSCP is regarded as a successful water trading venture and a good example of collaboration across diverse interests. It was recognized by the White House in 2016 as a positive example of “cooperation, collaboration, and innovation in long-term water management.” Funding has not yet been made available for future rounds of projects beyond 2017.

### **Summary: Colorado Innovations**

The programs described above are not an exhaustive list of water trading innovations in Colorado. Rather they are illustrative and convey a sense of the variety of approaches and the level of interest in making water trading less reliant on permanent dry-up of cropland and more responsive to water user needs. In the next section, econometric models explore Colorado transaction price patterns in two different time periods.

### **Econometric Models**

Econometric models have the potential to provide insight into how changes in key external

factors affect transaction prices, including changing policies governing water trading. Two data sources are utilized to model pricing patterns in transactions that have occurred in Colorado’s Front Range over two different time periods. The Front Range (located on the east side of the Rockies surrounding the Denver metro area and extending to cities located north and south of Denver) is Colorado’s most active area for water trading. These data sources are referred to here as ‘The Water Strategist’ (TWS) and AcreValue. Colorado does not require water transaction price to be reported, and the data for TWS and AcreValue are collected by private firms surveying transaction participants. These data sets may not include all transactions that have occurred, and there is no comprehensive registry of water transactions against which they can be compared. TWS has been widely used for past statistical analyses of water trading, and it is valuable to compare it to the new AcreValue data source. Due to the methods of acquisition, quality of these data cannot be observed directly. However, it is considered the best publically available water transaction data and the companies that procure it rely upon it as an integral part of their business.

There is a relatively small body of studies that have applied econometric analysis to data on water transactions. Prior U.S. studies generally have relied upon TWS data, made available by paid subscription for the years 1990 - 2009 and then discontinued (Stratecon Inc. n.d). Loomis et al. (2003) examined water transactions for environmental purposes in the western United States over the period 1995-99, finding that prices paid for environmental uses exceeded agricultural values for water in specific locations. Brookshire et al. (2004) analyzed statistical patterns in water trading in Arizona, New Mexico, and Colorado. They found that population change, per capita income, and drought have a statistically significant effect on the price at which water is traded, with higher trading prices in drier years. Brown (2006) examined water sales and leases and included transactions in 14 western states, finding higher lease prices in drier time periods in counties with larger populations, and for municipal and environmental uses. For water sales, Brown (2006) found that higher sales prices are associated with municipal use, surface water, smaller county populations, and smaller



volumes of water traded. Pullen and Colby (2008) identified water right seniority and components of agricultural profitability (such as hay prices) as key influences on transaction prices. Jones and Colby (2010) found lease prices to be statistically linked to per capita income, drier weather, and population growth. Basta and Colby (2012) found statistical relationships between price and urban housing prices, urban population, and drought. Drought in the area of a city's water supply origin had a more consistent influence on transaction price than drought in the urban area itself (Basta and Colby 2012). Hansen, Howitt, and Williams (2014) found that agricultural production levels and land values influence annual volumes of water traded, as do measures of drought and water supply variability.

TWS data used in this analysis were published in *The Water Strategist* based on data compiled by Stratecon Inc. on price/AF, quantity transacted, and other transaction and buyer/seller characteristics. Each observation was accompanied by a description of the transaction, usually detailing where it took place and additional terms of the sale/lease. For this analysis, 321 Colorado Front Range transactions from 2002-09 were analyzed.

The AcreValue data originate from a web-based application of the same name, managed by Granular Inc., an agricultural technology company. Granular Inc. recently partnered with WestWater Research to provide water transaction data as a part of their AcreValue platform. The web application consists of a Geographic Information Systems (GIS)-based map with transactions "placed" on the map. Price, volume, sale/lease, and locational information is available. Data from this application yield 288 Front Range observations from 2012-16.

The variable Colorado Big Thompson (CBT) Service designates a transfer of rights to Colorado Big-Thompson (C-BT) units. These units are fundamentally different from typical Colorado water rights. C-BT units possess attributes that make transfer of these units much quicker and cost-effective, within the CBT service area, compared to transfer of water rights. Consequently, C-BT units typically sell/lease at a higher price than water rights transferred around the CBT service area. Data on whether a transaction involved C-BT units were not available for the AcreValue data, so a proxy was used based on location as described in

Table 2. C-BT unit transfers (actual or by proxy) make up a majority of all transfers in the data.

The price variable shows a minor negative skew, while quantity shows a moderate positive skew. These trends are caused by a handful of transactions where a relatively large quantity of water is transferred for a relatively low price per acre-foot. For the AcreValue data, permanent purchases and surface water transactions make up the majority of observations in the AcreValue data, at 78% and 96% of the observations respectively.

Using these two data sets, three separate models were developed. In all models, the dependent variable is *Ln\_Price\_16*. The first "TWS" and second "AcreValue" models incorporated all the variables that are common among both datasets, allowing for direct comparison between the two models. In the AcreValue dataset, additional information on whether the transaction was a sale or lease, and whether the water right was for surface water or groundwater was available. To make use of this additional information, a third model, "AcreValue Modified" was estimated with two dummy variables for sale/lease and surface/ground characteristics. Note that TWS data do contain information on the sale/lease characteristic, but all observations in our chosen sample were sales. Table 3 provides summary statistics for variables used in econometric models. Table 4 shows the results of the econometric analysis. With respect to model specification, the "TWS" and "AcreValue Modified" models tested positive for heteroscedasticity; therefore, White's Standard Errors were utilized to run a Feasible Generalized Least Squares (FGLS) model. Results from the heteroscedasticity tests are presented in Appendix A.

### Discussion of Econometric Results

All three models confirm ex ante hypotheses for water trading variables. Considering the two models containing identical variables, "TWS" ( $R^2=0.505$ ) had higher explanatory power of price compared to "AcreValue" ( $R^2=0.389$ ). When lease and groundwater dummies were included in "AcreValue Modified," explanatory power doubled compared to "AcreValue."

There are two perspectives regarding the expected effect of quantity transacted on price.



**Table 2.** Econometric model variables and definitions.

Variable	Definition
<i>Ln_Price_16</i>	Natural log of the price per acre-foot of the transaction. Adjusted to 2016 dollars.
<i>Ln_Quantity</i>	Natural log of the quantity transacted.
<i>CBT_Service</i>	TWS: Dummy variable with a value of 1 if the water rights transacted were C-BT units, and 0 otherwise. AcreValue: Dummy variable with a value of 1 if the water rights transacted were located within the service boundary of Northern Water.
<i>SPI_SNOW_V5</i>	Variance of the 12-month Standard Precipitation Index (SPI), over the last 5 years, in Colorado climate division 2.
<i>HPI (Base=1995)</i>	HPI for the Denver metropolitan statistical area (MSA), with a base year of 1995.
<i>Alfalfa_16</i>	Price of alfalfa hay, measured in \$/ton. Adjusted to 2016 dollars.
<i>Lease</i>	Dummy variable with a value of 1 if the transaction was a lease, and 0 otherwise.
<i>Groundwater</i>	Dummy variable with a value of 1 if a groundwater right was transacted, and 0 if surface water was transacted.

**Table 3.** Summary statistics of econometric models.

Variable	TWS Model			AcreValue Model		
	Mean	Median	Standard Deviation	Mean	Median	Standard Deviation
<i>Price_16</i>	16,085	17,920	4,195	21,110	25,760	15,073
<i>Quantity</i>	46.33	9.10	136.99	101.78	13.40	381.58
<i>CBT_Service</i>	0.93	1.00	0.26	0.78	1.00	0.42
<i>SPI_SNOW_V5</i>	0.46	0.45	0.20	0.72	0.81	0.24
<i>HPI (Base=1995)</i>	189.76	190.68	6.19	235.08	225.09	31.99
<i>Alfalfa_16</i>	138.11	151.94	24.80	201.27	208.66	36.27
<i>Lease</i>				0.22	0.00	0.41
<i>Groundwater</i>				0.04	0.00	0.19

The first is that a higher volume transacted will result in a lower price/unit of water, consistent with economies of scale. The second is that larger transactions are associated with large TC due to more opposition to larger transactions, with the price/unit expected to be higher for larger transactions. In both “TWS” and “AcreValue” models, the sign of *ln\_quantity* is negative, which supports the economies of scale view. The relationship between price and *ln\_quantity* is marginally insignificant for the “TWS” model. For the “AcreValue” models, a coefficient range of -0.14 to -0.35 means that a 1 acre-foot increase

in the transaction quantity produces a \$3.15 to \$4.14 decrease in price per acre-foot. Looking at the variable *CBT\_Service*, the coefficient is positive, and it is significant for the “TWS” and “AcreValue” models. This particular type of water right is well established as more highly valued than other rights in the region due to clear, low cost trading procedures and the desirable location in which these rights are tradable.

An additional four variables are statistically significant in the “TWS” model, but not in the “AcreValue” model. First, our measure of climate variability, *SPI\_SNOW\_V5* is positive and

**Table 4.** Econometric model results.

Variable	TWS	AcreValue	AcreValue Modified
<i>Intercept</i>	9.17***	8.52	7.89
<i>ln(quantity)</i>	-0.01	-0.35***	-0.14***
<i>CBT_Service</i>	1.15***	1.80***	0.15
<i>SPI_SNOW_V5</i>	0.24*	0.29	0.26
<i>HPI (Base=1995)</i>	-0.001	0.0003	0.0007
<i>Alfalfa_16</i>	-0.003***	-0.0005	0.003
<i>Lease</i>			-3.74***
<i>Groundwater</i>			-0.86
<b>R-Square</b>	0.505	0.389	0.840
<b>N</b>	321	288	288

\*p-value = 0.010; \*\*\*p-value = 0.001

significant in the “TWS” model, indicating that when there is more uncertainty in the amount of precipitation in the region that supplies surface water to users, buyers tend to pay a premium for water rights. Second, when the price of alfalfa hay increases, prices for water rights decrease, but this relationship is only significant for “TWS,” where a \$1/ton increase in the price of alfalfa causes roughly a \$1/acre foot reduction in price. Interestingly, the effect of the Housing Price Index (HPI) is not significant in any of the models.

In the “AcreValue Modified” model, when the *lease* and *groundwater* dummies are added, the explanatory power of the model increases significantly, from 0.4 to almost 0.85, indicating that these variables together play a large role in explaining price variation. A coefficient of -3.74 for the lease dummy indicates that lease prices are around 40 times lower than sale prices. The sign for groundwater is negative, but is marginally insignificant.

### Importance of Improving Water Trading Data Availability

The models utilized available, but somewhat limited, data on water trading collected by two private water information businesses in two time

periods. In general, data on price and volumes traded are not reported as part of the transaction approval process, and this information is not publically available in the various locations in the U.S. where water trading occurs.

In Colorado, despite the innovations occurring, the most common type of transaction is still a change in water right from one use to another. However, verifying that a change in water use has occurred from public data takes considerable care to sort through. Purchase or lease of a water right may occur before or after formal filing for a change in place and/or purpose of use. Consequently, what we generally think of as a water right transaction (lease or purchase) can occur months to years before or after an entry in the state records system. Once filing occurs, public records emerge through publication of a Water Resume and creation of a CDWR case number. Contractual agreements to purchase or lease a water right are not recorded in a public database. The CDWR transaction database only indicates that a lease or purchase *may* have occurred when the holder of the water right files for a change in place and/or purpose of use, and the vast majority of entries in the CDWR database are *not* transactions in the general usage of that term. Agreements that involve acquisition of agricultural

water often involve nondisclosure agreements. Parties do not talk about them publically and there are no reliable data to track them in real time. In the CDWR transactions database, the word “transaction” is used to refer to a wide variety of administrative changes in water rights including corrections to the records. The CDWR database “Water Rights Transactions/Water Rights Transactions in Colorado” contains “the court decreed actions that affect amount and use(s) that can be used by each water right.” (Colorado Information Marketplace 2017b).

Improving transaction data is essential, both to stimulate development of water trading systems and to improve evaluation of trading and its effects. Australia recognized the importance of transparent water trading information, and now requires that price, volume, and other basic transaction information be reported. Database management and weekly updates are provided by the Australian Bureau of Agricultural and Resource Economics and Sciences. Transaction data are posted online and updated regularly (Australian Bureau of Agricultural and Resource Economics and Sciences 2017).

In the U.S., poor access to transaction price information means that urban and environmental water managers only learn what others have been paying informally. Price information is imprecise and sporadic. Agricultural interests also rely on hearsay and out-of-date information. Lack of easily accessible and reliable price information discourages participation in transactions. For those cities and environmental programs desiring to acquire water, it is difficult to develop a program budget for acquisitions and to get organizational buy-in when price is not known and hard to predict.

Ideally, the following information would be publicly available for each transaction:

- Price paid per unit of water and volumetric measures of water traded.
- Location and type of use before and after transaction.
- Change in seasonal pattern of use due to transaction.

Access to such information would greatly reduce informational barriers for those wishing to participate in transactions as buyers, sellers, lessors, and lessees. And, these data would allow

examination of water transaction pricing patterns over time, price dispersion patterns (an indicator of market maturity), and price paid for water compared to farm net returns per unit of water (one indicator of how agricultural sellers and lessors fare in transactions). Information on changing seasonal patterns of use assists in identifying effects on stream flows that provide environmental and recreational benefits.

Transparent transaction information allows comparison of price paid for water to farm net returns, which is useful in understanding how farmers selling or leasing water are faring in transactions, vis a vis urban and environmental buyers and lessees. This also provides insight into the bargaining power between water using sectors and into the market’s ability to reflect changes in the regional agricultural economy. Analyzing transaction pricing patterns over time allows consideration of how regional markets are performing. Econometric models are able to sort out the influence of many simultaneous factors on price and transaction activity and assess whether the market is maturing as evidenced by: prices responding rationally to shifting supply and demand factors and effectively conveying information about changing water values across agricultural, urban, and environmental uses.

## Factors Influencing Water Policy Change

The Punctuated Equilibrium Theory (PET) is a body of work proving useful for considering how and when significant shifts in policy paradigms occur (Brock 2006). The PET has been applied to complex shifts in water policy paradigms. Experience with water transaction policies in Colorado suggests the following PET themes apply to facilitating emergence of new policy paradigms.

### Economic Impetus for Policy Innovation

How high are the costs and how “broken” is the current system? For whom is it broken? Pressure for innovation comes from high costs of the status quo imposed on important stakeholders who influence whether a new policy can be successfully implemented. High costs provide the impetus needed to move a policy innovation from

its gestational core of supporters into an adopted policy (Baumgartner 2006; Jones and Baumgartner 2012).

This cycle of pressure-building impetus followed by a big shift shows up repeatedly in Colorado water transaction policy. While breakthroughs in Colorado policy often come through new legislation, the judicial branch has been key as well. In 2009, the Colorado Supreme Court adopted amendments to procedural rules for State Water Court Divisions in response to extensive criticism of costly delays in achieving final decree. Judicial officers were authorized to become active case managers from the outset of every water court filing and division engineers were required to conduct consultations with water referees and water judges. The rule changes had a positive, measurable impact in reducing unnecessary delay and uncertainty (Hobbs 2014).

### **Pilot Programs Create Economic and Cultural Shifts that Assist Policy Change**

Pilot runs of a new policy approach are set up with a specific end date that can deter naysayers from mounting significant opposition. Those who are opposed assume the new policy will fail and are reassured by its expiration date. New pilot programs to facilitate water transactions for environmental needs make payments to irrigators that create a shift in the regional agricultural economy and culture. Farmers come to appreciate the role of these revenues in their income portfolio, as well as the contributions of healthy streamflows in rural economies. This broadens support for permanent policy changes to improve environmental access to water.

### **Key Roles for Entrepreneurial NGOs and Researchers.**

The PET suggests that NGOs are central in water transaction breakthroughs (Ingram and Fraser 2006; Laird-Benner and Ingram 2011), and Colorado experience bears this out. NGOs have been instrumental in advocating for new pathways to acquire and dedicate water for environmental purposes, as well as for improving opportunities to conserve and transfer water. The PET notes that researchers develop innovative policy concepts that await opportunities to enter public dialogue,

with data and scientific studies ready to inform policy debate so that timely ideas are ready and substantiated. The Colorado water trading policy innovations described here involved substantial participation and idea-seeding from researchers at the state's universities, and continue to rely on research to improve implementation and measure program effectiveness.

## **Summary and Conclusions**

This study of innovations related to water trading in Colorado joins a small but growing number of studies that find the PET a valuable approach in understanding water policy. The PET perspective suggests policy emphases on pilot programs of the type described early in this article, on assessing support for new initiatives by weighing effects of current water policies on stakeholder groups, and on inviting active NGO and university research participation in water policy dialogue, design, and implementation.

Based on analysis of limited available data on transactions, it appears that transaction prices along Colorado's Front Range respond rationally to factors expected to influence water supply and demand. A recent water transaction data source (AcreValue) compares reasonably well, in econometric modeling, with a longstanding (but discontinued) data source (TWS). Most importantly, innovative water trading arrangements are being actively explored and applied to address water management challenges in Colorado. Initiatives underway there can provide ideas for other regions juggling agricultural, urban, and environmental water needs in the face of increasingly variable supplies.

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## Acronyms and Abbreviations

AF – Acre Feet

ATM – Alternative Transfer Mechanism

BOR – U.S. Bureau of Reclamation or Reclamation

CBT/C-BT – Colorado Big Thompson Project

CDWR – Colorado Division of Water Resources

CRB – Colorado River Basin

CWCB – Colorado Water Conservation Board

EWT – Environmental Water Transaction

FGLS – Feasible Generalized Least Squares

GIS – Geographic Information Systems

HPI – Housing Price Index

ISF – Instream Flow

IWSA – Interruptible Water Supply Agreement

MSA – Metropolitan Statistical Area

NGO – Non-Governmental Organization

NW – Northern Water

PET – Punctuated Equilibrium Theory

SCPP – System Conservation Pilot Program

SNAPP – Science for Nature and People Partnership

SPI – Standard Precipitation Index

SWSP – Substitute Water Supply Plans

TC – Transaction Costs

TWS – The Water Strategist

## Appendix A: Econometric Models Tests for Heteroscedasticity

**Table A1.** TWS Model

Equation	Test	Statistic	DF	Pr > ChiSq	Variables
ln_price	White's Test	87.96	19	< 0.0001	Cross of all vars
	Breusch-Pagan	36.88	1	< 0.0001	1, CBT_service

**Table A2.** AcreValue Model

Equation	Test	Statistic	DF	Pr > ChiSq	Variables
ln_price	White's Test	12.94	16	0.6773	Cross of all vars
	Breusch-Pagan	1.78	1	0.1824	1, CBT_service

**Table A3.** AcreValue Modified Model

Equation	Test	Statistic	DF	Pr > ChiSq	Variables
ln_price	White's Test	117.3	29	< 0.0001	Cross of all vars
	Breusch-Pagan	15.44	1	< 0.0001	1, CBT_service

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